Biologically Inspired Transparent Material as an Energy System

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Acknowledgements

I wish to thank my Supervisor, Professor Hisham Elkadi and Co-Supervisor, Professor William Swan, for their guidance and support. Their help is much appreciated and has been invaluable in the preparation of this thesis.

I am also very grateful for the assistance of Dr. Robert Barber of The Science & Technology Facilities Council, STFC Daresbury Laboratory UK.

A big thank you to all my colleagues at the University of Salford, for their encouragement and support during my study.

A special thankyou to my external examiners Professor Uta Pottgiesser and Professor Ulrich Knaak for their guidance and advice in shaping the final stages and content of the thesis as, it presented.

Finally, I would like to thank Sharon, Sue, Theo and Henry.

Declaration

I certify that this thesis is my own original work. It does not contain any material previously published or written by another without due reference in the text.

I have conducted all the research and no portion of the research referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institute of learning.

The various parts of associated research work have been published in international journals, conference proceedings, poster presentations and discussions amongst the wider scientific community. I have taken the lead in the dissemination and integration of knowledge to attain the impact of this research.

Abstract

Glazed envelopes on buildings play a major role in operational energy consumption as they define the boundary conditions between the climate outside and the thermal comfort inside a building. Glass façades are viewed as an uncontrolled load that sets the operational performance requirements for air-cooling mechanical systems. These façades are determined by code compliant performance levels set by a single prescriptive static, the U value. This is energetically weak, a dynamic IR absorber strategy is needed, since performance requires change by the hour, season, and weather conditions to sync with a warming earth atmosphere. A transparent dynamic IR absorber , will be modulated by temperature-dependance of the absorber by active tailored flows in a microfluidic based platform, than conventional IR static absorbers. Nature's characterization of materials is a thermally dynamic response in real time to a microenvironment. This functionality of heat seeking materials would advance a transparent material by energy capture and storage. The hypothesis demonstrates nature's use of fluidics to direct the structural assembly of a polymer into a thermally functional device, to actively regulate solar radiation as an IR absorber, to lower the polymer device phase transition temperature. This research determines this functionality by hierarchical multi micro-channel network scaling, as a leaf resistor.

Resistor conduit analysis defines flow target resistance through simulation to generate a multi micro-channel network, for enhanced solar radiation absorption. This is demonstrated by precise hydrodynamic control in a network using switching of water

flow as a thermal switching medium to regulate heat transport flow. Nature evaluates heat flow transport in real time that is not emulated in current glass façade static performance. The knowledge gap is therefore to advance a transparent material from a static function, to a dynamic IR absorber for solar modulation, and this is demonstrated in this research.

Chapter 1 Introduction

1.0 Introduction

This chapter presents the background to the study, the aim and objectives of the research, the research questions to be addressed, the limitations of the study and the original contribution to knowledge. It closes with an overview of each individual chapter in the thesis.

1.1 Background to the Study

Reductions of greenhouse gas emissions are a pan global aim through minimized operational building energy use and maximization of generated energy. Building envelopes play a major role in operational energy consumption as they define the boundary conditions between climate and thermal comfort within buildings. Opaque and glass façades are determined by code compliant performance set by a single unit parameter, the U value. Research and optimization of performance in opaque façades in achieving a high U value is well advanced analytically.

This is in contrast to glazed façade performance that is viewed as an uncontrolled load that sets the operational performance requirements for air cooling and heating mechanical plant that demands energy. These envelopes remain energetically weak to deliver a higher U value and minimize effective power outputs. The research will determine what is the current expected performance and what it could be, and this presents the knowledge gap that defines the step changes required to advance future transparent envelopes. To meet Zero Energy Building Performance goals, an envelope must change role from a static element to a dynamic element, since performance requires changes by the hour, season and weather conditions.

These characteristics of adaptive climatic materials already naturally exist: they are applied by nature. Nature has a fundamental understanding of material composition and has developed novel systems to interact within a dynamic environment. These materials have the ability to examine and measure thermal conductance at the interface between materials' layers. This heat seeking targeting system has the ability to monitor temperature with time at a nanoscale level. The investigation into nature's thermal properties of heat transport by observation and analysis has been undertaken, to apply these hierarchical strategies for optimization of a functional device. This research will determine a bio-inspired engineering approach to advance a transparent thermally functional device through tailored planar extensional water flow for IR absorption through temperature increase of water in steady state.

This chapter sets out the aim and objectives of the research to achieve an original contribution to knowledge and the constraints and limitations of the research. This is demonstrated in the structure of the thesis to set out the parameters in order to advance a thermally functional material by nature's characterization.

1.2 Aim and Objectives of the Research

The aim of this research is to apply natural vasculature networks for solar energy capture efficiency in an transparent material. This will be achieved through the following objectives:

1. To identify the principles and processes of natural systems' response to solar radiation.

2. To investigate the current constraints of contemporary transparent building skin technology, in applying natural principles and procedures.

3. To develop a transparent prototype that exhibits the possibilities to adopt natural principles and processes to control solar radiation.

4. To test the transparent prototype.

1.3 Research Questions

The following research questions were identified in order to achieve the objectives:

1. Can biomimicry of vascular networks be implemented into a transparent material for usage in façade technology?
2. How can biomimicry approach, advance a thermal functional transparent material?

1.4 Research Methodology

The research methodology follows a scientific method for conducting, developing and evaluating the research. The research method has been developed to advance a transparent thermally functional material, through a scientific method, defined by energy capture and storage parameters. These parameters directed the research scope to define current façade technology, to ultimately set the desired morphology of an IR absorbing functional material with enhanced ability for energy capture in the design and fabrication of a prototype device. This new approach in the controlling progress of an active IR absorber is tested in real time under laboratory experimental conditions.

The design assembly of the prototype is to quantify the heat harvesting properties as defined by material parameters, simulation, device solar radiation load to flow rate and experimental testing. This will be fully explained in Chapter 5.

Material parameters are determined by vasculature geometry, fluid and material. Nature uses these parameters in vasculature formations to regulate material composition for heat transport regulation. Nature uses microfluidics platform networks for the development mechanisms and mechanical support systems for all organisms. A network of constant flow at low pressure represents a highly regulated energy transport system. Transparency combined with thermal functionality to advance an energy capture and storage material is the directive. The material selection was a polymer used in aerospace applications to replace glass in high and low temperature applications, high pressure and resistance to UV. This material has unique material properties, hence its selection.

The challenges in the field of materials to direct the assembly of a dynamic IR absorber is addressed by a microfluidic based platform that is derived by cross-slot network geometry. An optimized network is determined of natural fractal patterns through analysis of vasculature, for advancement of an transparent thermal functional material.

Vasculature in nature are networks of circulation fluidics in multi microchannels geometries. These networks can be analzed through simulation for optium succession sequencing of channel formations as an analytical approach defined, as a resistor. The evaluation as a resistor circuit enhances a solution optimal flow design for the transportation of fluidics by a theoretical approach. This will determine resistance, pressure drop and flow rate optimization that is characterized in leaves. This functionality is significant to obtain a flow parabolic profile, for a fully developed flow rate to advance the structural assembly of a polymer into a functional material.

Thermal capture is achieved by fluidic heat transport across the polymer interface to enhance absorption and removal from the device. The microvasculture network of continously circulating fluid within it, through it and out of it, is a heat transfer cycle regulated through flow rate. This management of flow rate will determine interface heat transfer across the polymer / fluid. The amount of heat transfer gain is determined through temperature difference between in-coming fluidic supply and extract (delta t). Volumetric flow rates in the device will manipulate the postion of fluid-polymer interface as a switchable IR absorber. The laboratory testing of the prototype is not focused on thermal conductivity but on absorption of solar, non-thermal, IR. The transition temperature of the polymer will be characterized by the volumetric based steady flow rate. Solar modulation is achieved by a material acting as an IR radiation stop band with a lower phase transition temperature. Precise flow rates, as exhibited in nature, will progress the assembly of advanced materials for the desired functionality.

This research investigates nature's characterization of material assembly. Nature uses fluidic networks for photosynthesis acting within a structurally ordered system. These networks have multifunctional, mechanical measures for fluidic optimization by laminar flow. The network vein patterns are determined by responsive functions to capture solar radiation. A fluidic process, photosynthesis, is within a hierarchical fluidic distribution network, figure 1.0.

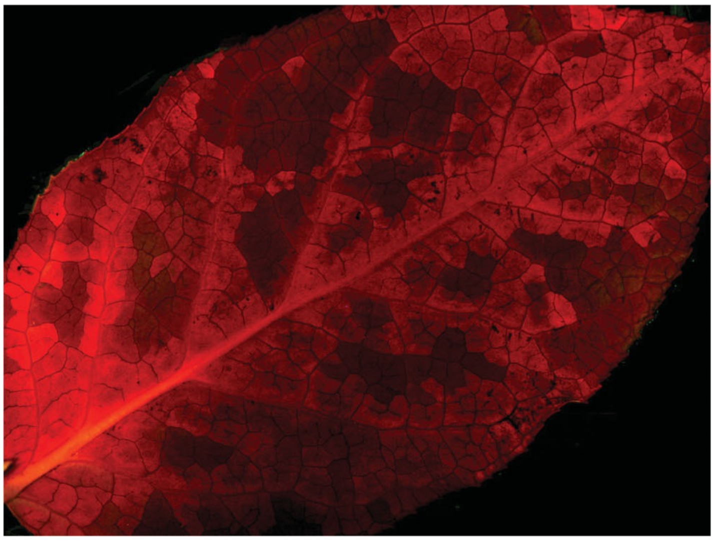
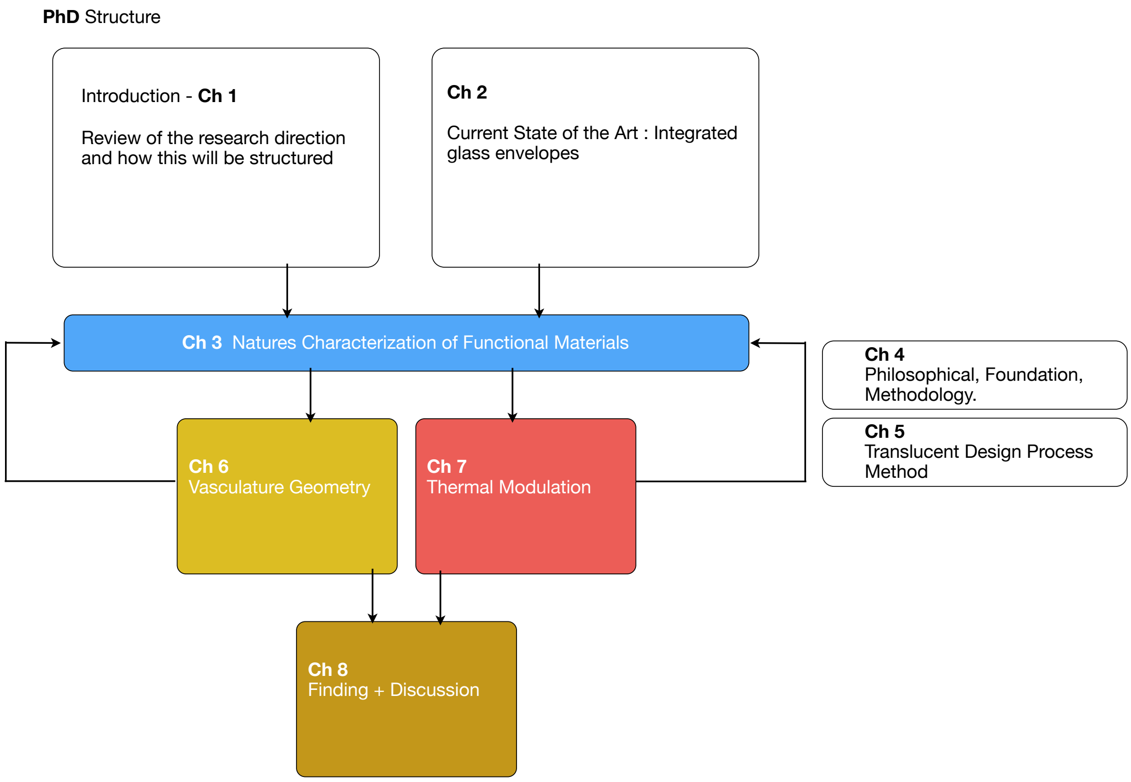


Figure 1.0 Leaf vasculature (Katifori ,Szollosi & Magnasco, 2010)

Leaf vein formations achieve this by distinctive spatial relationships of vein size order through a branching pattern diminishing order. These venations pattern are a closed loop network within leaf edge regions. Regulation of active heat transport flow is determined by planar extensional flow within multi microchannel slot networks. A controlled processing of a fluidic network in flow within a material aligns to natural systems in the physical world. Fabrication by prototyping with multi microchannel slot geometry will enable validation of outcomes through experimental testing.

Observing experimental facts by the scientific method will determine key learning for the evaluation of proof of principle results. This testing method will draw on observation by evidence to progress scientific knowledge of a new approach to advance a transparent energy capture and storage material. To quantify the aim, to be explored and developed, a transparent prototype is produced in order to embed the principles and processes of natural systems derived by analysis of leaf morphogenesis. New knowledge will emerge in the translation of the natural physical world, as opposed to human, or societal, or political interests of individuals and communities and regardless of social class. The scientific method aim is to establish laws and theories that relate to the natural world in establishing that the theory aligns with nature's patterns by replication in an artificial environment that mimics the natural world.

1.5 Thesis Structure Diagram



1.6 Research Problem

Opaque material conductance research presents a well-advanced analytical approach through comprehensive research to-date. These materials have the ability to modulate solar radiation and act as an energy collector and are well established and defined. Opaque materials already achieve high conductance and can outperform transparent façades, as these transparent materials still remain an energetic weak link in envelope performance. Current code compliant glazed façades are based on thermal conductance to resolve uncontrolled solar radiation loading that drives the active performance requirements of air-cooling mechanical systems with high energy consumption. This strategy also enhances conflict, between services and envelope fabric provision of heating systems, fighting cooling systems for human comfort conditions.

The knowledge gap is defined as that between the present code compliant glazed façades determined by a static value of performance, u-value, based on measures in the reduction of thermal conductance, and what it could be. The understandings of nature's characterization of heat seeking targeting materials are desired morphology to advance glazed façades. To progress a thermally functional switchable material would reduce the demand on active air-conditioning; increased daylight with the associated reduction in artificial lighting demand. Transparent, combined with thermal functionality, will give better mechanics, as a viable system on the market has yet to be determined. This research bridges this knowledge gap.

1.7 Original Contribution to Knowledge

The literature review establishes glass façade performance that is viewed as an uncontrolled energy load that sets the operational performance requirements in air cooling and heating of mechanical plant. Aluminium framed, glazed curtain walling is design to a single prescriptive value defined by a static response for solar modulation properties. What is needed is a dynamic reaction in optimizing the parameters of solar absorbing materials by activity adjusting IR absorption compared to conventional static systems. A dynamic response is required to sync with the changing climatic patterns of a warming earth atmosphere associated with fossil fuel burning. The understanding of the knowledge gap sets the strategy to bridge this gap though observation, analysis and quantification of thermal flow within a material, by material parameters, simulation, device solar load to flow rate relationship and experimental testing design. This is achieved through a microfluidic based platform to direct the structural assembly of a polymer into a functional device through energy capture and storage. A thermal flow strategy follows the path of natures approach to interface heat flow reactions of adaptive and self optimisation energy systems defined through composite structure. By multi functional chemical and mechanical functions determined using material hierarchy for temperature reactions, tailored to it's environment.

The research reviews the current state of the art of glazed facades and nature's approach to functional materials. The contribution to knowledge is contained within the vasculature geometry, chapter six, which demonstrates methods to use leaf vasculature formations to embed within an transparent material to act as an infrared block. This chapter will determine this functionality by hierarchical branch multi microfluidic network scaling to regulate laminar flow rate, as a resister circuit. Nature uses vasculature formations to regulate material composition of solar load absorption by laminar flows for dehydration and autonomous self-healing surfaces as a photoactive system. The research determines pressure equalization as a method of using precise hyrodyamanic control for modulating volumetric flow rates within a polymer. By a resister circuit can define flow target resistance optimization determined by an iterative procedure. This functionality is significant to obtain a flow parabolic profile, for a fully developed flow rate to advance the structural assembly of a polymer into a functional material. This simulation approach that generates a microfluidic network, is determined by pressure equalization in diminishing flow pressure variation within channel formations. This procedure to determine optimization of a network through resistance seeking targeting by hierarchical channel succession determined by leaf vasculature optimization.

Thermal modulation is demonstrated by a microfluidic approach that can direct the assembly of a thermally functional material in advancement of energy capture and storage. Using precise hydrodynamic control of a planar microfluidic platform is significant to attain uniform solar radiation absorption. This characterization in optimal fluidic transport flow is present in natural networks, leaf venation. Circulating a fluid using precise hydrodynamics is the mechanism for thermal material characterization to act as a switchable IR absorber. This absorber uses switching of water flow as a thermal switching medium to regulate heat transport flow. Key learning, chapter seven, of a adaptive temperature absorber is dependent on IR. A dynamic absorber is modulated by flow rate to lower its phase transition temperature that is dependant on solar radiation at high temperatures. The heating power profile over time shows heating of water by passage through the network. Heating power is a direct relationship to IR impact loads, the energy balance. Energy balance is determined by higher water heating power at high solar radiation at lower flow rates. Changing the flow rate we change the temperature increase of the water in steady state. The temperature difference between input fluid into the network and extraction fluid temperature (delta t) decreases inversely with flow rate over a range of flows. By low flow rate enhances IR absorption with higher flow rates gives increased cooling power of a material with decreased water heating. The consequence of higher material cooling operation diminishes high solar modulation properties. This characterization is heat transport regulation across the interface between fluid-material to act as an IR infrared block at high temperature, and this is observed by experimental testing.

1.8 Limitations of the Research

The research was undertaken through experimental testing in an artificial environment to replicate the real world. Experimental verification is through observational outputs as defined by SI units for thermal heat transport monitoring. The limitation of the research is the testing method under a controlled laboratory environment to replicate the real world. The boundaries of this research are limited by the nature of the experiment in order to assess energy flow generation results within the operating conditions. The primary focus of the experimental study is to test the ability of the device to adsorb IR by the controlling process parameters of energy capture and storage. The device testing method was contained within a controlled environment to replicate the real world through an artificial solar radiation load. This was undertaken in a temperature positive solar radiation spectrum. The testing method did not undertake negative experimental testing temperatures to analyze or evaluate temperature decay.

The device fabrication assembly process was alighted, oriented and directed by a laboratory artificial environment. The device was limited to a material scale that could be tested in a laboratory environment to apply an artificial heat load under controlled laboratory conditions. Up scaling of the device for large-scale experimental application testing in real world physical conditions was outside the scope of this research. The duration of the experimental study was determined in real time by the requirement to achieve planar fluidic flow generation in the network geometry. The polymer device is one tenth of the actual window size applied to a glazed building facade, hence output temperatures to solar load applied is scalable to deliver thermal heating power of the water, by temperature increase of the water in steady state.

The method to regulate flow rate was achieved by a syringe pump using distilled water from a reservoir tank to maintain flow rate through the network. This reservoir tank has a fixed volume of water and hence the time-line for the experiment was fixed by this parameter. A variable parameter that was not taken into consideration is the monitoring effect and influence of airflow movement changes across the surface of the device. The fluidic thermal flow results observed heat transport flow across the planar microfluidic device. Monitoring temperature decay (heat loss) through radiation, convective thermal transfer to surrounding air was not undertaken. These thermal effects would increase across the microfluidic planar device due to enhanced absorption temperature of the fluid in slot network channels. These effects would increase non-linearly with temperature difference between surrounding air temperature and device thermal capture. These effects would also apply to real world environment due to the influence of wind flow across the surface of the envelope and wind flow turbulence from surrounding buildings.

1.9 Research Problem

The challenge to advance glass envelopes from a static IR absorber ,of a mere material entity, to an adaptive IR absorber for solar modulation properties is a step change. A dynamic transparent IR absorber of precise thermal flow exchange and conductivity management by active, changeable flow rate fluidics is the new frontier. By a microfluidic based platform , used by nature, enhances regulation of fluidic flow and fluidic extract heat transport management. These capillary solar absorbing, water volume filled networks are activity flowing and circulating within a transparent polymer, advancing heat transfer as a thermal flow bridge. The network geometry embedded within the polymer is designed and orientated to the maximization of optimised flow with minimum requirement of pumping power for operation. Water flow efficiency of the network is intrinsically linked to capillary formation design of planar extensional flow generated in channels. This is achieved through precise hydrodynamic pressure control by simulation analysis. To achieve pressure flow equalisation in networks, are the principles applied by nature to regulate fluidics in functional materials.

This thermal flow energy system is a material matter / energy cycle relationship to high solar gain (climate). This transdisciplinary approach has emerged through reactive, responsive flow rate triggers sync to solar high temperatures. Through tailored flow rates to advance a transparent temperature dependent IR absorber, to conventional glass technologies static approaches. Urban building structures located within cities are components within it and therefore must react and be resilient to the surroundings climatic environment . Localized environmental conditions will influence thermal energy flow, that is dependent on input variables: orientation of the glass surface, relationship to surrounding buildings and microclimatic conditions (wind flow paths and diffuse solar gain via clouds). A multilevel approach is needed as the performance aims and functional role of current glass envelopes is a static response that does not adjust to environmental change, of a warming earth atmosphere.

The employment of a transparent dynamic IR absorber enhances optimization to control solar gains through modulating volumetric flow rates in glazed envelope assemblies by heat transport flow management of conductivity by fluidics. To create an energy resilient glass envelop to form the surfaces of buildings, as a intelligent layer. That can regulate its own thermal conductivity levels in response to performance requirement change by the hour, season and weather conditions for real time thermal flow management.

1.10 Thesis Structure

Chapter 1: Introduction

This chapter provides the background to the research, lists the aim, objectives, the research questions, constraints and limitations of the research and outlines the contribution to knowledge.

Chapter 2: Current State of the Art- Integrated Glass Envelopes

This literature review chapter investigates advanced technology research for glazing façades to modulate solar radiation as an energy system. This will determine the current state of the art for glazed building envelope innovation. This chapter will set out a perspective debate on what is current expected practice and what is under research development to progress glazed façade optimization. This chapter reviews the key parameters of: climatology, energy consumption, thermal comfort relationship to climate, envelope characterization and advanced glass façade systems.

Chapter: 3 Nature's Characterization of Functional Materials

This chapter investigates nature's characterization of materials by hierarchical strategies, as the central mechanism for material assembly. Quantification of nature's material functionality, based on dynamically modulating material function by precise rule orders, is achieved by a bottom up approach. Nature uses nanoscale thermal property reactions between neighboring molecules to regulate heat flow transport across the interface of materials at an atom level precision. The understanding of how heat transport is moved within and between material layers at a microstructure level would advance heat seeking targeting materials.

Chapter 4: Methodology

This chapter demonstrates the reasoning for the philosophical foundation adopted and the consequent choice of methodology. The goals of this chapter are to demonstrate how the scientific method was applied to the research questions for the investigation to advance a thermally functional material subjected to a solar load. This theory draws on evidence that is produced under artificial laboratory controlled conditions, by observation. This design methodology establishes the rationale of testing a theory, measured by real physical properties, to substantiate the research questions.

Chapter 5: Transparent Design Process Method

Setting out the design process method by the application of biologically inspired vasculature network implanted within a polymer to influence and change material IR absorption behaviour. Through the outlined method of material parameters, simulation, device solar radiation load to flow rate relationship and experimental testing method.

Chapter 6: Vasculature Geometry

This chapter demonstrates embedding leaf morphogenesis as a resistor for optimization to regulate pressure equalization by diminishing flow pressure variation by an iterative procedure. This analysis of circuit conduit optimization is validated against CFD simulation, within a closed loop network. This approach is resistance-seeking targeting to determine a microfluidic network as a resistor for optimized laminar flow rate in multi micro channels.

Chapter 7: Thermal Modulation

Thermal modulation is demonstrated using precise hydrodynamics as the mechanism for thermal material characterization to act as a switchable IR absorber. This absorber uses switching of water flow as a thermal switching medium to regulate heat transport flow with enhanced solar modulation properties.

Chapter 8: Findings and Discussion

This chapter sets outs the theoretical and experimental test results of the microfluidic platform based flows to advance the structural assembly of a polymer for energy capture and storage. The chapter summarizes the thesis by:

- Validation of the experimental testing methodology
- Review of the research aim and objectives
- Reviewing the limitations of the research
- Outlining the implications of the research on transparent façade engineering
- Conclusion of findings

1.11 Summary of Chapter One

This chapter has presented the research scope, justification and reasoning to advance a thermally functional material, as a bio-inspired engineering approach. The need for this research is to bridge the knowledge gap between what is the current expected performance of a glazed façade to what it could be. Understanding this gap to advance an envelope is defined by a single static value to a dynamic switchable value. Current envelope strategies are defined by prescriptive codes, rethinking this parameter through nature's characterization of switchable materials, is a step change, making present building codes irrelevant. The research aim, objectives, methodology, structure, research problem, contribution to knowledge, and limitations have been documented within this chapter.

Chapter 2: Current State of the Art - Integrated Glass Envelopes

2.0 Introduction

This chapter will investigate advanced technology research for glazing façades to modulate solar radiation as an energy system. This will determine the current state of the art for glazed building envelope innovation. This chapter will provide a selected range of different kinds of glass technological solutions of what is available within the market place and innovative solutions to progress glass facades

Current code compliant glass façades are based on thermal conduction to resolve uncontrolled solar radiation loading that drives the performance requirements for air-cooling mechanical systems. However, these façades provide natural day light and views that can be considered highly important in many countries in the 21st century. The resolution of these parameters will advance the assembly and functionality of transparent envelopes to conserve energy and to fulfill thermal comfort requirements.

Thermal comfort demands are driven by the prerequisite to moderate climatic regional environments for shelter. To maintain thermal comfort, the building envelope acts as a boundary, working with mechanical systems (heating/cooling, lighting) to regulate internal environments.

In opaque envelopes, the technological methods of achieving high conductance is well researched (https://catalog.data.gov/dataset/buildings-energy-data-book) However, transparent envelopes, in comparison, are poor insulators to lower phase transition temperature. Hence, this chapter will investigate the literature to determine the current state of the art for transparent façades. Tall glazed façades in cities offer high value visual and day light provision but there is a dynamic energy balance trade-off between thermal solar gain and heat loss. The total number of energy input sources defines this energy balance (heating, ventilation, artificial lighting and plug-in user loads), heat loss by the envelope fabric and solar heat gain inputs.

This chapter will review these parameters in terms of climatology, energy consumption, thermal comfort relationship to climate, envelope characterization and advanced glass façade systems.

2.1 Climatology Change

Global warming is one of the main concerns in society. Buildings are one of the main contributors (others transportation, commercial and industry) in high Carbon Oxide (CO_2) emissions in atmosphere, that is damaging the ozone layer. This depletion in the ozone layer is warming the climate and this has been documented through climatology global mapping, Koppens system (Peel et al.,2007). Excessive demand for energy use by fossil fuel burning , with associated rise of CO_2 levels in earth atmosphere has led to the development of energy saving technologies in the building sector. Highly glazed buildings depend on air conditioning to reduce and counteract solar radiation impact within building spaces. This places a burden on cooling systems performance operational modes to achieve energy saving consumption. Internal comfort in highly glazed buildings is at the cost of global warming through CO_2 emissions. These global gas emissions are thinning the ozone layer that protects the planet from strong solar radiation for life on earth. The reduction of the ozone layer has led to global warming by greenhouse gas emissions (GHG). Hence, global sustainability has been defined by the nine interdependent planetary boundaries (Rockstrom et al., 2009) in which humanity can safety inhabit this planet, as investigated by Rockstrom.

1) Climate change (CO_2 concentration in the atmosphere <350 ppm and/or a maximum change of +1 W m^{-2} in radiative forcing);
2) Ocean acidification (mean surface seawater saturation state with respect to aragonite ≥ 80% of pre-industrial levels);
3) Stratospheric ozone (<5% reduction in O_3 concentration from pre-industrial level of 290 Dobson Units);
4) Biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N_2 to 35 Tg N yr^{-1}) and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P);
5) Global freshwater use (<4000 km^3 yr^{-1} of consumptive use of runoff resources);
6) Land system change (<15% of the ice-free land surface under cropland);
7) Rate at which biological diversity is lost (annual rate of <10 extinctions per million species).

Two additional planetary boundaries for which a boundary level has not yet been determined, (Rockstrom et al., 2009) are chemical pollution and atmospheric aerosol loading. According to Rockstrom:

"*transgression of one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems.*"

Humanity has already transgressed three planetary boundaries: for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle, (Rockstrom et al., 2009). A recent study (Garcia et al., 2014) confirms the devastating impacts of climate change on biodiversity loss. The Cryosat-2 satellite reported an annual loss of 159 000 million tons of the Antarctic ice sheet. This represents 200% ice loss rate when compared to the 2005-2010 previous surveys. This means that adaptation to climate change as well as GHGs (Green House Gasses) should be a priority (Kwok et al., 2010). Human energy related (cooling, heating, lighting and plug-in devices) consumption are currently the major contributors to climatic change (Urban, 2010) and this impacts on urban climates.

2.2 Urban Climates

Reducing primary energy demand represents the key challenges, as our cities across the globe are responsible for up to 70% of global carbon emissions and 75% of global energy consumption . By 2050 it is estimated that 70% of the world's population will live in cities (Malcolm et al., 2013). This linked with an increasing population growth, 15.7% over the next 30 years (Wackernagel et al., 1999) will drive continued expansion of our cities at the present rate. Cities and urban areas, concentration of operational energy demand is at the centre of the problem to reduce CO2 emissions.

This concentration of energy demand into city regions, enables measures to contain city energy consumption flows. Through energy regulation of demands in building by the requirement of heating, moving air for cooling and lighting. Transparent glass facades play a major role in the consumption of primary energy (IEA,2009) in moderating solar radiation by reducing cooling ventilation and artificial lighting levels. To minimize operational energy building use and maximization of generated energy in reducing green house gas emission is a European Directive 2010/31/EU (2010). The COM 639 stated that our cities consume up to 80% of generated energy, which represents 70% of global carbon emissions (COM 639, 2010). These urban districts create microclimatic conditions, that impact on air temperature. In cities, this represents a temperature rise of 1 to 2^0C compared to surrounding rural regions. This temperature rise is associated with urban dense material surfaces, transport infrastructure and industrial activity.

Urban districts (buildings / ground surface planes) absorb and store, solar radiation enhances temperature raise within cities. This increased conductive heat storage in dense surface materials is greater than plants and soils in rural areas. The ability to store thermal gains in urban material surfaces increases air temperatures within city districts. This is compounded by emissions from transport infrastructure and industrial processes which disperse and absorb solar radiation, trapping this energy in the city atmosphere. Other factors that impact on heat island effects, is airflow. Airflow speeds within cities are slower (in comparison to surrounding regions) by the effects of greater air turbulence (Hough, 1995). Turbulence is induced by tall-density structures that diminish wind speed by increased wind direction change. These structures (especially towering buildings) influence and reduce natural cooling by creation of a microclimate. Microclimates impact on societal well-being by intensified urban high temperatures and increased cooling demand requirement of citizens, and this, in turn, heightens energy demand. This represents a significant problem; therefore, smart cities must implement strategy solutions. The Intergovernmental Panel on Climate Change (2007) (IPCC 2007) stated that:

'the efficient use of resources, affordable prices and innovative solutions are crucial to our long-term sustainable growth, job creation and quality of life' IPCC (2007).

Control of solar radiation to reduce thermal load of building interiors are the challenges of highly glazed facades for comfort conditions. These challenges are enhanced by high city temperatures in the reduction of cooling demand operational requirements in a warming climate.

2.3 Thermal Comfort and Relationship to Climate

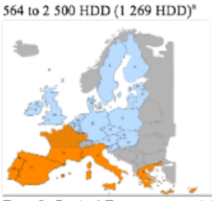
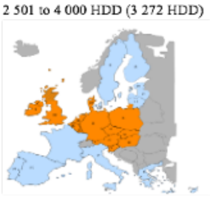
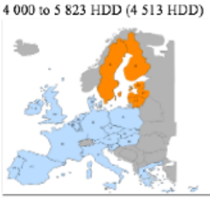
Building performance is dependent on the envelope to act as a boundary between indoor and outdoor environments to achieve human thermal comfort (section 2.4). This envelope performance parameters are dependent on solar-energy modulation to regulate heat gain and heat losses. Geographical regions of high solar intensity are increasingly becoming more dependent on cooling comfort conditions and Heating Degree Days. The IMPRO building project evaluated the potential, at a European level, to assess climatic effects to measure impacts for inherent measures for the envelope fabric. The project categorized refurbishment optimisation aims at the minimization of costs and environmental impacts while ensuring that the required residential building fabric performance was not diminished. To progress methods of the most beneficial refurbishment strategies to be determined by climate condition zoning for alternative refurbishment profiles. The primary energy demand and the GHG emissions crucially depend also on the quality of energy sources and on the efficiency of heat and power production and distribution. Climate conditions can be characterized with help of the number of heating and cooling degree day values (HDD), figure 2.1. The IMPRO project used the following division:

Zone 3: above 4200 heating degree days moderate

Zone 2: between 2200 and 4200 heating degree days and warm

Zone 1: below 2200 heating degree days.

Grouping of heating degree days

Range of heating degree days [HDD]	Corresponding countries			
	Country	HDD	Population in 2003 [Mio.]	Building stock [Mio. m²]
Zone 1: South European countries	Malta	564	0.40	11
564 to 2 500 HDD (1 269 HDD)[a]	Cyprus	787	0.72	40
	Portugal	1 302	10.41	337
	Greece	1 698	11.01	351
	Spain	1 856	41.55	1 454
	Italy	2 085	57.32	2 076
	France	2 494	59.64	2 109
Zone 2: Central European countries	Belgium	2 882	10.36	359
2 501 to 4 000 HDD (3 272 HDD)	The Netherlands	2 905	16.19	561
	Ireland	2 916	3.96	125
	Hungary	2 917	10.14	221
	Slovenia	3 044	2.00	45
	Luxembourg	3 216	0.45	21
	Germany	3 244	82.54	3 463
	United Kingdom	3 354	59.33	1 567
	Slovakia	3 440	5.38	82
	Denmark	3 479	5.38	230
	Czech Republic	3 559	10.20	237
	Austria	3 569	8.10	292
	Poland	3 605	38.22	706
Zone 3: North European countries	Lithuania	4 071	3.46	62
4 000 to 5 823 HDD (4 513 HDD)	Latvia	4 243	2.33	45
	Estonia	4 420	1.36	28
	Sweden	5 423	8.94	338
	Finland	5 823	5.21	151

a) Numbers in brackets indicate average weighted HDD
Sources: [Eurostat 2005a, Gikas & Keenan 2006]

Figure 2.1 Environmental Refurbishment Improvement Potentials of Residential Buildings (VTT, 2012).

Results indicated that in Southern European countries, cooling demand becomes increasingly important for the overall energy consumption of a residential building due to higher requirements for thermal control in the warm climate. The study found that in warm climatic zones the cooling demand can be reduced drastically by a combination of lowering the internal heat loads by greater control of thermal conductivity transmittance. Hence, HDD has a direct impact upon the total primary energy demand according to climatic zone and envelope characterization. This research clearly indicated the current issues with regard to thermal conductivity façade behaviour (VTT, 2012) of buildings and its implications on energy consumption increase for air cooling demands have a direct linkage to climatic conditions.

Control of solar radiation to reduce thermal load of building interiors are the challenges to regulate solar radiation loads. By reduction of active cooling measures to achieve a greater energy balance. The regulation of energy demands between the climatic environment, individuals and their perception of comfort. Passive system of Low Zero Carbon (LZC) technologies have been employed in the progression of active response to solar radiation and these measures have been determined by thermal insulating systems as undertaken by the IMPRO building refurbishment enhancement project. By the reduction in operational mechanical service cooling HVAC (Heating, Ventilation and Air Conditioning) systems. However, energy efficiency of a building is characterized by boundary conditions in relationship to geometry solar orientation and thermal contact conditions. Heat transfer between different material property layers, within the envelope fabric, defines the transition temperature through the envelope. This is a dynamic system represented by climatic / micro-climatic conditions and heat-air-cooling properties defined by thermal transmittance. Thermal transmittance is functionally significant for envelope skins in the moderation of indoor and outside conditions. This is represented by heating and cooling load in response to environmental loading (climatic / microclimatic effects) to achieve thermal comfort. The level of the energy consumption of a building depends on the building type and the climate zone where it is located. In addition, the level of economic development in the area is also influential in shaping the energy use pattern. Moreover, construction techniques employed plays an important role on buildings' energy consumption balance linked with required comfort levels in response to climate.

2.4 Thermal Comfort

"Minimum energy needed in adjusting to his environment" describes thermal comfort (Olgyay, 1973) through body temperature management as determined by thermoregulation. Thermoregulation maintains body core temperature by constantly monitoring skin temperature by sensory receptors. These receptors regulate blood flow in response to ambient air temperature. This mechanism to regulate human body temperature requires energy.

The human body is regulated by metabolism to maintain an internal core temperature of 36.7^{0}C that is constant. Metabolism is a complex internal generator of thermal energy that is governed by blood flow to maintain core temperature in response to skin / air contact. The human body has no method to store thermal energy and it requires generated body heat to maintain temperature. Thermal energy generation is a mechanism of using stored fatty acid molecules within the human body, as a chemical conversion process into energy. The human body uses this energy storage, from food, in fatty tissues which is a chemical energy storage system (Gray,2012).

This generated heat will be offset by surface skin though contact heat loss to its surroundings. Heat loss will vary dependent on air temperature, radiant temperature, air speed and relative humidity. These parameters will determine an individual's thermal comfort. The thermal condition is hence a balance, through metabolism in heat energy generation to human physical activity. A relationship of thermal comfort is defined by steady state comfort theory (Hens, 2011).

This is a function of skin temperature, contact clothing, metabolism and surrounding environment temperature (Fanger, 1970). Clothing provides increased thermal resistance of the skin to reduce heat loss and maintain core temperature. However, human surface temperature is not a system at constant temperature, as skin sensitivity is unable to monitor operative temperature uniformly across the body. This is not unexpected as clothing, metabolism and surface air / skin contact temperature will vary. Hence, thermal comfort for internal building environments can be presented as a temperature range of 24-26 ^{0}C. Internal building environments affect thermal comfort through body heat loss by evaporation and convection. Building surface temperatures and air velocity influences metabolism though solar radiation heat loads. These are dynamic real-time loads as they change by the hour, season and geographical location. However, current buildings are designed to fixed performance strategies based on thermal conduction. Nevertheless, humans will change their activity, location and level of clothing to adjust to temperature change. The envelope static performance will influence occupant comfort by heat transfer regulation through transmittance.

2.5 Visual Comfort

Tall building envelopes dominate the perspective view of cities. It could be argued that the most attractive feature in our cities is the view looking into our cities. This visual connection to the urban landscape can provide human satisfaction. The engaging benefits of views, colour and light intensity cannot be underestimated for human well-being . Transparent envelopes maximises daylighting within buildings to give visual aspect relationship to our urban environment and solar cycle. The human behaviour pattern or (Circadian) clock is synced to this solar cycle. By the human pattern release of melatonin as a 24 hour rhythm connected to solar radiation. This give tangible benefits to building occupant behaviour and well being that cannot be replaced through artificial lighting methods (Stevens et al, 2001). This daylighting relationship of the human clock enhances well-being related to the seasonal patterns. Glass surface areas provided the best solution to allow unhindered daylighting. However high solar gains are larger in transparent parts due to less insulation (higher U value) and short wave absorptivity of the external glass pane. Increasing the opaque envelope parts reduces daylighting.

Opaque envelopes material conductance for solar modulation is well researched and advanced analytically as an energy collector, that are established and currently outperforms transparent materials. Hence there is nothing of note to add here. However transparent envelopes for better mechanics to resolve solar modulation is currently unresolved. Maximisation of daylighting is a key parameter that influences human behaviour and visual comfort in our buildings for relationship connection to our environment.

2.6 Envelope Relationship to Climatic Regions

Envelope optimization of building energy performance is determined by several parameters, as listed below and illustrated in Figure 2.2:

1. Climate
2. Orientation
3. Building operational use
4. Building envelope components
5. Daylight
6. Shading
7. Wind loading

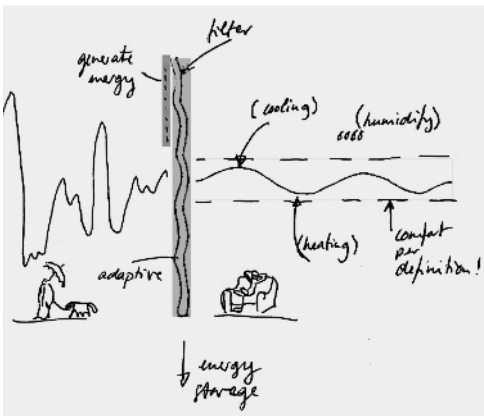


Figure 2.2 The Future Envelope 1 - A Multidisciplinary Approach. , (Knaack & Klein, 2008)

Thermal transmittance has the largest effect in terms of solar energy modulation (Klein et al., 2008) in the reduction of cooling and heating load demands. Lighting and cooling ventilation are key parameters to achieve optimum energy efficiency and thermal comfort. This can be determined by passive building design where primary energy consumption does not exceed 144 MJ/m sq without the requirement for mechanical cooling. Achieving a low thermal transmittance is desirable as this attains a higher insulated envelope fabric for lowering air temperature without affecting thermal comfort of air and high solar radiant gain temperature that are key characteristics of an envelope.

2.7 Envelope Characterization

The physical properties of an envelope traditionally have been characterized by structural depth to achieve a load bearing envelope structure. The materials that formed this construction are brickwork, stone, and blockwork. Structural openings to form a glazed window or door are limited by the ability to create a clear span. This limitation for a glazing aperture located within a load bearing masonry structure enhances solar radiation modulation for thermal comfort. This solar load reduction is achieved by the ratio of wall thickness mass area in comparison to a limited total window surface area.

However, this structural technique has limitations in building height due to lateral wind force loading, to maintain structural integrity. The development in materials (steel, concrete) enhanced building height through a structural frame solution. With the development of a frame as the principle means for primary structural support, an external load-bearing wall was no longer required. The envelope function in a structural frame solution acts as a component oriented non-load bearing system; a physical element that defines internal and external boundary conditions supported by the frame. The envelope interfaces between the internal comfort conditions and environmental influence loads. The current envelope performance strategy is based on measures in the reduction of thermal conduction, to resolve the conflicts between services and fabric provisions (heating systems fighting cooling systems).

2.8 Thermal Conductivity

Thermal insulation has the largest effect in terms of minimum energy use (U-value) that is calculable, as in the Building Regulations Approved Document L1A, UK https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l. In opaque and transparent buildings, achieving low thermal transmittance (conductance) becomes increasingly difficult. The reason for this is that long wave solar radiation inputs lead to overheating of internal spaces and increased cooling demands. Buildings with high internal gains loads, such as hospitals, offices etc. are dependent on cooling. This, coupled with building fabric load, represents key challenges in regulation and management of thermal transmittance. This is thermal conductivity management through material selection of ideal choice, where material envelope increasing thickness is unrestricted and transparency is not required. Opaque insulated envelopes can outperform transparent façades, as these transparent materials remain a weak link in envelope performance. In terms of transmission loss of less insulating transparent façades, it is better to replace by better insulated opaque assemblies. This is due to resulting inflow heat load that is dependent on the overall solar transmittance 'g' of the transparent façade including any solar shading.

However, reducing natural day light has a consequential reliance on artificial lighting demands.

2.9 Artificial Lighting

Electric power used in lighting has a side-effect. Over 95 percentage of used power for lighting today transforms into heat that must be cooled off. Therefore there is an extra 30% saving potential in terms of primary cooling power, (US DoE,2006). The energy efficiency in artificial lighting is based in two principles, to minimize the used electric power by lamps with low-consumption or dimmable lights and the hours of lighting usage with control systems. In order to minimize energy consumption the first strategy is to optimize the use of natural daylighting, by increased use of glazed areas without any glare. The importance of a glazed façade in urban city centres is seen by many building owners as a visual statement to the city with tangible benefits for visual comfort, health and well-being (Tianzhen et al 2010). Buildings that are highly glazed offer views and appearance that are seen as important marketability factors. A technical review to deliver energy potentials have been developed (Roaf, 1992) into external glazed thermal insulating systems within the market (passive, hybrid, vacuum , aerogels, thermochronic and solar active systems materials) has been undertaken.

2.10 Integrated Service System Approach

Performance and compliance to ever-increasing prescriptive building codes has led to the development of integrated façade systems, rather than individual envelope component assembly. This integrated approach is reshaping current approaches in viewing transparent envelopes, as a system-oriented performance based system.

Current Low Zero Carbon (LZC) technologies themes should lead to energy efficiency, energy effectiveness and energy optimization in reducing primary energy demands. LZC technologies of component assemblies are focused upon the building envelope. These components systems represent the main challenge in achieving energy efficiency strategies. The envelope acts as a environmental modifier as it interfaces and transcends between internal comfort conditions and climate. Greater demands have been placed to minimize operational building energy use and to maximize the generation of energy from solar renewable sources that are integrated within the building envelope. Despite this, technological progression of these systems lack a holistic approach to building energy strategies, as they are unable to sync with changing real time environmental condition or recognition of climatic regionalization. These technologies are not transformable adaptive systems; as they do not at present, give a holistic solution approach. This lack of integration of component assemblies technologies, must evolve at a multiscale design level and this is the new frontier of interdisciplinary thinking (Gutierrez et al,. 2013). Hence building of component assemblies must be revolutionized, conceived and investigated from the inception of material behaviour to the environmental influence, to advance glass envelope performance.

2.11 Current Façade Systems

During recent years different kinds of technological solutions have been developed in order to respond to the requirements of improved energy-efficiency and sustainability. A number of Science and Technology Universities (SINTEF, NTNU,LBNL) have undertaken a review of the current state of the art within the market place of performance glazing systems. This technical review into multi-functional glazed products within the market of vacuum , aerogels, electronic and phase change material has been undertaken, (Jelle et al, 2012). The outcome of this research indicated transparent applications of aerogels, vacuum, solar cell glazing are potentials solutions for technology progression within the glazed market industry. There is an economic shift of investment decisions to move away from minimum first cost to glazed integrated system performance. This is a technically complex mode of operation that is a fundamentally different façade model to those previously seen (Lee 1998). This mode of manufacture echoes automotive and aerospace industries of highly manufactured products. Aerospace and automotive technologies employ greater standardization due to the processes of product range, parts range, supply chain and the requirements of the necessary large number of differing company inputs and information feeds for continuous iteration of element components and finite modeling.

Component modeling enables progression of curtain walling as an individual element assembly to an integrated performance manufacturing system. Innovation of integrated systems is a technology shift of transparent façades being a net energy supplier rather than a net energy loss (Apte, LBNL-60146). Increased usage of glass provides views, light, connection to the city and outdoor environment. A tangible benefit, coupled with energy performance strategies, constitutes a new method of thinking. These integrated systems represent the main challenge in achieving energy efficient strategies that could possibly equal or better high performance opaque envelopes. Greater demands have been placed to minimize operational building energy use and to maximize the generation of energy from solar renewable sources that are integrated within the building envelope. These technologies include double facades, hybrid facades and decentralized mechanical services.

Envelope technologies enhancement is directed towards external thermal insulating systems; ventilate facades, double skin glass facades; solar shading (lamellas or panels, replacing windows with Low-E high-performing glass); passive solar energy systems (solar glazing balconies); active solar systems (solar collectors, photovoltaic modules) (Baetens et al,. 2010). Others system include water-water cooling, air-cooled and phase change materials to control solar absorbance. Electrochromic windows and transparent solid insulation material of light transmitting aerogel, both inhibit heat transfer to enable solar transmittance to regulate solar radiation. The development of these manufactured systems with possible integrations of solar (thermal,pv) and /or ventilation systems should in principle, advance multifunctional facades. The following proceeding pages reviews selected systems based on thermal insulating methods as a technology layering approach, Figure 2.3.

Figure 2.3 Layering Façades in Creating Desired Functionality (Knaack & Klein, 2008).

2.12 Integrated Glass Façade Systems

These multifunctional façades interact with the environment and / or user, by responding to external influences and change their performance behaviour and functionality accordingly. These integrated systems are able to adjust performance properties in terms of insulation, heat and day light transmittance, as they embed building service provision resulting in 'technicalization' of the façade envelope skin; so, to advance a curtain walling stick system, by technology. An example of this technicalization, is the integrated ventilation solution by Seele GmbH I DE, SCF, Self Conditioning Facade. SCF unitising pressure difference for solar modulation as a multi layered, ventilated integrative façade, that incorporates ultra fine filters to allow external air flow within the glass layer cavity to induce passive ventilation flow.

The composition, figure 2.4, of the curved glass laminated panes are bonded at the sides to a steel frame to allow for a compression moulding assembly top and bottom, that incorporated the filters to complete the bonding pane edges. The air flow through the filters uses thermal air buoyancy to release heat build-up, (Ismail, 2009). The driving force is temperature differential, natural air flow, due to the cooling action of the air stream. Through direct air flow to external air supply by control of cross-section air intake into the glass cavity, for passive ventilation flow regulation of solar gain. However, the effectiveness of the airflow window is determined by air flow resistance of the system, through the intake and extract of air through the filters.

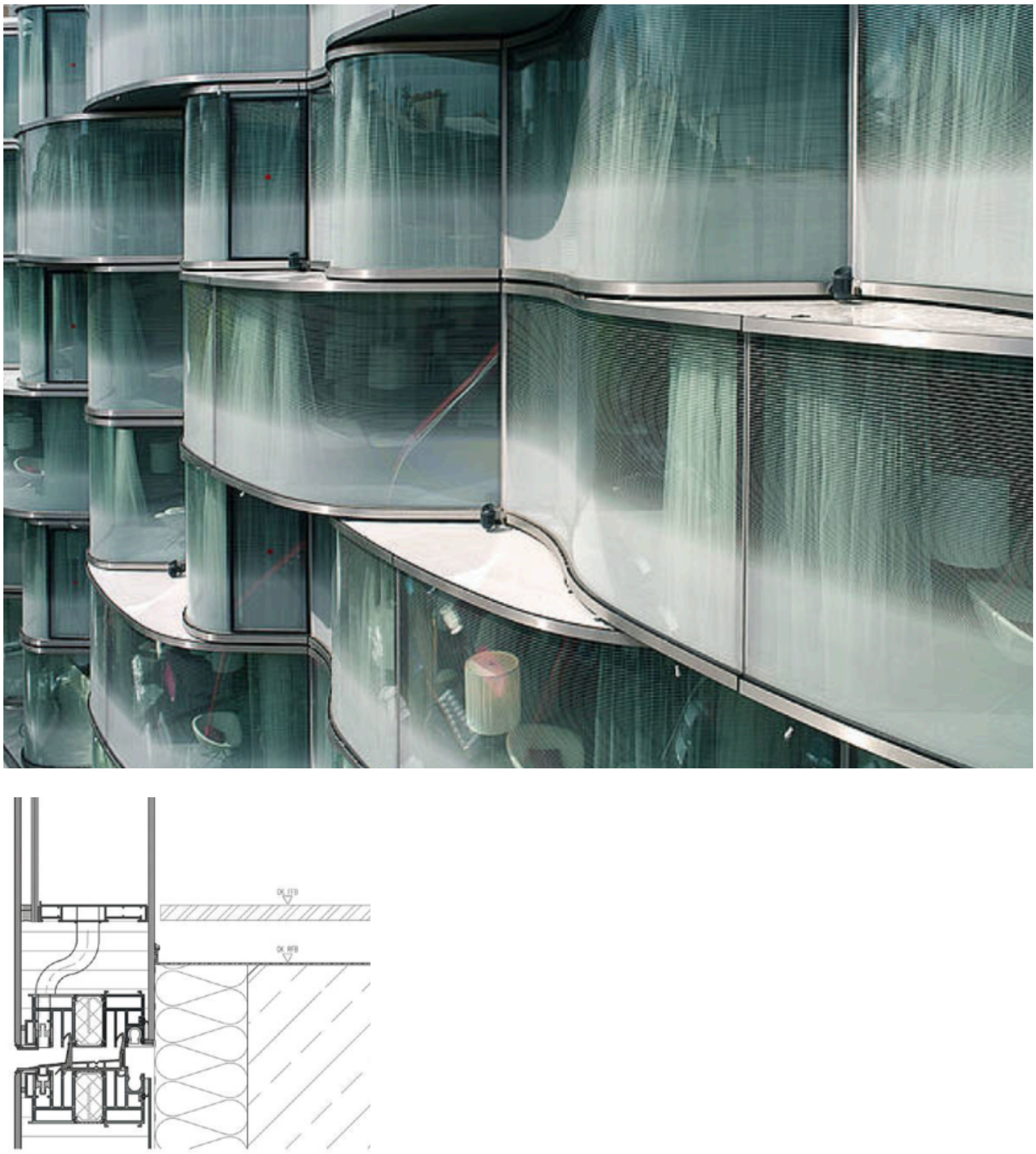


Figure 2.4 Hotel Wagram, Paris: Self Conditioning Fascade principle (Seele, 2017)

The differing pressure fluctuations within the cavity will influence solar loads and reduce the risk of condensation. The development of the system was a collaborative undertaking with the Fraunhofer Institute. For the first time, façades are progressing into a decision-making approach in the active management of thermal comfort as an integral part of building service provision. Some of these transparent envelopes are energy generating and others employ active solar shading and/ or ventilation when indoor thermal comfort so demands.

These systems are advancing the ecological building footprint as a new constructional approach to façade engineering geometry design by sensors, integrated ventilation extract and supply, heat recovery systems and energy generating (BIPV Building Integrated PhotoVoltaics). This is a new perspective shift in addressing the three key performance tasks:

1. Comfort and task performance
2. Energy demands
3. Localized energy and district energy micro-grids.

This is a new stepwise technology innovation path rather than the present passive curtain walling component system design. These passive systems cannot adapt to changing environmental conditions, as they are designed to static boundaries between air conditioned building interior spaces to outdoor fixed environmental conditions, as determined by U-value component performance.

2.13 Double Skin Ventilated Façades

Double skin façades aim to reduce solar heat gains in summer or winter periods to utilize these gains of solar radiation for controlling indoor comfort conditions. This is achieved by air ventilation methods to enable active cooling or heating to moderate thermal transmission, using passive ventilation strategies. This method of active control of solar gain can reduce total energy consumption of full air conditioning systems, HVAC. Figure 2.5 indicates passive use of solar energy in building façade double skins to reduce cooling demand loads.

Figure 2.5 Double Skins (photograph taken by the author)

Solar radiation through the double skin façade reduces the cooling demand loads via control of heat transfer from the outside air to the inside room temperature. This is achieved through the thermal characteristics of the void air gap between the outer glazed curtain wall and the inner curtain wall, as a convective loop and solar shading as shown in Figure 2.6.

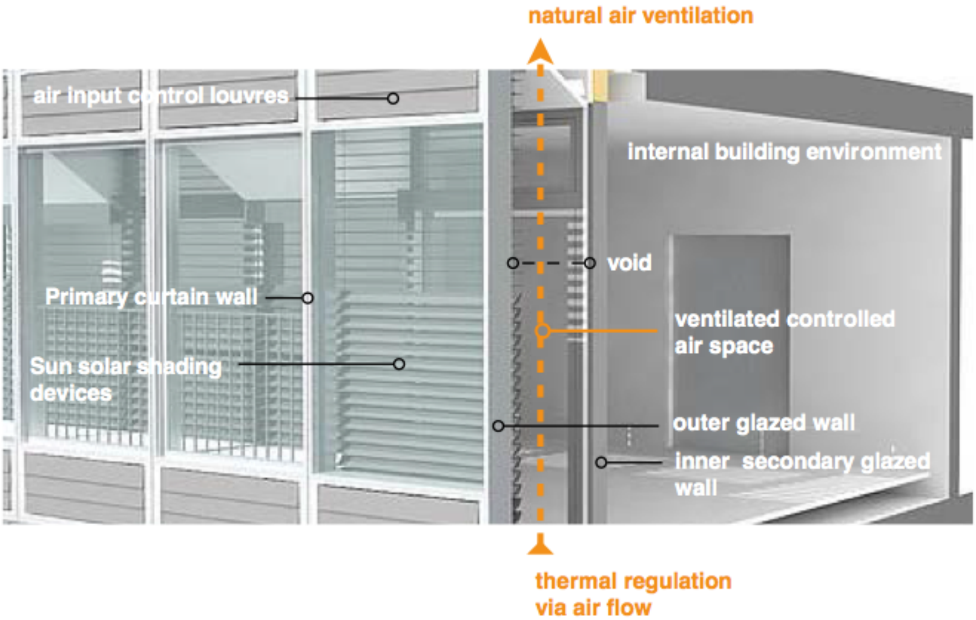


Figure 2.6 Connective Loop ,Thermal effect in the facade through air ventilated space. (Louter, et al 2014).

Figure 2.6 illustrates the inner glazed curtain wall that extends the envelope to accommodate the air ventilated space. The external curtain wall skin is separated from the inner glazed element creating an air layer. The external element layer performs the tasks of weather protection and solar shading surface for the building. The creation of the air buffer zone acts as a thermal buffer to capture solar radiation for removal by air ventilation flow. The introduction of an extended second glass layer advances the incorporation of building service provision via heat recovery systems to actively manage air for heating and cooling ventilation (Loonan, 2013). These double façades are able to operate in high wind speed locations and are used to block traffic city noise to enable natural ventilation for human comfort demand. The air-ventilated cavity acts as a sound absorption barrier to reduce air borne sound transmission in cities. Coupled with sound absorbing glass (laminated) panes, this further reduces sound infiltration.

There are different operational strategies for double skin façades, as shown in Figure 2.7, from individually ventilated box façades (3) to fully ventilated vertical façades (1) and the hybrid between these two system approaches (2).

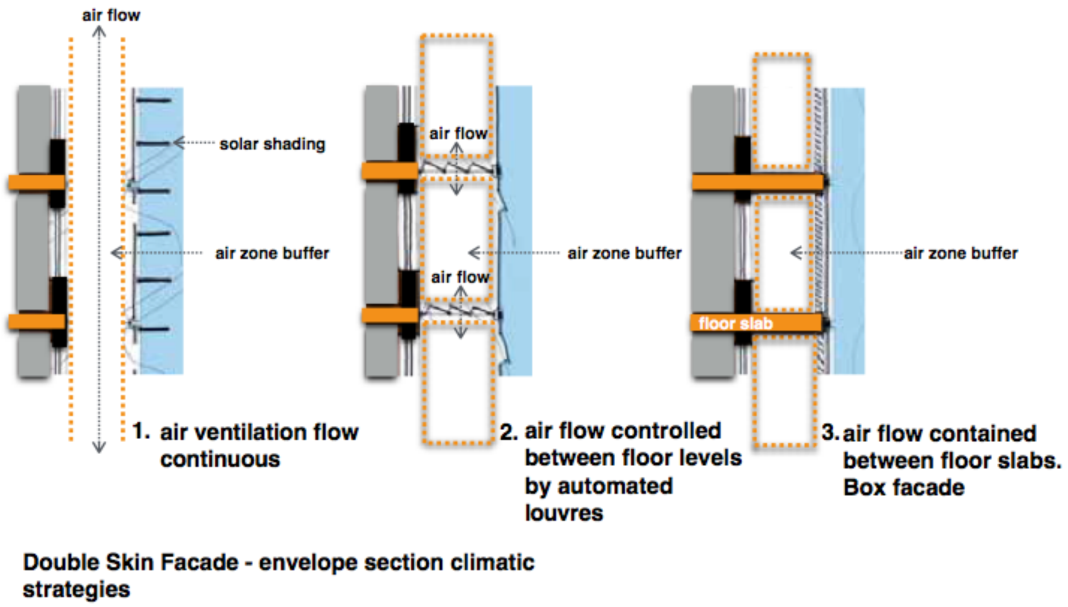


Figure 2.7 Controlled Ventilation Strategies (Borodiņecs et al., 2012)

This multi-layered structure reduces the energy consumption by this additional glass layer to enhance envelope functionality in response to solar radiation and heat island effects. This enables reduced active cooling demand supply ventilation methods. In winter, this façade will absorb solar radiation within the air buffer zone to re-distribute this captured thermal energy into the building interior spaces, to reduce the demands for heating energy. The summer performance mode is focused on reduction of cooling demand load by heat transfer mechanisms to capture outside heated air to stop heat wave shift transfer to the building interior. This is achieved by manipulation via passive or mechanically driven air ventilation methods of the air buffer zone to achieve a greater control of thermal conductivity transmittance. However, this arrangement and strategy of layering by insulating glass panes can also present significant challenges in performance. If natural ventilation within the air buffer zone is not controlled effectively this would lead to overheating of the air cavity space by the creation of a greenhouse. This overheating of this air space would increase heating loads and heat transfer from the outside to the internal building spaces. This will impact on the greater need for cooling demand. Cleaning and maintenance of this façade is also more difficult, as indicated in Figure 2.8.

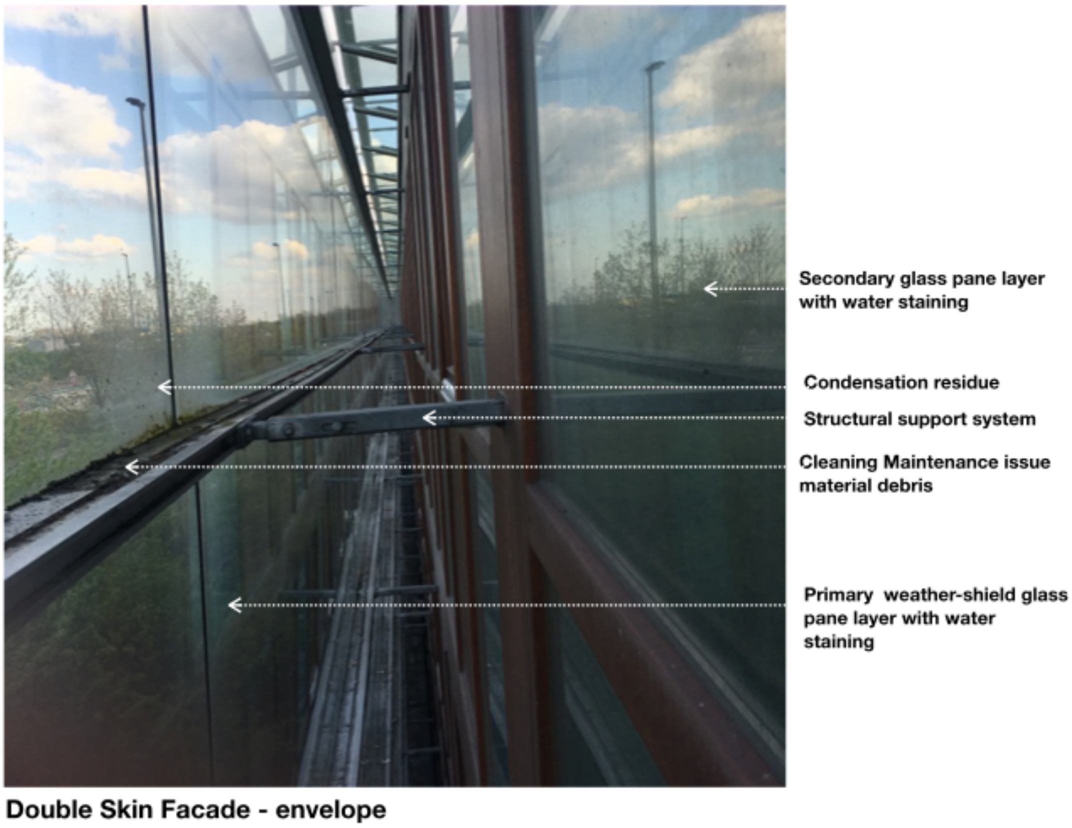


Figure 2.8 Double Skin Façade (photograph taken by author)

Condensation on the exterior, inner glass pane will occur in winter conditions via opening windows of the thermal insulated inner layer, due to lower outside air temperature. This envelope is susceptible to overheating of the cavity in summer, condensation risk in winter and extremely high maintenance costs associated with this system.

Double skin façades give performativity functions in thermal comfort to regulate solar radiation, heat transfer by airflow and acoustic comfort as an upward scaling solution for envelope transparent skins in urban environments. These façades have differing structural orientations, which have been developed in relationship to the mechanisms for damp and heat wave shift. The heat transport cycle focuses upon capturing solar radiation to enable the release of thermal energy in order to dissipate or convert heat (via heat exchangers) in response to the seasons. In winter, the performativity mode is for heat recovery and pre-heating internal building spaces. In summer, solar driven ventilation for natural cooling of a building's indoor spaces becomes important. However, overheating of the air buffer cavity, as shown in Figure 2.8, causes a risk of condensation and extremely high maintenance costs then impact on the building performance behaviour.

2.14 Radiant Glazing

Low e (low emissivity) glass is a technology used to increase a glass pane insulating performance by using transparent conductive oxides. These nano-coatings act as a conductive layer to increase radiant surface temperature to enable decreased cooling demands in building interiors. The application of these thin film materials has thermally improved glass pane technology in maximization of transparent properties, solar gain control and day light control. This coupled with movement away from single glazing pane application that achieved U-values in a range of U ~ 0.6 W/m2K. Introduction of Argon or Kryton gas filled glazing cavities have increased the performance technological potential, as shown in Figure 2.9.

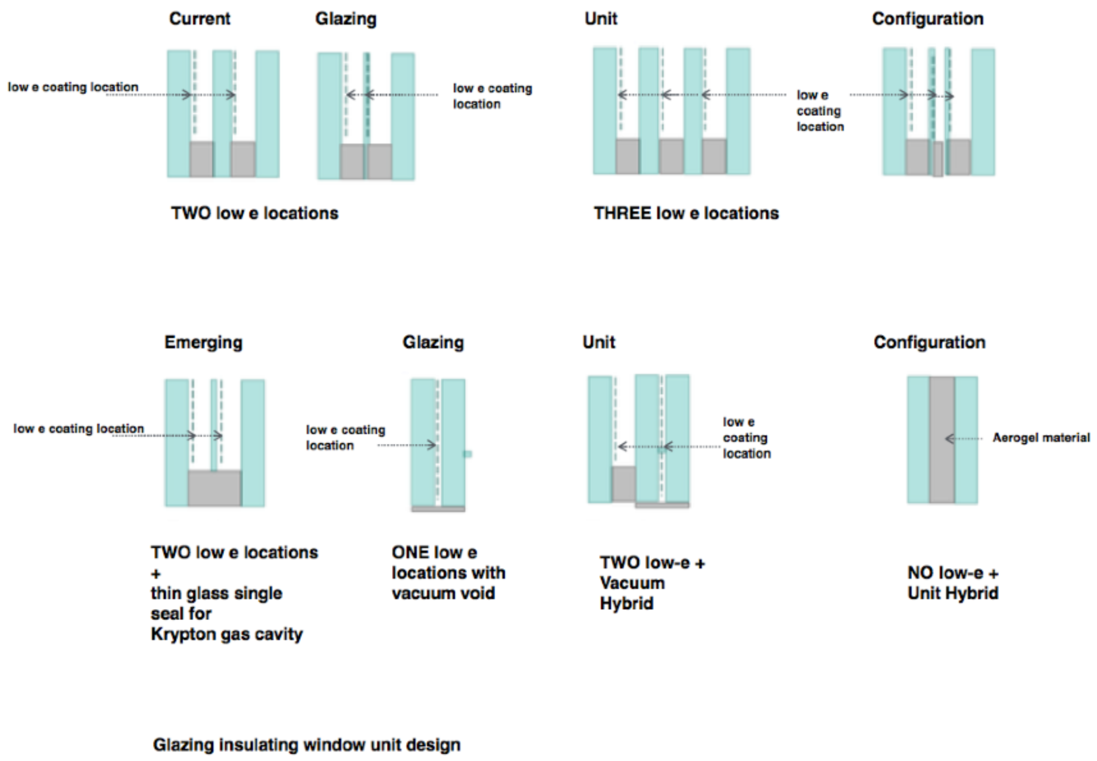


Figure 2.9 Glazing Unit Configurations

The progression of this thermally advanced multi pane glazing application is driven by, Figure 2.9, of double, triple, gas filled cavities and low e nano coatings. Low emissivity , low-e coatings refers to a low emissivity over the long wavelength portion of the light spectrum, (Taylor & Kerr, 1941) . Low e coating (in colours of gold, silver and copper) gives solar control through this thin film coating. The thickness of the coating 1 μm is comprised of 3 layers; a metal layer that is embedded between two dielectric layers, ASHREA, 2005. These coating are either hard or soft that is deposited on a flat glass pane and thin plastic film.

This integration of low-e gazing into multiple leaf glass configurations allows significant reduction of radiative surface to surface heat transfer between glass panes. It can be seen the U - value of a clear glazed unit reduced by 32-53% compared to a single pane counterparts (Bahaj et al, 2008). Increasing the depth of multi-pane windows by a third and four layer improved the insulation further (Eicker et al, 2008). However air filled cavities are subject to air flow movement within the cavity space due to buoyant induced air currents. The air absorbs solar gain that is carried to the top of the window that consequently creates a cooler air pool at the lower window inner pane section (Manz, 2003).

Replacing the air filled cavity with krypton enhances better thermal insulating properties and reduces overall window depth for a thinner section profile. Combining this glass filled element with low-e coatings, the radiative surface to surface heat transfer can be reduced to below 0.1 W/m2 K , (Manz, 2008). The introduction of a vacuum to replace air and gas filled cavities will further reduce the depth separation between glass panes. This narrow vacuum separation space is typically 12mm that will require spacers to maintain this dimension by an array of pillars, spacing that is 25-40mm (Fang, 2007). The integration of low-e thin film to the inner panes (for radiant heat transfer) with a vacuum cavity, a thermal transmittance of 0.4 W/m^2 is achievable, within a double -vacuum glazing (Manz, 2008). However manufacturing of an effective vacuum seal to resist wind pressure at cavity edges, for long term durability remains an issue for this multiple panes solution.

The emerging developments of this technology in focused on materials in thin multi-layering insulated glass unit configurations for U value performance, weight reduction and reducing costs of glazing unit (Jelle, et al., 2012). Transparent insulation materials aerogel have been integrated into glazed cavities as they present greater insulation properties for glazed unit configurations. Aerogel material is light transmitting (comprising of 95% air) in nano-sized pores, that inhibit heat transfer, have been developed. This material has thermal and transparent properties to enable solar transmittance. However, the transmitted light does have a tendency to scatter and reduce day light potential.

The progressions of multi-layered configurations are methods of spectrally glazing selection to control visible and near IR spectrum wavelength by thin nano technology coating. This transparent technology achieves 90% of visible light and less than 10% of near IR spectrum transmitting wavelength. These glazed pane configurations represent fix transmission losses that have led to decreased thermal transmittance. However, these glazing configurations have to comply with the following constraints in moderate climatic regions.

- Limit glass area to 1 /5 of floor area.
- Solar orientation positioning southeast over South to Southwest and Northeast over North to Northwest in the Southern Hemisphere.
- Vertical glazed pane orientation for winter solar gains.

- Extensive glass oriented East over South, (North in the Southern hemisphere) to west will risk overheating of internal building spaces in springtime, summer and autumn. Cooling demand would be required in a moderate climatic region. (Hens, 2011)

This performance is conceptually acceptable for colder climates where daylight admittance is important. However, in warmer climatic regions of strong direct sun light, regulation and moderation of solar radiation to control thermal transmittance and day lighting, these glazing solutions are mechanically weak. Radiant glazing without day lighting controls are mechanically suited to cooling climatic regionalization. In climatic regions of high thermal transmittance and solar glare, active or passive solar shading are required. However, despite performance driven design in optimization of these systems, artificial lighting efficiency has an impact in energy consumption efficiency on net energy demand. This represents significant challenges in the development and refinement of these systems as an integrated transparent façade approach, as in the New York Times Headquarters (Fernandes, 2013).

2.15 Thermo-Chromic and Electro-Chromic Systems

Smart nanotechnology coatings have been developed to provide dynamic control of windows in balancing thermal control, day lighting and glare to reduce cooling demand loads. These are based on two technological methods:

- Thermo-Chromic – temperature activated
- Electro-Chromic – electrically switched

These solutions offer enabled flexible optimized solar radiation moderation of solar gain and increased use of day lighting potential by nano film technology, shown in Figure 2.10.

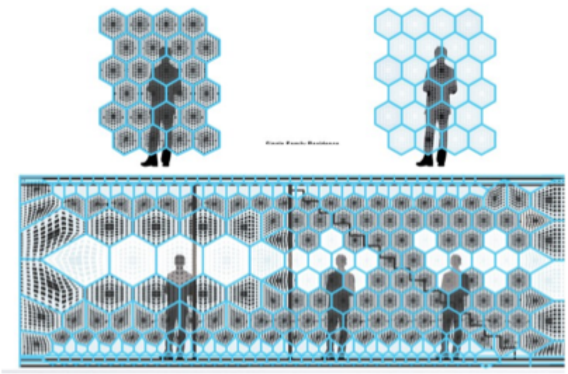


Figure 2.10 Switchable Light and Heat Sensitive transparent Glazing (http:// info@sageglass.com)

Electrochromic oxide film materials have electrical conductivity ions to enable changes in the transparent properties of glass by the influence of an electric field and then return to the original state once the field is reversed. A five layer thin metallic coating comprised of nickel, tungsten oxide between two transparent electrical conductors gives switchability function for optic change to control solar radiation. The employment of crystalline tungsten oxide film makes this surface infrared reflecting/adsorbing (Granqvist, 1995) creating an electrochromic that can self-colour when exposed to sunlight. This is active solar control linked to sensors and building automation systems to respond to external temperature to enable dynamic switching response to maintain thermal comfort conditions. This switching functionality is effectively dimming of the transparent glazed façade to change material transparent properties.

However, both thermos-chromic and electro-chromic transmitted light does have a tendency to scatter (Granqvist, 2014). As a consequence of using the current technology, buildings consume significant level of energy [over its life cycle] due to the increased artificial lighting levels to compensate for the loss of natural lighting and the reliance of AC systems to cool the buildings (Paceco-Torgal et al., 2013).

These dynamic electro-chromic and thermo-chromic glazed panes of switchable transparency are currently in an experimental stage. The application of this technology is sporadic. This is due to durability, lifetime costing and reliability response time switching speed (DeForest, 2015). Nano film switchable technologies are solutions for advanced glazing, however, performance and costing are issues that are affecting market acceptance.

2.16 Automated Solar Collectors, BIPV Photovoltaic Modules

Energy generating façades with integrated services technologies have been developed. Photovoltaic glazing offers both electrical energy generation and solar screen shading as a method to regulate total heat gains (Fung, 2008). The area of the solar cells has significant effect in the reduction of radiative heat transfer for solar modulation into internal room areas. The majority of the cells are mono-crystalline silicon wafer (c-

Si), a technology that was developed for semi-transparent solar cells on glass. At present however the investment cost to output efficiency and life span durability present challenges for application. Development into solar thin film cells, has improved photovoltaic efficiencies and offer potential for future application in glass pane multi -layered assemblies (Green, 2003), figure 2.11.

Figure 2.11 SoloPane l® SP1 second-generation, flexible photovoltaic module, Solopower.

This façade system approach of integrated building service provision does, however, have higher maintenance costs due to the increased number of decentralized modules that form the transparent envelope. This technology is driven by an integrated system to respond to thermal comfort conditions by active sub component element reaction to solar gain. Building Integrated Photovoltaic (BIPV) is the module integration of PV that are fabricated into a laminated glass layer of overall area 20-70% generally, as an active electrical generating and shading element. Automated shading blinds are in some cases integrated into the module system to give further solar radiation protection from glare, self-powered by the PV power production. The system configuration can be characterized by PV cell generation, day lighting to reduce artificial lighting, cost and glare reduction in connection to comfort conditions, presenting differing optimal system configuration, shown in Figure 2.12.

Figure 2.12 Spandrel BIPV and PCM Panel: an Energy Generation Façade Module (Image courtesy of **LNEG** - National Laboratory on Energy and Geology, Lisbon, Prof Laura Aelenei).

BIPV enables real-time response actions for capture and storage of energy as an integrated approach for energy generation and solar shading. PCM (Phase Change Materials) store this generated heat energy as a thermal battery. This storage of heat gives management of energy as an automotive process via heat recovery methods (Aelenci et al., 2014). PCM have also been integrated into glazing via cavity injection to enhance U- value and g value to enable greater light transmission levels. Experimental testing was undertaken to reduce air leakage, cooling demands and heat transfer. Energy consumption using this integrated façade reduced energy consumption by 60% than that of a static curtain walling stick system for a Danish climate. Hence the area of glazed fenestration can be increased from the present 20% static façade to 90% with an energy consumption of 38 Wh/ m²/ year, (Lui et al.,

2013) Figure 2.13. Below is the experimental test Cube module at Aalborg.

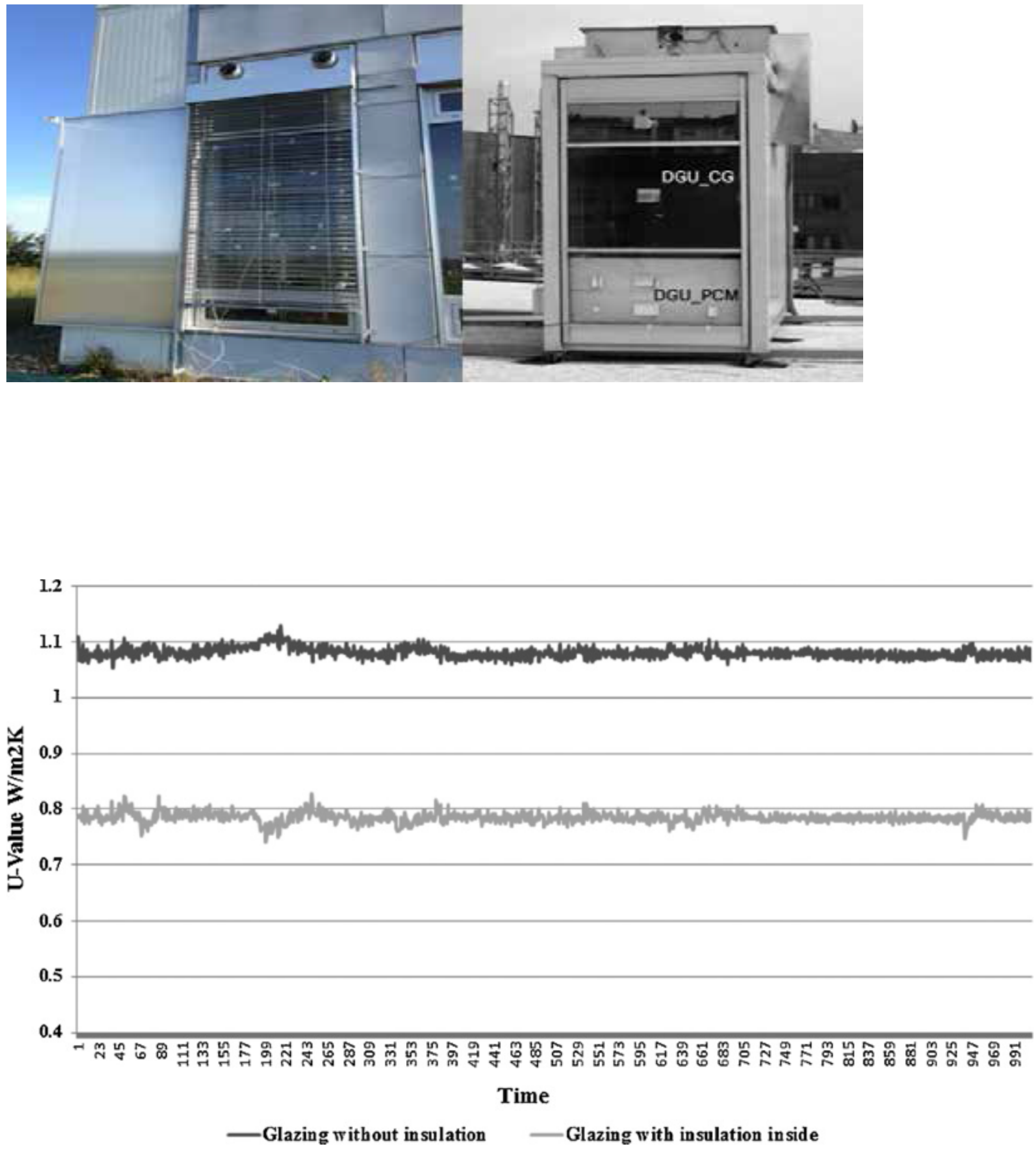


Figure 2.13 Integrated Façade Module with PCM Glazing Design (Lui et al., 2013).

The experiments indicated night-time insulation was 30% lower than a curtain wall static façade as illustrated by the U value graph. This experimental module achieved reduction in cooling demand and reduced night cooling, reducing heating demands.

Light transmittance and glare were controlled by active solar shading measures. The experiment did not undertake heat loss and gains as an operative façade linked to building control service strategies. However, this experimental façade does provide concepts for achieving greater energy reduction for cooling and heating boundary conditions. The performance potential of these energy generation and heat transfer intelligent modules are strategies of holistic control to regulate solar radiation input loads. This is operational energy generation that is dependent on high levels of thermal insulation to change performance behaviour in real time. This is achieved through reduction in heat loss to ambient temperature as an energy balance (Jelle, 2015). Reduction in cooling loads generated stored energy for module power unit supply with the benefits of increased day lighting to replace artificial lighting, shown in Figure 2.14.

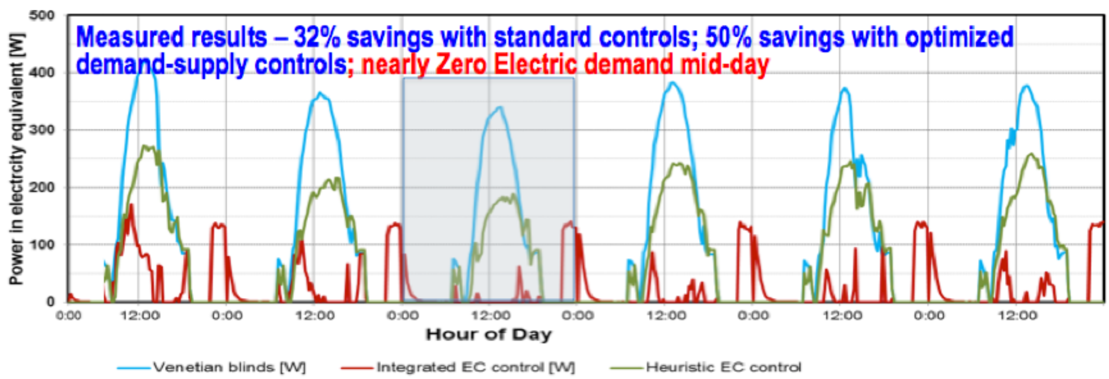


Figure 2.14 Advanced Façade Test Facility LBNL (Lee et al, 2009)

Figure 2.14 shows the experimental testing data results from the Lawrence Berkeley National Laboratory measuring the loads with smart controllers for integrated façade with PV and electrical storage for façade behaviour control. The three systems that were tested are:

- Venetian blinds W (blue) - façade with interior automated blind controls.
- Integrated EC control (red) – PV cells energy generation / storage and control activators and sensor mechanisms
- Heuristic EC control (green) – electrochromic window with sensor controls.

The data clearly indicates electrical load can be obtained to near zero during a 24-hour period in a commercial office building in meeting electrical demand requirement. Schüco E2 Façade is a prototype intelligent façade developed by Schueco R+D department, shown in Figure 2.15. This integrated building service façade incorporates decentralized ventilation, low e nano coating technology, active solar shading and PV cell energy generation.

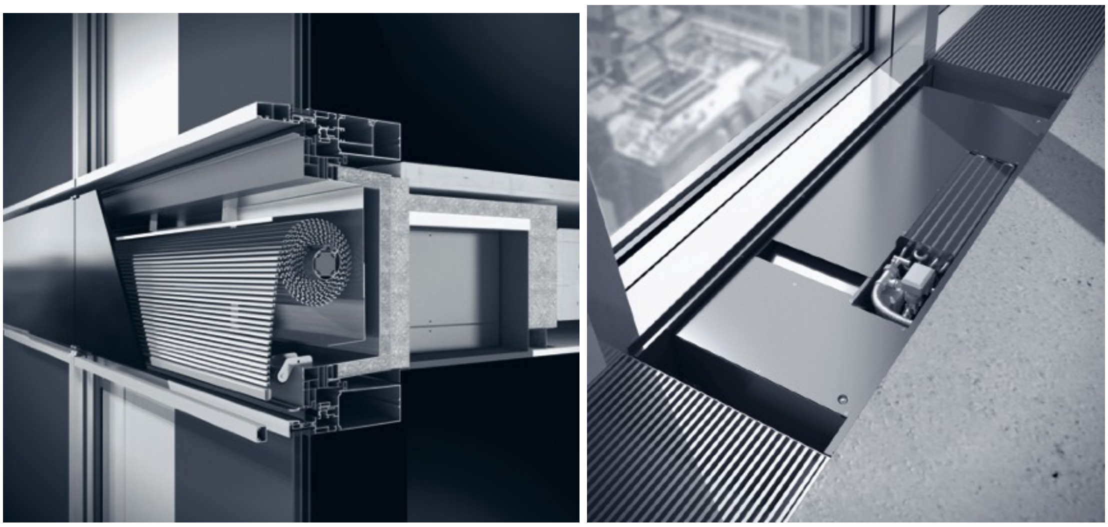


Figure 2.15 Intelligent Façade, Schueco Prototype (Illustrations from © Schüco E²-façade system, Schüco International KG)

This prototype was developed by Schüco and computation analysis estimated the module ventilation system could achieve 30% in energy costs saving compared to conventional air ventilation strategies. However, this BIPV module façade, has not been put into production and remains as a façade concept.

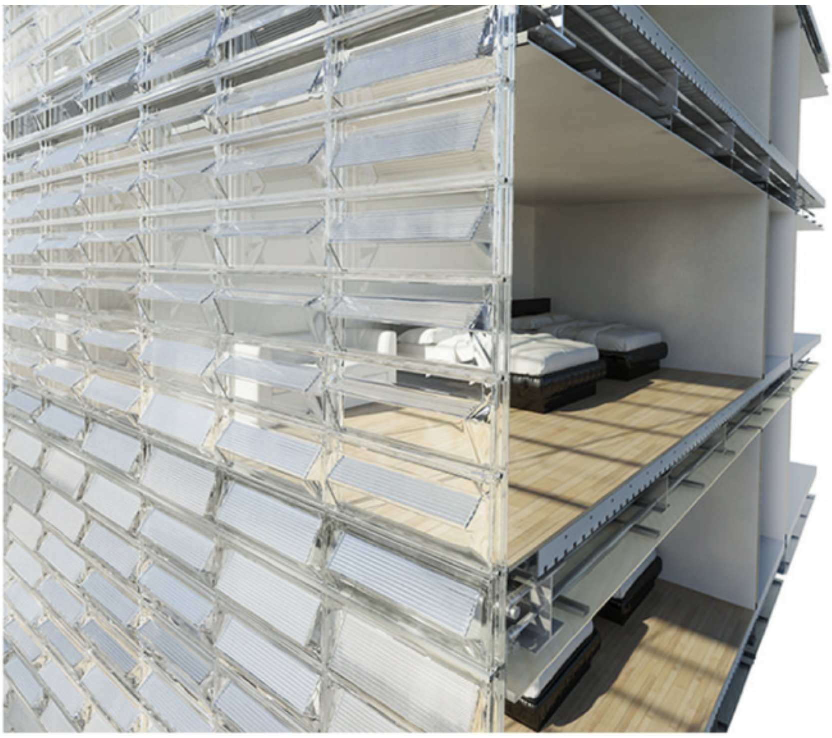


Figure 2.16 Integrated Technology into the Glass Façade Envelope, (http://www.som.com).

This schematic diagram, shown in Figure 2.16, illustrates the principles of a consolidated building service approach to optimize thermal comfort and energy demand reduction by integrated performance function as a system of controls. This is achieved through admission of desired incoming heat load and rejection for thermal unwanted heat load for building occupants comfort. However, integration of façade building service modules into a holistic service provision are founded on curtain walling stick system construction. This systemization approach of module integrated building services has of this date, not been implemented into large-scale transparent façade applications. This is predominantly due to performance complexity of decentralized modules and the maintenance of such systems. It is also due to the foundation basis of this integrated service approach, reliance on a large number of parts that are derived by curtain walling (stick system) as its template for module façade construction.

2.17 Kinematic Façades

Kinematic façades provide buildings with the flexibility to vary solar energy transmittance by acting as a solar radiation shield. This flexibility is achieved through adaptive performance to variable climatic conditions, for the benefit of building occupant preferences by decision-making response. This is an optimized design concept of real-time varying behaviour of a dynamic envelope for low energy building operations. These systems use actuators to activity manipulate structural components elements by rotation and force transfer in response to solar orientation, as shown in Figure 2.17. The structural configuration mechanism, is controlled by light sensors and a building information management system (BMS). This transformative structure will respond to solar radiation, active wind loading and climatic solar variation by structural configuration manipulations.

Figure 2.17 Kinematic Mechanism (http://www.stylepark.com/en/architecture/the-intelligent-façade/303779)

These transformative structures of controlled movement respond to solar orientation directly linked to sun path tracking, by a ridged structure that changes in geometry by volume to reduce irradiance directly entering the building interior spaces. This array of component elements acts as an active system that changes in geometry formation that indirectly influences solar interior comfort conditions, shown in Figure 2.18.

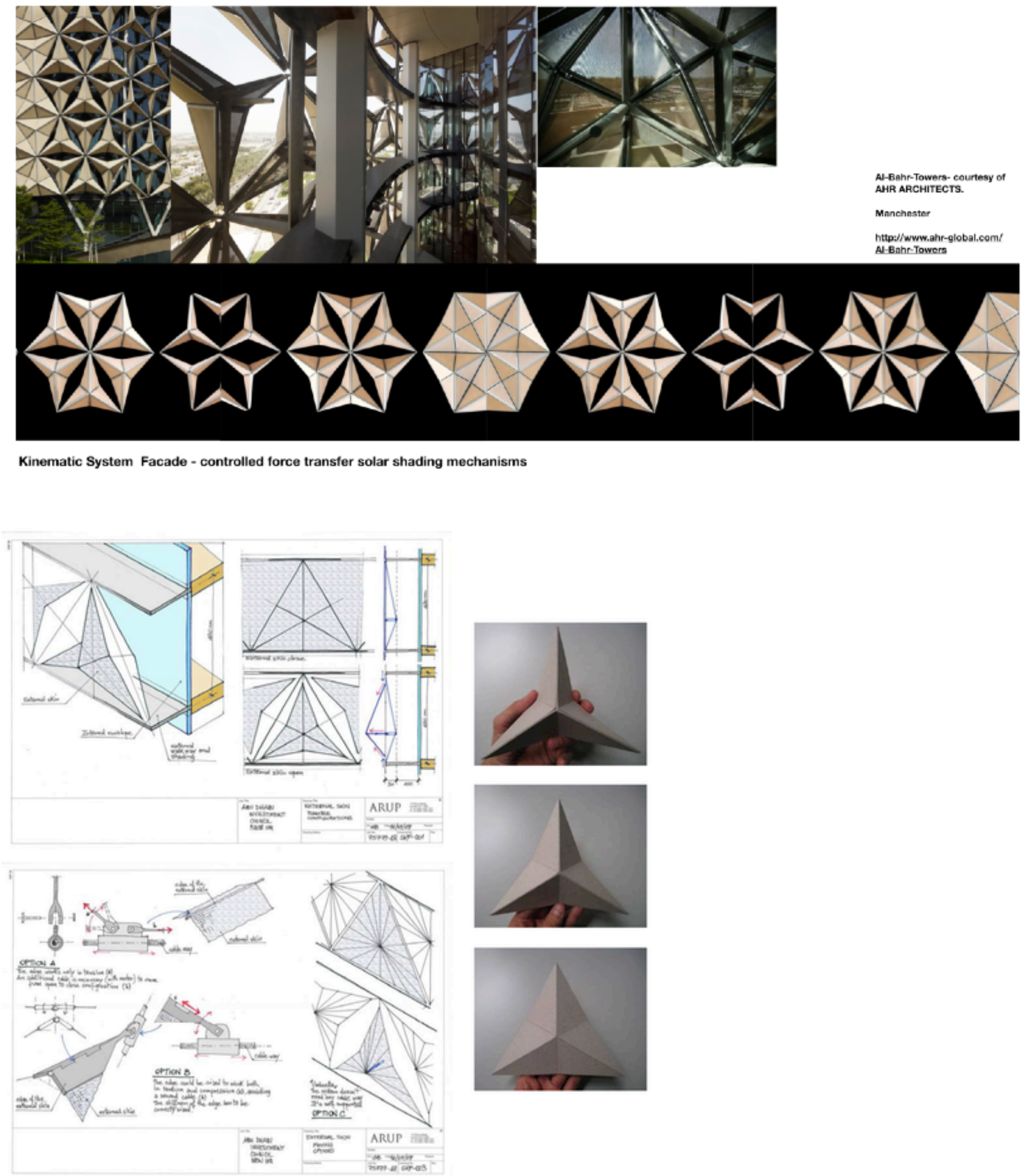


Figure 2.18 Adaptive Façade (Louter et al., 2014) http://www.ahr-global.com/Al-Bahr-Towers.

This time variable behaviour performance mode is supported by computational software that directs the system structural mechanism responsive movement in relationship to internal heat load temperature. Other methods have been investigated, although to a lower success rate than this solution. Institute du Mondu Arabe proposed a solution of moving mechanisms located within the cavity space between two panes of glass to act as a solar radiation control system. This system utilized a metal array of moving iris shutters that are controlled by pistons and associated rods to control iris apertures (Adriaenssens et al., 2015) shown in Figure 2.19. This system method to achieve solar modulation was difficult to maintain consistent operation, due to the complexity of the shutter mechanism modes, most, if not all have failed to work.

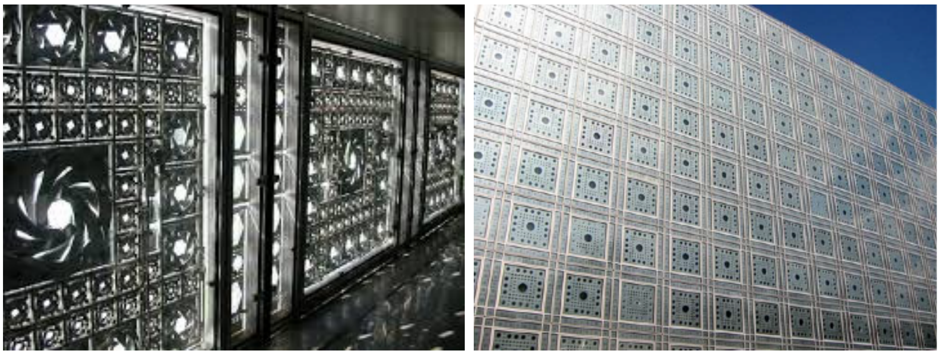


Figure 2.19 Institute du Monde Arabe, Paris. (https://www.pinterest.com/pin/507499451745237573/)

This form of responsive diaphragm shutter shading represents significant challenges as this solution form finding geometry of active solar shading needed to be examined to building façade functions to specific climatic classification (HDD). The geometry systems interact and respond to the surrounding environment (Lazarovich et al., 2011). These climate adaptive building shells (CABS) depend on real-time configuration changes by complex operational condition modes that are required to change and predict comfort conditions and retain performance robustness (Loonen et al., 2013). This proposal is not a holistic solution for global application, as it represents a high-profile building typology with a high budget requirement. By achieving the reaction response aims of solar control can be gained by simpler approaches. An alternative approach is a panel movable sun shading systems that will actively adjust for near maximum daylighting. To reduce unwanted solar gain by screening or absorption to reduce cooling load in summer and benefits of solar heating in winter. This controlled active adjustment to seasonal solar variation will reduce room heat gain for cooling seasons demands and glare. By adding the application potential of a solar screen to the insulated thermal glass layer, enhances solar protection to transparent façade, figure 2.20. The use of a highly reflective surfaces will increase daylight reflection and reduce radiation heat transfer, (Schittich, 2006).

Figure 2.20 , Coloured glass solar screen (Schittich, 2006)

Opaque shading systems have been employed to act as a control system to regulate and limit solar gains through movement. These solar shading systems of lamellas, fins or panels are extensive (aluminium, textiles, laminated timber, etc.). However, for this case study, the focus is fibreglass reinforced plastic by a manufacture Flectofin. A kinetic fin system that activity induces torsional bucking, to induce bending (fin movement) through elastic deformation of the fibreglass, by a small compressive vertical force (Knippers, et al, 2012). This system removes the need for complex sliding joint systems, hinges and extensive part assembly for kinetic movement. This shading system was applied by Soma architects; Thematic pavilion Expo, 2012, figure, 2,21.

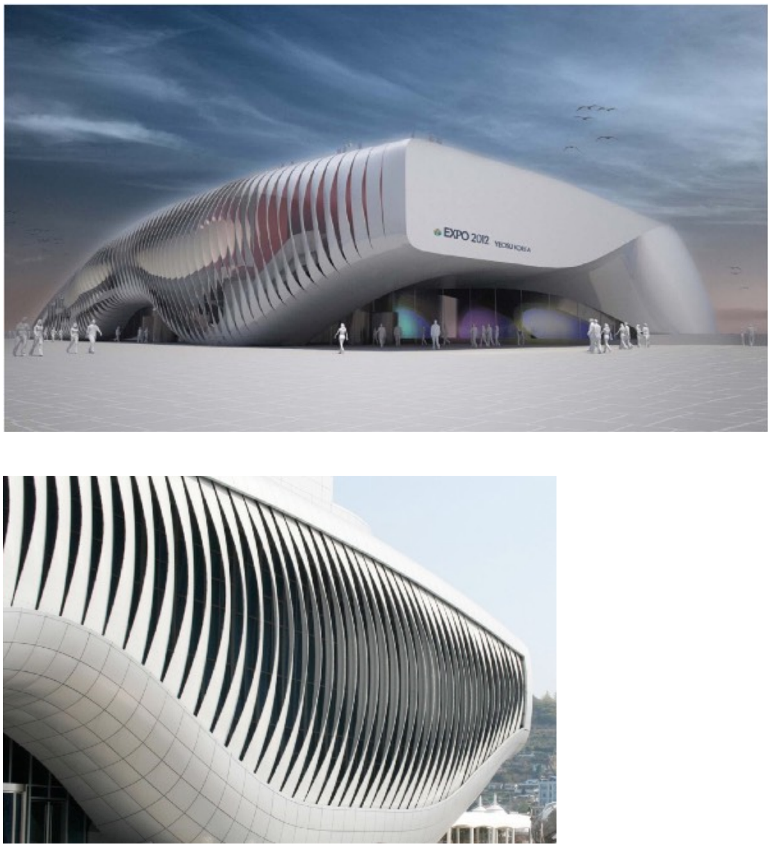


Figure 2.21 Thematic Pavilion EXPO 2012, (Knippers, et al, 2012)

This shading system of curved fiberglass-reinforced fin plates ,9mm thick, moved when an applied vertical load induced bending to create the curved facade open geometry, figure 2.21. However, the amount of daylighting that is diminished and the requirement for artificial lighting demand is a limitation to opaque system by the maximization sun light in transparent facades.

These flexible mechanical systems respond to real-time changes in solar orientation by geometry movement tracking to reduce direct IR into building interior spaces. Structural shading modules use dynamic response geometry configuration change by described predicted performance. However, this defined adaptability of these mechanisms requires maintenance performance robustness during building life cycle. The resolution of this geometry design requires a relational engineering approach and this should be judged to energy related constraints. By the performance requirements of minimum effective power flow, energy loss, minimum geometry change for maximum solar radiation shading. The resolution of the system must be driven by rational engineering approaches in connection to energy related use and energy consumption reduction. The structure of adaptive solar shading is prone to trapping of hot air between the shading solution and the glass façade, increased wind loading to the structure and regulation of water run off present challenges. Hence, adaptive solar geometry application remains restricted to high profile, high building budget projects. The question remains of whether static solar shading approaches could give greater value in return than these solutions, shown in Figure 2.22.

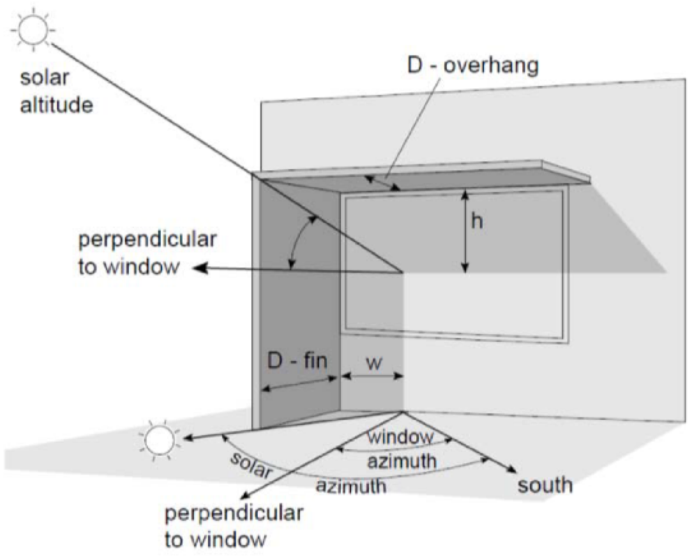


Figure 2.22 Static Solar Shading (U.S. Department of Energy, Lawrence Berkeley National Laboratory, 1997)

2.18 Micro Algae Systems (Solar Shading)

A solar thermal collector project was a collaboration partnership of Colt, Arup, SSC funded by Zukunft Bau who developed a flat panel collector to absorb solar radiation as a photo bioreactor to generate energy, shown in Figure 2.23.

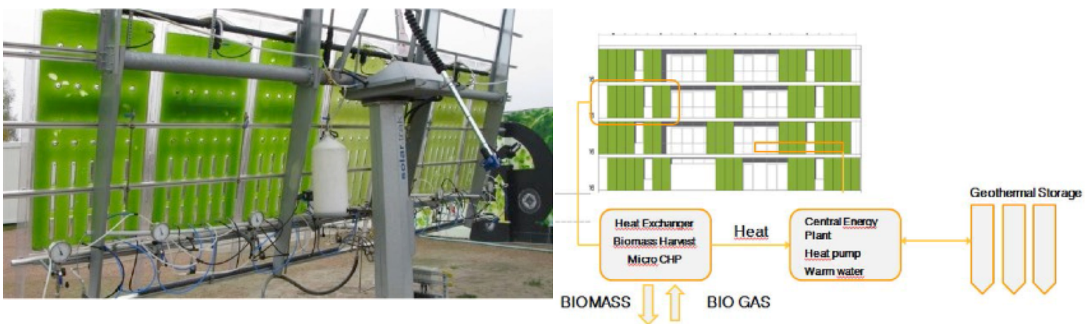


Figure 2.23 Plate Panel Micro Algae Collector (http://www.arup.com/projects/solarleaf)

Solar-Leaves use micro algae suspended in water that is in a circulative flow distribution system to enhance the ability to capture solar radiation to generate energy. The fast-growing algae is used as the primary source for biomass thermal generation, shown in Figure 2.24.

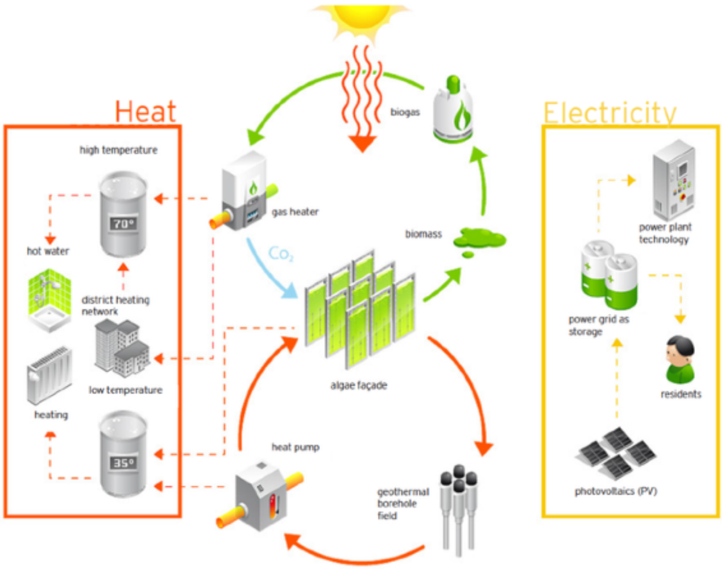


Figure 2.24 Algae for Biomass Thermal Generation, (IBA Hamburg GmbH, 2013)

Each panel size was a height of 2.6 m, width 0.7m, water volume area 24 liters and a water filled weight of 200kg. The envelope acts as an energy system to generate electricity and thermal energy for the use within the building. This is achieved by the algae acting as an absorber of solar radiation for growth that is contained within the water volume. This thermal energy is gained by heat exchanges that is used for hot water demand or diverted to geothermal storage. Harvesting the micro-algae from the water volume through drying acts as the primary source fuel for generated electricity by a microCHP unit. This combined heat and power unit is the primary heating system and also generates electrical energy (via exhaust gas, turning a turbo fan unit) for the BIQ building. Efficiency of the system in terms of thermal energy for hot water heating is 38% efficiency. Space heating by the biomass microCHP achieved an efficiency level of 8 - 10% with 80% of the biomass is converted to methane due to the progress of microalgae drying conversion from a ‘liquid’ state to a ‘solid’ state for CHP fuel (IBA Hamburg GmbH, 2013). The biogas (methane) is supplied into a district heating system.

Algae systems do present an interesting solution for an integrated energy harvesting and storage for an envelope. The prototype IBA is very dependent on an organic living material ability to modulate solar radiation within an active flowing distribution system, for solar shading absorbency. This engineering solar liquid panel solution follows a similar path to liquid filled windows and the associated issues that follow.

2.19 Liquid Filled Windows

Research has been undertaken to introduce fluidics into windows. This investigation focused on using the cavity void between glass panes, by infusion of water by conductivity absorption of solar radiation, as shown in Figure 2.25.

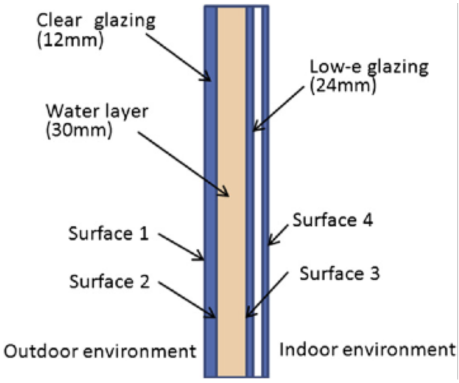


Figure 2.25 Liquid Filled Solar Glazing Design (Chow et al., 2013).

Figure 2.25 indicates the glass configuration of the water layer to reduce transition temperature. The research indicated water flow gave cooling of glass surfaces by naturally flowing upward buoyancy and extraction of water for heating applications (Chow et al., 2011). The use of water enabled higher conductivity for effective window cooling designs in warm climates (Chow et al., 2013). Findings indicated absorption of heat energy from solar gain was achieved. Hence, indoor heat absorbency by thermal convection and radiation exchange gave a temperature difference of 10 degrees between the inner glass pane. Water flow in the experiments was set at 200 ml/min with the greater efficiency gained in higher incidence of solar radiation for working efficient conditions. However, the lack of fluidic flow management within the free-flowing volume resulted in flow turbulence and water movement uncontrolled by gravity. The introduction of a liquid within the previous air cavity space, changes the U value in a dynamic way. The water is acting as a heat absorption medium in connection to specific heat capacity and for water this is 4.18 KJ/L. However, the water is subjected to variation in solar radiation impact due to window surface exposure. This created variations in temperature within the water volume between the two glass plane surfaces. The water itself will be subjected to liquid expansion by thermal solar heating and this has led to bowing of the glass panes by liquid expansion. This is a structural issue but also more an aesthetic one.

FluidGlass prototype (5.1 million euro) project was developed by a team from the University of Applied Science and Technology in Switzerland ,University of Liechtenstein and the Technical University of Munich. The project aim was to enhance the control of solar transmittance through a solar absorbing fluid. This fluid of anti-freeze and metal particles was contained within two fluidic chambers , 2mm width, within a triple glazed unit. The configuration was determined by the two fluidic chambers acting as absorption layers to regulate solar radiation that were thermally detached by krypton gas, figure 2.26.

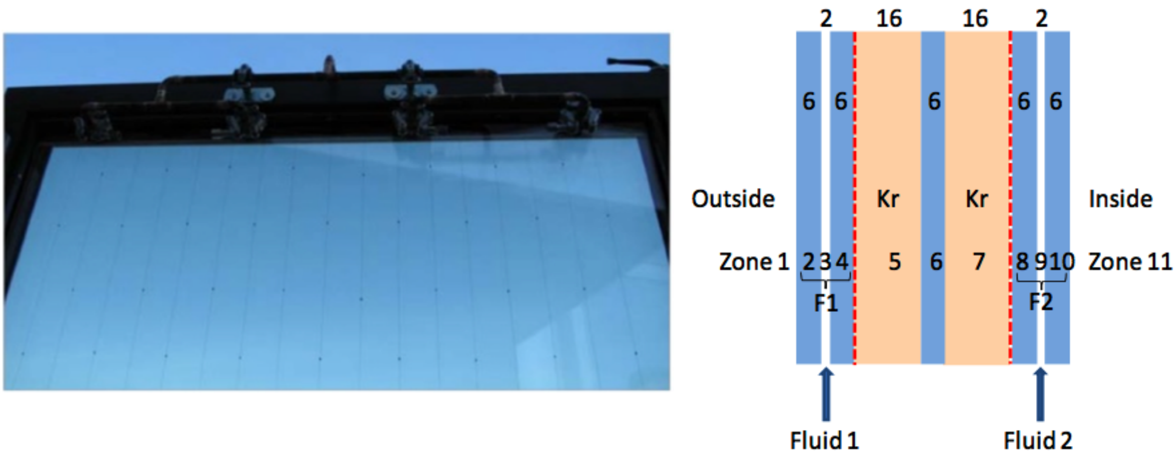


Figure 2.26 Glazed unit configuration , FluidGlass (Stopper et al.,2013)

This triple glazed unit composition is comprised of 6mm layers of clear glass (Planilux) to zone; 2,6,10 and Low-E coated glass Planitherm One to zone; 4,8 that were thermally isolated by a 16mm voids of krypton gas. The fluidic chambers are to regulate energy flows through a window to achieve potential benefits of net-zero heating and cooling (FP7/2007-2013). The research demonstrated optimized results in a dyed metal particle anti-freeze fluid ,through the reduction in cooling demand energy , 39%, through the passage of the fluid in the outer chamber by reducing solar gain. The dyeing of the fluid actively enhanced solar thermal absorption and temperature raise of the fluid chambers. A different approach to multi-fluidic chambers was determine by a double glazed unit with a configuration of 3mm glass panes with a fluidic chamber of 8mm volume filled water. The fluidic extract and supply was connected to a hot water storage tank. The proposed energy exchange system was a pre-heating circulation of water by solar gain to increase cold water temperature for domestic use. For energy consumption reduction in cooling demand and supply of hot water. It was observed the water chamber reduced the in-door temperature to 26.14 C in comparison to convection double glazed air filled unit of 37.72C at summer solstice (Lopez et al, 2012), figure 2.27.

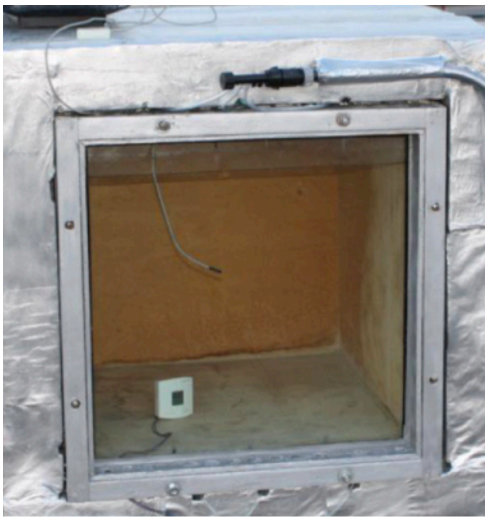


Figure 2.27 Water Chamber glazed unit , (Lopez et al, 2012)

This circulating volume filled chamber reduced thermal heat gains through energy capture in water by temperature raise. The critical issue of water chamber approaches is flow velocity rates; this was considered to have great impact on the effectiveness to enable reduction for internal cooling load by fluid heat removal. The associated weight of a full volume, water cavity fill dramatically added to the structural loading of the external wall. Hence, for a single window within a wall this could be contained. However, applied to a tall building with dynamic structural forces, wind pressure force directions, air velocity, frequency wind range, temperature differential and gravity the effectiveness applied to this building typology is reduced. Full volume water cavity window configuration has not been applied to floor-to-ceiling height glazing certain walling. The complexity of applying this to conventional curtain walling assembly components, frames, mullions, waterproofing gaskets and drainage channels would be considerable.

This solution approach of a thermally functional window developed through a fluidic platform offers attractive characteristics for this research. This is a fluidic flow focus system of transparency. This research into liquid filled windows has established water acting as an IR absorber gives attractive properties in visible transmission and solar modulation. This system is characterized by using volume filled water as a method to modulate solar radiation by water flow rate between glass panes assemblies. By modulating flow rate in the window, the system is able to change solar absorption rate through heat transfer. This thermal switching function has the ability to capture solar radiation and store the thermal heat gain (in the liquid) acting in real time response to solar loading. These approaches in window development as a switchable energy capture and storage system progresses desired functionality for window design. The transparent characteristic of the window was retained that was lost in micro algae systems.

However, volume filled water thermal fluidic expansion through solar radiation heat transfer and glazing deflection of the water under gravity presents challenging issues for this research, which remain unresolved. The liquid contained within the glass pane structure adsorbed solar radiation at differing absorption rates and this is due to solar exposure. This difference in temperature, through natural heating buoyancy created temperature variation in the liquid volume. This variation in temperature heating and decay increased thermal expansion issues and diminished control of the liquid volume for solar absorption optimization. The volumetric weight of the liquid within the assembly is significant if applied to floor-to-ceiling glazed façade engineering that further reduces the application effectiveness.

2.20 Conclusion

Building fabrics are vitally important to reduce energy demand in buildings through different kinds of technological solutions that have been developed in order to respond to the increasing requirements for improved performance. These suggested technologies include external thermal insulating systems, hybrid facades, double skin glass facades; solar shading; passive solar energy systems and active solar collectors, photovoltaic modules. The technical energy measures are determined by solar insulating systems and a selected range of what is under development to progress glass facade optimisation to deliver energy - efficiency has been investigated.. A global initiative is to advance optimum glazed façade system performance in meeting rigid prescriptive building codes. The integration of building service provision into glazed assembly has progressed indoor thermal comfort provision by technological component application. However, the ability of these façades to interact with the environment by constant readjustment of functional performance is still unresolved. There is a chasm between present code compliant glazed façades determined by a static value of performance, u-value, based on measures in the reduction of thermal conduction, to what it could be.

In order to meet the demanding Zero Energy Building performance goals, an envelope must change its role from that of a static element to a dynamic element, since performance requires change by the hour, season and weather conditions (U.S.A Federal Research and Development Agenda, 2008) US Department of Energy. The integration of technology into various glazing systems to provide better effective management of solar radiation are in the market place. A selected range of these transparent system have been reviewed to assess the control process methods to reduce solar loads for thermal comfort, through minimizing operational cooling and artificial lighting levels. This system oriented design approach is however static in response. These systems are unable to fine tune operational performance to solar gain in real time, for environmental comfort and well-being of occupants.

The capacity to respond in a dynamic manner to the physical changes of a warming climate is the challenge to advance new and innovative transparent material solutions. To move towards occupant comfort and well-being that is not based on statistical averages but one that is fine-tuned to responsiveness to change. This is the approach of nature that have developed adaptive functions. The proceeding Chapter 3 researches 'Natures Materials Characterization' to generate multi-functional materials with unprecedented levels of complexity and precision tailored to dynamic environments.

Chapter 3 Nature's Characterization of Functional Materials

3.0 Introduction

This chapter will review the application of nature's characterization of materials by methods to control material assembly and functionality by hierarchical strategies. This is the central mechanism for self-assembly of these materials without a blueprint.

Nature generates materials with defined parameters to move neighbouring atoms within and between materials at a micrometer or nanometer levels. This interface reaction between different materials is driven by chemical composition and temperature with unprecedented levels of complexity and precision, called deoxyribonucleic acid, or abbreviated to DNA. DNA is the central cell of all mammals that emerges from a singular pattern to create three-dimensional networks of diverse formation. The complexity of formation is defined by the hierarchical level to determine the developing organism structure and characterization of function. Nature monitors temperature gain and decay to evaluate heat flow at an atomic level. This is a thermal measurement system of precise modulation response as a dynamic reaction system, as in the human body, (Grey,2012).

This approach to control the structural complexity of a material function is a heat flow targeting theory that is aligned and oriented to nature's characterization of materials, a cell. By nanoscale thermal monitoring temperature with time as a measurement system. Achieved by hierarchical precise rule orders, to define material function in response to microenvironments. This is a bottom up approach to direct and sculpt the controlling process of a material function. These are desirable properties to rethink the metrics of glass façades function through a biomimetic research approach.

Biomimicry is a principle of research into biological sciences to derive novel systems for new technological outcomes. Sarikaya states this drive in the assembly of synthetic materials as a 'Revolution on par with the Iron Age and industrial revolution. We are leaping forward into a new age of materials' (Sarikaya et al., 2003).

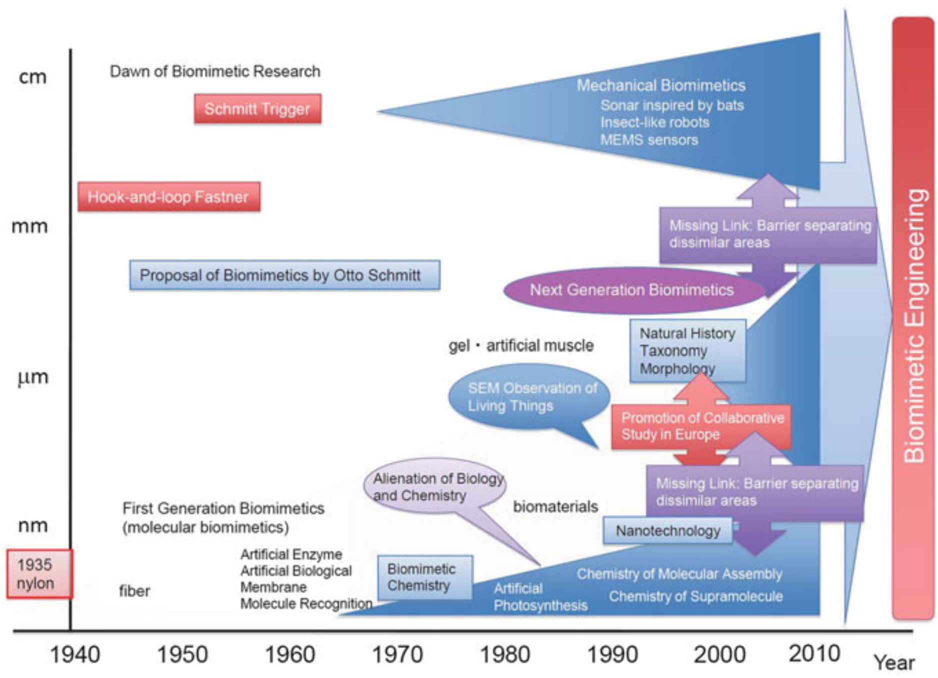


Figure 3.1 Biomimicry Research Impact (Shimomura, 2010)

Nature has evolved the functional characteristic of materials to perform strategic tasks. These materials have emerged through hierarchical self-assembly from nanoscale components to determine composite structure. These structures can absorb solar radiation with minimum energy loss. The capture of solar energy is driven by vasculature formations to regulate material composition for photosynthesis reaction, a leaf. Each leaf is a single unit acting within a transformable daylight capture system, a tree. This is characterized by autonomous self-healing and intelligent surfaces.

This chapter provides a review of the physical mechanics of nature's hierarchical ordering characterized in monitoring heat loss and decay at an atomic scale. The understanding of heat transport within and between material layers at a microstructure level would advance heat seeking targeting materials. Molecules have the ability to manipulate the environment as they grow to sculpt this function for tailoring itself to a dynamic environment. These biological systems represent networks that obey rules to determine minimum energy loss and minimized effective power outputs, a leaf. The question is, why is this characterization of function not emulated in man-made transparent envelopes?

These optimization functions of temperature with time are represented in the built environment. Thermal flows in buildings follows a similar pattern and are dependent upon conduction losses, ventilation and infiltration loss i.e. air leakage, solar heat gains and heating system efficiency. The building envelope skin is characterized by boundary conditions in relationship to solar orientation, thermal contact conditions between component layers, climatic / micro-climatic conditions and heat-air-cooling properties (Eames et al., 2013). Current strategies for glazed façades are determined by a static response defined by a single prescriptive value. This code prescriptive requirement diminishes the ability of a glazed façade to interact with the environment by constant readjustment of performance (Wackerernagel et al., 1999). This is a knowledge gap: between present code-compliant glazed façades, based on measures in thermal conductance, to what it could be. Glazed façade envelopes remain energetically weak to deliver higher U values and minimized effective power outputs.

The challenge in the field of glazed façades design is the ability to direct the assembly of advanced transparent materials for desired energy capture and storage. To understand the functional principles of nature, in energy transport flow management will progress the current static response in transparent materials to a dynamic one. That is determined by hierarchical rule based orders defined by steady state theory, in the control of solar heat load. Nature has developed heat seeking materials that are multifunctional, to regulate and measure nanoscale thermal conductance. Ecosystems on this planet are evolving systems as they learn, defend, communicate, and protect themselves by the mechanisms of synergy to environmental influence (Page, 2004). Biomimicry approaches would progress new material assembly as we are currently hindered by our ability to control functional materials due to the lack of understanding of structural complexity. Nature uses solution chemical composition fluidics to form and sculpt three-dimensional forms, in sea shells, for example. At a molecular chain level, nature has developed materials of complex self-assembly, self-ordering, governed by a rule based system of intelligence, a cell.

Nature develops materials that are multifunctional, mechanically fluidic systems as leaves. Leaf vasculature is characterized by hierarchical material functionality, to regulate material composition in response to solar radiation capture. These multi microchannel networks self-adapt to changing ambient temperature by functional fluidics of chemical composition for solar absorption. These nanostructured materials are aligned and oriented for desired functionality. Embedding leaf morphogenesis into materials has significant advantages for material innovation to act as an energy capture and storage system. The understanding of nature and the engineering mechanisms to control material properties by biologically inspired principles would advance material knowledge.

This chapter will gain insight and propose a strategy for developing a transparent thermally functional material. By review of nature's desired morphology in functional materials at a nanoscale, that presents an unprecedented level of complexity and precision.

3.1 Nature's Approach to Material Ecology

Nature has developed organisms that are in real time sync with the pattern changes in their environment. This is driven by the requirement for the research of water, food, oxygen and proliferation as an ecological system. Ernst Haeckel (Haeckel, 1900) defined ecology as a study of the natural environment through the relationship of organisms to each other and their surroundings as energy, matter connection.

This is a multi-level relationship approach both as a physical connection to the environment and species-specific self-adaptive alignment to geographical location whether in water or in air. Allen and Starr defined this multi-level approach as "a number of levels of resolution with different spatial and temporal scales" (Allen and Starr, 1982).

Nature uses material properties of structural alignment to organism function in connection to their environment, by mechanical material performance tasks, to deliver through multifunctional structured material properties. These tasks are defined by the following parameters, as classified by Chen et al, (2012), under fracture / impact resistance, defence / armour, cutting edges, aero composites and bonding:

- Fracture and impact resistance: Fracture toughness mechanics is connected to bones that are a composite material composed of protein, mineral and water formed together to assemble a hierarchical ordered structure. This structure has a number of functions to support a body, protect organs, create blood cells and act as a mineral storage system. The structural composition of a single bone element changes in response to bone geometry location. Changes in bone density are determined by linear elastic fracture mechanics for shear strength of fiber ligament bridging in relationship to structural loading resilience to geometry location within the bone element.
- Defense and armour: these materials predominantly relate to marine life for defensive shields, protective coating and flexible armour in fish and mammals. The mechanisms of growth are determined by chemical deposition of aragonite or calcium carbonate by formation of a single crystal (or hexagon) tile that is oriented in a horizontal axis to create an organic layered structure

called mesolayers. These microstructure mosaic crystals form complex cross laminar sheets of multi layering built up to form a composite structure.

- Cutting edges: nature uses sharp edges and tooth serrations for protection and as a defensive mechanism in a number of diverse pattern formations in plants, insects, marine environments and mammals. These organic materials have a material strength and hardness that can be equivalent to stainless steel in some species.
- Aero composite material dynamics have unique properties through the combinations of strength and density that are associated with flight. This is achieved through feathers and skeleton lightweight structures. Feathers perform a number of functions, thermal insulation, water resistance and enable powered flight. The formation of a feather is centered on the primary structure represented by the core shaft that creates the central spine to support the birds in a herringbone pattern. This central core material is a sandwich construction to enhance maximum flexural strength to weight as a quantitative relationship. The surfaces of the shaft change in composition from a smooth surface to roughness topography, to decrease air flow drag for energy conservation. This surface change in topography is created by melanin, as this influences stiffness to leading edge airflow surfaces. The internal structure of the central shaft is composed of axially oriented cellular foam comprised of fiber interconnecting filaments to increase stiffness and fractal strength. Skeleton lightweight structures in bats and birds for flight is dependent on species, however in all it represents 7% of body mass. This weight saving is gained through less dense bones. The structures of the bones have increased mechanical properties in

comparison to non-flight skeletons. This is achieved in part by the interconnecting reinforcement struts within the hollow bone structure. These internal ribs and struts provide additional strength and mechanical stiffness with associated weight reduction. The bone chemical composition has additional strength by minimal contact of the bone for the requirement of landing and take-off.

- Bonding and attachment to surfaces in nature is achieved by chemical / mechanical processes that are applied in a number of differing environments. These environments range from marine life, shells, (mollusks), mammals that can climb vertical surfaces (frogs, lizards) and insects. The mechanisms to attain this function are determined by interlocking of a physical mechanical attachment (a plant seed temporary connection to a host), friction (surface toughness topography for chemical forces attachment) and bonding (through differential pressure applied through suction) and molecular bonding chemical deposition.

Chen said that 'Continually refining and adjusting shape, chemical and mechanical signaling for protection and adjustment to their environment' Chen et al., (2012). Nature achieves these multifunctional objectives by material layer interface reactions by composite material structures. This multifunctional approach to learn and self-organize material composition by biochemical mechanisms is the process of continued development of materials at an evolutionary perspective. These materials have emerged through hierarchical self-assembly from nano scale components to determine the composite structure without a blue print. DNA is an example of nature's methods to form structure adaption. These living cells are the ultimate intelligent materials to give reactive response to the environment and understanding of their environment. DNA are the building blocks of life that are formed from complex self-assembly and self-ordering (Paun, 2000).

These cells are at a molecular scale of programmable complex optimization developed from a single unit that generates into more complex structures (Reif et al., 2004). DNA structures are governed by a rule based system to perform task solutions through genetics. Genetics characterization is the understanding of multi-cellular organisms and their behaviour to form nanostructure colonies and self-replication to performance tasks in a dynamic environment (Teuscher, 2004). This adaptive response is achieved by a biological chemical process through the connectivity of molecules and relationships created between them. This functional relationship is achieved through step commands defined by cell relationship connection. A solution approach in developing understanding of the problem and the measures needed to address is an evolving cycle (Darwin, 1859). DNA is characterized by molecular reaction networks formed and executed by chemical function sets by cell molecules as an interface reaction. These sets of molecules can evolve and create spatially formed structures by self-arranging themselves to form 3 dimensional nanostructures, called DNA origami, as shown in Figure 3.2.

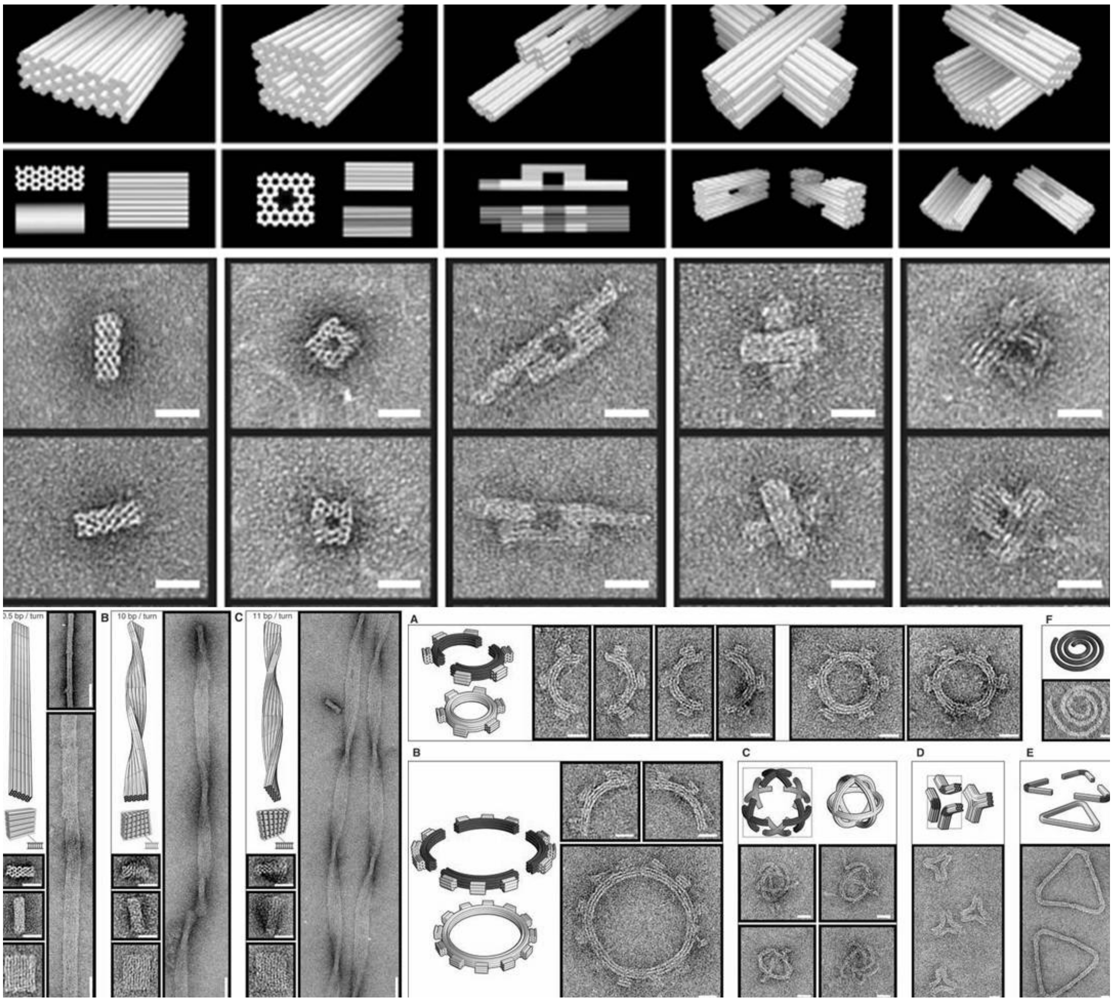


Figure 3.2 Self-Assembly 3D Origami Nanostructure (Reif et al., 2010)

This precise material assembly in real time forms these microstructures by distinct growth patterns through temperature and chemical solution composition. This microarchitecture of complex geometry has emerged by reaction-chemical diffusion, chemical wetting and material connection mechanics. These mechanisms direct the assembly to create 3D microstructures that can generate diverse patterns.

Nature's drives the controlling processing of structural material assembly into functional materials by novel material compositions. This ability to direct the assembly of advanced materials for desired functionality is the challenge as presented. This strategy in nature has delivered material with performativity function in relationship to high pressure (ocean depths), extreme temperature ranges, autonomous self-healing, and fracture resistance (shells) (Chen et al, 2012).

These natural materials have unique characterization, as they are mechanically strong and resistant. Examples of this response are organisms at extreme ocean depths that have developed composite sandwich structures in response, to high pressure loading. They are multifunctional as they have the ability to learn, adapt and self-organize to real time changes in relationship to their environment. These are mechanical systems that have emerged through hierarchical material layering formed through self-assembly of nano scale components, without a blue-print. These desired functionalities of the controlling processing of functional materials are achieved by chemical composition in an active manner. The material assembly morphology in nature for a functional material is a bottom up trajectory. Through the formation of a material by self-assembly of micro scale structures in relationship to a specific task. An example of this is shown in Figure 3.3.

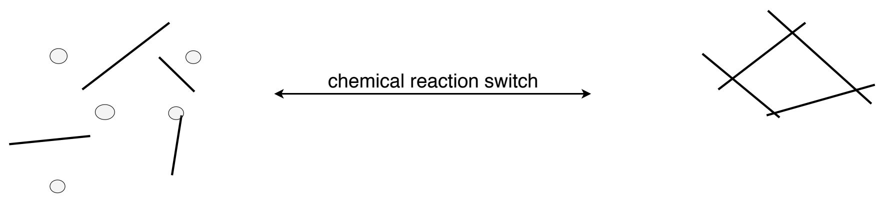


Figure 3.3 Sea Cucumber Chemical Armour Switching (by author)

Sea cucumbers have skins composed of very fine cellulose fibers. When a predator, in the ocean environment approaches them, surrounding cells secrete molecules around these fibres. This starts a reaction that causes the fine cellulose fibers or "whiskers" to attach together by chemical reaction bonding. This chemical fiber bonding creates and forms the defensive structural armour to protect the organism from a predator. Once the danger has disappeared the chemical attachment bonds are relaxed. This reaction to release the chemical bond is triggered by cells within the body of the sea cumber. These cells discharge plasticizing proteins to loosen the cellulose fibers chemical bonds. Once these bonds are released the sea cucumber is able to swim away and resume feeding and protection in rock crevices where it resides.

This switching is also present in marine organism shells where the environment of the developing shell is manipulated to allow for shell growth. A chemical reaction diffusion controlled processing to generate a complex pattern by active changes in the chemical material composition for growth (Ball, 1999). This ability to regulate and control the assembly of a structural material in two switchable states is an example of the controlled processing of a functional material characterization by nature.

The function of a material to switch in two differing material states is of particular interest for this research. Through thermal switching that acts to control the flow on or off (or variation of) to manipulate the effects of heat transport for new avenues in transparent materials. A switchable function in U-values would enhance materials to actively manage the energy balance (thermal loads inside buildings and solar radiation). To remove unwanted heat through transition temperature as switchable heat flow properties. A switchable state is heat transport flow management to regulate load and unload thermal energy transfer. This switchable function is achieved in nature through an energy matter relationship to modulate nanoscale thermal conductance.

Nature transports energy within and between materials at a nanometer level. This energy transfer represents novel ways of advancement in thermal conductance at the interface between material layers. This is a highly-refined energy reaction system for enhanced thermal properties of energy flow between neighbouring layering of materials. This is heat transport of energy across the interface between materials as a system that nature has a fundamental understanding of. A nanoscale measurement system for heat seeking targeting characterized by energy flow is shown in Figure 3.4.

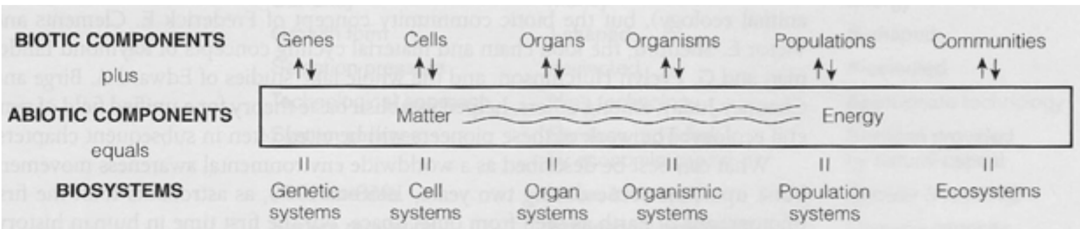


Figure 3.4 Ecological Levels of Organization of Living Biotic (organisms) and Nonliving Abiotic (physical) Element (Odum et al., 2005)

Matter and energy is a dynamic relationship that is achieved in nature at differing scales achieved through material diversity (species) and material connectivity (chemical compounds). This defines material characteristics by material controlling processes to modulate energy and matter. Solar energy modulation drives and influences nature and its response to high temperature application.

Nature selects and evolves materials for specific functions to determine the flow of energy as a mechanism to regulate and control material properties. This characterization is defined by a nanoscale thermal measurement system to modulate energy transport processing change as a usable energy form. This is achieved through individual material layer hierarchies to manage the stepwise flow of energy. This function is driven by material layers, which are nested together to form the overall material emergent composition. Materials that are self-optimized through dynamic interface reaction of an individual material layer acting within a system (Bak, 1996).

This is centered on fluidic metabolic material energy flow in vasculature multi microchannel networks. These micro-channels conform to hierarchical ordering by rules of minimum energy loss, minimum effective power flow rates and minimum pressure drop. The method of achieving this function is through layered material hierarchy by vascularization tissue networks (mammals) and cold phloem venation network (leaves). Nature uses vasculature formations to regulate material composition through temperature monitoring and thermal flow across the interface of materials. This is achieved by laminar flow for dehydration and autonomous self-healing surfaces as a heat transport flow system. Morphogenesis of vasculature natural networks have emergent properties to capture and storage of energy in materials.

By adaptive material stimuli mechanisms are in relationship to solar radiation loads. This is a self-regulatory thermal absorption system through active multi-functional material layering response. The following sections will determine this characterization through human cardiovascular and cold phloem leaf vasculature geometry networks.

3.2 Cardiovascular

The human cardiovascular system is a biological system that responds and adapts to changes in its external environment. This is determined through a vascular network to regulate body temperature by blood flow. This is a multi-functional system to control temperature by an active flowing fluid that has other key functional tasks for self-healing of tissue and repair to bone.

The cardiovascular system (blood flow arterial networks) is the biological mechanism for thermal flow characterization for temperature monitoring sensing, to develop an understanding of the thermal control processes and mechanisms applied by the human body to measure nanoscale thermal conductance. The human body is a heat seeking targeting system defined by cells. This perspective frame could advance materials. These living cells are the ultimate intelligent material at a molecular level, assembled by chemical composition. Cells are generated by complex patterns, DNA, formed by an internal molecular framework at a molecular scale.

This nanometer framework is called cytoskeleton. This internal framework is made of complex molecular filaments patterns to direct self-assembly of each cell. Cells are the building block of life. These cells are mechanically strong, resilient and an information system to determine body temperature. They form hierarchical self-assembly, adapt and self-organize in real time response to microenvironment change. They have the ability to learn in targeting diseased cells acting in a dynamic environment.

The human body is a complex system of controlled mechanisms in response to changing environmental influences to protect and regulate body temperature. This regulation is achieved by the cardio-vascular system that is represented by multi microchannel networks to monitor temperature decay. The surface temperature of the skin drives temperature decay or body heat loss through evaporation and convection regulated by metabolism. Metabolism is a complex internal generator of thermal energy that is governed by blood flow to maintain core temperature in response to skin / air contact.

This is a vascular network aligned and oriented to precise control of fluidics, blood, the cardio-vascular system. A definition of the Cardio-vascular system is that it comprises the heart and the blood vessels with their contained fluid, the blood. The heart is the central organ of the entire system to pump blood to all parts of the body through a complicated series of tubes termed arteries, capillaries and veins. These channel networks enable blood flow throughout the human body as a series of vessels that are defined as a circulation system (Gray, 2012). This is determined by blood flow in relationship to body temperature, shown in Figure 3.5.

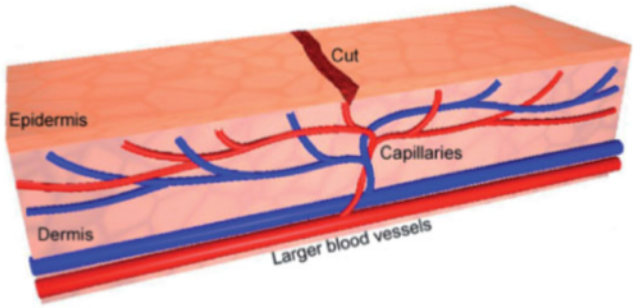


Figure 3.5 Cross Section of Human Skin Tissue Layer and Capillary Vasculature Network (Hansen et al., 2009)

The heart is a self-adjusting muscular pump, that is formed by two parts, working in unison. The heart propels the blood through the blood vessels. The right side of the heart receives venous blood and pumps it to the lungs where the blood becomes oxygenated. The left side of the heart receives the oxygenated blood from the lungs and pumps it into the aorta for distribution to the body (Moore, 1985). The four main functions of the Cardio-vascular system are:

- To transport nutrients and oxygen to cells around the body and remove carbon dioxide and waste from cells.
- To protect the body from infection and blood loss.
- To help to maintain a constant body temperature – Thermoregulation
- To help maintain the fluid balance within the body.

3.3 Thermoregulation

Humans have the ability to tolerate great variations in the temperature of their external environment. Humans can survive and indeed live in parts of the world where the temperature may reach as low as -65C or as high as 50C. In some parts of the world there are daily temperature changes of as much as 35C.

The core temperature range for a healthy adult is between 36C and 38C with 37C regarded as the average normal temperature. If the core drops below this range it is called as hypothermia and above this range hyperthermia (Saffrey et al., 2001). As the temperature moves further into hypo or hyperthermia, it becomes life threatening. The body works continuously to maintain the temperature in a healthy range. This is thermoregulation and is a classic homeostatic mechanism. Temperature changes within the body are detected by sensory receptors called thermo-receptors, which relay information about the changes to the hypothalamus within the brain stem. The hypothalamus's chief role is homeostasis, which is mediated by the autonomic nervous system (Ashcroft, 2001).

When a deviation in temperature outside of the core range is detected by the thermo-receptors, the hypothalamus initiates mechanisms to control the temperature.

There are four main adjustments:

- *Sweat Glands*. In hyperthermia, the sweat glands are stimulated to secrete sweat onto the surface of the skin. This allows heat to be lost through evaporation and cools the skin.

- *Smooth muscle in arteriole walls.* In hyperthermia, smooth muscle around the arterioles walls, relax causing vasodilation, which increases the volume of blood nearer to the skin allowing heat loss through convection. In hypothermia, the smooth muscle contracts around the arteriole walls, reducing blood flow and therefore heat loss.
- *Skeletal muscle.* In hypothermia, skeletal muscles shiver, which are fast small muscular contractions, which produce heat to help warm the blood.
- *Endocrine glands.* In hypothermia, the hypothalamus stimulates the release of hormones e.g. thyroxin and adrenaline which increases the metabolic rate and therefore heat production.

Humans are exceptional in their ability to cope with extreme conditions (McLaughlin et al., 2007). The ability to adapt is through the mechanism of thermoregulation, which is central to the bodies' ability to survive, shown in Figure 3.6.

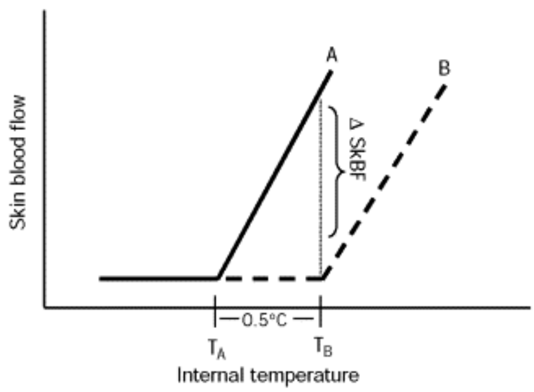


Figure 3.6 Skin Blood Flow Responses during Whole Body Heating (McLaughlin et al., 2007).

T_A and T_B represent internal temperature difference. SkBF = change in skin blood flow temperature (0.5°C apart) with the vertical line representing differences in skin blood flow at a given internal temperature (Charkoudian, 2003).

Human vasculature is a distribution sink fractal network. This is characterized by fluidic (blood) flow from a central single source supply (the heart) for fluidic wide distribution into microscopic capillaries to material regions. This sink fractal pattern is also reflective in river networks. The heart that determines the metabolic rate regulates the rate of blood flow in the human body. Metabolic rate is the blood flow transport in vasculature to regulate temperature and energy supply for body active functions. However, this metabolic rate and vasculature formations is species-specific and varies in all mammals. This is due to the variation in geometry body shape of an organism and size of the species. Hence the vasculature geometry as a sink fractal network will adapt the capillary formation in response to species.

Velocity of blood flow in these networks has a direct relationship to capillary cross sectional dimensions. Blood material flow will increase or decrease depending on volume source velocity supply contained within the network per unit of time. A change in modulating volumetric flows will be dependent on the energy requirement. This requirement is determined by the active or inactive state of the human (or any other mammal) body at rest or under stress conditions. Hence the cross-sectional volume of supply vasculature channels will change in dimensional geometry (width and depth) in response to fluidic volumetric changes. The geometry change will be directly proportional to the spatial regional location of the capillaries position within the sink fractal network, shown in Figure 3.7.

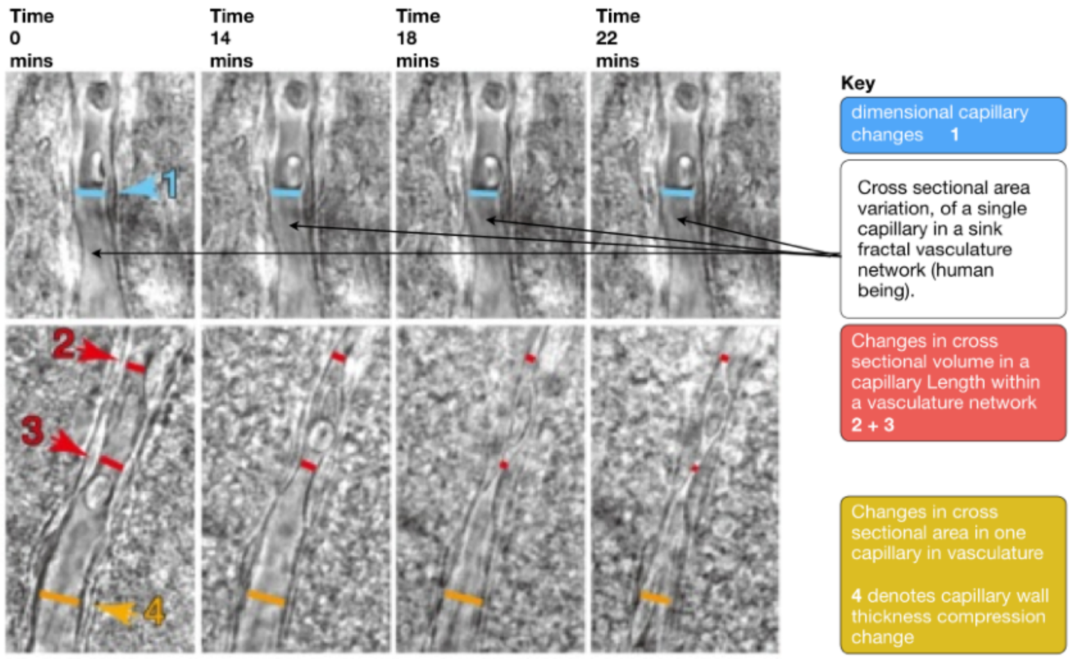


Figure 3.7 Vessel Diameter Geometry Changes in Capillaries over time (Hall et al., 2014)

This ability to increase or decrease capillary geometry variations by modulating volumetric blood flow supply is achieved by material compression of surrounding tissue. This function is specific to blood flow vasculature networks.

In warm blood species cardiovascular is defined as a sink fractal network of in multi micro capillary formations. These networks comprise of arterial capillary vessels, supplied by a single fluidic source (the heart). This supply of fluidic material (blood) regulates and manages, core body temperature for optimum functions. The flow rate of the fluid within the network formation is regulated by metabolism (the heart) in response to activity level to maintain core temperature.

This fluidic material within this network does not return to the origin source point. This is significant as the principle function of the network is a thermal energy generation system to maintain core body temperature 36.7 ^{0}C achieved though tailored blood flow supply. This vasculature network is an exothermic system for thermal heat release by heat radiation and heat convection. This sink fractal vasculature system in human beings (and mammals) is not a re-circulative network.

A re-circulative multi microchannel network will advance the controlling state of a material by the parameters of switching. Switching mechanisms is the ability by oscillating a material state between two material parameter conditions. This characteristic is exhibited in leaf vascular patterns in the absorption of solar radiation. This solar load is converted by solution chemistry by photosynthesis into nutrition for growth.

These cold phloem vascular patterns are characterized by the intimate relationship between vein leaf pattern and leaf foliage scale for solar radiation capture, and this is investigated in the following section.

3.4 Leaf Vasculature Species

Biological leaf materials react and give adaptive strategies in response to external stimuli (solar radiation) by environmental climatic influence. These organic materials are multifunctional systems as they are mechanically strong and resilient formed by chemical composition. They are information systems that can self-adapt to changes in ambient conditions by chemical and mechanical signals (Turing, 1952). This ability to learn and self-organize material composition by biochemical mechanisms is the process of continued development of materials at an evolutionary perspective. These materials have emerged through hierarchical self-assembly from nano scale components to determine composite structure. These living microstructure tissues cells are intelligent materials tailored to a dynamic environment. This is evident in trees that are transformable structures as they respond through geometry to solar orientation, shown in Figure 3.8.

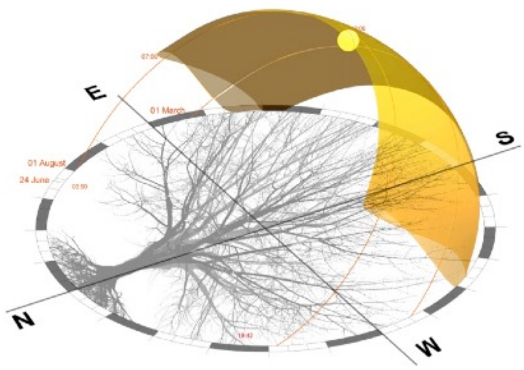


Figure 3.8 Tree Structural Geometry in Relationship to Solar Orientation (by author)

The structure of a tree is a direct response to solar orientation as the shape and distribution of the branches defines the tree structure. This geometry orientation has developed in response to the maximization of day light capture by leaves.

Leaves have autonomous self-healing and intelligent surfaces (leaves) that will adapt to their climate, (Alston, 2014). They are transformable as each leaf reacts and responds to changes in wind direction, orientation and adjust surface exposure to harvest solar radiation. The structure of a tree is a direct response to solar orientation, Figure 3.9, as the shape and distribution of the leaf surface and fluidic channels captures solar radiation. This geometry orientation has developed in response for the maximization of day light capture.

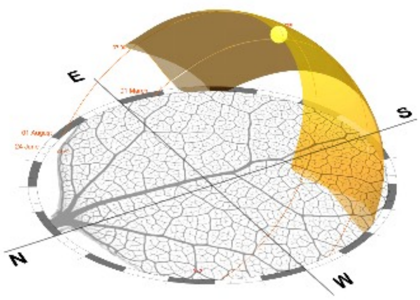


Figure 3.9 Leaf Structural Geometry in Relationship to Solar Orientation (by author)

Leaves act as a collective unit to capture solar radiation that is defined (interception of the leaves for photosynthesis processes) by rule based geometry, canopy volume, total leaf area density and angular distribution of leaf surfaces. This approach to solar orientation and absorption of light energy by biochemical processes, are responsive measures a dynamic system; where each leaf and its relationship to geometry solar orientation is for the maximization of solar radiation. Each leaf is an independent photosystem acting as a unit within a whole canopy geometry structure. This multiscale function of photosynthesis is material level assembly and damage light stress regeneration is regulated by biosynthesised molecules in response to solar absorption that has evolved by leaf species. This characterization of leaves has evolved through absorption of solar radiation using microfluidics circulation in a network composted of multi micro-channels.

3.5 Leaf Vasculature Networks

Leaves and plants are able to control solar absorption via photosynthetic measures by constant fluidic flows for dehydration and autonomous self-healing surfaces as a photoactive system by bio-venation networks. These networks obey higher order rules of minimum energy loss to absorb solar radiation for photosynthesis. Leaf vasculature networks are formed by chemical composition to create a multi micro-channel network. These active chemicals create the vasculature network to form leaves, without a blue print.

Leaf vascular vein tissue is created by auxin. This molecule chemical triggers behaviour enables self-organization of leaf vein network formations of isotropic auxin flows between cells (Feugier et al., 2005). Auxin flux is a carrier protein that flows between plant cells. This singular carrier protein is pumped between the intercellular spaces between cells, the plasma membrane. The reaction transport of this protein out of one cell into another cell, determines isotropic auxin movement flux strength reaction. The flux strength and rate through cells determines the vascular network patterns. If the flux rate is weak, the diameter of the network will decrease and fade away in correlation to auxin strength that creates a diminishing vein network in response to this (Kull et al., 1995). This is self-generation of leaf venation network formations generated by molecule influence of auxin. The qualitative disposition of the auxin flux has a direct impact on venation leaf geometry patterns. The dynamics of auxin flux strength creates vein formations is in response to the regulation and carrier flow protein patterns concentrations, determines microfluidic veneration networks. These network vein patterns are determined by responsive function as a carrier protein regulation for vascular tissue formations.

These networks are formed by chemical solutions creates a hierarchical ordered material. Venation networks circulate chemical fluids of ions, water and photoactive molecules to absorb solar radiation (Blonder et al., 2011). Leaves use embedded microfluidic networks as a means for multifunctional, mechanical measures for transport of photosynthetic fluidics. There are multiple ranges of venation, reticulated network pattern that have been created. However, these networks are categorized by a re-circulative channels nested in a closed loop vascularization patterns categorized by two species, dicot and monocot species.

These species formations of venation networks that determine leaf network pattern, in response to light capture. Each leaf vasculature conduit networks is a re-circulative system of ions, water and photoactive molecules within a closed loop formation network. This venation network is not a distribution sink fractal network. Characterized by thermoregulation metabolism (of mammals) from a single source supply scaling through minimization to material regions for fluid (blood) supply. A non-fluidic return network to source of supply. However, leaves of embedded multi microfluidic in a closed loop network have precise hierarchical patterning.

These biological conduit networks of hierarchical branch scaling conform to rules of: minimum energy loss, minimum effective fluidic power flow rates and minimum pressure drops and maximization of absorbed nutrients for photosynthesis. Photosynthesis underlying principles of vascularization pattern conduits are networks of steady state flow, pressure, that are characterized by highly regulated fluidic transport (Dengler et al., 1997).

This fluidic transport networks are characterized by monocot and dicot vein formations. Monocot is primarily a leaf blade veneration centered on a number of lateral regular veins. These veins are diminishing to a point with some transverse veins interconnecting between the principle vein strands. This formation is exhibited in leaf grass blades, maize etc, shown in Figure 3.10.

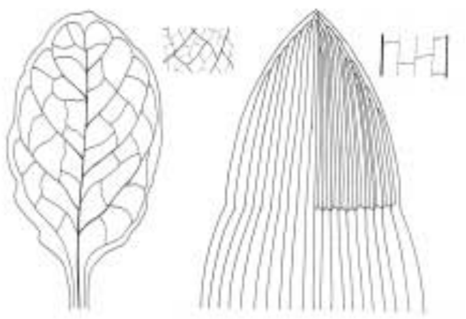


Figure 3.10 Dicot (image on the left) Monocot (image on the right) Species (Dengler et al., 1997)

Monocot have vasculature diminishing to a point to permit flow within the closed loop system. However, this pattern network presents a reduced hierarchical vein network of micro capillary diminishing order. Monocot venation is limited by their relationship between leaf scale and foliage leaf vasculature patterns function. This formations presents reduced hierarchical multi microchannel of higher order. However, Dicot vasculature has evolved by greater complexity of vein formations through evolution and diversification in the development and regulation of leaf venation patterns. These hierarchical patterns present enhance vasculature pattern development for greater distinctive scalability attributes. The dicot species have unique functional properties. These properties are centered on hierarchical vein branching network-scaling patterns. The microfluidic network in dicot formation changes in vein thickness, vein angle divergence, redundancy functionality, stem vasculature fluidic supply and have vein hierarchical order. Dicot leaves, shown in Figure 3.11, have a variety of shape, forms and dorsiventrality, however all exhibit complex optimal veneration networks.

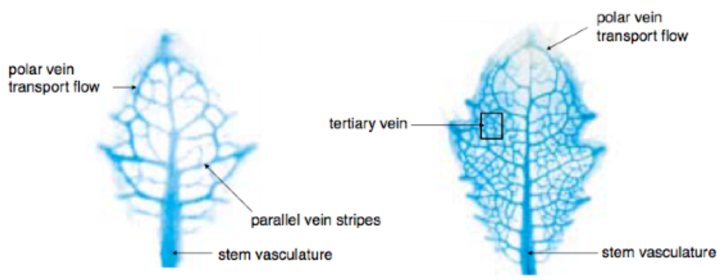


Figure 3.11 Dicot Vasculature Vein Pattern (Mattsson et al., 2000)

These multi microfluidic networks of constant liquid flow have distinctive spatial relationships and central to this network is the stem vein.

This geometry venation network is composed of:

- The stem vasculature acts as the fluidic entry point and extract for fluidic transfer flow within the vascular network. This is the main point of liquid flow into the two dimensional (longitudinal pattern) of continuous, branching features are hierarchical ordered with primary veins importing water and export of photosynthate.
- Flattened leaf blade vein patterns centers on secondary vein features; mid-vein and parallel vein stripes that create the leaf vein network formation, with the minor veins (tertiary veins) completing the regionalized leaf vein network geometry.
- Leaf veins typically have dorsiventral symmetry as the structure of each leaf vein is composed of two vascular collateral tissues called xylem. These conduits create each leaf vein and have dorsiventral symmetry of an upper leaf surface, adaxial, and a lower leaf surface, abaxial, creates the leaf vein structure. However, this vascular leaf structure form can vary depending upon plant groups as some exhibit biocollateral formations, three-conduit pattern to each vein.

Parallel and tertiary veins have distinct vein size diminishing order to form the closed loop network. The polar vein is a significant conduit as it closes the network as a circulative pattern for fluidic flow regulation. Each vein has a significant regulatory role, in the resolution of the working formation, in tolerance to damage, under water stress conditions and redundancy. Leaf species exhibit vein size diminishing order, as all veins classes contract in size distally from the main fluidic stem vasculature input point. However, fluidic input and export flow within these hierarchical networks are subject to flow resistance and flow rate of photosynthetic fluids. This resistance is determined by pressure, fluidic flow, volume and conduit dimensional aperture, shown in Figure 3.12.

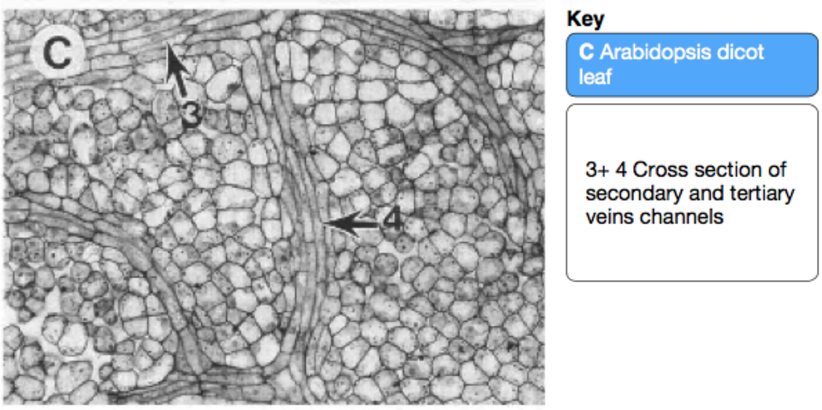


Figure 3.12 Dicot Vasculature Vein Cross-Section (Sinoquet et al., 2005)

All veins diminish in size distally from fluidic input supply. This arrangement of diminishing vein size order by primary veins and secondary is the relationship to leaf apex scale (Turing, 1952). Vasculature patterns are linked to material scale in the formation of conduit network geometry as they perform regulatory roles. The fluidic input and export flow within these hierarchical networks are subject to flow resistance and flow rate. Hydraulic resistance in fluidic conduits channels conform to minimum fluidic flow to achieved reduced pressure drop for fluidic flow efficiency. This is determined by hierarchical structure to minimize resistance R for optimal fluidic transport. The resistance is determined by mechanical energy when a flowing liquid is subjected to a change in direction.

Hence, fluidic supply loops enable flow to be circulated in response to minimized energy loss at low fluidic flow rates. The geometry distribution and branching network patterns of leaf veneration determines fluidic flow for photosynthesis, are determined at a molecular multiscale biochemical approach.

This biochemical process used by leaves is called the Krebs cycle. This aerobic citric acid cycle uses a chemical reaction chain as responsive reactions to generate energy for photosynthesis and mechanical support (Mattsson et al., 2000). These underlying mechanisms of vascularization pattern conduits are networks of constant flow conductivity distribution. This characteristic feature, pressure, represents a highly regulated fluidic transport system. These fluidic reactor chemical solution networks conform to minimum energy loss, lowest pressure drop and minimized the effective power output.

Plants have been practicing and perfecting combinatorial chemistry on an evolutionary timescale. This synthesis of molecular behaviour enables multiple path ways embracing and evolving chemical material connectivity as an adaptive influence to climatic patterns. Leaf structures' vasculature networks are evolving pattern networks and assembled from a bottom up approach, to capture and convert solar energy through hierarchical networks assembled without a blue print. This is a multi micro-channel network, with an unprecedented scale of complexity and created through microstructure precision.

3.6 Conclusion

Nature uses material switching in differing states as a central mechanism for material composition and active function change in real time. This is material structural diversity, defined by function, assembly and modulation to an environment.

In the field of materials, the ability to direct the assembly of a material for desired functionality through self-assembly is a bottom up approach. This is demonstrated in nature as a continuous process of precision of hierarchical material ordering. Chemical solution composition, chemical wetting and material connection mechanics derive this strategy of dynamically modulating nanostructures materials. Achieving this nanoscale functionality is a source of complexity and hierarchical ordering but will ultimately lead to the desired morphology in man-made functional materials. Using precise fluidics management in networks as characterized by nature's advances in optimization of material functions. Research has been undertaken into active fluidic control methods for solar modulation (Fluidglass , chapter 2) to advance thermal management functions of transparent glass facades. This and liquid filled windows (Chow et al., 2013) indicated water flow behaved as a cooling plane for glass surfaces. This research established water as an active IR absorber in response to solar loading for conductivity regulation and management.

Nature uses active changes in liquids to manipulate conductivity of constant change in real time. Achieved by material layering, with each layer having a defined function. This layering strategy can be directly applied to transparent glass envelope, figure 3.13.

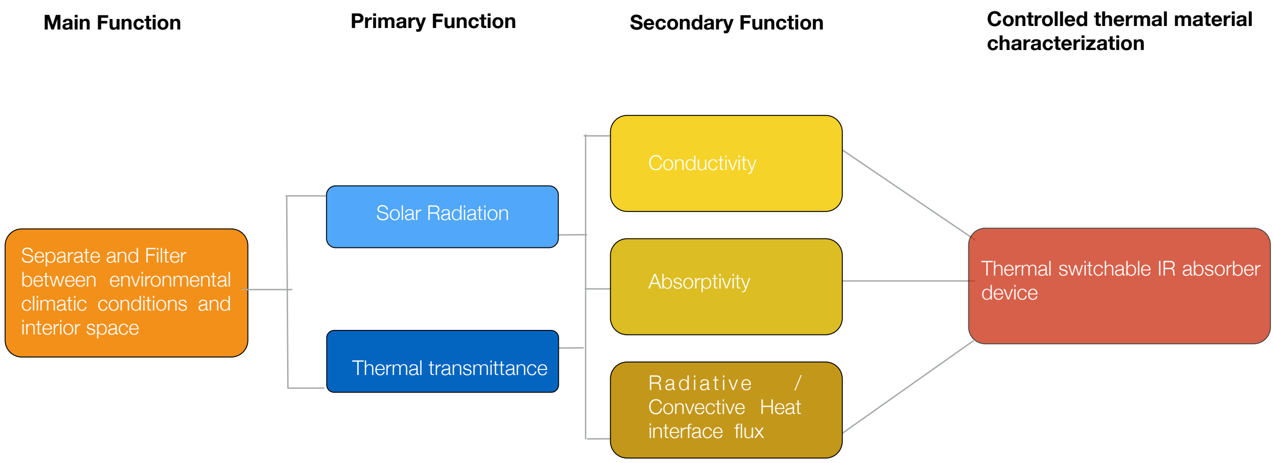


Figure 3.13 Material Layering approach, transparent glass envelope.

Switch ability approach of a thermally functional material can be achieved by water volume and thermal heat absorption rate in response to solar loading. Heat flow is characterized by thermal conductance regulation that is an energy capture and store cycle. Leaves perform this very same role through fluidic networks, acting as a chemical process cycle for solar energy conversion into chemical energy, photosynthesis. Leaf functions offer interesting properties as they are characterized by hierarchical order determined through venation networks.

Venation networks are a two dimensional (longitudinal pattern) of continuous, branching features. These vascular patterns form a complex hierarchical pattern for the transportation of fluidics for photosynthesis mechanisms. Characterization of leaf vein formations are desirable morphology for solar modulation properties by microfluidics for transition temperature decrease in a thermally functional material.

Using a microfluidic-based network of steady state flow in multi micro-channels across the material pane will advance a polymer for desired thermal functionality. Achieving a microfluidic network of hierarchical order by rules of minimum energy loss, minimum effective power flow rates and minimum pressure drop are networks characterized by nature. A fluidic material flow without turbulence and shortcuts pathways to derive solar absorption.

These multi micro-channel geometry pattern functionalities could act as a thermal transport network for IR transmission temperature interface, for capture of solar radiation. To enhance the structural assembly of a polymer of microfluidic-based flow will lead to the desired morphology to direct a photo-absorbing material to act as an IR stop-band block. This capture and store of energy is achieved by thermal absorbing fluidics in steady state flow through a network. The research goal of the network is solar energy modulation efficiency using water flow as a thermal switching medium. The assembly of tailored flows in modulating volumetric flow resistance and pressure drop are functional significant in a materials ability to low phase transition temperature.

This is the approach of nature's characterization of materials that will forge a new direction for transparent building envelopes. To advance glazed façades by steady state characterization as a blue print for intelligent thermal surfaces. Achieved by fluidic transportation by optimization of flow, as a thermal trigger to regulate material thermal functionality. Analyzing venation hierarchical networks of modulating volumetric flow in a multi microchannel network would advance the structural assembly of a polymer.

Through optimized fluidic networks of branch network order scaling by defining fluidic flow modulations in channel slot geometry. This will be undertaken in Chapter 5 in analysis of volumetric flow rates for heat flow transportation optimization. The challenge is the ability to direct the assembly of a polymer material for desired thermal functionality to drive the assembly using planar flow generation. A microfluidic based tailored flow for energy capture and storage in a polymer composite, will advance clear materials for desired functionality. By modulating tailored flow for solar modulation properties characterized by nature, through a bio-inspired engineering approach. Leaf vasculature presents optimized networks using precise control of fluidics to capture and absorb solar radiation. These hierarchical muilti microchannel networks will be analyzed as a resistor circuit to develop a microfluidic platform to drive the assembly of a thermally functional device. This is achieved by resistance simulation analysis by circuit channel optimization for transport fluidic flow. The optimization of the network will be validated against CFD (computational fluid dynamics) simulation within a re-circulative closed loop network, as undertaken in Chapter 5.

Chapter 4 Philosophical Foundation, Methodology and Methods

4.0 Introduction

This chapter will demonstrate the reasoning for the approaches taken in this research by articulating the philosophical foundation and methodology. The goals of this chapter are to demonstrate how the scientific method was applied to biologically inspired composite as an energy system. This research question is the investigation to advance a thermally functional material to gain understanding of conductivity behaviour of a material that is subjected to a heat load. To observe an transparent material's ability to regulate conductivity under heat load experimental testing. This research investigation aim is the evaluation of a material in the physical world that is drawn from a scientific theory to control material conductance. This theory draws on evidence that is produced under artificial laboratory conditions of a controlled experiment, by observations. These observation outputs or facts will establish whether a transparent material can capture and store energy. This design methodology establishes the rationale of testing a theory, measured by real physical properties to answer the research questions, by the thesis objectives as listed below:

1: To identify the principles and processes of natural systems' response to solar radiation.

2: To investigate the current constraints of contemporary transparent building skin technology, in applying natural principles and procedures.

3: To develop a transparent prototype that exhibits the possibilities to adopt natural principles and processes to control solar radiation.
4: To test the transparent prototype.

Observations of the physical world by applied science are every day practice, as they establish and secure if the philosophy of the theory is substantiated. The scientific method is founded in scientific knowledge that is proven knowledge. Scientific theory is derived by rigorous testing from the facts achieved by experiments acquired by observation (Chalmers, 1980). This is a process of validation in testing assumptions by practical application by experimental outcomes that are determined by the nature of the physical world, rather than societal. The research path is not grounded in hypothetical reasoning methods of the social sciences and behaviour to specified laws of an individual or strategies of management. The establishment of certainty founds the research question, biologically inspired composite as an energy system. The theory is tested under simulation and laboratory conditions that replicate the real world physical conditions. The sociological research methodologies, can be defined by the following social science approaches;

- Case studies are an empirical investigation of a particular contemporary phenomenon within a real life context using multiple sources of evidence (Robert, 1993). This is interpretivism of a theoretical perspective based upon behaviour of events in which there is no control of the outcome, as it is determined.

- Survey research is a ‘collection of standardized information from a specific population or sample from one, usually, but not necessarily, by means of a questionnaire or interview’ (Rivkin, 2000). Surveys explore descriptive research questions in which there is no control over the results as they are dependent upon the nature of the individual who appraise it. This is depended upon an individual’s judgment, intuition and belief (Marsh, 1982).
- Action research ‘is a small scale intervention in the functioning of the real world and a close examination of the effects of such interventions’ (Cohen et al., 1994). It looks into human practices in a specific context to propose changes to procedure focusing on human behaviour and events.
- Ethnography ‘is the art and science of describing a group or culture’ (Fetterman, 1998) with observations of behaviour patterns of people and interpretation of these patterns to derive analysis. This is data gathering in order to derive results to answer a descriptive research question. There is no control over the results, as they are obtained and depend upon human initiative judgment.
- Grounded Theory is to search ‘to generate or discover theory, an abstract analytical schema of a phenomenon, that relates to a particular situation’ (Creswell, 1998). This is founded upon subjectivism by inductive reasoning by seeking to answer exploratory or descriptive questions without any control over the behaviour of the outcome.
- Historical research is to seek analysis from the past by archival analysis or biography (Cohen et al., 1994). This research seeks archival assessment and analysis from historical records and past phenomena.

These methodologies apply an empirically based hypothesis to prove or disprove theory. These theories of behaviour or strategy management frameworks in the field of social science can be applied to the Newtonian philosophy. The methodologies: case study, survey research, action research, grounded theory, historical and quantitative research are associated with sociological foundations. Newtonian research is founded on an observational statement as a basis to prove the laws and theories of the natural world can also be applied to other disciplines including social science and not just the natural world. The research into biologically inspired composite, as an energy system is a material scientific investigation to enable control of thermal conductivity. The direction of the research is to prevent uncontrolled thermal conduction, to enhance optimization of a high emissivity, absorptivity material.

4.1 Methodology Design of the device

This section will discuss the research method to derive the conclusion to advance a transparent thermally functional material through the scientific method, by a microfluidic based platform to direct the structural assembly of a polymer into a functional material through:

1. **Material for energy capture**

Absorption of shortwave irradiance / infrared spectrum NIR through the controlled process of a fluid in flow for heat transport by real time reaction using precise hydrodynamic control to capture energy (IR absorbed in the fluid) obtained for energy removal.

2. Material energy storage for energy removal

To improve the capture and storage of heat (via IR impact non-thermal), by modulated fluidic laminar flow to advance conductance of a polymer. Multi-micro vascular channels (embedded in the material) of full volume fluidic laminar flow will regulate heat conductivity of a polymer, as this liquid is acting as a heat sink. This approach is the progression of an transparent material combined with thermally switching selectivity for IR impact.

In order to observe these properties in relationship to the objectives, it will be determined by SI unit measurement. SI units will enable assessment of thermal transport across a material and the effects through observation, analysis and quantify thermal flow across the interface of a composite material. The observational outputs will be measured against the ability of the composite to modulate solar radiation. This is determined by multi microchannel network circulating a fluid in active flow, through and out of a polymer by the ability of energy capture and storage. These SI units will give values to observe interface heat transfer flow across the microfluidic network that is dependant on flow rate. Heat transfer flow is characterized by temperature with time. Using precise hydrodynamics control of the microfluidic platform will manipulate the position of the fluid-polymer heat transfer that is determined by delta t. Delta t is the difference in temperature between input and extract fluid temperature (through the device) that will determine optimization to capture solar radiation. The scientific method is used to progress investigations in order to test and shed light on scientific theory to advance scientific knowledge. To advance a polymer material that can lower its phase transmission temperature for energy modulation. This method is the testing of the theory to advance scientific knowledge through real world observations.

4.2 Scientific method

The scientific method is the collection of facts by means of careful observations and experiments to derive subsequent derivation of laws of theories from those facts by logical procedure. The philosophy of scientific knowledge is the improvement of human well-being for the inhabitation of earth. To advance new knowledge of the natural physical world, as opposed to human societal, social political interest of individuals, communities or social class. Biologically inspired composite as an energy system is based on real world experimentation in assessing material behaviour in connection to energy capture and storage. This aim is to seek, discover, explore and understand new theories in connection to nature that employ method to regulate conductance. The scientific method is to develop, explore and nurture new knowledge in the progression of human beings. This is the feature of modern scientific advancement that has led to the major scientific innovations. Scientific knowledge has gradually revolutionized under the influence of observation and continuous expedient discovery. The reasoning for this is the understanding of the scientific spirit underlying the activity that is tested by the scientific community to enable validity of applied science. This process of empirical evidence to advance a hypothesis can be applied to the social sciences. The premise of science is subject to continuous modification. Every theory proposition of science is the scientist's decision to accept the observations as fact. This process of continued testing of a hypothesis to prove or disregard theory bridges material and social sciences. The community to repeat the experimentation and enable new observations will test these facts. If there is a conflict or the material facts are refuted then the progression of theoretical theory is undermined. This is scientific interpretation of the facts and leaves the accepted facts are unchanged, this is the fundamental basis of scientific knowledge, as a "Pattern of Discovery" (Hanson. 1958). Henri Poincaro, also described in Science et Méthode a phase of discovery represents a process of spontaneous emergence by the strength of the scientist to drive for problem solving (Poincaré, 2007). This drive to determine the facts is applied to all hypotheses in social and material science in testing of theories to discover meaning. Every established scientific theory enters into scientific method of validation to accept the scientist decision by observation of the facts. This may be disregarded as unsound once the scientific community repeats the experiment and gives validation for advancement in knowledge. However, personal judgment in science and acknowledgement is dependent on this process that may be in conflict with epistemology, this also applies to the social sciences. Scientific advancement is not individualist approach; it is ultimately justification by the scientific community. This community is founded upon the reality of emergent meaning of truth (Polanyi, 1964). This is a continuous reinterpreting of the tradition of science rests on self-renewal and faith in its fundamental principles of scientific integrity in applying principles.

This is seen as a positivists view as a 'unified theory of science' (Hanfling, 1982) and assumes the notion of science is based upon secure foundations as a universal characterization of science. The positivist aim to legitimate science as observations based solely on facts to create a derive theory. Archimedes, Newton, Aristotle and Galileo established these techniques to test scientific laws under artificial conditions. To control the experiment to justify a theory in the world of experience that was present at that time. However

'*the nature of scientific knowledge, the way in which it is justified by appeal to reason and observational procedure, changes historically. To understand and identify it we must analyse the intellectual and practical tools available to scientists in a particular historical context. To attempt to characterize scientific methods by looking to human nature is to look in the wrong direction.' (*Chalmers, 1999).

Newtonian mechanics presented a utopian positivists view for more than two centuries (Lakatos, 1978). This theory has now been replaced with a more successful rival quantum-based theory, Einstein 1905, and it progressed to quantum mechanics. Newtonian theory in spite of the unsolved problems was a pioneer of modern methods of science and in this aim Newton was revolutionary. Scientific discovery is the survival of the fittest theory in the face of testing. This process approach to establish a hypothesis is also applied to the social sciences, as a Newtonian method. The observation and experimental discovery is not a matter of subjective opinion but objective fact to prove or disprove law and theory. Could empirically based theory be a matter of opinion or epitomized attitude, skepticism? Hence, there is either a universal account of the positivist view or a skeptical relativism of science being a matter of faith (Feyeraband, 1975). This standpoint presents challenges in defending epistemic claims so the concerns of the sceptic motivation for issuing the challenges will be met by skeptical argument by the tradition of debate. A skeptical stand point is claiming that, all we know, all we might establish will always be in error (Grayling, 2008).

Scientific advances are appraisal by adopted experimental methods and standards that is not a matter of subjective opinion, but a matter of objective facts by observation. Galileo was the first to introduce methods and techniques to observe the natural world. Galileo developed artificial conditions by controlled experimentation as a means to observe planetary mechanics that laid down the foundation of Newtonian mechanics that replaced the medieval observations of Aristotle. Galileo described the actual experimentation in detail in order to derive and distinguish between velocity and acceleration of free falling objects by the laws of insertia (Drake, 1967). However, these theories could be considered from an epistemology perspective of 'falsificationism'. This view is the understanding there could be a possible discrepancy between prediction of law and theory and the observable outcome by experimentation.

'I have always stressed the need for some dogmatism: the dogmatic scientist has an important role to play. If we give in to criticism too easily, we shall never find out where the real power of theories lie' (Popper, 1972).

Observation of experimentation to obtain results and facts, can conflict with the principle theory or law that is proposed by scientific theory. These conflicts may be anomalies rather than the undermining of the central ideas to the scientific programme, yet that does not present falsification. These anomalies may, however, become falsifications if another theory successfully explains and gives justification by observation to present new scientific hypothesis. Modifications to the original theory can be undertaken and a falsificationist would welcome such changes. However are these modifications and movements in the direction of the research diminishing the essence of the scientific theory? This would lead to an indeterminate path and these are difficult decisions to be made. Misrepresentation of the exposure of the observable facts to the scientific community is one of great concern. Falsifying observable facts in relationship to scientific laws and theories in the description of hypotheses and how it may behave is a sophisticated falsificationist's position. However, these may have been misinterpretations of observable experimentation results by the individual. A falsificationist position can lead to bold conjecture in advancement of scientific discovery. These represent (if proven correct) significant advances in science in marked discovery that was previously unheard of, or considered by the community to be highly unlikely.

Einstein and Eddington are among this group and their predictions were considered by others to be risky conjecture. This position establishes what is thought to be problematically true was in fact false. This path of scientific discovery establishes theories that are considered to be a foundation of scientific discovery are merely points in time, until other bold hypotheses can disprove it. '*Confirmation of novel predictions resulting from bold conjecture are very important in the falisficationist account of the growth of new knowledge' (*Chalmers, 1999). Poppers *(*Poppers, 1979) explanation of falsificationism is the seeking out of new theories of high empirical content and another could replace a theory, hypothesis progression applied to both material and social science. Scientific knowledge by newly accepted theory, of even high empirical content than its processor is at the core of scientific advancement. This is classed as the measures of substantive claims in the understanding of natural systems as defined by laws and theory. Popper concluded the greater the empirical claim proposed by theory, the more open to possible falsification the empirical content becomes to skeptical attack. Collins describes science as fallible, open ended and reversible (Collins, 1985). This scientific method is considered as a path of discovered separated into a number of phases. These phases of discovery were observed in mathematical exploration by Wallas and he described this as: preparation, incubation, illumination and verification (Wallas, 1926). The scientific method is applied science to establish laws and theories that relate to the natural world, to determine through a research process method (4 phases) that differentiates from social science. In establishing that the theory is in parallel with nature's patterns by experimentation.

4.3 Four Phases of Scientific Method Discovery

4.3.1 Preparation

This phases of discovery start with an establishment of doctrine that brings together knowledge of natural systems that has embedded within them the methods of dealing with thermal energy exchange. The investigation into previous experimental work of scientists in the same field of thermal capture and heat flow transfer materials. The advancement of scientific knowledge is to firstly determine natural systems to appraise and observe the natural world.

The understanding of thermal conductance is not bounded to the human societal world, but to physical world of material conductivity behaviour in connection to thermal energy transfer. Nature has evolved material functionality on an evolutionary perspective to employ mechanisms to regulate energy exchange. The philosophy of the scientific method, as described by Francis Bacon, is the understanding of what has gone before.

This theoretical perspective is considered positivist as the theories are derived by observation (Ayer, 1936).

4.3.2 Incubation

A theory is a component within a network of belief between which there are complex relationships. These relationships are a network of belief in the discovery and foundation role which presents a particular pattern of scientific discovery. Personal belief gives the direction of scientific research and this is an individual perspective that can change the path of the scientific discovery. This can present new scientific paths of theoretical discovery that is followed by others. The advancement of scientific knowledge is in the resolution and the capacity to observe the natural world (Popper, 2002; Bachelard, 1934).

4.3.3 Illumination

The understanding of planetary works by the scientific community will progress and build upon established result to progress scientific knowledge in new and previously unconsidered areas. Biologically inspired polymer composite as an energy system will lead to undertaking research into thermal conductivity and absorptivity of natural systems to progress current scientific knowledge. Each scientific theory or discovery is potentiality seeking a scientific proposition, in prospect to nature seeking realization in our minds (Rhine, 1934). Investigation and progress of scientific enquiry is a matter of devotion to the scientific ideal. To gain greater understanding of the thermal processes and energy exchange mechanisms as a bio inspired engineering platform.

4.3.4 Verification by Observation

Verification by observation is to support scientific theory under artificial conditions by expérimental design to replicate the real world. Verification is a continuous process by observations in testing the scientific theory for refinement of new lawful relationships in discovery of them (Kuhn, 1996). Observations are a decision making process either by reading instruments or interpretation and making sense of new facts or even rejecting some facts as anomalies. Science is founded on assumptions that are tested by observation, that are considered at the time to be plausible by experimental laboratory work in support of a scientific theory. Experimental verification by the fabrication of the prototype device will give observational outputs as defined by SI units that set the design parameters of the device. The design methodology of the device is to quantify the heat harvesting properties of a thermally functional material.

4.4 Conclusion

New knowledge and understanding is the scientific spirit underlying the approach that is tested by the scientific community to enable validity of the science. This has been undertaken by journal paper publications and presentation to the community, through the following publications.

- Scientific Reports , Nature Publishing Group: Alston, M. E. and Barber, R. Leaf venation, as a resistor, to optimize a switchable IR absorber. Sci. Rep. 6, 31611; DOI 10.1038/srep31611 ,2016.
- Alston, M.E, Leaf Vasculature Patterns to Regulate transparent Exothermic Material, 11th Conference on Advanced Building Skins, ISBN: 978-3-98120539-8, 2016.
- Alston, M.E., Natures Buildings as Trees: Biologically Inspired Glass as an Energy System. Optics and Photonics Journal, 5, 136-150. http://dx.doi.org/10.4236/opj.2015.54013 , 2015.
- Alston ME, Energy Adaptive Glass Matter. J Archit Eng Tech 3: 115. http://dx.doi.org/10.4172/2168-9717.1000115, 2014.

Research investigation aim is the evaluation and behaviour of a material in the physical world that is drawn from a scientific theory to control material conductance. To define a microfluidic network to enhance the visible transmission and ability to lower its phase transition temperature by microfluidics is new. This theory was presented to scientific conferences;

- Guest speaker, 3nd International Workshop on Natures Inspired Manufacturing (NIM) part of the Living Machines: biomimetics and bio-hybrid systems, 2015 Conference, Barcelona.
- Sustainable Materials Inspired by the Living World for Energy (SMILE 2016) organized by IFP Energies and the French Academy of Science - 2016.

- Poster presentation, EUROSUNMED Symposium GG: Advanced Materials and Technologies for Renewable Energies (AMREN-2), EMRS - European Material Research Society - EMRS , Conference, Lille, France, 2016.
- 11th Conference on Advanced Building Skins, ISBN: 978-3-98120539-8, 2016.
- Poster presentation, MRS – Material Research Society (USA), Boston Fall Meeting ,Symposium Sessions: NM4—Nanomaterials-Based Solar Energy Conversion, 2016.

The theory of microfluidics based flows to direct the structural assembly of a polymer into a thermally functional material, is new. This new approach was presented to scientific conferences and received validation by the community. Experiential testing within a laboratory (of restricted secure access) established the theory under real world physical testing conditions. The outcomes of these facts are presented in chapter 6: Vasculature Geometry, chapter 7: Thermal Modulation. The proceeding Chapter 5 sets out the process method to enhance solar modulation properties of a transparent polymer. By encapsulation of a capillary network within the polymer for a fluid to act as an absorber of solar gains. Through determining optimisation of the capillary network geometry, the introduction of an active fluid in a material and the direction of the device design process. By Chapter 5 defining the design of the device through vasculature geometry, fluid medium, material selection and simulation.

Chapter 5 Transparent Design Process Method

5.0 Introduction

Current glass envelopes represent a static IR absorber response to lower building energy demand response to climatic zone. Energy demands in buildings brings together a range of complex relationships between the environment, individuals and their perception of comfort. This is in contrast to nature that has developed multifunctional biological systems. These systems are reactive materials of multiple structured functionality that respond to climatic changes to enable proliferation. These materials respond to the influence of ambient temperature, solar radiation gain, exposure to wind and changing micro climatic variation. Nature's use of vascular formation to give adaptive functions can be implanted into a composite material for IR absorptivity management. To change the surfaces of a glazed envelopes, from being a mere material entity to a dynamic energy system by the application of biologically inspired engineering, this is new. These are adaptive strategies to influence and change material IR absorption behaviour. To advance photosynthetic polymer by nature's vasculature through a bio-inspired engineering approach.

This desired morphology to enable thermal conductivity regulation, by exothermic (release of heat) management to advance a glass envelopes. This path of progression is outlined by material parameters, simulation, device solar radiation load to flow rate relationship and experimental testing that is contained within this chapter.

5.1 Material Parameters

These parameters are determined by vasculature geometry, fluid and material. Nature uses these parameters in vasculature formations to regulate material composition for heat transport regulation, by laminar flows for dehydration and autonomous self-healing surfaces. These functions are dependant on fluid flow in a parabolic profile, for a fully developed flow rate in vasculature geometry channel networks.

5.2 Vasculature Geometry

Nature uses microfluidic platform networks for the development mechanisms and mechanical support systems for all organisms. Leaf vein formations are of particular interest as they absorb solar radiation for energy conversion (photosynthesis). These vein formations have uniform spacing patterns of spatial regularity and conform to ordered hierarchical sequence patterns. A network of constant flow at low pressure represents a highly regulated energy transport system. This is a multi microchannel network represented by branching cross-sectional channels, distinctive vein (channel) dimensions to spatial material regions and hierarchical channel order. Leaves are microfluidic platforms set by hierarchical geometry attributes for solar modulation.

5.3 Fluid

In cold phloem networks (plants) and vasculature (mammal) use combinational chemistry, of functional fluidics to increase temperature monitoring and reaction heat absorbtion characterization. Leaves, however, are of particular interest due to their unique proporties to absorb solar radiation. Leaf vasculture fluids are of chemical composition for photosynthesis mechanisms. This unique proporty to generate energy through chemical compound reactions is a solar energy conversation method. However, scientififc research to replicate this fluidic mechanics is unresolved at this moment.

Chemical engineering of fluidics are formulated to create new compound solution materials. This is a chemical fluid designer molecule approach synthesizing the material for enhanced energy transfer in a newly created fluid solution. To activity construct the thermal absorption potential using the periodic table of elements for enhancing fluidic function. The composition of the fluid using chemical material elements is progressed through chemical engineering optimization. Chemistry scientific research to synthesize a fluidic formulation is determined by chemical behaviour and chemical element bonds at a molecule atomic level. Developing a new fluidic compound formula is not part of this research, as this is determined by element material compound engineering through chemistry. Hence, access to replicate a chemical solution particles could not be progressed for this research. The fluid that was selected was distilled water. The reason for the selection was determined by high specific heat capacity, availability and cost.

5.4 Material Selection

Artificial lighting and cooling are the two main factors for energy consumption in buildings. This applies to fully glazed buildings where directly transmitted natural light often needs to be controlled by shading in order to avoid glare problems and an unfavourable distribution of light within the room. Furthermore, transmitted solar irradiation leads to additional solar gains which in turn increase the cooling load of buildings. Replacing glazing elements with an absorption element will lead to heating of the absorber. A polymer is an ideal material for reducing the heat load as an absorber layer, with the additional benefit of using the absorber layer as a solar thermal collector. Polymer materials are widely used as windows in the aerospace industry, with proven durability , impact loading and resistance to UV. The integration of microfluidic based platform, capillary flow as a possible solution for filtering out the invisible irradiation near IR range offers a new direction in facade engineering.

5.5 Simulation for Optimization of Fluidic Networks

Plant venation geometry presents unique functions as they are a close loop network for recirculation of fluidics in multi microchannels. This characteristic is not present in any other vasculature channel system. A closed loop network can be analysed through simulation to generate optimum succession sequencing of channel formations as an analytical approach. Leaf vascular networks of optimal fluidic flow design can be defined as a resistor to evaluate resistance of transport fluidics by a theoretical approach. This will enable resistance, pressure drop and flow rate optimization that is characterized in leaf vasculature networks.

This research will demonstrate a resister circuit can define flow target resistance optimization that is determined by an iterative procedure. This functionality is significant to obtain a flow parabolic profile, for a fully developed flow rate to advance the structural assembly of a polymer into a functional material. This algorithm approach that generates micro-fluidic network based flows, is determined by pressure equalization in diminishing flow pressure variation within channel formations. This research will propose this self-optmization of resistance seeking targeting by modulating flow rate to capture IR by hydrodynamic control. The research will define a microfluidic network as a resister through a theoretical approach enables self-organised channel resistance with it's own resistance potential for pressure drop regulation. By optimum successive conduit sequence to an accuracy in slot geometry network architecture of 1 micron, that sets the underlying flow distribution.

5.6 Device Physical Testing under Solar Radiation Load and Relationship to Flow Rate

Quantifing thermal flow in a multi microchannel network from input fluidic supply and extract fluid output is dependant on flow rate. The variation between input and extract liquid temperature (delta t) will determine heat transport optimization to capture, store and remove thermal energy.

The amount of heat transfer gain (fluid – delta t) is dependant on heat load (solar radiation) impact to the polymer. The fluid is therefore acting as a solar radiation absorber to capture the energy through thermal heat transfer. By volumetric flow rates in the device will manipulate the postion of fluid-polymer interface to capture, store and remove energy. To observe these parameter functions, a prototype device was fabricated to analzse heat flow data through experimental testing. Differing solar loads applied in an artificial laboratory condition to replicate real world physical condition enables solar modulation assessment. This would quantify the thermal characteristics to ultimately lead to desired morphology in a thermal functional material.

5.7 Experimental Physical Testing

The optimization of a thermally functional device is determined by thermal conductivity as a heat flow transfer model, and that forms the basis of the experimental testing parameters, shown in Figure 5.1.

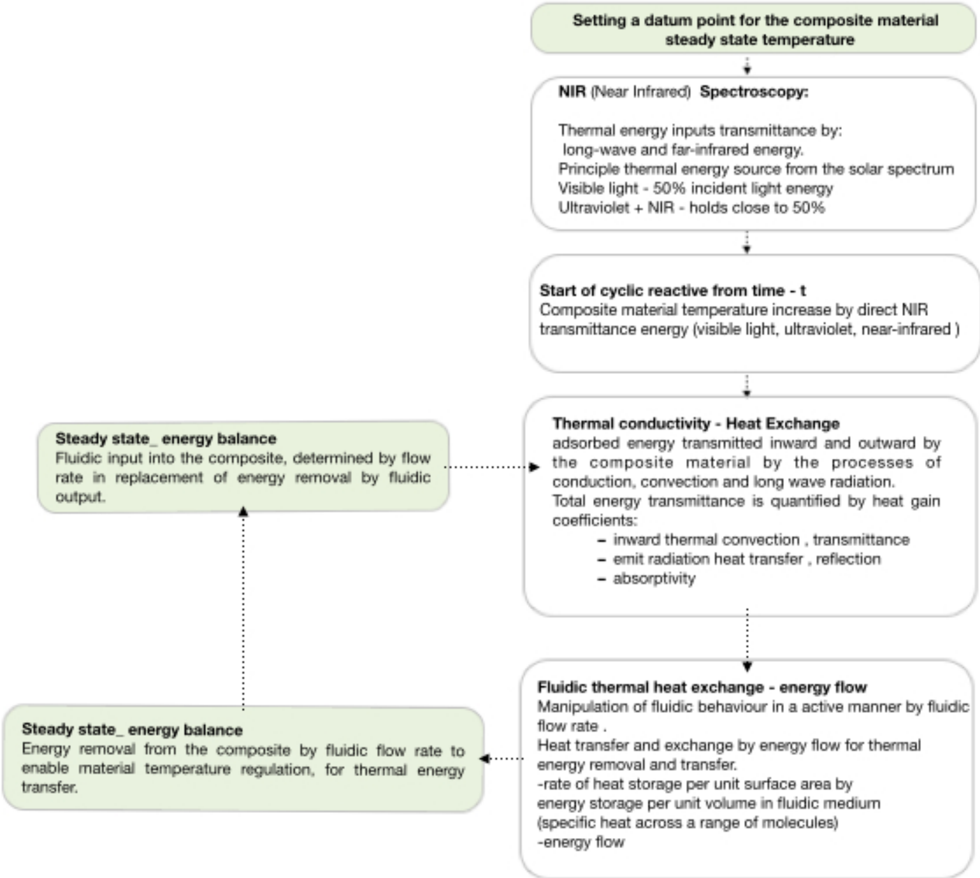


Figure 5.1 Experimental Parameters (by author)

Figure 5.1 is an energy thermal flow cycle that is determined by absorbed solar IR [W/m2] by observable experimental testing design. This will be undertaken by the fabrication of a composite prototype device to assess thermal management and regulation in connection to heat load impact. The energy flow path is dictated by the heat source. Hence the selection of this active heat source is solar radiation. Solar radiation was selected, as it is the primary driver and mechanism that influences climatology of this planet and the proliferation of life on earth. Solar radiation is driven by wavelength. This wavelength spectrum, ranges from ultraviolet to radio waves, with visible light 0-4- 0.7µi accounting for 50% of incident energy (angle of the sun to an object). It is, however, the ultraviolet and near infrared (NIR) that are the critical wavelengths. Ultraviolet wavelength is 0.3-0.4 µw and near infrared (NIR) is 0.7-2.5µ(. Both of these wavelengths represent the remaining 50% of the solar spectrum. Solar irradiance hitting a surface and its ability to absorb energy is determined by conduction, convection and long wave radiation. Hence the experimental design will review other experiential methods that have been undertaken to assess a materials ability to regulate thermal behaviour, when subjected to a heat load.

5.8 Experimental Testing Design

The experimental testing method will evaluate conductivity by the mechanisms that can regulate heat transfer of a composite material though:

1. Energy Capture: Absorption of shortwave infrared, to capture and store energy for removal by fluidics.

2. Thermal Transport: To influence material conductivity by active management of circulating fluidics within networks, by heat transport flow rate.

Material research in NIR absorption materials has been undertaken with a aerospace gauge carbon fibre epoxy composite panel 152x152mm had embedded within its structure twenty-four stainless steel tubes. Each tube was 178 mm long with two sets of diameters 102 µ0 and 203 µm, within a parallel

6.4 mm spacing network cast into an epoxy composite, shown in Figure 5.2. The first tube was 3.2mm from the edge of the composite device. Fluidic feed in and extract was achieved through tube gathering into a 25.4mm stainless steel terminal. A yor-lok connector (an adapter fitting to achieve a leak free connection) connected the terminal to flexible peek tubing, where thermal measurements were taken. Figure 5.2 illustrates the absorbing heat carbon fibre device.

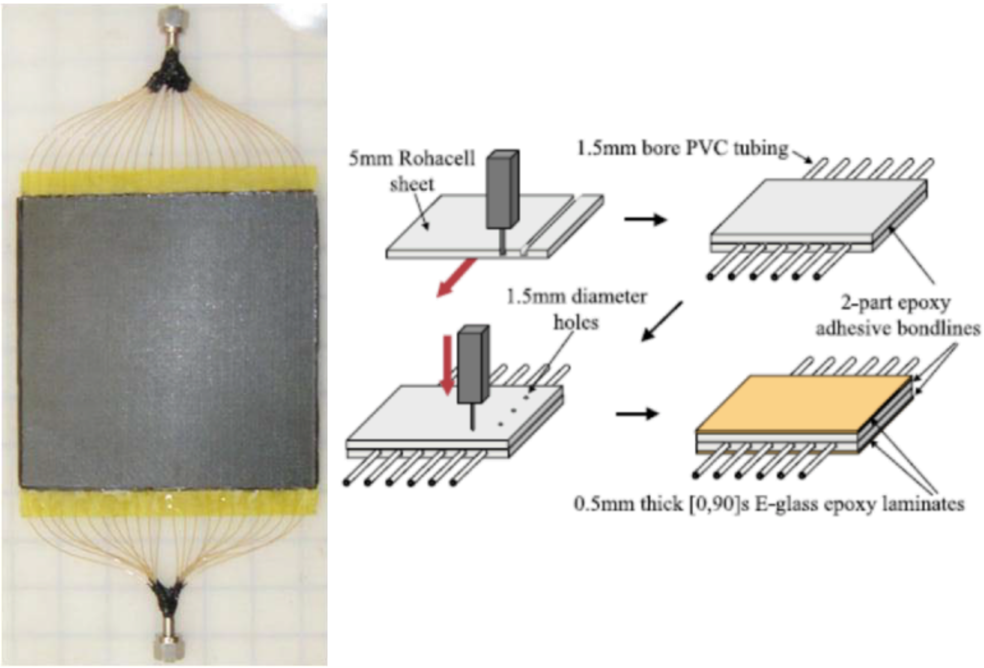


Figure 5.2 Multiple Tube in Two Layers of Aerospace Grade Carbon/Epoxy Laminates (M.R Rierce University of Dayton, School of Engineering,2010)

The experimental testing method proposed placing the device into a convection oven, where atmosphere temperature was controlled. The device was laid horizontally to enable maximization of natural heating in a oven for even heat loading. Exposed tubing, as shown in Figure 5.2, was protected by fibre glass insulation to ensure heat transfer result concentrated on the device.

A fluid that was pumped to obtain a set flow of 25ml/minute and liquid temperature was monitored by a thermocouple, with pressure measured by a transducer. Water was used as the fluidic material within the network. Emissivity of the device was measured two dimensionally by an infrared camera for surface temperature monitoring. The atmospheric temperature was adjusted to fix settings, input fluidic temperature was adjusted to fix settings and flow rate was also adjusted to fix setting.

This experimental laboratory testing, establishes material conductance behaviour as method to test and gain observations. The aerospace gauge epoxy with cast-in tubing set a principle of a microfluidic network, to regulate material thermal transfer by fluidic re-circulative flow. The convection oven (heat source) acted as a uniform heat load with device thermal absorption changing in response to variation in: flow rate, temperature fluidic input, and output fluidic temperature. The aim of this experiment is based on steady state theory, in order to assess energy heat transfer of the carbon fiber composite.

The calculation to assess steady state temperature of the fluid was:

$$\dot{m}\mathrm{H}_{\mathrm{inlet}0} - \dot{m}\mathrm{H}_{\mathrm{outlet}0} - Q = 0$$

$\dot{m}$ Flow rate of the fluid

H Fluid to absorb heat energy

$_{\mathrm{inlet}0}$ Inlet temperature

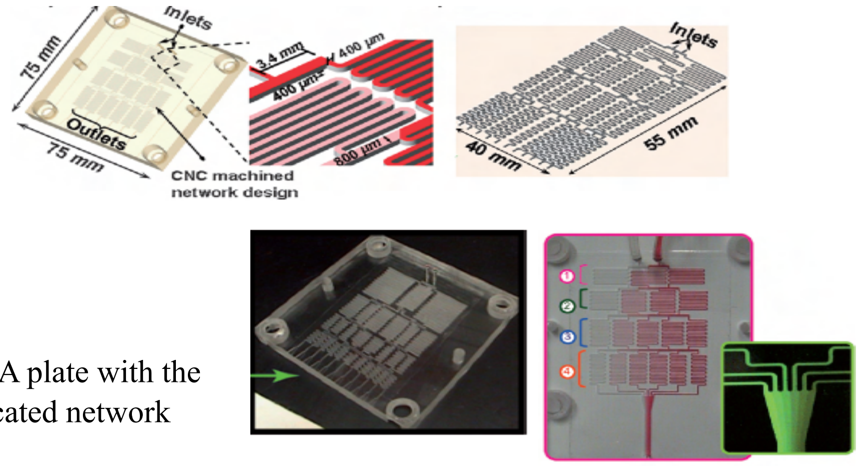
$_{\mathrm{outlet}0}$ Outflow temperature

Q Heat Flow

M.R Rierce, University of Dayton, School of Engineering, 2010.

However, the applied heat source method of a convection oven, in this experiment, was atmosphere temperature increase and this is different to solar radiation. The reasoning for this solar radiation, is governed by wavelength, ultraviolet, thermal infrared and near-infrared (NIR).

A microfluidic network has been tested to measure the impacts of NIR (Yusuf et al., 2008). The experiment was to measure the microfluidic gradient generation as an transparent detection system. This material a 10mm PMMA plate, poly(methyl methacrylate). The size of this device: 75x75mm square chip. Two inlets were drilled into the plate at a diameter of 1mm. A CAT3D M6 Computer Numerical Controlled milling machine using a 0.4mm tungstencarbide milling tool fabricated, the vascular network. The network design geometry configuration is indicated below, in Figure 5.3.



PMMA plate with the
Fabricated network

Figure 5.3 Schematic of the PMMA Microfluidic Network (Yusuf, et al, 2008)

The fluidic material selected for the experiment was deionized water within the network. The justification for using deionized water as the medium for capture and thermal transfer is related to its unique properties of a high thermal heat capacity and availability of the material to use in the experiment. Other fluidic formulations with equal or better water heating capacity requires a chemical engineering approach, using the periodic table of elements to derive a newly created fluidic formation. Deionized water was fed into the network, as follows. Two syringe pumps were connected to the microfluidic network through a narrow-bore PTFE tubing via two screw-in luer lock connectors. Two syringe pumps controlled the flow rate by a program called

LabVIEW. This enabled adjustment in fluidic flow rates through the network. A tungsten halogen lamp acted as the heat source. The scientific method of this investigation did observe the effects of hydrodynamic resistance, multi microchannel geometry layout and viscosity effects of the fluid. These parameters influenced material behaviour in response to heat load.

The laboratory results indicated pressure resistance of a flowing liquid in multi microchannel networks will impact on thermal energy transfer. This method of testing has synergy with the proposals for my experimental testing method.

5.9 Proposed Experimental Testing

In order to propose the experimental testing parameters it is first necessary to define the calculation method. This will enable assessment of SI units in which to test, if the composite can regulate thermal conductance. The calculation is in fact two. The reasoning for this, all materials have a capacity to absorb energy as determined by specific heat capacity c_p. This thermal capacity is dependent upon heat transfer q. To enable regulation of q, the method of applying vascular networks as inspired by nature uses fluidics. Hence, fluids are dependent upon mass flow rate and specific heat capacity of the fluid to absorb and transfer thermal energy. The differential temperature of the input fluidic temperature and output fluidic extract can measure the absorption rate, delta t.

This will determine the heat absorption by the fluid in response to solar radiation. By the calculation method of :

$$q_H = \dot{m}\, Cp\ \Delta t$$

q_H Heat load

$\triangle t$ Temperature difference

$\dot{m}$ Mass Flow rate

Cp Heat Capacity

However, any fluid within a channel network in nature (plants and cardiovascular, the human body) and man-made fluidic systems, all are affected by fluidic flow directional movement. Resistance to flow within a fluidic network defines this movement and this can be described by pressure. Pressure is a measure of the resistance to flow and this will impact on the fluidic absorption rate.

The Pressure Resistance to fluidic flow within the fluidic network calculation is:

$\triangle p = Q_0 R_0$

$\triangle p$ Pressure drop between inlet and export stem vasculature

Q Fluidic Flow

R Resistance

The laboratory testing of the prototype is not focused upon thermal conductivity but the absorption of solar (ie non-thermal) IR, which then will heat up the polymer device. Transition temperature of the polymer will be characterized by modulating microfluidic based flow in steady state. This capture of energy by solar modulation will progress a thermal function polymer as an IR radiation stop band with lower phase transition temperature. These properties will be measured by laboratory testing and this is described below as a series of step stages.

Structural Assembly of the Polymer Device: Two plates of 5mm polymer form the prototype device. The base plate contained the microchannel network that is fabricated by laser cutting into the surface of the base plate. This channel geometry will contain the microfluidic based flows. The polymer counterplate acts as the solar radiation absorber pane. These two plates have been bonded together to form the structural assembly-testing device, shown in Figure 5.4. The justification of the geometry network, to develop a multi microchannel formation is determined in Chapter 6, Section 6.6: Network Geometry Evolution. Two plates of PMMA 5mm thick were cut to a dimensional size of 158mm width and length 220mm. One of the plates was inscribed , through laser application to fabricate a geometry arrangement of micro channels. These channels formed the volumetric areas of water contained within the depth of the plate. This geometry formation plate was resin bonded to the remaining counter plate to assemble the microfluidic device.

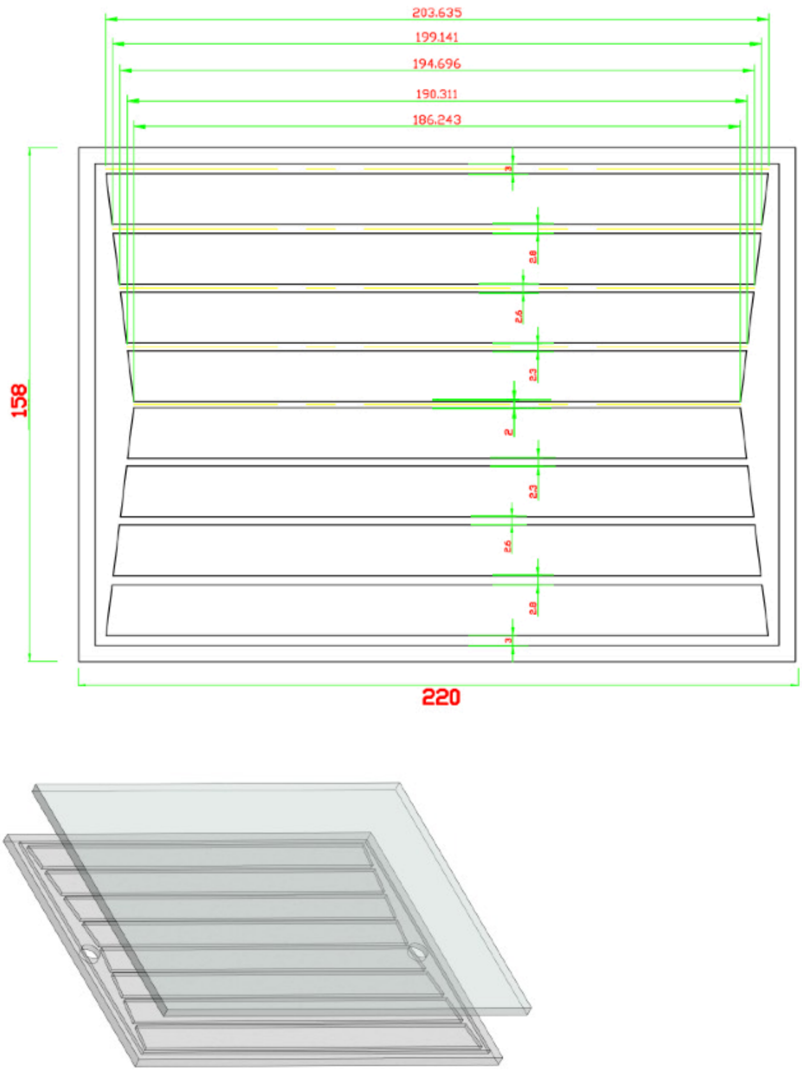


Figure 5.4 PMMA Composite Device (by author), dimensions in mm.

Using a microfluidic platform of steady state flow in cross slot channels by precise flow rate in the device enhances fluid to material (transparent polymer) heat transfer for thermal energy capture and storage. Optimization is determined by microchannels hierarchical order regulated by rules of minimum energy loss, minimum effective power flow rates and minimum pressure drop. The controlling process of a thermally functional microfluidic polymer device is determined by flow generation in the network to absorb solar radiation and this is determined through pressure equalization within a closed loop network. Resistance is the parameter to enhance modulating flow rates optimization to manipulate thermal heat transfer, to evaluate this. These characteristics are exhibited in the uniform spacing patterns of hierarchical sequence vascularization patterns (veins) in advance leaf species.

Heat Conductivity Regulation by Fluidic Thermal Exchange: The absorption of solar IR in the PMMA counterplate will heat up. The introduction of the microvasular channel network will enable a liquid to circulate and interact with material temperature regions of the device. This liquid encapsulated within the channels acts as an absorber of thermal temperature. Hence the channel network within the device will be connected to a fluidic source to enable this heat exchange interaction by fluidic import and export measures, shown in Figure 5.5.

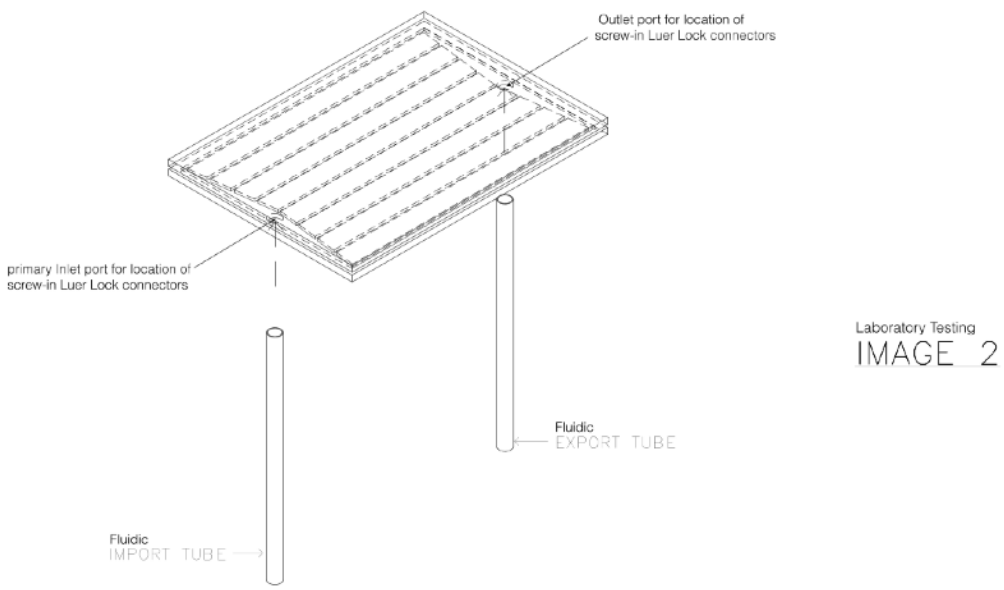


Figure 5.5 Fluidic Connection Input into the Vascular Channel Network (by author)

Fluidic Flow: The inlet port tube is attached to the device. However, fluidic pressure feed is required to create volume liquid flow within the device, shown in Figure 4.4. This pump introduces pressure via fluidic flow through the channel network geometry and the outlet port will enable removal. The establishment of pressure, measurement of flow rate and fluidic extract temperature can then be defined. This syringe pump will have a large fluidic reservoir to pump water into the device to create the flow and maintain this flow rate. Thermocouples temperature sensors undertake temperature monitoring of fluidic absorptivity, shown in Figure 5.6.

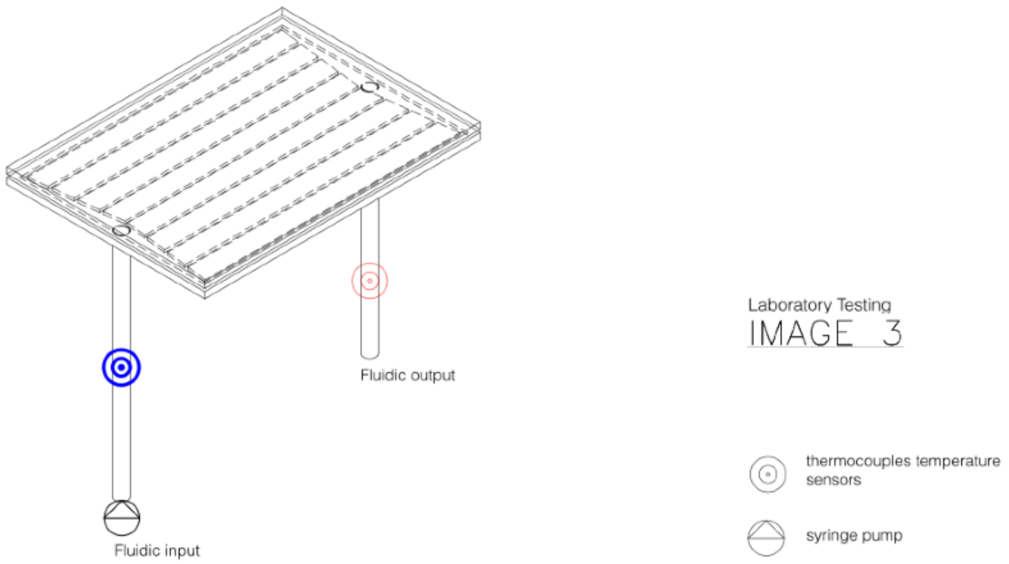


Figure 5.6 Fluidic Flow and Temperature Fluid Monitoring (by author)

Introduction of a Heat Source: The transparent polymer is subjected to an artificial solar (incandescent light) source that emitted IR wavelength 1000 watts per m^2. Solar heat load increase the surface temperature of the polymer surface pane. Distilled water is be pumped through the channel network that directed the structural assembly of the polymer. The fluidic input and extract temperature into the manifolds channel was monitor by thermocouples. Switching of the water flow for solar IR absorption regulates the heating effect from the panes. Sensors monitored material–fluid thermal interface transport exchange. A thermal infrared IR camera will obtain these measurements. This analysis will enable assessment of thermal switching to manipulate PMMA material phase transmission temperature. Figure 5.7 illustrates the schematic of the experimental testing design.

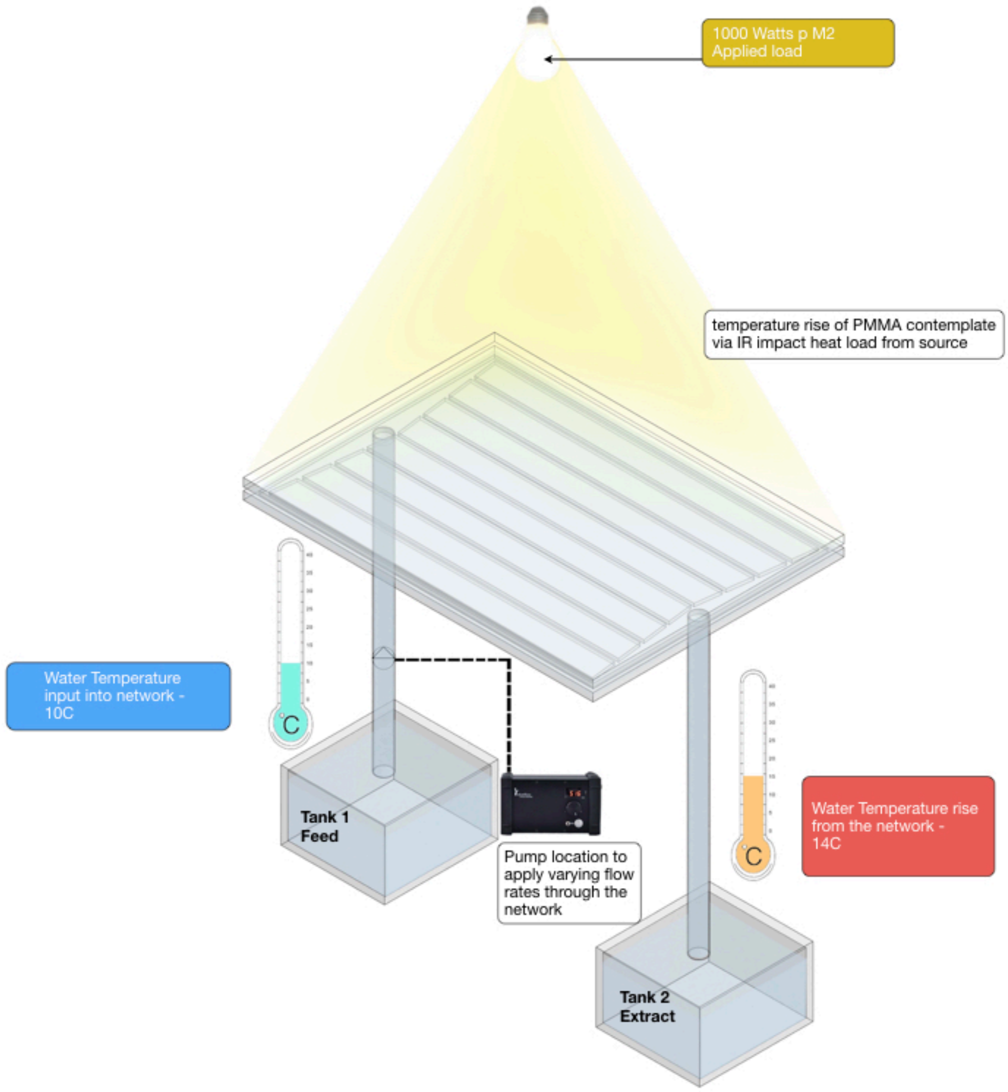


Figure 5.7 Experimental Design Testing Schematic (by author - note no photography of this experiment was allowed, due to the secure facility where the testing took place)

The value of this experimental testing design will assess thermal switching selectivity for IR to material regions. Laboratory Test to assess photo type composite by experimental testing: A syringe pump will be used to control the distilled water solution flow within the composite epoxy. A 1000W incandescent light will be placed above the composite material approximately 80 cm away as a heat source to the composite material, an initial temperature of 35 increasing to a maximum of 40 C. Thermocouples will be used to assess fluidic input and extract temperatures. There are limitations imposed on this test and these are reviewed in Chapter 8, Section 8.4: Review of Limitations and Constraints. However, there is one particular limitation to highlight here, which is the time period of the experiment itself. All syringe pumps are used in experimental testing to establish precise fluidic flow rate of a fixed volume of water in microchannel use tank reservoir. These reservoirs contain a fixed volume of water to determine the flow rate (pumping pressure) through the multi microchannel network. The fixed volume of water at a predetermined flow rate within a network is determined by time, through water volume reservoir capacity. This establishes the time frame, and duration of the experiment, at 50 minutes. Temperature monitoring greater than 50 minutes could not be achieved by the syringe pumps reservoir fixed water capacity. This time frame is therefore a limitation of the research.

5.10 Conclusion

Nature's biological systems are living multifunctional mechanical information systems of chemical composition. They have the ability to learn and adapt to changing climatic conditions by self-regulation of solar absorption, to achieve thermal management. To embed this functions into a polymer to advance a transparent material as an energy capture and storage system. Through the process of flow, pressure, heat transport by real-time reactions by precision hydrodynamics control as defined by a leaf is new.

Bio-inspired solution to progress from a static IR absorber , a mere material entity, to a dynamic one to interact with the environment of real time performance change by the hour, season and weather conditions as a energy flow cycle. The following chapter 6 defines natures leaf vasculature formations to evolve material function as a thermal flow system aligned and oriented to thermal monitoring temperature with time through optimisation of capillary channels geometry networks.

Chapter 6: Vasculature Geometry

6.0 Introduction

Leaf vascular patterns are the mechanisms and mechanical support for the transportation of fluidics for photosynthesis and leaf development properties. Vascular hierarchical networks in leaves have far-reaching functions in optimal transport efficiency of functional fluidics. Embedding leaf morphogenesis as a resistor network is significant in the optimization of a transparent thermally functional material. This will enable regulation through pressure equalization by diminishing flow pressure variation. This chapter investigates nature's vasculature networks that exhibit hierarchical branching scaling applied to microfluidics, to enable optimum potential for pressure drop regulation by simulation. This analysis of circuit conduit optimization for transport fluidic flow resistance is validated against CFD simulation, within a closed loop network. The chapter will propose this self-optimization, characterization by resistance seeking targeting to determine a microfluidic network as a resistor, to advance a thermally function material as a switchable IR absorber.

Nature uses vascular formations to control delivery of nutrients, removal of waste, temperature regulation and damage repair by a functional fluid. A leaf is an independent unit within a tree canopy structured system that is regulated by solar orientation for daylight capture. Each leaf is an individual photosystem that is defined by rule based geometry, canopy volume, total leaf area density and angular distribution of leaf surfaces (Sinoquet et al., 2005), Beer's law shown in Figure 6.1.

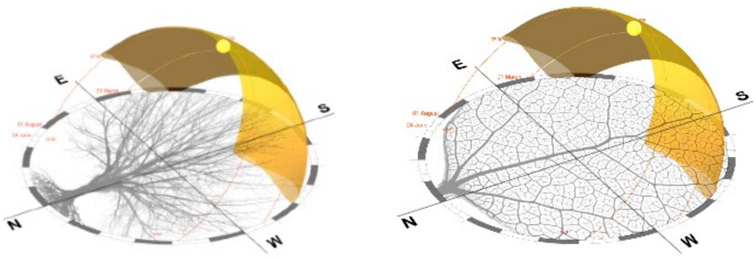


Figure 6.1 Tree and Leaf Structural Geometry in Relationship to Solar Orientation

Vascular patterns are development mechanisms that are the mechanical support systems used by nature (Odum et al., 2005). This is centered on fluidic metabolic material flow in cold and warm-blooded venal networks. Microchannels conform to hierarchical order by rules of minimum energy loss, minimum effective power flow rates and minimum pressure drop. This characterization will advance a thermal functional polymer as a switchable IR absorber. Thermal switching is achieved by fluidic flow to advance a photo-absorptive polymer.

In cold phloem leaves vascular patterns are characterized by the intimate relationship between vein leaf patterns and leaf foliage scale, as determined by auxin provascular activity (Blonder et al., 2011). These are highly regulated with species-specific vascular pattern formations. Vascular formations have uniform spacing patterns and exhibit spatial regularity by hierarchical sequence patterns in advanced leaf species (Nelson et al., 1997). The underlying mechanisms of vascularization pattern conduits are networks of constant flow conductivity distribution and pressure (Feugier et al., 2005). This reticulate closed loop geometry is formed by changes in vein thickness, vein angle divergence, redundancy functionality, stem vasculature fluidic supply and vein hierarchical order, (Dengler et al., 2001) shown in Figure 6.2.

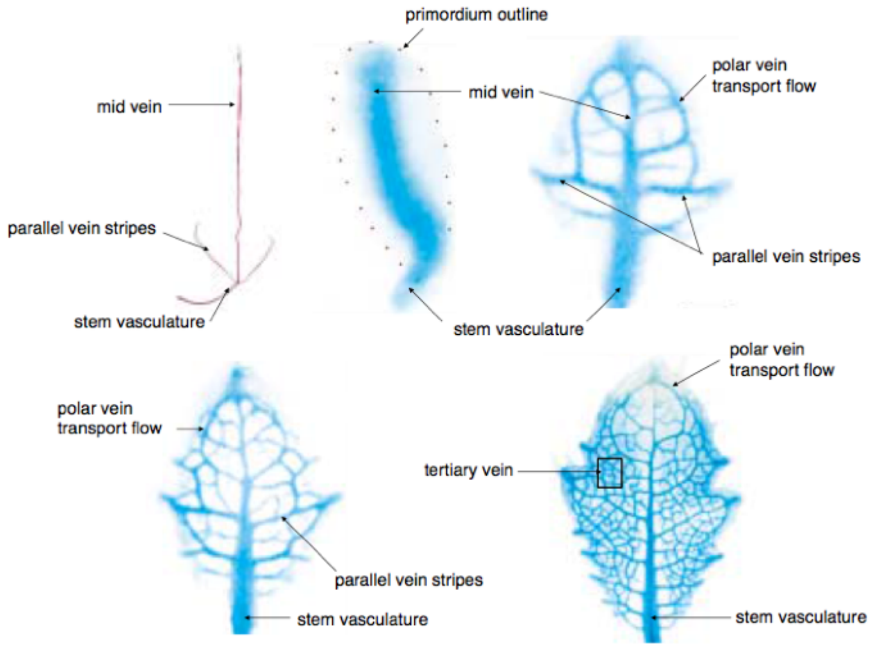


Figure 6.2 Leaf Vasculature Formations (Mattsson et al., 2000)

A venation network is a two dimensional (longitudinal pattern) of continuous, branching features. These vascular patterns form a complex hierarchical pattern for the transportation of fluidics for photosynthate mechanisms. Characterization of leaf vein formations are desirable morphology for solar modulation properties by microfluidics for transition temperature decrease in a thermally functional material.

Using a microfluidic-based network of steady state flow in multi microchannels across the material pane will advance a polymer for desired thermal functionality. Achieving a parabolic and laminar profile characterization to be obtained immediately from fluidic input into the network is significant. Manifold feed in and output channels perform significant roles to reduce turbulence, non-linear effects and shortcuts pathways to derive smooth flow (Oh et al., 2010). All other multi microchannel geometries represent the thermal transport network for IR transmission temperature interface, for capture from the polymer surface pane. Using microfluidic based flows into a structural assembly of a polymer device will advance the materials desired energy capture and storage functionality. This steady state flow network of continuously circulating a fluid within it, through it and out of it, by microfluidic based flows to direct the structural assembly of a polymer (Olugebefola et al., 2010). This uniform parabolic flow will remove stored liquid temperature out of the polymer for solar energy modulation efficiency. If this liquid is replaced with incoming fluid, this creates a photoabsorptive system. This approach enables thermal switching selectivity of a polymer device in response to heat load, IR. This research is not focused on thermal conductivity but the absorption of solar (non-thermal) IR by heat built up. This represents a thermal exchange transfer cycle of fluidic absorption through vascular channels. The micro vascular network will determine thermal switching optimization to material temperature regions. The multi microchannel network will regulate material temperature by management of:

1. Resistance Optimization (Chapter 6)
2. Radiative / Convective heat interface transfer (Chapter 7)

These parameters will give optimization of a thermally functional material in relationship to surface temperature fluctuations. The heating effect from a surface material pane is regulated by water uniform parabolic and laminar flow profile for transition temperature decrease, shown in Figure 6.3.

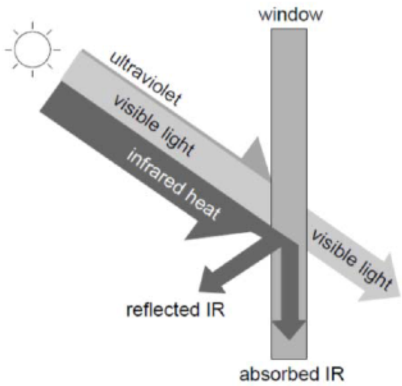


Figure 6.3 Polymer as an IR Block (Lee, E., et al 2009)

This is management of thermal flow across the planar microfluidic platform to act as a thermal flow bridge. This is a dynamic heat seeking system to progress a current static façade to a thermally functional adaptive layer (Alston, 2015). The integration of artificial microfluidic networks of solar absorbing fluid in active flow is a new methodology. Future progression is to determine thermal modulation (Chapter 6) of the device by thermal switching for heat flow targeting. Structural assembly of a polymer of microfluidic-based flow will lead to the desired morphology to direct a photoabsorbing material to act as an IR stop-band block, through the underlying mechanisms of vascularization leaf patterns.

6.1 Leaf Vascularization

Vein formations of primary (stem), secondary (mid, parallel, polar - circulative boundary vein) and minor veins (tertiary for localized fluidic flow) deal with specific leaf material regions (Turing, 1952). This is functionality significant for material characterization, as it represents vein conduit sequences succession (Kull et al., 1995; Berleth, 2000). This working formation hierarchy is in response to tolerance to damage, water stress conditions and redundancy. The polar vein completes the network of nested conduit loops to maintain fluidic flow from stem and mid vein vasculature.

All veins diminish in size distally from fluidic input supply. This arrangement of diminishing vein size order by primary veins and secondary is the relationship to leaf apex scale (Mattsson et al., 2000). Vasculature patterns are linked to material scale in the formation of conduit network geometry as they perform regulatory roles. The fluidic input and export flow within these hierarchical networks are subject to flow resistance and flow rate. Hydraulic resistance in fluidic conduits channels conform to minimum fluidic flow to achieved reduced pressure drop for fluidic flow efficiency. This is determined by hierarchical structure to minimize resistance R for optimal fluidic transport. The resistance is determined by mechanical energy when a flowing liquid is subjected to a change in direction.

6.2 Vasculature as a Resistor

Nomenclature

L overall length of tapered manifold (measured to the centreline of the outermost channel) = 74 mm – 1.5 mm = 72.5 mm

L_m length of each tapered manifold section ($L_m = L/4$)

R_0 hydraulic resistance of central longitudinal channel

R_i hydraulic resistance of longitudinal channel i

R_4 hydraulic resistance of outermost longitudinal channel

Rm_1 hydraulic resistance of manifold section feeding channel 1

Rm_i hydraulic resistance of manifold section feeding channel i

Rm_4 hydraulic resistance of manifold section feeding channel 4

Q_0 volumetric flow rate through each channel (total volumetric flow rate = 9 Q_0)

w_0 width of tapered manifold at the location of the central channel = 12 mm

w_i width of tapered manifold at the location of longitudinal channel i

w_4 width of tapered manifold at the location of the outermost channel = 3.365 mm

$\overline{w}_1$ average width of manifold feeding channel 1

$\overline{w}_i$ average width of manifold feeding channel i

$\overline{w}_4$ average width of manifold feeding outermost channel

Δp_1 pressure drop across Rm_1

Δp_i pressure drop across Rm_i

Δp_4 pressure drop across Rm_4

D_h hydraulic diameter

Re Reynold number

Po Mean flow velocity

Optimal transport efficiency in natural fluidic pattern formations can be defined as a resistor. This is flow resistance evaluation in determining channel conduit scaling of vasculature branching networks. Channels that are distally positioned from fluidic input are affected by pressure drop in fully developed laminar flow. Veins will be subjected to increasing resistance or rather pressure drop for any given flow rate. To evaluate this hydrodynamic question essentially rules by Hagen-Poiseuille's law, which suggests a constant flow resistance, a pressure loss linearly increasing with flow rate. Poiseuille number, (Po) can be applied to vascular leaf formations and represented as a resistor conductance circuit, shown in Figure 6.4.

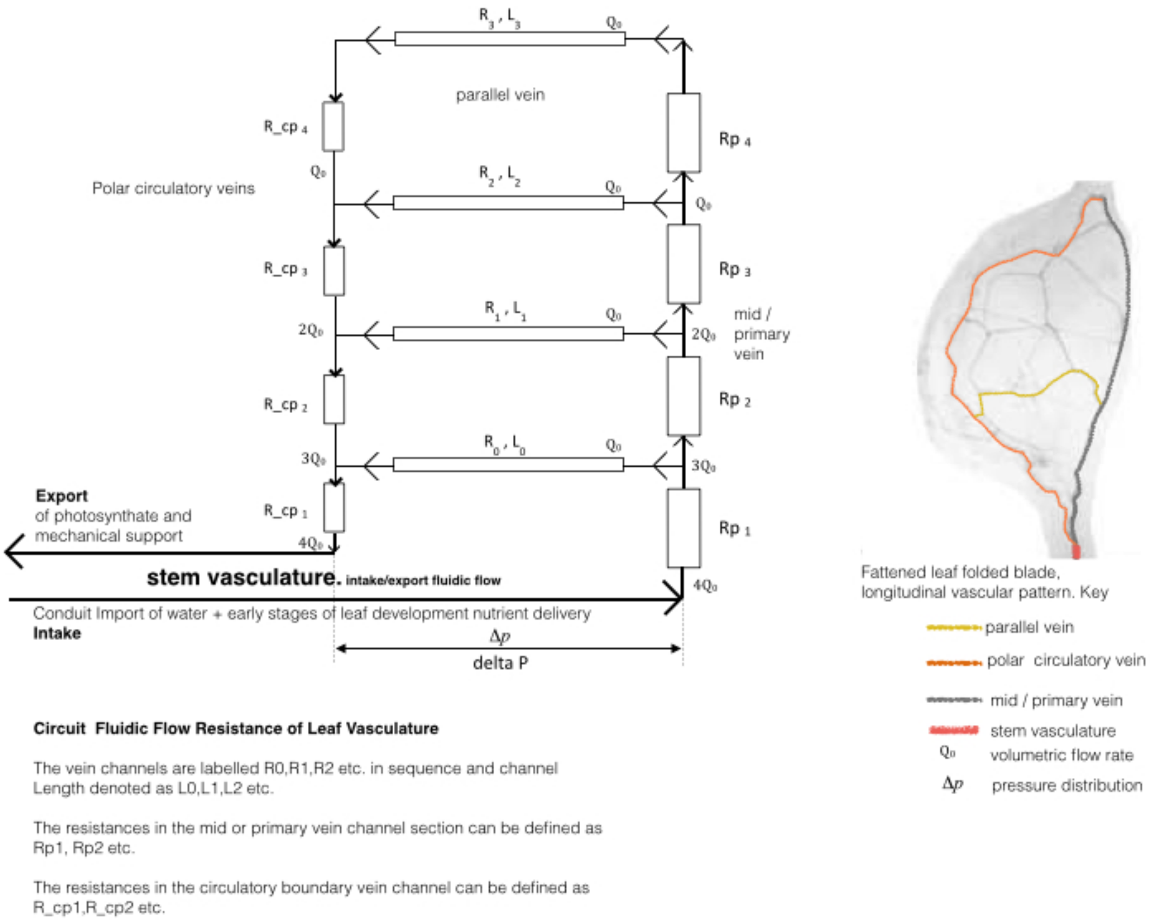


Figure 6.4 Resistor Network by Branching Network Scaling

A range of electrical potential can determine leaf vasculature optimization by conductance circuit increases. This is a relationship to channel length, radius and hierarchy, shown in Figure 6.5.

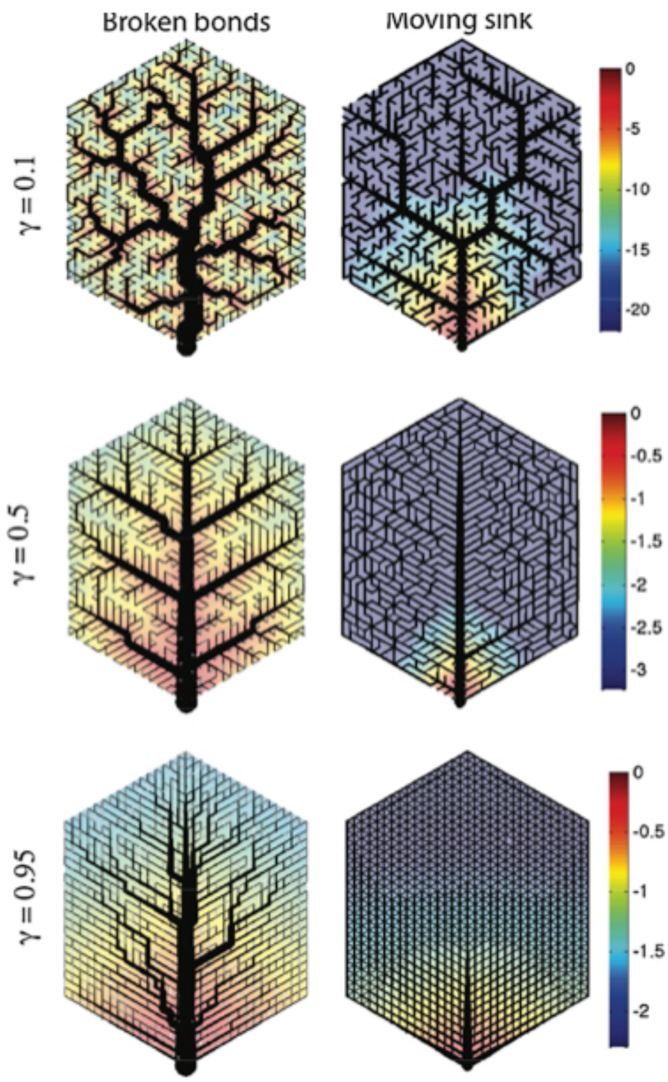


Figure 6.5 Patterning Mechanism, (Katifori et al.,2010)

Figure 6.5 illustrates the patterning mechanism of two vascular closed looped networks in connection to pressure drop and channel geometry. Fluidic flow will vary in changes in cross-sectional channel sections within venation network (Katifori et al., 2010). This:

(a)Defines a network hierarchical multiplication order with a circulative loop network in connection to flow pressure.

(b)Represents a non- hierarchical loop network in relationship to flow pressure.

(c)Colour plot bar denotes fluidic pressure

(d)Y denotes (dissipation) hierarchical network loop efficiency of flow and conductance distribution.

This is called a sink model fractal network of branching sequential order. Figure 6.5 denotes the importance of establishing a fixed pressure (or electrical potential) by optimum resistance from fluidic source input. In leaf venation networks this is concentrated in the outermost edges of the leaf of high resistance conductance. Each channel within leaf vasculature is self-organized with its own independency for optimum potential. This hierarchical fluidic transport efficiency for optimal channel networks, Figure 5.5, is defined by $y = 0.75$. When y is small enough, $y = 0.25$, there is an increasing breaking down of fluidic flow and flow resistance in connection to fluidic source input (Brodribb et al., 2007, Dobbs, 2010). When $y > 1.0$ the network has no hierarchy with uniform order with nonzero conductance to leaf edges (Saffrey et al., 2001). This represents increased pressure, resistance and concentration of channel cross sectional area focused on fluidic input into the network, (McLaughlin et al., 2007; Gray, 2012). Fluctuation changes in optimum structured networks is a correlation of laminar fluid flow and resistance (Koch et al., 1994). Varying independent channel optimum resistance will determine fluidic transport hierarchy and minimization of pressure drop. This pressure drop will vary resistance in the network between fluidic multi micro channels. To determine pressure drop in longitudinal channels R, L0 to R, L3, Figure 6.4, is dependent on upstream (Rp1 to Rp4) and downstream (R_cp1 to R_cp4) micro channels.

Analysis for both the upstream and downstream channels can be determined, to evaluate if the upstream and downstream resistances are different. Knowing the pressure drops (delta P) will allow an estimate of the actual flow resistances. Analysis of delta P will determine optimization of resistance by microchannel sequence succession. Multi micro channels widths are significant as longitudinal microchannels length and microchannel depth is determined by material scale. If we assume flow rate is equal within multi microfluidic channels, we can evaluate flow; to predict pressure variation by analysis. Volumetric flow is evaluated by: u_bar (velocity coefficient,) Dh (hydraulic channel diameter), Re (Reynolds number based on hydraulic diameter), Po (Poiseuille law), tau (mean wall channel shear stress) and delta P, along each channel. Resistance is then evaluated from R=delta P/Q flow rate. Fluidic inlet flow to feed distally channels by optimization, is achieved through pressure equalization by diminishing flow pressure variation. This equalization of resistance transport flow is resistance-seeking targeting that can be presented as a resistor network, shown in Figure 6.6.

5.3 Network Formations as a Resistor

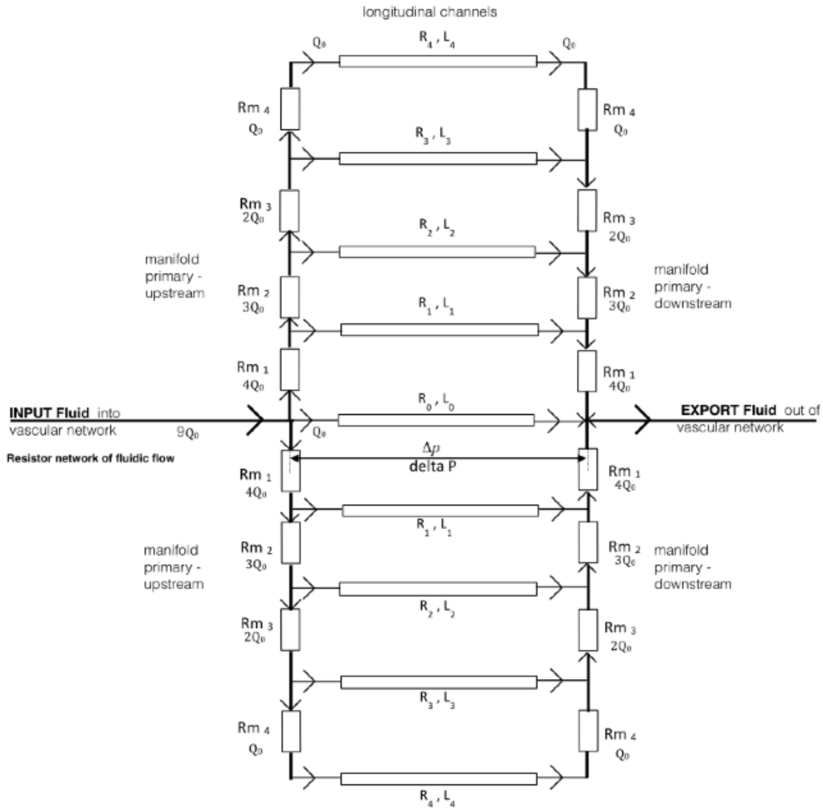


Figure 6.6 Fluidic Resistor Network

Evaluation of resistance optimization is centered on a single microchannel that all other channels succession sequence will emulate. This resistance-seeking targeting is defined as having, R0 and length L0. This microchannel presents the path as least resistance for fluidic flow through the vasculature network. The greatest resistance to flow is presented by R4 as it is distally removed from fluidic input. Other channels are then labeled R1, R2 etc. in sequence from the target resistance channel. If we assume that we know R0 the aim is to design the channel geometry to give equal flow rates through all the microchannels. Fluidic feed in and out flow manifold micro channels are denoted by Rm1, Rm2 etc. Resistances of each longitudinal channel is evaluated and designed to an individual particular resistance function. The equation for the resistances follows a recursive pattern:

Consider the flow channel R1:

$$\triangle p = Q_0 R_0 = 8Q_0 Rm_1 + 6Q_0 Rm_2 + Q_0 Rm_1$$

Fluidic flow rate Q, can be cancelled out, as flow rate will be constant, assuming equal flow resistance is achieved. Hence, analysis of target resistance for the following channels can be considered:

$$R_0 = 4Rm_1 + R_1 + 4Rm_1$$

$$R_0 = 8Rm_1 + R_1$$

$$R_1 = R_0 - 8Rm_1$$

Channel R2:

$$\triangle p = Q_0 R_0 = 8Q_0 Rm_1 + 6Q_0 Rm_2 + Q_0 Rm_2$$

$$R_2 = R_0 - 8Rm_1 - 6Rm_2$$

Channel R3:

$$R_3 = R_0 - 8Rm_1 - 6Rm_2 - 4Rm_3$$

Hence, the sequence will continue for R4.

An algorithm is used by increasing the width of the channel in fixed increments of delta w (delta w to be equal to 0.1 microns, to enable 1 micron accuracy). If the resistance of the channel is greater than the "target" hydraulic resistance (of the central channel), then the program increases the width by delta w. Hence, a ratio of the maximum resistance to minimum resistance can be optimized. This approach of defining individual channel resistance is the same approach applied in leaf vasculature. This analysis will then automatically feed into calculating the target resistance of the various side upstream and downstream distribution manifold Rm channels. Target resistance is required to give the same flow rate through each channel with the resistance of the outermost channel, R4, needs to be approximately 25% lower than R0. Once optimized widths are achieved the flow rate can be estimated to test whether the proposed method of optimization is successful against CFD simulation in a polymer device.

6.4 Channel Depth Geometry Analysis

Steady state flow of a fluid in unified flow rate across a planar surface will attain uniform solar radiation absorption and capture that is significant. A fluid in steady state flow requires reduced power to push the fluid in the network, to attain a lower-pressure drop that enhances uniform flow velocity within a network to capture IR, by a fluidic medium, acting as a heat sink to absorb and transfer thermal energy within the network. The geometry formation of the network is determined by unified fluidic flow transportation while maximizing volumetric fluidic material as an active thermal carrier absorber. This optimization determines the multi microchannel geometry for solar modulation application. In this network architecture, a cross sectional area of each channel in a branching fractile geometry is determined by fluid volume flow that is the sum of the primary input flow channel. The maximization of uniform flow through a network is exhibited by nature in leaves, cardiovascular and tracheas. Individual cross sectional area channels within a tree branching formation define these biological networks. Each channel within this tree branching network will vary in cross sectional dimensional volume, as determined by depth, width, length and spatial relationship to each other within a precise ordered geometry formation. This non-uniform cross section conforms to hierarchical ordering of sub channels of varying fluidic transport diameters. To replicate the sequence succession patterns into an artificial multi microchannel network requires depth of the channels to be a constant. Depth as a constant variable, in an artificial network will determine the capacity of the fluid (water) volume to absorb solar IR. If the depth were too shallow, this would limit the ability of the fluid to absorb solar IR for capture and storage of thermal energy. In leaf formations, the depth of the vein patterns are at a nanoscale in cross sectional depth that commence from 50 μm minor veins to 100μm secondary veins. To amplify thermal capture of IR in microchannel successive length for heat flow transport, depth is greater than leaf vasculature in a biomimetic design approach.

This microchannel depth will influence optimized fluidic flow by hydraulic resistance, R, within vasculature. To define hydraulic resistance effects on flow was determined by a fixed known 3mm microchannel width. The depth through simulation was varied to ascertain changes in resistance relationship to fluidic flow, shown in Table 6.7.

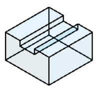
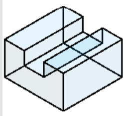
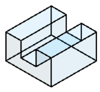
Micro-channel Geometry PMMA depth 5mm	Channel Depth	Length of Channel Centre Line m	Optimum Width m	target Resistance R (kg m^-4 s^-1)	Poiseuille no Mean Flow Velocity	Resistance achieved
	1mm	0.202920	0.003000	R-0.91448096E+09	17.08967207	R-0.91451954E+09
	2mm	0.202920	0.003000	R-0.15375808E+09	14.71176211	R-0.15376650E+09
	3mm	0.202920	0.003000	R-0.063441782E+09	14.22707689	R-0.063446011E+09
						or 0.63446011E+08 power to 10^8

Table 6.7 Microchannel Depth Analysis

Table 6.7 shows the value of resistance monotonically decreases as microchannel depth increases as this was determined by the following resultant hydraulic resistance values of R= 0.914 x 10^9, 0.15 x 10^9 and 0.063 x 10^9 as the depth increases as expected. The depths of least resistance was the 3mm and 2mm microchannel, with the greatest resistance to flow presented by a depth of 1mm. Microchannel depth selected to determine progression for the experimental testing device was the R value

0.15 x 10^9, 2mm. The reasoning for this microchannel depth selection: minimization of fluidic volume, associate weight reduction, maximization of fluidic absorption and minimization of fluidic expansion. This resistance optimization analysis defined the depth of the network. This parameter acts as the constant to determine the sequence succession of microchannel widths of variation. This is hydraulic resistance equalization, as demonstrated by leaf vasculature networks, Figure 6.8 by resistance evaluation.

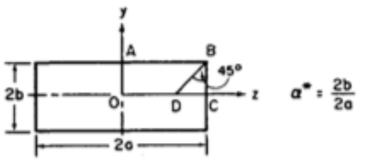


FIG. 36. A rectangular duct.

Figure 6.8 Laminar Flow Forced Convection in Ducts (Shah, 1978)

The selection of a non – circular, rectangle / square single microchannel cross section was determined by increased surface area exposure as pathway channels to absorb solar IR as heat sinks. Shah (1978) determined this relationship for rectangular microchannels with constant depth. Neighbouring distribution channels width and length present the variable parameters in channel succession, however, depth remains constant for water transport capacity. Circular channels can be fabricated to create a network; these channels have reduced surface contact area in proportion to a rectangular / square channel for maximized heat transfer. By magnified flow heating effects of rectangular / square channels by interface fluid – material heat transfer is enhanced through a larger contacting surface area.

Vasculature formations of leaves are characterized by leaf geometry and scale tailored to species-specific vascular patterns. These characteristics are reflected in the generation of the multi microchannels matrix network as the prototype device scale was determined by space allocation for the experimental testing to be carried out within the laboratory.

Simulation analysis was undertaken to adjust the value of the microchannel width W to establish cross sectional area resistance to achieve the lowest pressure drop applied to various channels, to determine hydraulic channel resistance balancing of the multi microchannel network. To determine minimized pumping flow pressure and pressure drop each microchannel has a fixed, known length and fixed known depth; to enable analysis of resistance and flow rate through the network. This simulation method by computation, determines microchannel width sequence optimization for target resistance. This analytical solution for resistance is dependent on pressure drop that reduces flow rate through a microfluidic platform device defined by the difference between the outermost microchannel and central microchannel resistance values. To analyze pressure drop impact within a microfluidic device to determine the effects of maximum resistance to minimum resistance, was observed by a 1mm depth multi microchannel network by simulation.

Results indicated a very high resistance, R, originated within a 1mm depth network. This high resistance is directly related to the shallowness of depth and volume of fluid under flow. Channel depth influences, network resistance balancing to achieve a full-developed laminar flow for the microvasculature network, shown in Figure 6.9.

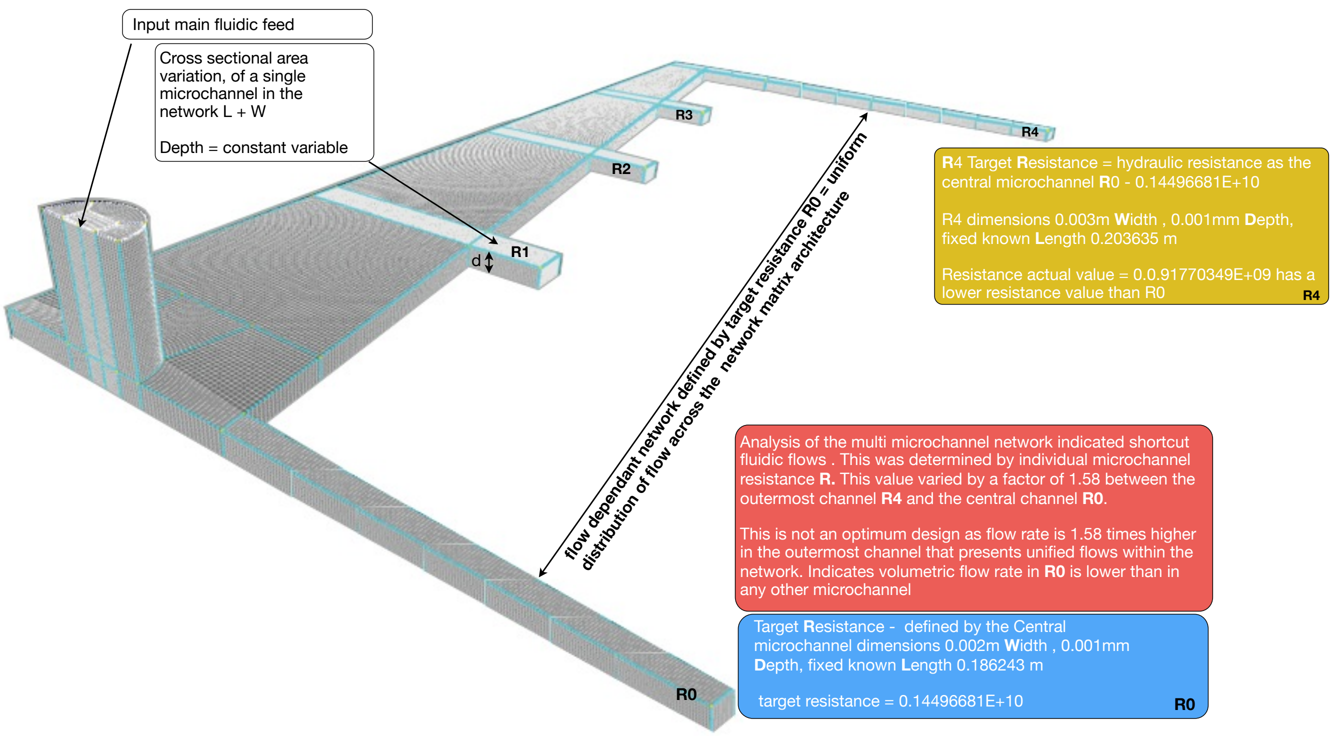


Figure 6.9 Computational Mesh Analysis of a 1mm Network

The impact of this resistance factor to a fixed applied pressure would vary flow rate within a multi microchannel networks, by the same factor, 1.58. The highest resistance value of the non-equalized resistance sequence, was the central microchannel 0.2mm x 0.1mm that created unified laminar flow within the network. This simulation was run again by changing the value of depth to 0.002mm in the code to evaluate pressure drop. Results indicated the hydraulic resistance and pressure drop of the central channel is 5 times lower than the previous study (results above) using 1.0 mm microchannel depth. By increasing fluidic volume flow reduced the impact of resistance. This is significant as optimization of resistance determines regulation of equalized fluidic flow rate across longitudinal microchannels.

If planar extensional flows are not equalized this impacts on the fluids ability to absorb solar radiation uniformly across the microfluidic platform device. Simulation resistance results are indicated in Figure 6.10.

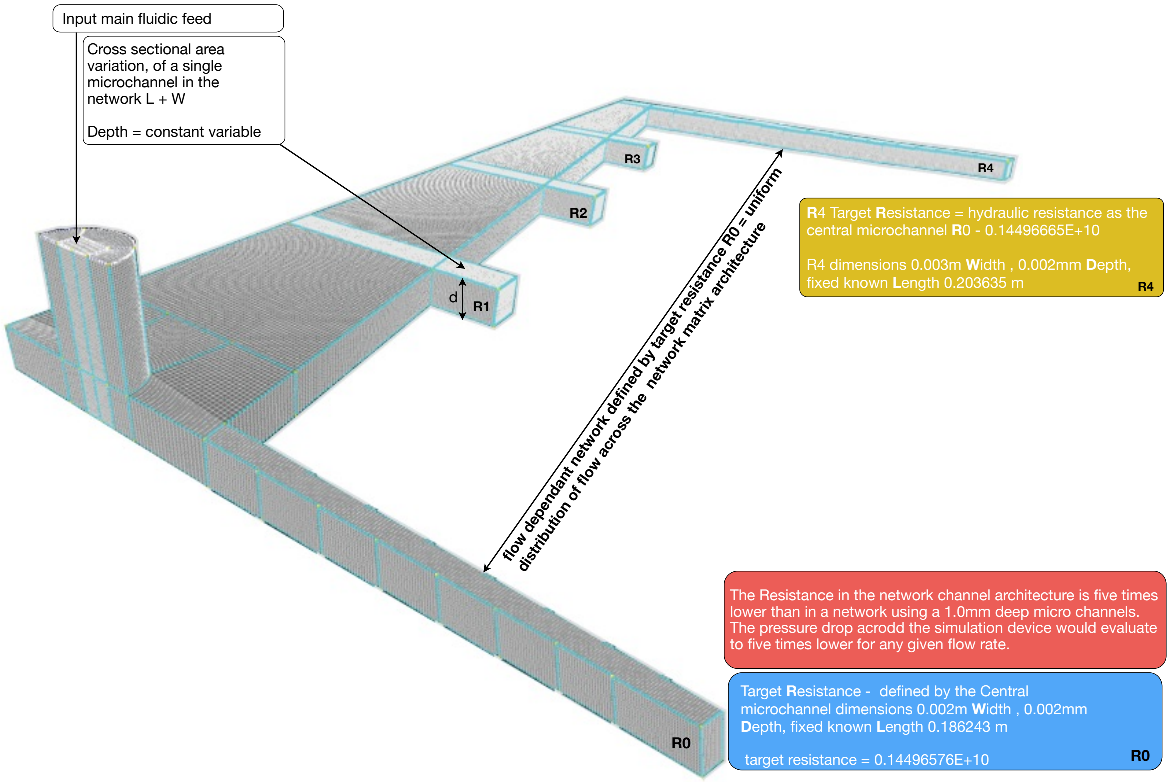


Figure 6.10 Computational Mesh Analysis of a 2mm Network

The data results above indicate hydraulic resistances of multi microchannels widths are almost uniform to each other and pressure drops along multi longitudinal microchannels are also identical.

These results by a computation algorithm approach will need to be validated. The accuracy of this algorithm procedure by resistance seeking targeting can be determined by CFD (Computational Fluid Dynamics). A CFD simulation is a verification method to determine pressure distribution, pressure drop and resistance to flow within the network. CFD computational method results were compared to the computational test data and are in agreement for microfluidic network optimization, this gives validity to this approach.

6.5 Polymer Material Selection

The material selection for the domain is significant, as the material must be transparent of high thermal adsorbing properties. If the material was not transparent this presents an established current research path. A great deal of research has already been undertaken into non-transparent composite materials as solar collectors. This research has been around for some time already. Hence, the research would be following a path that is currently well advanced analytically, phase change composite materials etc.

The real value of this approach is transparent combined with an IR stop band functionality. Without such properties, there are already viable systems on the market and except maybe for better mechanics for system performance, there is nothing of note to add to this research. This material research represents advancement by multiple structural functions of an transparent composite by thermal heat seeking regulation mechanics. The selected material was PMMA (polymethyl methacrylate).

The mechanical properties of PMMA led to this choice, in terms of thermodynamics of polymers (Wong et al., 1999, Skotheim et al., 1998). These properties are; transparence, high resistance to UV, temperature/air/hydrolysis and stability to impact / fracture toughness and surface hardness of this material. These material properties are determined by Young's modulus, tensile strength and fracture toughness of polymers (Landel et al., 1994). PMMA has replaced glass in many applications in the automotive and aerospace industries for its ability to manage high stress applications.

Their are two methods to create multi microchannel networks in a polymer by injection moulding and tooling. Both approaches are an automation design process through operational qualification (OQ) and performance qualification (PQ) methods, (Astarcor, 2017). These fabrications methods of multi microchannels are used to form microfluidic devices in clinical and laboratory applications for analysis of microparticles for experiments. The machine tooling method was chosen due to the associated cost of manufacture, in comparison to injection moulding approach to generate a one off device. Microchannel formation is achieved by Computerized Numerical Control (CNC) machines that are capable of producing slot geometries in order of tens of microns. These machines can produce a microchannel network within a sub-micron tolerance resolution. Selection choice of the cutting machine in fabrication of the network on the surface of the PMMA, is dependent on tolerance accuracy acceptability and cost of fabrication. Two methods of achieving micro-fabrication are direct milling and laser applications. Direct milling is used to control tolerance accuracy from 2 micros medical science and computerized chips technology

20 micros. Laser cutting tolerance accuracy commences from 0.1mm used in aerospace to 0.2mm in other high tolerance demand engineering applications. Laser cutting was selected as it gave the best ratio between costs of fabrication to tolerance accuracy of 0.1mm, (ufluidix, 2017). Channel geometry can be formed by two methods, shown in Figure 6.11.

Figure 6.11 Channel Geometry Options

The channels as illustrated (a+b) can be formed with direct milling, however, b can only be created by laser application. The thermal energy absorption is dependent on the volume of fluid flowing through the channel to capture IR. This impact of an absorbing fluid is determined by microchannel cross sectional volume and heat capacity of the fluid. The fabrication method of a rectangular to square ratio microchannel enhances thermal conductivity transfer through increased fluidic volume to surface interface contact, in comparison to microchannel (a).

6.6 Network Geometry Evolution

The initial simulation network formation was determined by diamond channel network geometry as shown in Figure 6.12. This multi microchannel network was evaluated for resistance optimization approach.

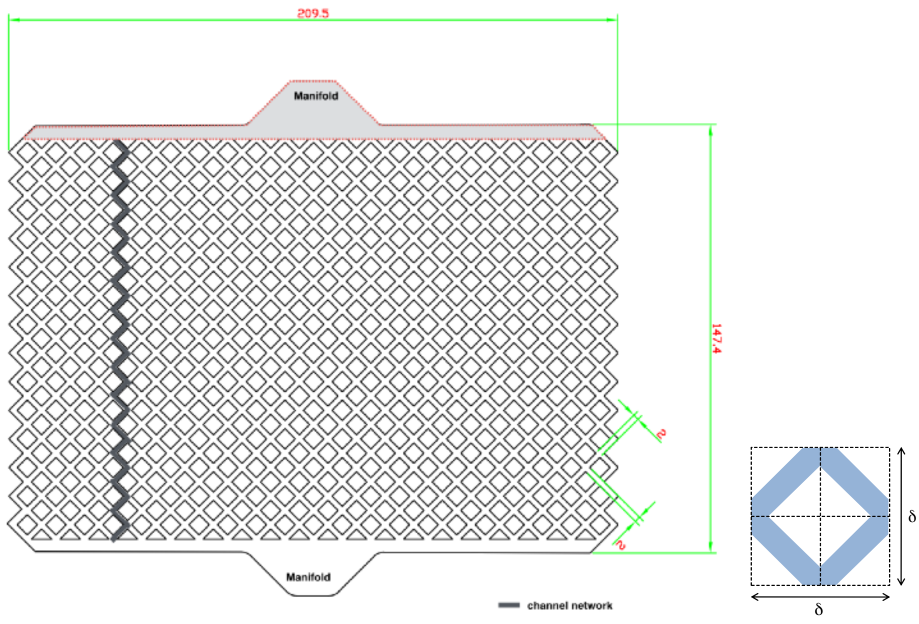


Figure 6.12 Channel geometry network initial design. The dark grey colour denotes a single channel geometry for pressure analysis.

The diamond configuration geometry was defined by maximization of fluidic volume to a planar surface to enhance heat transfer reaction to absorb solar IR through multiple fluidic pathways. This diamond network was determined by a single microchannel of constant depth, constant length and constant width. The network matrix architecture is not a biomimetic design as this was determined through analysis of pressure driven laminar flow. Results from the analytical simulation indicated significant pressure drop within the multi microchannel diamond network. The network reaction in laminar flow presented high turbulence of unsteady state flows in the diamond network branching microchannels. Pressure gradient along a microchannel was uniform in this flow dependent network. The diamond network had considerable flow resistance, pressure drop and flow rate variation within the microchannel slot geometry. This formation presents none equalized fully developed laminar flows. The fluidic flow pathways in the diamond geometry matrix architecture was found to be a network of uniform flow path distribution. The design required simplifying by systematic resistance networking of multi microchannel succession inspired from biology, a bifurcated formation. The input and extract microchannels (manifolds) play a primary role for feed in fluidics for the network longitudinal channels. To advance network geometry through simulation was undertaken to focus on successive channels widths, to develop a hierarchy, as in Figure 6.6, that emulates leaf vascular principles as a closed loop network. This optimized sequence of channel widths is determined by flow input and export channels to accommodate and distribute incoming fluidic flow into the network. Successive channel width will increase in relationship to increasing flow path length that is determined roughly by square root of flow to channel path length, figure 6.13.

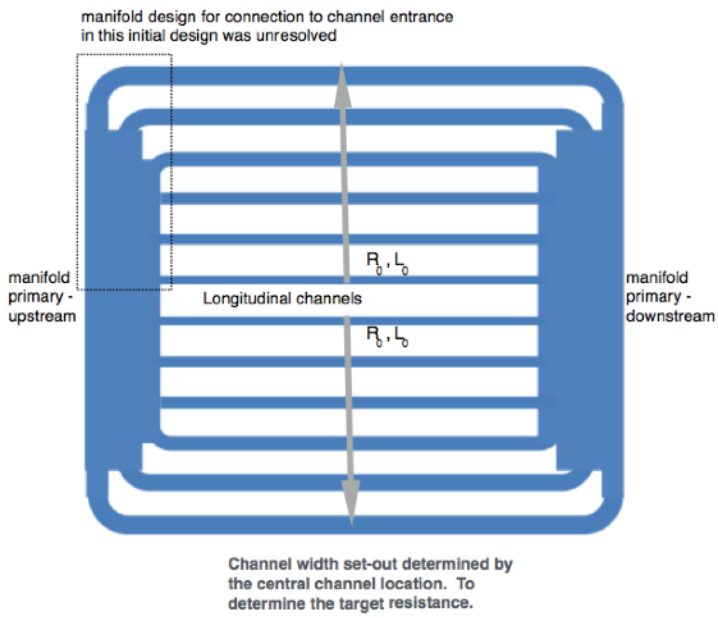


Fig. 6.13 Vasculature Geometry Successive Width Hierarchy Determined by Resistance Targeting

The initial feed in and outlet manifolds geometry, Figure 6.13, created increased flow resistance due to fluidic flow turbulence and resistance by the formation of eddies at the inlet and outlet longitudinal channels. These primary distributions upstream and downstream manifold microchannels will change the fluidic pressure to each individual longitudinal (R_0, L_0) slot channel entrance and exit. This presents a non-optimized resistance network. In avoidance of unwanted effects, input and extract microchannel geometry was advanced to gain a direct fluidic flow path from the manifold primary upstream and downstream channels, as presented by a tapered manifold, shown in Figure 6.14.

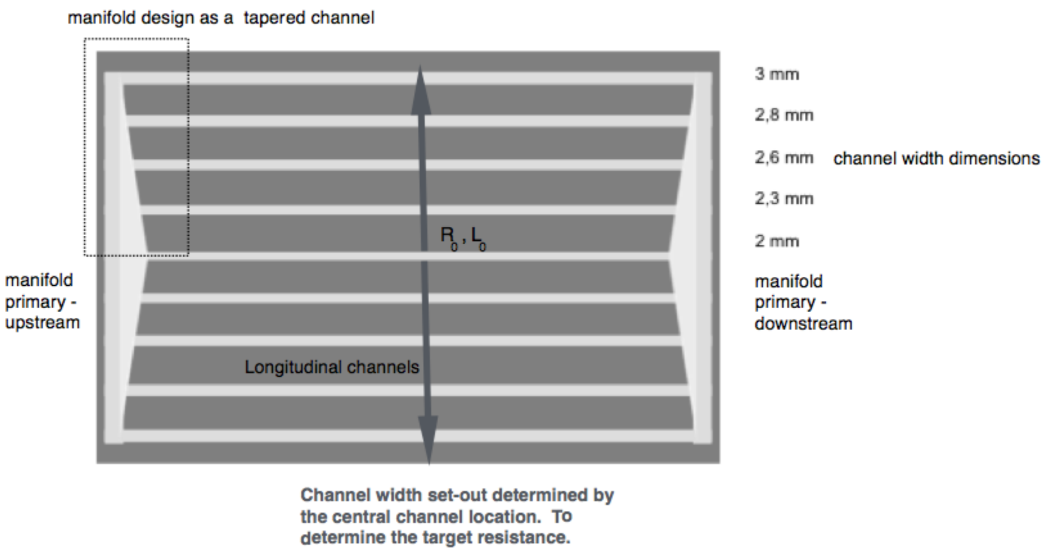


Figure 6.14 Reduction in Resistance of the Primary Feed in Fluidic and Extract Channels

The geometry of the tapered manifold gave distribution of fluidic flow through pressure equalization by diminishing flow pressure variation for a fixed fluidic volume. The network formation analytical approach is presented in the next subsequence sections. This approach of vasculature geometry determined by equal volumetric flow rates, resistance applies optimization by leaf formations. To regulate fluidic resistance and pressure drop through channel width succession for sequence hierarchical orders.

6.7 Microfluidic Device through Simulation

The channel vascular geometry design in the polymer device was set at longitudinal channels equal spacing pattern formation of 15.575mm, with channel widths of: R0-2.0mm, R1-2.3mm, R3-2.6mm, R4-2.8mm and the outermost channel R4-3.0mm. Hence, target hydraulic resistance of the central channel is determined, as indicated below. This experimentation by an algorithm is an analytical solution for resistance, by channel width succession for sequence optimization.

Hydraulic resistance of central channel (2.0 mm wide x 2.0 mm deep)

Assume a constant temperature of 25ºC. At this temperature, the dynamic viscosity coefficient is equal to

$p = 997\,kg/\mathrm{m}^3$ density of the fluid (water) $\mu = 8.9 \times 10^{-4}$ Ns/m^2 viscosity

(Alston & Barber, 2016).

The pressure drop for fully-developed flow along a section of channel of length, *L*, can be determined by balancing the pressure forces and the wall shear forces:

$$\Delta p A = \bar{\tau} P L \quad \Rightarrow \quad \Delta p = \frac{\bar{\tau} P L}{A} \tag{1}$$

where $\bar{\tau}$ is mean wall shear stress and *P* is the wetted perimeter of the channel, $\bar{u}$ mean flow velocity in the channel.

The Reynolds number of the flow is defined by

$$\mathrm{Re} = \frac{\rho \bar{u} D_h}{\mu} \tag{2}$$

where D_h is the hydraulic diameter of the channel, defined as

$$D_h = \frac{4 \times \text{area}}{\text{wetted perimeter}} = \frac{4A}{P} \tag{3}$$

Assuming the flow is laminar, we can then use the Poiseuille number to calculate the average wall shear stress. The mean wall shear stress, $\bar{\tau}$, can be related to the

Fanning friction factor, f, which in turn can be expressed as the ratio of the Poiseuille number, Po, and Reynolds number, Re:

$$\bar{\tau} = \frac{1}{2}\rho \bar{u}^2 f = \frac{1}{2}\rho \bar{u}^2 \frac{\mathrm{Po}}{\mathrm{Re}} \tag{4}$$

Substituting for Re in Eqn. (4) gives

$$\bar{\tau} = \frac{1}{2}\rho \bar{u}^2 \frac{\mathrm{Po}\,\mu}{\rho \bar{u} D_h} = \frac{\mu\,\mathrm{Po}\,\bar{u}}{2D_h} \tag{5}$$

Substituting the shear stress into Eqn. (1) gives

$$\Delta p = \frac{\mu\,\mathrm{Po}\,\bar{u}}{2D_h}\frac{PL}{A} = \frac{\mu\,\mathrm{Po}\,\bar{u}}{D_h}\frac{PL}{2A} = \frac{\mu\,\mathrm{Po}\,\bar{u}}{D_h}\frac{2L}{D_h} = \frac{\mu\,\mathrm{Po}\,\bar{u}\,2L}{D_h^2} \tag{6}$$

Finally, the *hydraulic resistance*, *R*, of the channel is given by

$$R = \frac{\Delta p}{Q} = \frac{\mu\,\mathrm{Po}\,\bar{u}\,2L}{D_h^2} \times \frac{1}{A\bar{u}} \tag{7}$$

Hence,

$$R = \frac{\mu \, \mathrm{Po} \, 2L}{A D_h^2} \tag{8}$$

This is identical to Eqn. (Koch et al., 1994) in (Emerson *et al.* 2006).

Consider a 2 mm wide by 2 mm deep channel, 186.243 mm long. The hydraulic diameter of the channel is defined as

$$D_h = \frac{4 \times \text{area}}{\text{wetted perimeter}} = \frac{4 \times 0.002 \times 0.001}{2 \times (0.002 + 0.001)} = 1.33\dot{3} \times 10^{-3} \text{ m} \tag{9}$$

From Table 42 in Shah and London (20), the Poiseuille number, Po, is 14.22708 for a square duct 2:2 aspect ratio.

Thus,

$$R = \frac{\mu \, \mathrm{Po} \, 2L}{A D_h^2} = \frac{8.9 \times 10^{-4} \times 15.54806 \times 2 \times 0.186243}{0.002 \times 0.001 \times (1.33\dot{3} \times 10^{-3})^2} = 1.450 \times 10^{9} \text{ kg m}^{-4}\text{s}^{-1} \tag{10}$$

The algorithm follows the same procedures detailed above, with the exception that the Poiseuille number, Po, for a given h, channel height and aspect ratio, α , is found using the analytical solution involving an infinite series summation (obtained by combining equations from Shah and London).

$$\mathrm{Po}(\alpha) = \frac{24}{\left[1 - \frac{192}{\pi^5}\frac{1}{\alpha}\sum_{i=1,3,5...}^{\infty}\frac{1}{i^5}\tanh\left(\frac{i\pi\alpha}{2}\right)\right]\left(1+\frac{1}{\alpha}\right)^2}$$

where $\alpha = h / w$. (11)

Once R0 is known, choosing the optimized value of resistance to achieve equal flow rate through all channels can be determined. This mathematical design procedure predicted pressure drop results of the outermost channel are in good agreement for a fully developed laminar flow that gives validity of the algorithm code. However, the ratio of the maximum resistance / minimum resistance = 0.29477840E+09/0.15429990E+09 = 1.91. of the initial channel sequence was high. Resistance variations in the channel sequence are far to high as an optimized solution. If a fixed pressure was to be applied across the test device, then the flow rates would also vary by the same factor of 1.91. High resistance of the central channel would imply that the volumetric flow rate in the central channel is lower, than that in any of the other channels. The issue is, Figure 5.5, the pressure at the start of the longitudinal channels vary considerably by fluidic input channel resistance for the tapered channel sections Rm1 to Rm4.

These distributions input and export manifolds, will change the fluidic pressure to each individual longitudinal channel R0 to R4 entrance and exit. Hence, this variation can be predicted in the pressure applied to the individual channels. If the pressure variation in Rm, manifolds channels, is great in comparison to the pressure drop along the channels, the optimization strategy must account for this. Hence, the formulated design procedure in terms of the mathematical algorithm can be determined by analysis in a two-stage approach., The second stage program calculates the widths (longitudinal channels) that have been considered in the previous equations.

6.8 Determining the Widths of the Manifold at the Location of each Longitudinal Channel

The change in manifold width between each successive longitudinal channel is given by

$$\Delta w = \left(w_0 - w_4\right)/\,4 \tag{1}$$

Thus, $w_1 = w_0 - \Delta w$ (2)

$$w_2 = w_1 - \Delta w \tag{3}$$

$$w_3 = w_2 - \Delta w \tag{4}$$

Generalizing:

$$w_i = w_{i-1} - \Delta w \quad \text{for} \quad i = 1,2,3 \tag{5}$$

Determine the average width of each of the tapered manifold channels:

(i.e. determine the width of the manifold half-way along each section)

$$\bar{w}_1 = \frac{(w_0 + w_1)}{2} \tag{6}$$

$$\bar{w}_2 = \frac{(w_1 + w_2)}{2} \tag{7}$$

$$\bar{w}_3 = \frac{(w_2 + w_3)}{2} \tag{8}$$

$$\bar{w}_4 = \frac{(w_3 + w_4)}{2} \tag{9}$$

Generalizing:

$$\bar{w}_i = \frac{(w_{i-1} + w_i)}{2} \quad \text{for} \quad i = 1,2,3,4 \tag{10}$$

In order to determine the hydraulic resistances of the manifold channels:

From the previous analysis, we know that the hydraulic resistance, *R*, of a rectangular channel having a constant cross-sectional area is given by

$$R = \frac{\mu \, \mathrm{Po} \, 2L}{A D_h^2} \tag{11}$$

If we assume that the angle of the manifold taper is small, then the individual flow resistances in the manifold can be calculated using the cross-section at the mid-point.

Thus,

$$Rm_i = \frac{\mu \, \mathrm{Po} \, 2L_m}{A_i D_{hi}^2} \quad \text{for} \quad i = 1,2,3,4 \tag{12}$$

where A_i and D_{hi} are the area and hydraulic diameter at the mid-point of the manifold channel,

i.e.

$$A_i = \bar{w}_i h \quad \text{and} \quad \mathrm{D_{hi}} = \frac{4A_i}{2(\bar{w}_i + h)} \quad \text{for} \quad i = 1,2,3,4 \tag{13}$$

It should be noted that Po in Eqn. (12) is a function of the aspect ratio ($\alpha = h / \bar{w}_i$) of the channel.

It is informative to calculate the individual pressure drops along the manifold, as these can be checked against CFD results.

Fundamentally, the pressure drop along a section is simply the product of the flow rate and the hydraulic resistance, *i.e.* $\Delta p = QR$. Thus,

$$\Delta p_1 = 4Q_0 Rm_1 \tag{14}$$

$$\Delta p_2 = 3Q_0 Rm_2 \tag{15}$$

$$\Delta p_3 = 2Q_0 Rm_3 \tag{16}$$

$$\Delta p_4 = Q_0 Rm_4 \tag{17}$$

Generalizing:

$$\Delta p_i = (5 - i) Q_0 Rm_i = (4 - i + 1) Q_0 Rm_i \quad \text{for} \quad i = 1,2,3,4 \tag{18}$$

Equation (18) is for the case with four channels either side of the central channel. In the case of *N* side channels:

$$\Delta p_i = (N - i + 1) Q_0 Rm_i \quad \text{for} \quad i = 1,2,3,\ldots,N \tag{19}$$

Finally, we calculate the required hydraulic resistances of the longitudinal channels:

The pressure drop across the central longitudinal channel is given by:

$$\Delta p_0 = Q_0 R_0 \tag{20}$$

We can then determine the required resistances of the other longitudinal channels:

Consider channel 1:

$$\Delta p_0 = Q_0 R_0 = 4Q_0 R_{m1} + Q_0 R_1 + 4Q_0 R_{m1} \tag{21}$$

Hence, $$R_0 = 4R_{m1} + R_1 + 4R_{m1} \tag{22}$$

or $$R_1 = R_0 - 8R_{m1} \tag{23}$$

Consider channel 2:

$$Q_0 R_0 = 4Q_0 R_{m1} + 3Q_0 R_{m2} + Q_0 R_2 + 3Q_0 R_{m2} + 4Q_0 R_{m1} \tag{24}$$

Hence, $$R_0 = 4R_{m1} + 3R_{m2} + R_2 + 3R_{m2} + 4R_{m1} \tag{25}$$

or $$R_2 = R_0 - 8R_{m1} - 6R_{m2} \tag{26}$$

Substituting Eqn. (25) into Eqn. (26) gives

$$R_2 = R_1 - 6R_{m2} \tag{27}$$

Similarly, it can be shown that

$$R_3 = R_2 - 4Rm_3 \tag{28}$$

and

$$R_4 = R_3 - 2Rm_4 \tag{29}$$

The resistances therefore can be determined recursively using:

$$R_i = R_{i-1} - 2(5-i)Rm_i \quad \text{for} \quad i = 1,2,3,4 \tag{30}$$

or

$$R_i = R_{i-1} - 2(4-i+1)Rm_i \quad \text{for} \quad i = 1,2,3,4 \tag{31}$$

In the case of *N* side channels:

$$R_i = R_{i-1} - 2(N-i+1)Rm_i \quad \text{for} \quad i = 1,2,3,...,N \tag{32}$$

Once we have determined the required resistances, R_1 to R_4, we can then calculate the optimized channel widths. The methodology for this has already been considered to optimize the channels so they each had the same resistance, R_0. An identical procedure is used here but the "target resistance" needs to change slightly for each individual channel to compensate for the additional pressure drop in the distribution manifolds. Flow rates will never be equal to each other, as there are other influences effecting flow rate, such as entrance effects and flow curvature at the start and end of the longitudinal channels. The experimentation analytical solution analysis for the resistance (1-32) requires validation against CFD simulation.

6.9 Computational Fluidic Dynamics

Results of a CFD simulation of the inlet manifold for 2 mm deep set of channels sequences has been undertaken. CFD analysis of the manifold, Figure 6.15, focused on the symmetry boundary condition along the centerline of the channel. Prescribing an arbitrary inlet pressure of zero ran the algorithm. A mass flow rate was specified across the outlet boundaries (mdot=1.66166x10^-5 kg/s) for the full-sized outlets and half this mass flow rate at the central outlet to account for symmetry.

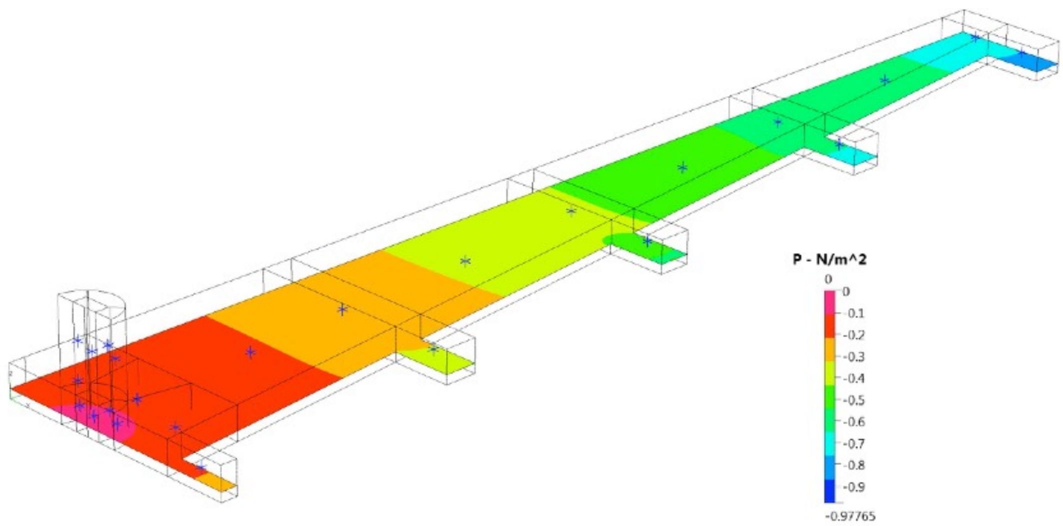


Figure 6.15 Pressure Distribution for Input Fluid Manifold.

Symmetry boundary conditions are employed along the centerline of the manifold.

The CFD results show that the pressures at the start of the longitudinal channels vary quite considerably. Hence the pressure at the entrance to the central channel is approximately -0.2 N/m2 whereas the pressure at the entrance to the outermost channel is about -0.75 N/m2. All pressures are relative to the inlet of the modeled flow polymer device. Hence the pressure difference of 0.55 N/m2 exists between the various channels. This compares with a theoretical pressure drop of 4.91 N/m2 along the central channel. The pressure drop in the inlet manifold may be up to ~10% of the pressure drops in the main channels. CFD modeling of the device with optimized widths will estimate the flow rate variation between the channels is shown in Figure 6.16, 6.17.

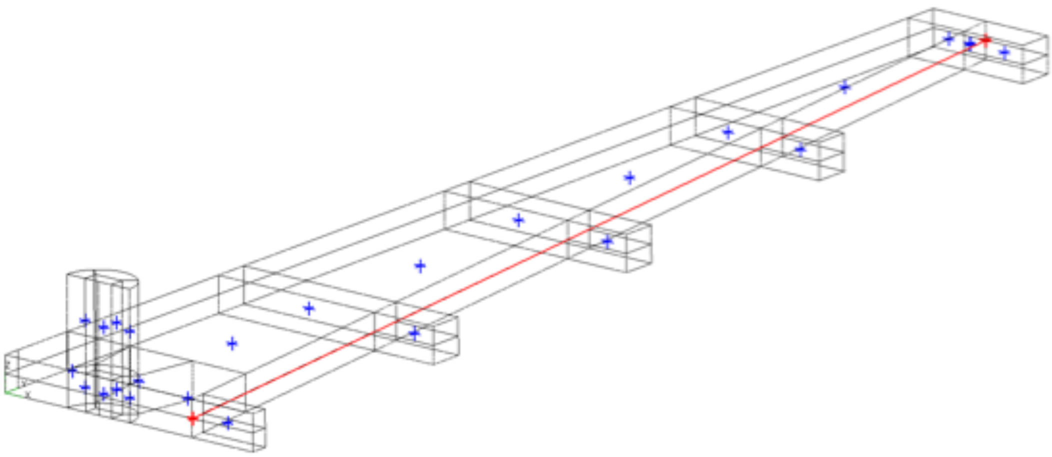


Figure 6.16 The probe line is located slightly downstream of the manifold so as to highlight the pressures in the channels

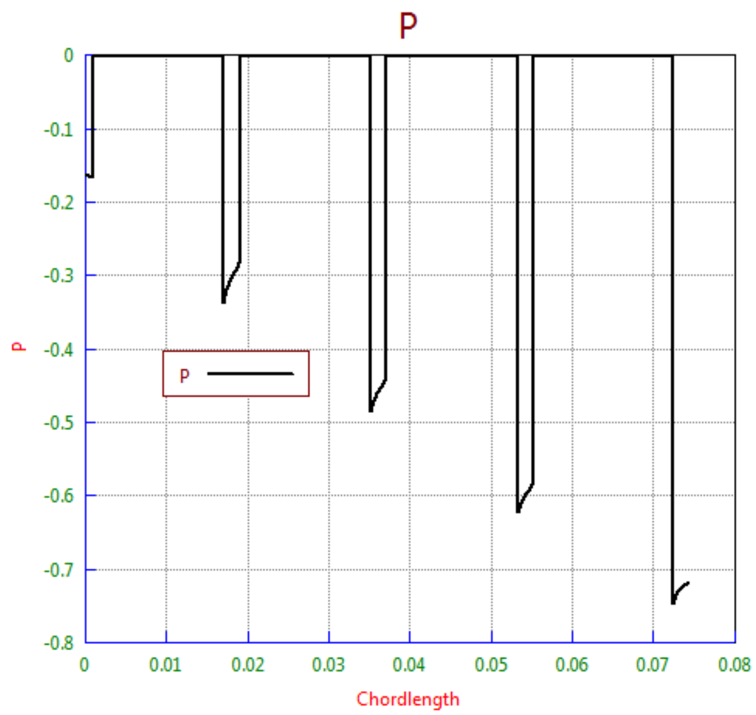


Figure 6.17 Pressure Distribution along the Line Probe

CFD simulation gives comparable pressure drops in the four tapered sections and comparable estimates for Rm1 to Rm4. Analysis indicates the approximating the taper by using cross-sections, half way along the section is valid for this device. These are the new target resistances, that give channel succession steady state flow targets. Note that the resistance of the outermost channel, R4, needs to be approximately 25% lower than R0. The second stage is calculating the target resistance of the various channels. Hence the outermost channel R4 was undertaken to assess flow resistance to the target central channel. Below is the CFD simulation of 3.0 mm x 2.0 mm outermost channel:

CFD model data:-

Channel width = 3.0 mm

Channel depth = 2.0 mm

Channel length = 203.635 mm

$\rho = 997\ \mathrm{kg/m^3}$ density of the fluid (water)

$\mu = 8.9\times10^{-4}\ \mathrm{Ns/m^2}$ viscosity of the fluid

A computational mesh composed of 30x20x400 cells (= 240,000 cells) has been used for the CFD simulations.

The volumetric flow rate, Q, is specified to be

$$Q = 1\mathrm{m}l/\min = \frac{1\times10^{-3}}{60} 1/s = \frac{1\times10^{-3}\times10^{-3}}{60}\mathrm{m}^3/s = 1.66\dot{6}\times10^{-8}\ \mathrm{m}^3/\mathrm{s}$$

However, the CFD code (CFD-ACE+) needs the flow rate to be specified as a mass flow rate, m in kg/s. Thus,

$$\dot{m} = \rho Q = 997\times1.666\times10^{-8} = 1.66166\times10^{-5}\ \mathrm{kg/s}$$

The mass flow rate was specified at the inlet boundary whilst the pressure was set to zero (atmospheric conditions) at the downstream boundary.

Results from the analytical solution:

Input channel width 0.003 (m), channel length 0.203635 (m)

alpha = 0.66667 Po = 14.71183884

u_mean = 0.00277778 m/s

Dh = 0.00240000 m

Re = 7.46816

tau = 0.00757728 N/m2

deltap = 2.57167 N/m2

Resistance = 0.15429990E+09

The CFD simulation was setup to estimate the overall pressure drop along the channel for a mass flow rate of 1.66166×10^{-5} kg/s (corresponding to 1 ml/min). Nature determines energy conservation in fluidics as the sum of pressure drop in a closed loop path is zero, which is exhibited by leaf vasculature pattern. Flow rate through a multi microchannel network is dependent on pressure drop through pressure driven laminar flow. Leaf formations are driven by the rules of minimum energy loss (lowest pressure drop in networks) to minimize fluidic power loss by microchannel cross sectional volume for maximizing flow rate. Maximizing total flow rate in distribution multi microchannels is a flow dependent transport system determined by pressure gradient along a channel that is optimized, shown in Figure 6.18.

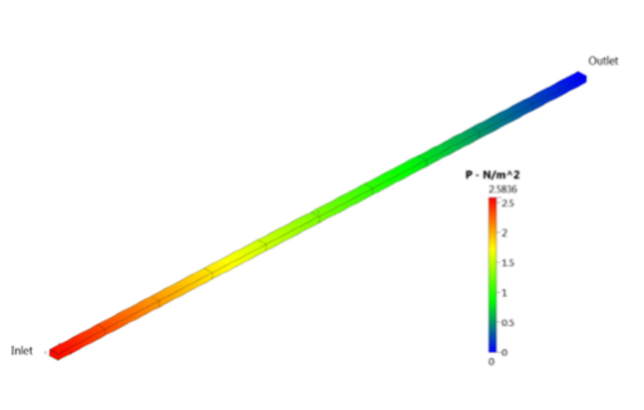


Figure 6.18 Predicted Pressure Distribution R_4

Figures 6.19 and 6.20 illustrate that the predicted pressure drop along the channel R_4 is 2.5836 N/m^2, which is in very good agreement with the analytical solution of 2.57167 N/m^2.

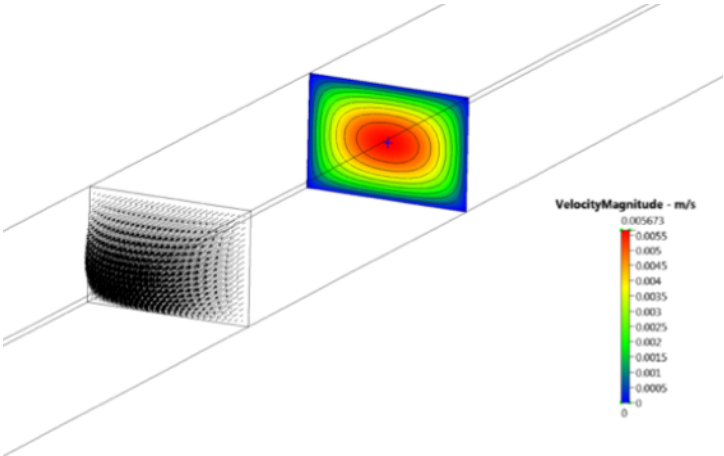


Figure 6.19 Predicted Velocity Distribution R_4

Computations indicate the hierarchical optimized sequence of longitudinal channel widths should be in the following sequential order: R0-2.000 mm, R1-2.095 mm, R2-2.202 mm, R3- 2.317 mm and R4- 2.431 mm, shown in Figure 5.20.

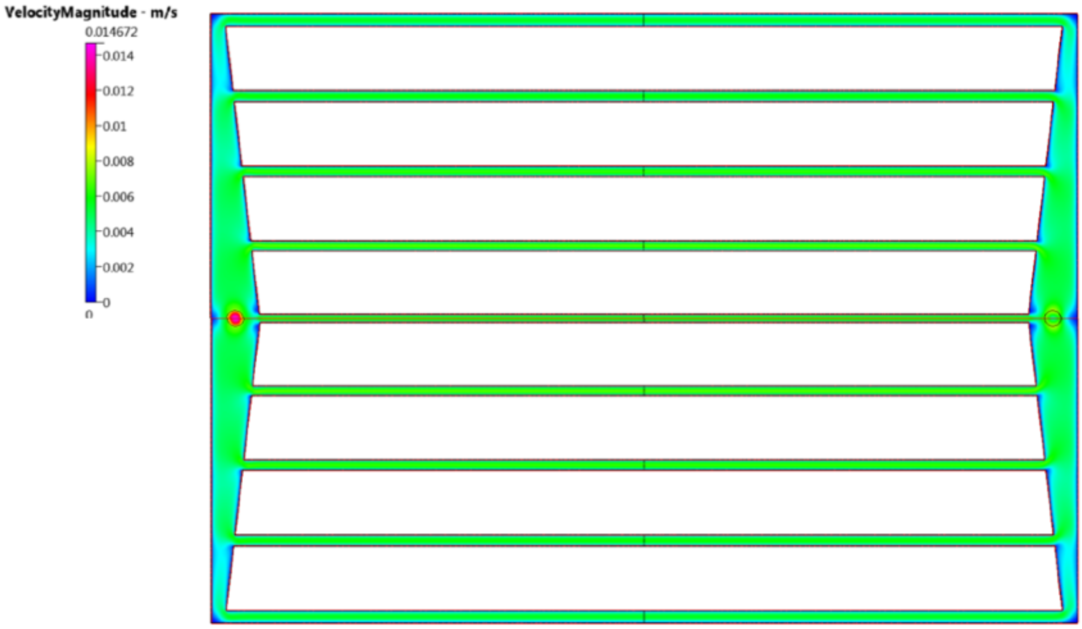


Figure 6.20 Predicted Velocity Distribution at a Flow Rate 9.0 ml/min

We could also use the CFD results, Table 6.21 and 6.22, to compute the actual hydraulic resistances in the manifold, i.e. Rm1 to Rm4. Table 6.21 shows the CFD results: pressure distribution in the manifold for a flow rate of 1 ml/min through each outlet channel (0.5 ml/min through central channel due to flow symmetry)

Channel #	P_left (N/m^2)	P_right (N/m^2)	P_average (N/m^2)	Deltap relative to previous channel (N/m^2)
0	0.163	0.160	0.162	—
1	0.334	0.278	0.306	0.145
2	0.478	0.434	0.456	0.150
3	0.616	0.577	0.597	0.141
4	0.732	0.717	0.725	0.128

Table 6.21 CFD Results

Channel #	Delta p relative to previous channel (N/m^2)
0	—
1	0.167
2	0.161
3	0.151
4	0.127

Table 6.22 Analytical Solution for the Pressure Channel Distribution

$$Rm_1 = \frac{\Delta p_1}{4Q_0} = \frac{0.145}{4 \times 1.66\dot{6} \times 10^{-8}} = 0.2175 \times 10^7 \ \text{kgm}^{-4}\text{s}^{-1}$$

$$Rm_2 = \frac{\Delta p_2}{3Q_0} = \frac{0.150}{3 \times 1.66\dot{6} \times 10^{-8}} = 0.3000 \times 10^7 \ \text{kgm}^{-4}\text{s}^{-1}$$

$$Rm_3 = \frac{\Delta p_3}{2Q_0} = \frac{0.141}{2 \times 1.66\dot{6} \times 10^{-8}} = 0.4230 \times 10^7 \ \text{kgm}^{-4}\text{s}^{-1}$$

$$Rm_4 = \frac{\Delta p_4}{Q_0} = \frac{0.128}{1.66\dot{6} \times 10^{-8}} = 0.7681 \times 10^7 \ \text{kgm}^{-4}\text{s}^{-1}$$

Analytical resistances are generally in good agreement with the CFD results in Table 5.2 and 5.3, with a maximum error of ~15% for Rm1, a 7% error for Rm2 and Rm3, and a 1% error for Rm4. This procedure obeys the rules of minimum flow velocity rates, minimum resistance to achieve the lowest pressure drop within a microfluidic network. Each micro channel within this artificial network will influence thermal conductance if subjected to impact heat load. The fluidic medium is therefore acting as a heat sink. A microfluidic-based platform of fluidic laminar flow rate regulation will determine and influence thermal interface transport exchange to a transparent material device.

5.10 Conclusion

This iterative procedure demonstrated optimization of vasculature employing resistance seeking targeting by hierarchical channel succession, as a resistor networks. This optimization process is determined by selection of a known hydraulic resistor value R_0, to enable evaluation that determines vascular channel network geometry, to give flow equalization as a development mechanism as denoted by:

$$Q_1 = Q_2 = Q_3 = Q_4 = Q_0 \tag{1}$$

The pressure drop across the outermost longitudinal channel is given by

$$\Delta p_4 = Q_0 R_4 \tag{2}$$

We can then determine the required resistances of the other longitudinal succession channels R_1, R_2, R_3 etc that can be determined as a recursive pattern:

$$R_i = R_{i+1} + 2(4 - i)Rm_{i+1} \quad \text{for} \quad i = 3,2,1,0 \tag{3}$$

Feed in principle upstream and down stream channels, manifold resistance, Rm_1, Rm_2, Rm_3 is determined by N side channels (N denoting the total number of channels is $2N$=1):

$$R_i = R_{i+1} + 2(N-i)Rm_{i+1} \quad \text{for} \quad i = N-1,....3,2,1,0 \tag{4}$$

This computation design methodology of the device predicted pressure drops results in the manifold are in good agreement with CFD results. Results indicate resistances of the longitudinal microchannels are similar to the theoretical results. The tapered sections resistances are in good agreement, except for the tapered section involving the inlet port. This is expected since the computation solution cannot take into account the flow expanding away from the circular inlet port. Computational analysis conclusively demonstrates being able to design microfluidic networks using a theoretical approach, to achieve optimization of circuit resistance of transport fluidic flow. Optimization is achieved through pressure equalization by diminishing flow pressure variation. This is functionally significant in the analysis of hydraulic resistance to compute simulations of flow rates in microvasculature channel networks. Predicted pressure drop and flow analysis within channel network is in agreement with the analytical solution for fully-developed laminar flows, giving validity to the algorithm code as an iterative procedure.

The morphogenesis of leaf vasculature formations in uniform spacing patterns and spatial regularity sets an underlying process of flow distribution, pressure, fluidic transport and resistance. These mechanisms as demonstrated will advance a microfluidic transparent material by equalization of resistance and pressure drop ratio distribution, determined by computational theoretical analysis of resistance seeking targeting, a bio-inspired engineering approach from a leaf. A network defined by spatial hierarchical sequence patterns, channel cross sectional area and channel length for the transportation of fluidics. The proceeding chapter will demonstrate the thermal modulation properties of the network acting as an IR radiation stop band.

This chapter and the proceeding Chapter 7 findings form the underpinning of a manuscript that was submitted and published in Nature.

Chapter 7 Thermal Modulation

7.0 Introduction

This chapter proposes methods to use leaf vasculature formations to develop an infrared block polymer. This chapter demonstrates the use of micro-fluidic based flows to direct the structural assembly of a polymer into a thermally functional material, to regulate and manage solar radiation, in order to lower a polymer device phase transition temperature. This research determines this functionality by hierarchical multi micro-channel network scaling, to regulate laminar flow rate to capture solar radiation.

As explained in the previous chapter, nature uses network formations to manage solar radiation to absorb this energy by micro-channels of fluidic flow. These networks are a photoactive system to capture day light. This function is determined by regulation of fluidics within a multi micro-channel system characterized by hierarchical optimization of active flow networks, determined through pressure drop as a method of regulating fluidic flow. A fluidic flow network is a desired morphology, in a thermally functional material to enhance its ability to capture and store energy. The research demonstrated (in Chapter 6) that a resistor conduit network can define flow target resistance that is determined by an iterative procedure and validated by CFD. This approach, of hierarchical multi micro-channels, is defined by pressure equalization in diminishing flow pressure variation to gain laminar, smooth flow within a network. This is functionally significant in achieving absorption of solar radiation that is equalized across the plane surface of a material.

Precise hydro-dynamics is the mechanism for thermal material characterization to act as a switchable IR absorber. This absorber uses switching of water flow as a thermal switching medium to regulate heat transport flow with enhanced solar modulation properties, and this will be demonstrated in this chapter.

7.1 Network Geometry Optimization

Micro-fluidic slot channel geometry networks cut into the planar surface of a polymer enhances the thermal properties of the material. This is determined by active flowing fluidics in a cross sectional slot channel constantly absorbing solar load. Network architecture will direct the assembly of a device to enhance heat transport as a thermally functional device. Using precise hydro-dynamic control of a micro-fluidic platform is significant to attain uniform solar radiation absorption. This characterization in optimal fluidic transport flow is present in natural networks, i.e. leaf vasculature. Leaves use micro capillary networks for the transportation of nutrients and carbon dioxide for photosynthesis mechanisms. These fractal formations of tree-like branching architecture are governed by rules of minimum energy dissipation, low-pressure drop and uniform flow velocity. Nature uses fractal structures that are driven by maximizing low dissipation rate for steady state uniform flow, defined by resistance. Hydraulic pressure driven flows can be determined by electrical circuit theory (Oh et al., 2010). Leaves use negative pressure to induce flow that scales linearly in channel networks for fluidic transport that is defined by hierarchical branch network scaling (Hickey et al.,1973). Each channel (vein succession sequence) is aligned to a specific formation order within a closed loop network. Hagen-Poiseuille's law of constant flow resistance will define a fractal network for analysis to advance a man-made micro-fluidic platform. This is a relationship to pressure loss that linearly increases with flow rate within longitudinal channels. This analysis will determine optimal networks of smooth laminar flow velocity in multi micro-channels.

This characterization is defined by hierarchical, sequence succession resistance networking. Leaves are examples of this approach, possessing resilient self-healing, mechanical adaptation, and a photoactive system of chemical chain reactions. Understanding nature's characterization of materials develops innovation through biologically inspired engineering and yields effective composite materials solutions. Composite designs are currently hindered by the ability to regulate structural complexity; however, nature has developed multifunctional materials based upon adaptive strategies. These nanostructures are founded by a reaction interface, achieved by nanoscale ordering aligned to capture and store energy in a space. That is determined in nature by minimum energy loss for effective fluidic flow within networks (Hubbard et al., 2001. Murray, 1926). The objective of natural networks is to attain minimum energy output for reduction in pressure drop that is defined by cross section channel geometry and flow rate.

The micro-channels optimal spatial geometry is determined by pressure driven laminar flows that are proportional to vein density, connection to micro-channel hierarchy and flow rate (Nardini et al., 2001. Wang et al., 2014. Boyce et al., 2009). Leaf channel networks geometry are generated in response to leaf scale and shape formation. Active fluidic flows in these networks are subject to flow resistance and flow rate. These hydraulic resistances in fluidic conduit channels conform to minimum flow rate to achieve a reduced pressure drop. Pressure drop is dependent on resistance to flow within the channel network architecture, to minimize resistance R for optimal fluidic transport. Using precise hydro-dynamic control of a micro-fluidic platform is governed by fluidic feed in (manifold) channels that can be evaluated as a resistor circuit for unified flow resistance across a network, as shown in Figure 7.1.

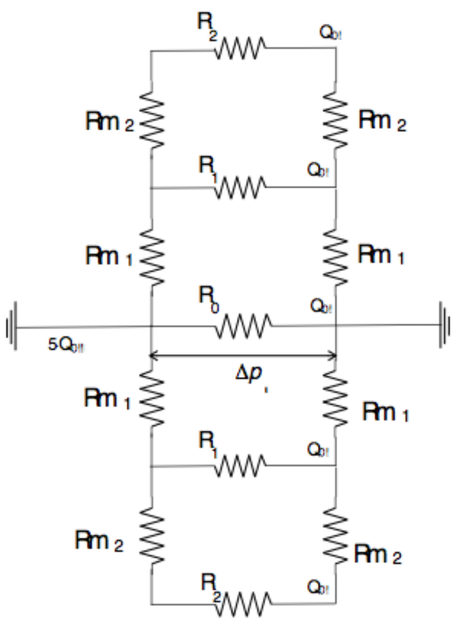


Figure 7.1 Micro-Fluidic Device as a Resistor Circuit in Determining Pressure Driven Flows

Rm denotes the feed in and extracts manifold resistance and R represents parallel fluidic resistors. Delta P (pressure distribution) is the parameter coefficient that is dependent on current flow and circuit resistance. To evaluate pressure distribution within a planar network, precise systematic resistance networking and unifying feed in manifold (Rm) flows are required. Manifolds upstream and downstream tapered fluidic feed-in flow will reduce turbulence in avoidance of unsteady state flows at network node channel branching. This method follows the principles of leaf vein hierarchy of non-uniform channel cross-sectional geometry (Brodribb et al., 2007. Salleo et al., 2000. Noblin et al., 2008). Each vein has a specific order set within a flow fraction network to reduce pressure drop by fluid flow transportation, in maximizing flow rate. This principle was applied to a micro-fluidic flow dependent network to optimize pressure distribution to achieve uniform steady state flows, by simulation resistance analysis. Evaluation of resistance optimization is centered on a single micro-channel that all other channels succession sequence will emulate that is defined by analytical analysis in Chapter 6, as shown in Figure 7.2.

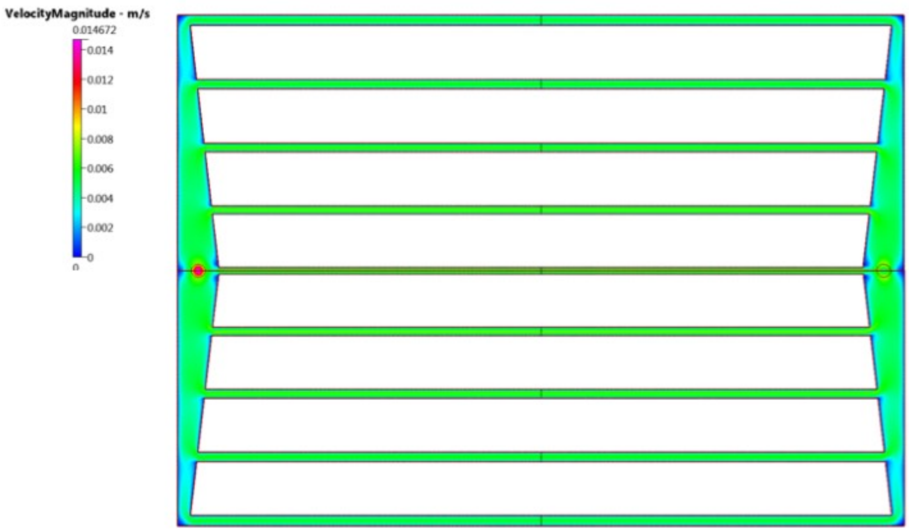


Figure 7.2 CDF Flow Analysis through the Network, determined by Analytical Solution

This theoretical resistance approach by resistance networking, was determined by a single central micro-channel. This resistance seeking targeting worked outwards from the center to define multi micro-channel width succession sequencing for tailored flow rates. To determine uniform parabolic velocity and pressure gradient profile across the micro-fluidic flow dependent device will enhance optimized heat transport flow. Defining the optimal network by iterative analysis progressed the device fabrication of the prototype using laser-cutting techniques as described in Chapter 6. Network geometry was defined as; 2.0,2.3,2.6,2.8 and 3.00mm, in Chapter 6, shown in Figure 7.3.

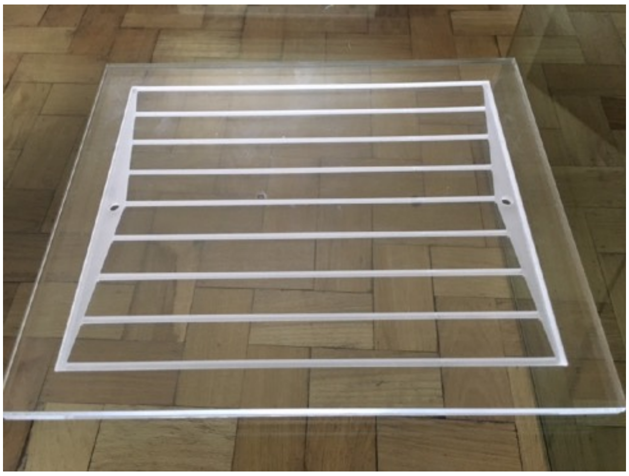


Figure 7.3 Device Fabrication

Each micro-channel within this artificial network will influence thermal conductance if subjected to impact heat load. The fluidic medium is therefore acting as a heat sink. Hence, fluidic laminar flow rate regulation will determine and influence thermal interface transport exchange to the device. Embedding these aims to direct the assembly of composites will advance and develop new materials. These properties currently do not apply to transparent materials that are presently energetically weak in visible transmission and offer limited solar energy modulation efficiency.

Using a micro-fluidic-based network of steady state flow in multi micro-channels across the material pane will advance a polymer for desired thermal functionality. Achieving a parabolic and laminar profile characterization to be obtained immediately from fluidic input into the network is significant. Manifold feed in and output channels perform significant roles to reduce turbulence, non-linear effects and shortcut pathways to derive smooth flow. Regulation of flow rate within multi micro-channel geometries will influence thermal conductance at the interface between the polymer material and fluid for energy harvesting. This is achieved through thermal transport for IR capture from the polymer surface pane, by modulating volumetric flow rates of fluid–material interface.

This capture and storage of energy is achieved by thermal absorbing fluidics in steady state flow along the channel node length. The characterization of the network is solar energy modulation efficiency using water flow as a thermal switching medium. The establishment of tailored flows in modulating volumetric flow resistance and pressure drop are functionally significant in a material's ability to lower phase transition temperature.

7.2 Experimental Testing Method

The laboratory testing of the prototype is not focused upon thermal conductivity but the absorption of solar (i.e. non-thermal) IR, which then will heat up the polymer structural assembly. Transition temperature of the polymer will be characterized by volumetric based steady state flow. Fabrication consisted of two plates of 5mm polymer to create the structural assembly. The polymer material selected for the fabrication polymer counter plate and base plate was aircraft grade Pol 76 MIL-P-5425 military specification for its unique properties in ultraviolet absorbing and ultraviolet transmitting. The base plate contained the micro-channel network that is fabricated by laser cutting into the surface of the base plate. This channel slot geometry will contain the micro-fluidic based flows. The polymer counter plate acts as the solar radiation absorber pane. These two plates have been bonded together to form the structural assembly testing device, as illustrated in Chapter 5.

7.3 Introduction of a Heat Source

The transparent polymer is subjected to an artificial solar (incandescent light) source that emitted IR wavelength 1000watts per m^2. Solar heat load increased the surface temperature of the polymer surface pane. Distilled water was pumped through the channel slot network directed the structural assembly of the polymer. The fluidic input and extract temperature into the manifold channels was monitored by thermocouples. Heating of the fluid under flow gave a temperature profile. Sensors monitored the material–fluid thermal flow across this interface by measuring extract water temperature. This analysis will enable assessment of thermal switchable IR absorber by water flow. Figure 7.4 illustrates the experimental testing design.

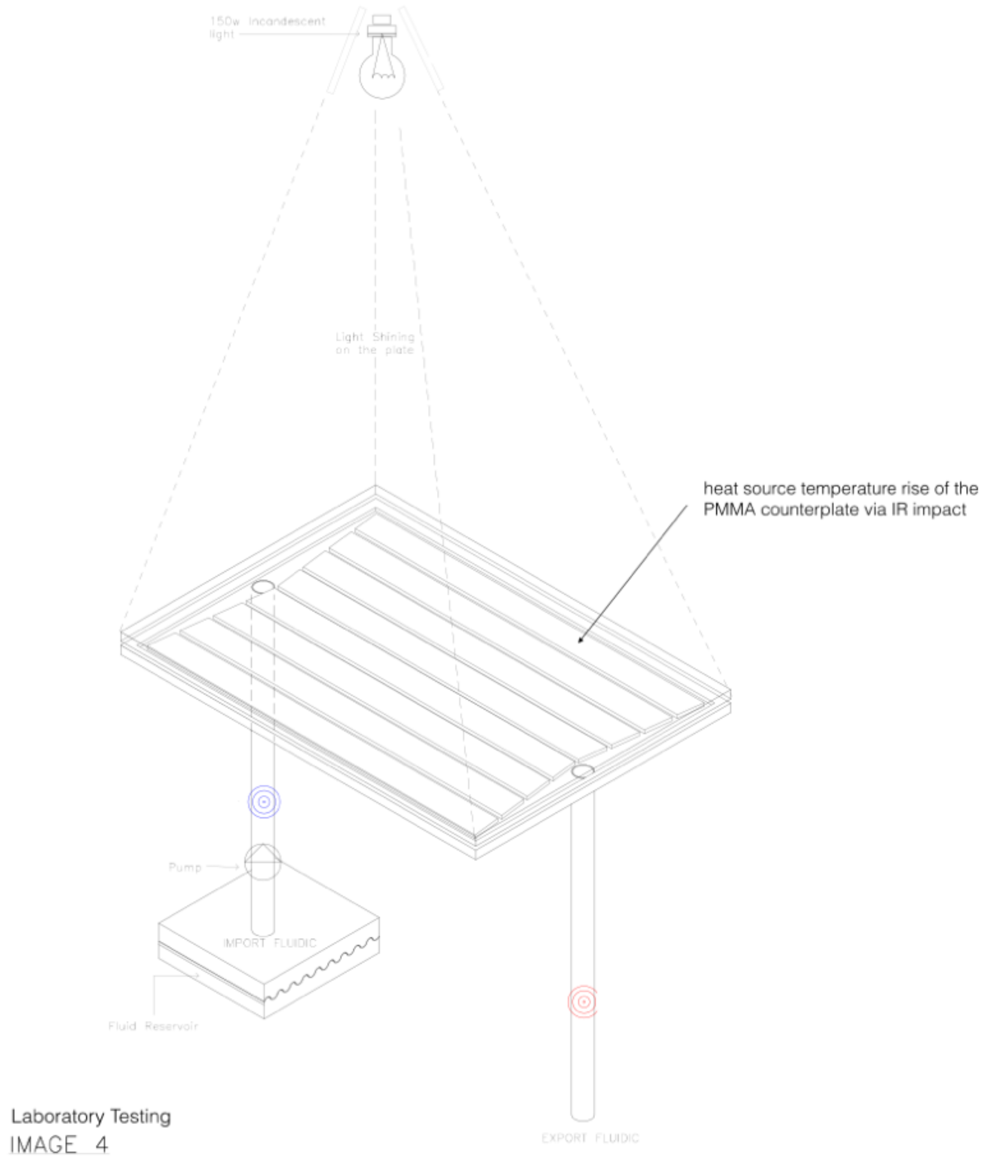


Figure 7.4 Device Thermal Measurement

The thermal properties of the experimental system monitored water temperature increase of fluidic input (upstream manifold) and extract fluidic temperature (downstream manifold) to observe water-heating power, as a thermal measurement system, evaluated by Δ t (delta t). Distilled water acted as the thermal carrier for experimental testing. Circulating volume tailored flows within the multi micro-channel architecture enhanced thermal energy capture by absorption. Quantifying thermal flow across the micro-fluidic network is dependent on flow rate. Heat transfer flow is characterized by temperature with time across the material plane. Monitoring temperature increase or heating power by the absorption and heat transport is related to flow rate. To observe absorption of solar load applied to the device the following parameters were evaluated:

- **Heating Power**: the amount of energy absorbed by water temperature through passage within the multi micro-channel network being heated by solar load. Heating power is extracted by monitoring of the downstream water reservoir tank data.
- **Time** is a fixed parameter that is defined by the syringe pump reservoir capacity of a fixed volume of water. This pump determines the precise hydro-dynamic control of the micro-fluidic platform. This time line is 50 minutes.
- **Flow Rate:** a range of tailored flow rates set at: 2,3,4,5,10,20,30 and 50 I/h/ m^2. To observe heat network losses from flow rate variation in cross-slot channel geometry. This will determine the fluid's ability to capture and store energy in the network.
- **Solar Load:** two-radiation density applied 1000 W/m^2, 1150 W/m^2 to assess radiation density impact at low flow rates and higher flow to modulation solar radiation.

These parameters will determine the heat losses coming from the flow network as determined by the experimental information. Setting varying flow rate by precise hydraulic manipulation to analyze and quantify thermal heating power flow extraction is the characterization of the device. The optimization to determine precise hydraulic manipulation for steady state uniform pressure and resistance enhances capture and stored energy by unified heat transport. To extract heating power over pragmatic flow rates for lowering of phase transition temperature by quantified thermal flow. Precise hydro-dynamic control of the micro-fluidic platform will manipulate the position of the fluid polymer heat transfer within the vasculature network, Δ t. Knowing temperature difference, Δ t, between upstream and downstream (input and extract manifolds) will determine the optimization to capture solar radiation. This analysis of heating power is acting as the mechanism to determine solar modulation properties. The dynamics to harvest solar radiation is dependent on fluidic flow rate. Variations in micro-fluidic based flows will influence and change thermal conductance heat flow characterization. The advantage of this, the footprint for the controlling processes of a thermally functional material is defined by steady state in real time (flow rate within the network) delta t, shown in Figure 7.5.

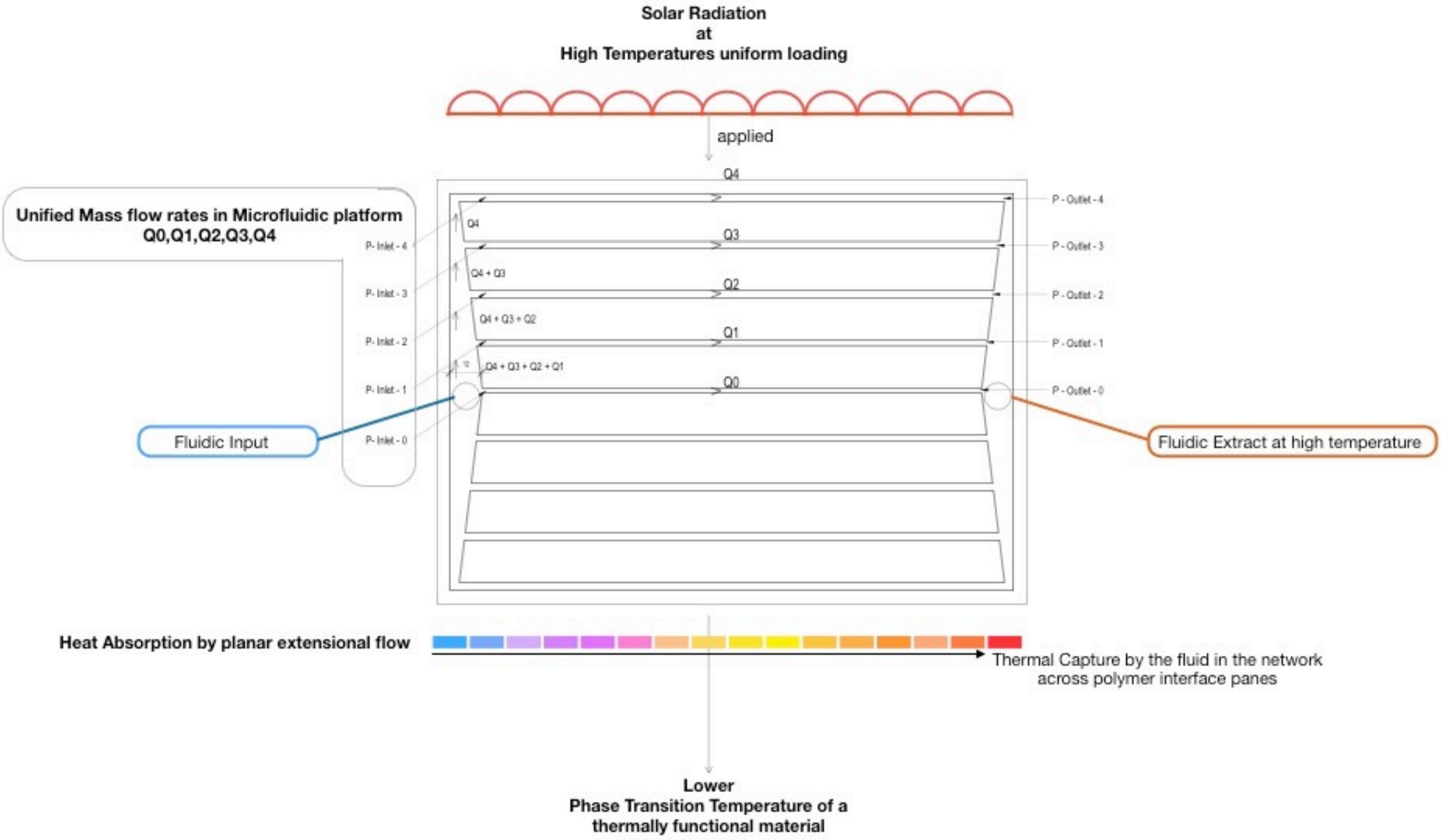


Figure 7.5 Thermal Heating Power Measurement

Solar modulation in a thermally functional device is a function of Δ t by modulated volumetric flow rates. Output water temperature, heating power will quantify thermal flow capacity to absorb energy as determined by specific heat capacity C_P (water). The differential thermodynamic temperature will define the heating power in Watts.

Heating power is determined by solar IR absorption through heat transport flow within the network. This heat transfer cycle is directly related to solar load; hence, fluctuations in solar radiation will vary fluidic temperature and give characterization to the device. Examining and measuring interface thermal transfer is determined by heat flux through the device W/m^2. Heat flux is defined by interface heat transport between differing material layers. In this case, this is water (in slot channels) and the polymer.

Observation of the experimental method gives understanding of how a polymer can move and transfer thermal energy. By modulating volumetric flow rates to manipulate the heat flux of a material-fluid interface to extract thermal energy for solar modulation.

7.4 Experimental Testing Outcomes

The following graph illustrates the output energy data by the described experimental testing method. Figure 7.6 shows the heating power of the water downstream reservoir to ascertain heat losses coming from the multi micro-channel network in relationship to flow. Heat losses contributed to the fluid's ability to absorb and transport thermal energy out of the network. Output-heating power optimization is fluidic efficiency to absorb solar IR from the network at a flow rate range.

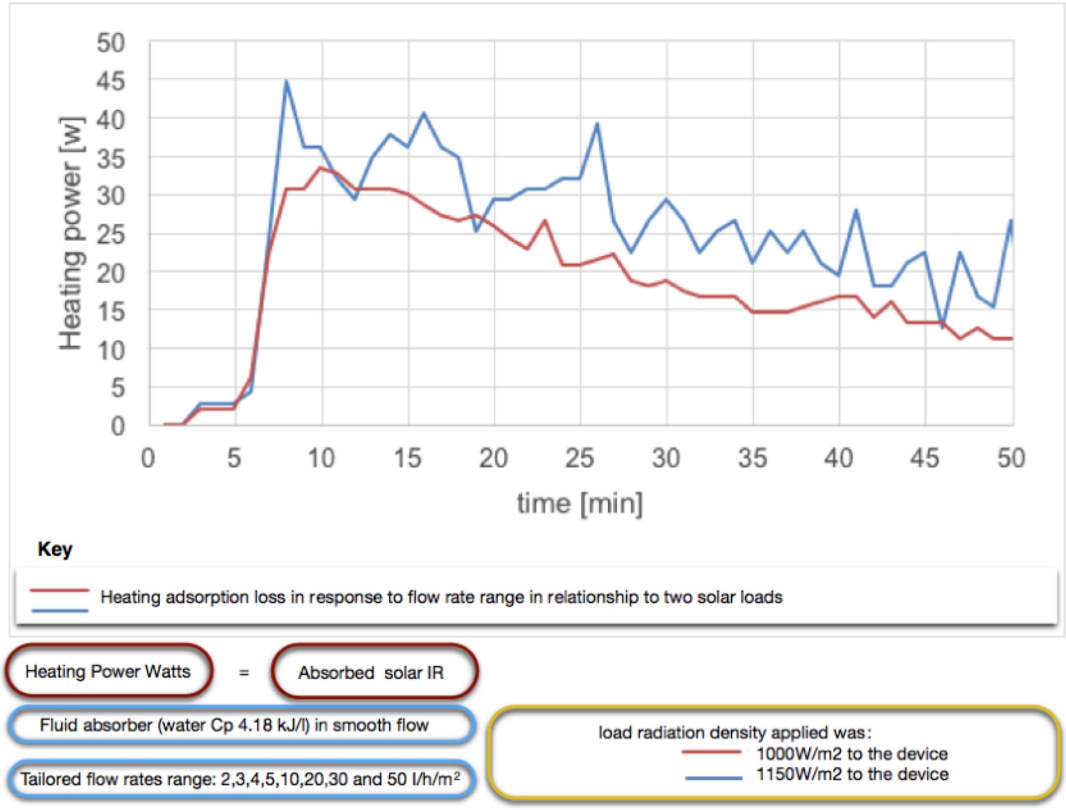


Figure 7.6 Heating Power of the Fluid to Absorb Solar Radiation from the Device

Figure 7.6 demonstrates that higher flow rates decrease the heating power that is directly related to reduced IR absorption. This energy balance is a relationship to solar irradiation power that is dependent on flow rate with a declining temperature difference as flow rate is increased over time.

Thermal properties are the result of, Δ t, for studying the effects of heat transport across the device by tailored flows to absorb solar radiation. The heating output measured in Watts over time clearly illustrates heating of water by the passage of a fluid through the multi micro-channels slot network. The heating power of water, through this slot geometry, under fully developed smooth laminar flow, illustrates the impact of flow rate variation.

In summary, the key learning points and encouraging proof of principle results are demonstrated. The thermal heating power data observes lower absorption at low solar IR densities, contributing to reduced water temperatures. Higher absorption rates (heating power) is achieved by increased solar load for higher water temperatures, as shown in Figure 7.7.

By changing flow rate, the temperature increase of the fluid changes in the network in steady state. The dependence of the device as a dynamic absorber will be modulated by water temperature. At low flow rate, it will act as a constant absorber; at higher flow rates this function decreases more strongly due to the combined effects of higher cooling power and reduced IR absorption. The results demonstrates absorption by filtering out near IR range, will lead to heating of the absorber at low flow rates. Through modulating volumetric flow rates in a device to manipulate the fluid – material interface within a microfluidic platform. By switchable control for conductance states to make the material switch on for high conductance or switch off for low conductance as a heat seeking targeting system for heat flow characterizations and this is new.

The results indicate temperature difference to decrease inversely with flow rate over a range of flow rates. At lower flow rates, it presents high IR solar absorption and increased high thermal fluidic temperature. Higher flow rates, over a pragmatic range of flows, diminishes thermal fluidic temperature with lower (Δ t) differences. The results above do not take into account heat loss to surrounding air temperature. Surface temperature of the device will affect fluid temperature in the network. At higher water temperatures than PMMA pane temperatures above and below the device vascular channels, convective cooling effect of air flow gave fluid temperature losses to the circuit as presented in the heating power fluid graph, figures 7.7. That indicates this effect by water temperature variation and the reason why a smooth heating power curve is not achieved, figure 7.6, by heat losses coming from the flow circuit.

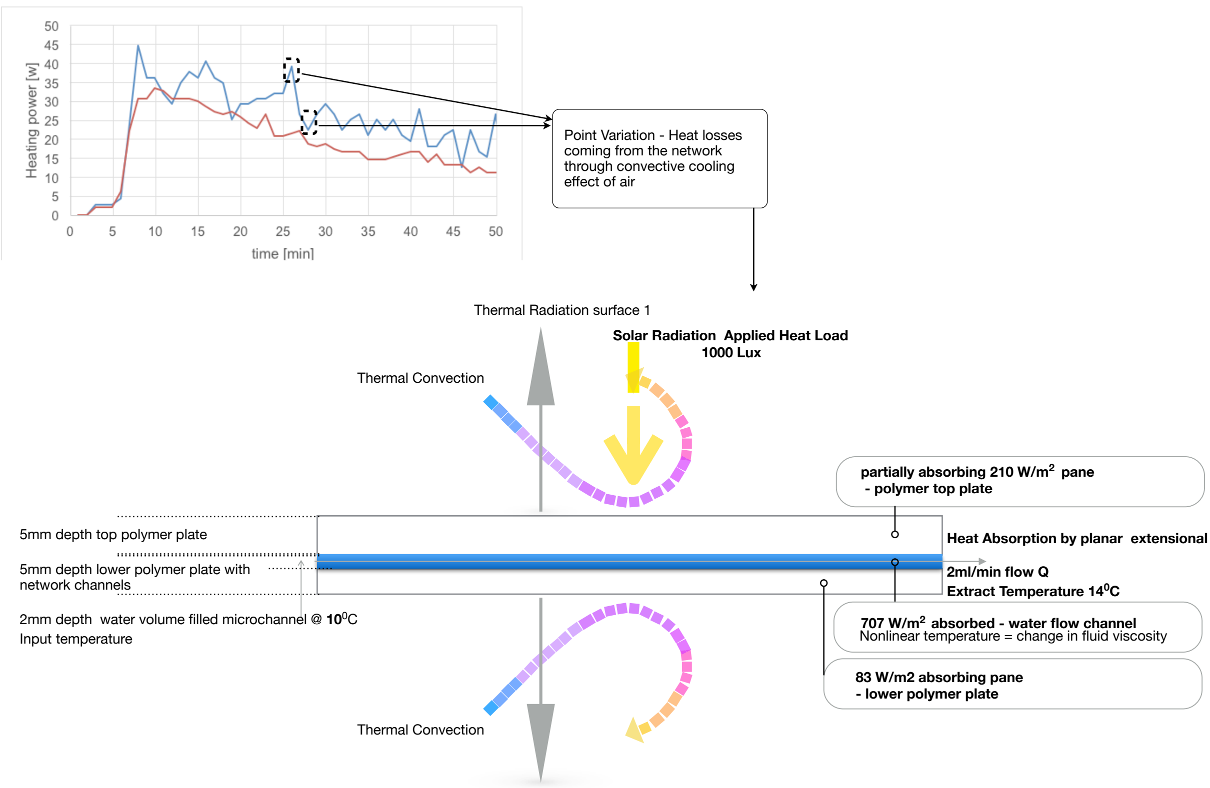


Figure 7.7 Convective Cooling Effect by Air Flow

From the experiment carried out in the laboratory we have observed the heating effect from the polymer panes achieves switchability as an IR absorber through the switching of fluidic flow rate. The abstract learning from the data is solar IR thermal switching for a device is achieved using precise hydro-dynamic control of a micro-fluidic platform.

7.5 Discussion

Precise geometry, hydro-dynamic design can direct the assembly of a micro-fluidic platform device for desired thermal characterization. Optimization of this flow dependent network is achieved by precision water flow rates to enhance a material's ability to capture and store energy. Modulating volumetric flow rates in a device will determine heat transport across the interface between fluid-material. This ability to lower its phase transition temperature is dependent on an individual micro-channel within a network's ability to absorb and transfer thermal flow across the interface of polymer material layers.

A single micro-channel in this network is acting as a heat seeking, thermal circuit by extraction of thermal energy from a specific material region. In order to attain uniform thermal transport extraction across the material pane, all multi micro channels will adsorb solar IR load at a uniform thermal flow rate. Creating a cooling uniform pane to regulate and manage material temperature extraction. This uniform thermal conductance extraction is dependent on steady state pressure drop. Pressure drop is managed by pressure equalization of unified smooth flow within the network across the micro-fluidic platform. This is achieved through diminishing flow pressure variation in all micro channels. Feed in micro-channels of upstream and downstream extraction perform significant roles to reduce turbulence flow within the network to derive smooth flow in longitudinal micro-channels for solar IR absorption.

Longitudinal slot channel geometries represent the thermal transport network for IR transmission temperature interface, for capture from the polymer surface pane. This capture and store of energy is achieved by thermal absorbing fluidics in steady state flow at the channel node. The research goal of the network is solar energy modulation efficiency using water flow as a thermal switching medium. Hydraulic resistance in fluidic conduit channels conform to minimum fluidic flow to achieve reduced pressure drop for fluidic flow efficiency. This is determined by a hierarchical structure to minimize resistance R for optimal fluidic transport.

Analysis for both the upstream and downstream channels can be determined, to evaluate if the upstream and downstream resistances are different. Knowing the pressure drops (delta P) will allow an estimate of the actual flow resistances. Analysis of delta P will determine optimization of resistance by micro-channel sequence succession. Multi micro-channel widths are significant as longitudinal micro-channel length and micro-channel depth is determined by material scale.

Resistance is evaluated from R=delta P/Q flow rate. Resistances of each longitudinal channel are evaluated and designed to an individual particular resistance function. The equation for the resistances follows a recursive pattern as defined in Chapter 6.This approach of defining individual channel resistance is the same approach as that applied in leaf vasculature. The channel vascular geometry design in the polymer device was set at longitudinal channels equal spacing pattern formation of 15.575mm, with channel widths of: R0-2.0mm, R1-2.3mm, R3-2.6mm, R4-2.8mm and the outermost channel R4-3.0mm. Hence, target hydraulic resistance of the central channel is determined, this hierarchical branching network scaling was validated by CFD.

Resistance has an influential effect to achieve systematic resistance networking of multi micro-channel succession for unified laminar parabolic flow across the network. Fully developed smooth laminar flow from a channel node under steady state parabolic flow optimizes heat transport across an individual micro-channel. The heating effect from the polymer surface pane and a switchable IR absorber were observed by experimentation. Heat transport across the fluid and polymer material interface was evaluated for energy capture. Fluidic, under uniform velocity profile, acted as an IR absorber to lower device phase transition temperature.

The higher flow rate anticipated results expected high turbulence of unequal distribution of flow across the planar device of increased short cut pathways. This reaction would influence (delta t) temperature decay (or heat loss) with time, diminished through thermal fluidic interface transfer. These short cut pathways would directly impact on heat flow transport characterization within the micro-fluidic network configuration. However, the 50.0ml/min flow rate distribution almost achieved uniform steady state parabolic flow within this flow dependent network. These results gave validity to the approach of hydraulic resistance knowledge, to calculate pressure drop across a planar device for tailored flow rate, without the need for CFD. When the micro-fluidic network device was subjected to IR impact 1000 W/m^2 (UK solar radiation heat load) the device achieved a temperature difference to decrease roughly inversely with flow rate over a pragmatic range of flow rates.

This was reflected in the thermal property, Δ t, over a pragmatic rate of absorbed solar IR wavelength. It was observed that absorbed solar IR heat load, transfer into a functional fluid acted as a constant IR absorber to advance a polymer, to lower its phase transition temperature. This controlling processing of a functional material of a micro-fluidic based platform, using extensional flow generated in channels acted as an IR stop band. Each micro-channel within the network is a heat seeking absorber by fluid-material interface to regulate material regions as a thermal flow bridge. By modulating volumetric flow rate in the device, thermal conductance heat flow was regulated.

- The IR impact 1000 W/m^2 (UK solar radiation heat load) heat transfer through the material interfaces was observed.
- The 5mm polymer counter plate acted as a partially absorbing 210 W/m^2 pane by solar radiation impact.
- The rectangular micro-channels of pressure driven laminar flow at, 9.0 ml/min, adsorbed 707 W/m^2.

Heat transport IR transmission temperature through the remaining polymer was 83 W/m2. Thermal functionality is determined by the fluid absorber (water C_p 4.18 kJ/l) in smooth flow, without non-linear, turbulence effects. Multi micro-channels of a flow parabolic profile, for a fully developed flow low rate, acts as a constant IR infrared block. However, at greater flow rates within the flow dependent network that achieves uniform pressure gradient, thermal conductance is decreased. This lower material transmission temperature is centered on the fluid (water) thermal properties to absorb IR for heat transport across the planar device. Increased flow rate will reduce the thermal flow capture more strongly due to the combined effects of higher cooling power of the device, and the reduction consequence of this, is lower IR absorption. Although higher cooling is achieved in the micro-fluidic device, material phase transmission temperature to act as an IR block is reduced. This part of the experimental laboratory output data indicated the curve at this point is unwanted for solar modulation properties. By modulating volumetric flow rate, we change the temperature increase of the fluid in steady state, as a switchable IR absorber.

An increased flow rate gives high transmission temperatures with increased material cooling effects. This functionality offers limited solar-energy modulation and thermal flow transport across the micro-fluidic platform. In order to evaluate thermal transport flow it depended on a fluid–material interface to achieve an energy balance. This energy balance of solar irradiation energy absorption is determined by the manipulation of hydro-dynamic position by flow rate for steady state pressure within flow networks.

Results indicated heating of water connected to a partially absorbing pane by passage through the micro-fluidic based flow gave thermal switching characterization.

Tailored flow rates gave a controlled processing of a thermally functional polymer by micro-fluidics for desired solar absorber characterization. However, increased flow rate, impacts on uniform thermal conductance across a micro-fluidic device, for enhanced energy capture. Each micro-channel is extracting heat from a material region and this is dependent on fluidic thermal flow. The analysis, observations and quantification of thermal flow across the interface of the polymer device layers was published in Nature (scientific reports, 2016) Alston et al., 2016.

7.6 Conclusion

The geometry flow design network of systematic resistance networking uses a simulation approach to advance a thermally functional polymer. Fluids in this slot geometry network are in uniform planar extensional flows are close to the optimized condition for solar load capture. This conclusively demonstrates that optimization procedure using a precise hydraulic resistance is a valid approach. Such optimization efficiency will advance transparent composites in energy generation flow design for advanced materials. However, for a network at higher flow rates, the ability to lower its phase transition temperature is diminished. Low volumetric flow rate in steady state enhances solar modulation properties with reduced energy pressure requirement.

Energy conservation in flow fraction network is dependent on pressure drop and this has been demonstrated. A dynamic IR absorber, characterization is modulated by temperature-dependence of the absorber in precise laminar flow rate has been evaluated. This design methodology demonstrated a micro-fluidic device in uniform distribution of flow, to direct the assembly of a thermally functional switchable IR absorber for desired functionality.

Chapter 8 Conclusion

8.0 Introduction

Reducing building energy use and reduction in carbon emissions are the challenges in operational and occupancy of buildings. To maintain thermal comfort, building envelopes shape energy use as these façades are viewed as uncontrolled loads to provide occupancy amity. To maintain thermal comfort, the envelope is a boundary, working with mechanical systems (heating / cooling, lighting). Opaque façades technological method in achieving operational and comfort performance is well researched. However, glazed envelopes are energetically weak in their ability to lower phase transition temperature. Current performance strategy is based on a single prescriptive code compliant value to resolve the conflict of heating systems, fighting cooling systems that load shape operational performance of mechanical systems.

The knowledge gap is determined by what is defined by a single prescriptive value to what it could be. A dynamic strategy, since performance requires change by the hour, season and weather conditions, to deliver energy performance and comfort. Nature has evolved material functions as a heat flow targeting system that is aligned and oriented to thermal monitoring of temperature with time. This is achieved through hierarchical rule orders to determine material function in response to solar radiation. This is a dynamic system in real time synced with the pattern changes in their environment. The research proposes methods to use leaf vasculature formations to advance an transparent material to act as an infrared block. The research defines the use of microfluidics based flows to direct the structural assembly of a polymer into a thermally functional material. To advance a transparent material to act IR radiation stop-band to lower a polymer device phase transition temperature. The research determined this functionality by hierarchical multi microchannel network scaling, to regulate laminar flow rate by analysis as a resistor circuit. The research structure through the chapters determines nature's approach to heat flow transport in real time to advance a thermally dynamic transparent material for solar modulation properties.

Chapter one defined the aims and objectives of the research to demonstrate an original contribution to knowledge and the constraints and imitations of the research to advance a biologically inspired transparent material as an energy system. To understand the state of the art perspective frame of glazed façade innovation was determine in chapter two. By exploration of leading edge technology, to deliver intelligent operational controls for glazed façades as a zero net energy contributor for building energy operation and occupancy. However, what could be, may be delivered by a biomimetic design approach in advancement of a thermally functional material as a heat seeking targeting system, inspired by nature.

Nature's formation of materials is defined by hierarchical rule orders to evolve the developing organism structure and the characterization of its function. Nature activity monitors temperature gain and decay as a method to sculpt itself to a dynamic environment. Chapter 3 reviewed the relationship to energy and matter through thermoregulation and autonomous self-healing and intelligent surfaces of leaves. Characterization of leaf vein formations would advance as a blue print hierarchical multi microchannel networks for energy capture and storage to act as a thermally functional material. This theory, in testing the philosophy through simulation and an artificial laboratory environment, enables evaluation of material conductance. By philosophical foundation of the scientific method, is to derive subsequent verification of the theory, discussed in chapter 4. The scientific method aim is to seek, discover, explore and understand new theories in connection to nature. The scientific method is the collection of facts by means of careful observations and experiments to derive subsequence theories by logical procedure.

By evaluation of leaf vascular networks, it was possible to determine optimal transport efficiency of an artificial multi microchannel network. This was observed by hierarchical network matrix to minimize pressure drop to achieve minimum effective power flow rates for optimized fluidic transport, chapter 5. Pressure equalization defines pressure drop by diminishing flow pressure variation by resistance. Equalization of resistance transport flow can be evaluated as a resistor, discussed in chapter 6. This research generated a biomimetic artificial network through an iterative procedure, demonstrated an optimization of resistance seeking targeting for fully developed laminar flows. Uniform parabolic flow across a planar surface enhanced fluidic thermal energy capture (if subjected to IR load) and if replaced with in coming fluid, creates an energy capture and storage system. Modulation of volumetric flow rates across the planar microfluidic platform acts as a thermal flow bridge. Experimentation testing of the fabricated device observed the thermal side of IR solar radiation absorption at high temperature, discussed in chapter 7. Determined capture and storage of thermal energy is achieved by thermal absorbing fluidics in steady state flows using water flow as a thermal switching medium, by modulating flow rates in the microfluidic platform to manipulate planar temperature of the device in response to IR impact.

This chapter reviews the theoretical and experimental testing method to implant a microfluidic network to direct the assembly of a thermally functional polymer, demonstrated in this thesis. Embedding biologically inspired engineering by a microfluidic-based platform enhances thermal switching characteristics of the polymer. Continuously circulating a fluid within a material, through it and out of it, by fluidic flows enhances absorption and heat flow transport through flow rate regulation. The research demonstrates solar radiation absorption is dependent on a precise flow rate for thermal switching. This characterization is determined by uniform smooth flow within a network which will remove the stored liquid temperature out of the polymer for solar modulation. If this liquid is replaced with incoming fluid, this creates a photo absorptive system. This approach enables thermal switching selectivity of a polymer device in response to heat load from IR. This research is not focused on thermal conductivity but the absorption of solar (non-thermal) IR by heat built up. This represents a thermal exchange transfer cycle of fluidic absorption through vascular channels. In summary, the objectives of the findings and discussion and the structure of the chapter are presented by:

- Validation of the experimental testing methodology
- Review of the research aim and objectives
- Reviewing the limitations of the research
- Outlining the implications of the research on transparent façade engineering

- Conclusion of methods

These are now discussed in detail.

8.1 Validation of the Experimental Testing Methodology

The scientific method is the investigation in material science by observations of the physical world by applied science to establish the philosophy of the theory that has been undertaken to advance an energy capture and storage device.

Scientific discovery is to establish theories that are considered to be the foundation of science in understanding nature (Chalmers, 1999; Popper, 2002). In accordance with the methodology and methods this was achieved by the experimental testing method to evaluate conductance by heat transfer mechanisms of a polymer material through:

- Resistance Optimization
- Radiation / Convection Heat Interface Transfer

SI units define the experimental testing assessments of these parameters. Observable data was gained through measurement readings to assess the prototype absorption of solar, non-thermal IR (see section 7.4). The heating effect from the polymer surface pane and switchability IR absorber was evaluated through experimentation. Heat transport across the fluid and polymer material interface was analyzed for energy capture. A fluid in active flow in slot geometry channels, under uniform flow, acted as the IR absorber to lower device phase transition temperature. This was demonstrated by heat flux through the material layers. A load radiation density applied was 1000 Wm^2 (UK climate solar radiation load) to the device. The counter plate acted as a partially absorbing 210 W/m^2 pane, the fluid absorbed 707 W/m^2 and the remaining 83 W/m^2 was transmitted by radiation through the polymer. This is verification by observation and supports the scientific theory of using artificial conditions by experimental design. This replicates the real world to establish new facts by the fabrication of the prototype device tested in laboratory conditions to qualify thermal functionality.

Results indicated heating of water connected to a partially absorbing pane by passage through the microfluidic based flow gave thermal switching characterization. By modulating volumetric flow rates in the device enabled a temperature difference to decrease roughly inversely with flow rate. Tailored flow rates gave a controlled processing of a thermally functional polymer by microfluidics for desired solar absorber characterization.

The validation through experimental testing to derive subsequent derivation of natural vasculature networks into a thermally functional material has been observed. The scientific knowledge of leaf formations will advance understanding to lower a materials phase transition temperature for enhancing solar modulation properties.

The extract of learning on the basis of the present experimental information is demonstrated by heat loss coming from the network. This was determined by water heating temperature from the downstream extract micro-channel into a reservoir tank. Experimental data analysis monitored the thermal properties by assessment of temperature difference of fluidic input (upstream manifold) and output fluidic temperature (downstream manifold). To observe heat power transport, as a thermal measurement system, evaluated by (Δ t). That is represented by a temperature raise between input supply and fluidic extraction. This data analyzed heating of water from the network. To extract the heating power of the water reservoir from the data to observe temperature depended on the absorber at flow rate. Figure 7.6, (Heating Power of the Fluid) verifies the energy balance of the device that is connected to solar radiation power and flow rate. For a polymer as a dynamic IR absorber, the temperature of the water within the network would be expected to decrease inversely with flow rate over a range of flows. This relationship is determined by changing flow rate; changing the temperature of the water through reduced solar absorption influences heating power.

Monitoring input fluidic supply and extracting evaluated heat flow and effect of heat transfer interface was conducted. Setting varying tailored flow rate by precise hydraulic manipulation to analyze and quantify thermal flow extraction was undertaken. The data findings supported the conclusion that the footprint for the controlling processes of a thermally functional material is defined by steady state in real time (flow rate within the network). By modulating volumetric flow rate, the temperature increase of the fluid changes, as a switchable IR absorber.

Results indicated heating of water connected to a partially absorbing pane by passage through the microfluidic based flow gave thermal switching characterization. Tailored flow rates gave a controlled processing of a thermally functional polymer by microfluidics for desired solar absorber characterization. This discovery, exploration and understanding of a new theory is connected to nature that employs this method in leaves to capture solar radiation.

8.2 Review of the Research Aim and Objectives

- Explore and develop a transparent prototype in order to embed the principles and processes of a natural system.

The research aim can be tested based on the thermal data results (Δ t) to quantify multi microchannel slot networks, derived by resistor analysis of leaf vasculature architecture.

This characterization of natural leaf networks is determined by circulating a fluid using precise hydrodynamics. This mechanism will advance a thermal functional polymer to act as a switchable IR absorber. This absorber uses switching of water flow as a thermal switching medium to regulate heat transport flow. The results demonstrated a fluidic network, as a resistor, to enhance the visible transmission and solar modulation properties by microfluidics. By modulating volumetric flow rates we can manipulate the temperature dependence of the IR absorber.

These parameters will give active management for thermal characterization of an transparent device in response to energy capture and storage. A blueprint, to advance the structural assembly of a microfluidic device to enable dehumidification of external surfaces subjected to high transition temperatures. This is achieved by fluidic mechanics (pressure drop, resistance, flow rate, absorptivity) by thermal properties. This is regulation of heat transport by observation, analysis and quantified thermal flow management.

Using precise hydrodynamic control of the microfluidic platform will manipulate the position of the fluid – polymer heat transfer within the vasculature network, delta t. By modulating volumetric flow rates in a device to manipulate fluid /polymer interface in micro-channels is the desired morphology to advance a functional material. The justification of this path to validate the scientific discovery by applied experimental fabrication and laboratory verification testing, enabled thermal data results.

The research objectives were defined as:

1. To identify the principles and procedures of natural systems response to solar radiation.
2. To investigate the current constraints of contemporary transparent building skin technology, in applying natural principles and procedures.
3. To develop a transparent device that exhibits the possibilities to adopt natural principles and procedures to control solar radiation.
4. To test the transparent device.

8.3 Principle and Procedures of Natural Systems

Chapters 3, 5 and 6 demonstrate this objective: by analysis of leaf vasculature formations, as these networks present hierarchical optimization in solar radiation modulation. Leaves represent a highly regulated model with species-specific vascular pattern formations. Vascular formations have uniform spacing patterns and exhibit spatial regularity by hierarchical sequence patterns in advanced leaf species. The underlying mechanisms of vascularization pattern conduits are networks of constant flow conductivity distribution and pressure. This reticulate closed loop geometry is formed by changes in vein thickness, vein angle divergence, redundancy functionality, stem vasculature fluidic supply and vein hierarchical order.

Leaf vascular patterns are the mechanisms and mechanical support for the transportation of fluidics for photosynthesis and leaf development properties. These networks regulate the control delivery of nutrients, removal of waste, temperature regulation and damage repair by a functional fluid. These geometry networks in a leaf act as a photosystem that is defined by hierarchical fluidic resistance. Each leaf is an independent unit within a tree canopy structured system that is regulated by solar orientation for daylight capture. This is determined by rule-based geometry, canopy volume, total leaf area density and angular distribution of leaf surfaces. Leaves are venation networks, which are a two dimensional (longitudinal pattern) of continuous, branching features. These vascular patterns form a complex hierarchical pattern for the transportation of fluidics for photosynthesis mechanisms. Characterization of leaf vein formations are desirable morphology for solar modulation properties by microfluidics for transition temperature decrease in a thermally functional material.

Vascular hierarchical networks in leaves have far-reaching functions in optimal transport efficiency of functional fluidics. Embedding leaf morphogenesis as a resistor network is significant in the optimization of a transparent thermally functional material. This will enable regulation through pressure equalization by diminishing flow pressure variation. Using a microfluidic-based network of steady state flow in multi micro-channels across the material pane will advance a polymer for desired thermal functionality and this was observed through simulation in Chapter 6 and applied to the device fabrication process.

8.4 Current Constraints of Contemporary Transparent Building Skin Technology

Chapter 2 determines this objective: Current State of the Art: Integrated Glass Envelopes. This chapter investigated advanced performance envelopes to conserve energy and to fulfill thermal comfort requirements. This is a literature review into transparent façades as defined by climate, thermal comfort and energy consumption demands. In this chapter, opaque insulated envelopes are investigated as they outperform transparent façades, as these transparent materials still remain a weak link in envelope performance conductivity.

Performance and compliance to ever-increasing prescriptive building codes has led to the development of integrated transparent façade systems rather than traditional curtain walling assembly. This integrated approach is rethinking current approaches in viewing transparent envelopes, as a system-oriented performance. Utilizing these systems gives better solutions for improvements in working conditions for higher performance, in response to glare, thermal comfort and increased day light through controlled systems.

Integrated glazed systems offer tangible benefits coupled with energy performance strategies, and is a new method of thinking. These integrated systems represent the main challenge in achieving energy efficiency strategies that could possibly equal or better high performance opaque envelopes. Greater demands have been placed to minimize operational building energy use by maximizing the generation of energy and daylight as an integrated model. However, integrated service façades still remain a static element in response to real time performance dynamic change that is required by the hour, season and weather conditions.

Nature uses real time responsive functions to manipulate and determine material composition. Biological materials react and have adaptive strategies in response to environmental stimuli. These organic materials are multifunctional systems as they are mechanically strong and resilient, formed by chemical composition. Chapter 3 investigates these parameters and methods that nature employs in adaptive responsive functions.

8.5 Development of a Transparent Device

Chapter 7 demonstrated this objective by methods to use leaf vasculature formations to advance a material to act as an infrared block. This chapter demonstrated the use of microfluidics based flows that can direct the structural assembly of a polymer into a thermally functional material to manage IR radiation as a stop-band to lower a polymer device phase transition temperature. This research quantifies this functionality by hierarchical multi microchannel network scaling to regulate laminar flow rate to capture solar radiation. By using precise manipulation of tailored flows it is possible to direct the assembly of a microfluidic device for desired thermal characterization. This is demonstrated by using switching of water flow as a thermal switching medium to regulate heat transport flow with enhanced solar modulation properties.

This approach follows nature; that has developed mechanisms to regulate material functional properties by active measures. The application of this characterization will advance new functional materials based on microfluidic-based platforms. This is achieved by fluidic transportation by optimization of flow, as a thermal trigger to regulate material functionality. Defining a network as a resistor through simulation approaches derived from leaf formations addresses hierarchical network functionality. This simulation approach defines the multi micro channel succession in branch network scaling. This is optimization of microfluidic precision flows to direct the structural assembly of a polymer determined by biologically inspired engineering.

The ability to capture and store energy by modulating volumetric flows for solar capture is characterized by nature.

8.6 Testing the Transparent Device

Chapter 4: Philosophical Foundation, Methodology and Method outlines the experimental method for the device. The methodology for the scientific method is to advance new knowledge of the natural world by real world experimentation. This is the underpinning of the philosophy of the theory to modulate solar radiation by a microfluidic device. The scientific method is founded in scientific knowledge that is proven knowledge through experimental testing methods under artificial laboratory conditions.

Research indicated the direction of the experimental method applied to heat transfer measurements. By fluidic active management of circulating fluids in a network directed the proposed method. The monitoring of temperature through evaluation of Δt (temperature input variation to extract fluidic temperature to define heat power capture with time) is quantified in Chapter 7.

8.7 Review of Limitations

8.7.1 Laboratory Experimentation Temperature Spectrum

The development of this novel microfluidic platform device for examining and measuring energy conduction capture and storage (fluid) is confined to laboratory verification. The device scale (220x158mm) was subjected to an artificial solar radiation load in a controlled environment. This was undertaken in a temperature positive solar radiation spectrum. The testing method did not undertake negative experimental testing temperatures to analyze or evaluate temperature decay.

8.7.2 Material Scale

The device was limited to a material scale that could be tested in a laboratory environment to apply an artificial heat load under controlled laboratory conditions. Validation of the scientific theory to develop a thermally functional device was observed. Scientific methods of observable experimentation results in an artificial environment to recreate the natural world is the limitation of the experimental method. Up-scaling of the device for large scale application experimental testing in real world physical conditions was outside the scope of this research, however, it is the next step.

8.7.3 Experimental Testing Time

The method to regulate flow rate was achieved by a syringe pump that used distilled water from a reservoir tank to maintain flow rate through the network. Tailored flow rates range set at: 2,3,4,5,10,20,30 and 50 l/h/m^2. This reservoir tank had a fixed volume of water and hence the time-line for the experiment was fixed by this parameter. The time line was 50 minutes. By modulating volumetric flow in the device was undertaken to observe the polymer ability to capture and store (in the fluid) energy. Temperature monitoring greater than 50 minutes could not be achieved by the syringe pumps reservoir fixed water capacity. This time frame is a limitation to the research.

8.8 Microfluidic Network Resistance Optimization

The fluidic thermal flow results observed heat transport flow across the planar microfluidic device. Monitoring temperature decay (heat loss) through radiation, convective thermal transfer to surrounding air was not undertaken. These thermal effects would increase across the microfluidic planar device due to enhanced absorption temperature of the fluid in slot network channels. These effects would increase non-linearly with temperature difference between surrounding air temperature and device thermal capture.

A selected individual channel resistance R0 determined the resistance footprint of the microfluidic network. R_0 value is the target resistance defined by the central channel. This central channel establishes the systematic resistance networking of sequence succession of multi micro-channels within the network (as defined by leaf vasculature formations). The analytical results using theoretical resistance are based on R0. The weakness of this approach is represented by R1 and R0 micro-channels within the network. CFD simulations already indicate that flow rates through R4, R3 and R2 are almost identical.

These micro-channels present a smaller resistance in comparison to R1 and R0. Tailored flow rate distribution of these R1 and R0 almost achieved uniform steady state parabolic flow within this flow dependent network. For future research optimization, dimensional slot channel geometry could be adjusted for R0, R1.

Central channel R0

Resistance = 0.29477840E+09

Channel R1

Resistance = 0.29477829E+09

Channel R2

Resistance = 0.29477556E+09

Channel R3

Resistance = 0.29477620E+09

Channel R4 – outermost channel

Resistance = 0.29477822E+09

If smaller resistances are present in a parallel microfluidic platform this represents proportionally greater carrier flow. This increased carrier flow creates shortcut pathways through the microfluidic network, however, the variation in R is very low as presented in this network. Each microchannel is heat seeking, to extract thermal energy from a material area, region, by heat transport. The IR absorber is temperature-dependence through flow rate in the transport of waterpower heating in micro channels.

An alternative approach is to set the target resistance microchannel to the outmost material edge. This solution gives an up scaling direction of the microfluidic-based platform to drive the assembly. If the network is constrained to device (220x158mm), multi microchannel sequence succession could start from the outermost channel and work inwards for R3, R2, R1, and R0. The attraction of this is the footprint of the network stays constrained to a 148mm width with the outermost edge 3mm microchannel. This method is a reverse analysis as the outermost channel width is unknown to begin with and so the width of the device cannot be known in advance. This approach would advance the device’s thermal characterization, however, it is outside the scope of this research.

8.9 Implications of the Research on Transparent Façade Engineering: Future Progression

Using microfluidic based flows into a structural assembly of a polymer will advance materials desired energy capture and storage functionality. This steady state flow network of continuously circulating a fluid within it, through it and out of it, by microfluidic based flows to direct the structural assembly of a polymer. This uniform parabolic flow will remove stored liquid temperature out of the polymer for solar energy modulation. If this liquid is replaced with incoming fluid, this creates a photo absorptive system. This approach enables thermal switching selectivity of a polymer device in response to heat load, IR. This research is not focused on thermal conductivity but the absorption of solar (non-thermal) IR by heat built up. This represents a thermal exchange transfer cycle of fluidic absorption through vascular channels, as in Figure 8.1.

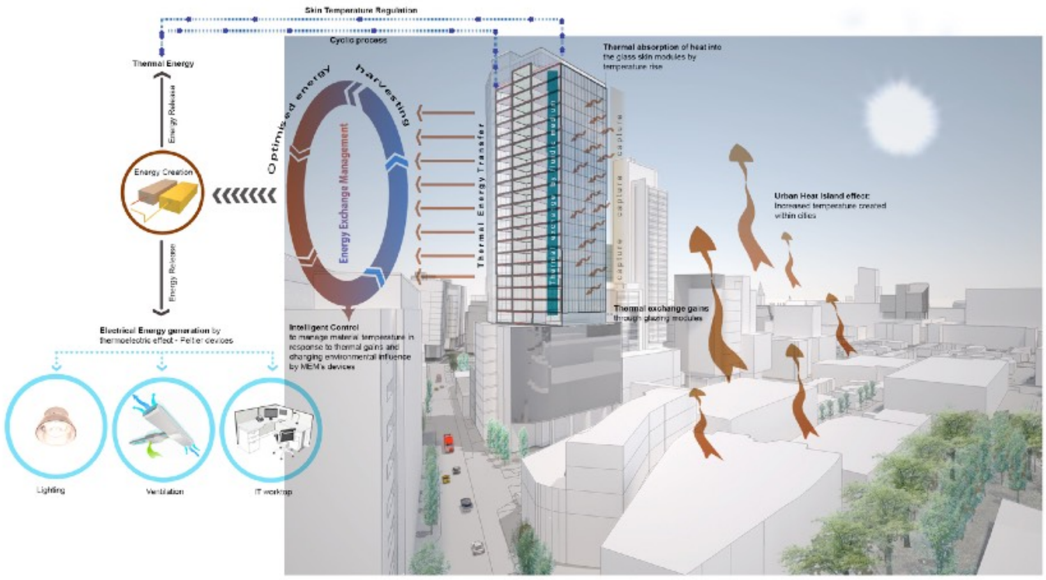


Figure 8.1 Thermal Exchange Cycle

The micro vascular network will determine thermal switching optimization to material temperature regions. Multi microchannel networks will regulate material temperature by management of:

- Q, Flow resistance for multi microchannel networking succession defined by volumetric flow rate as denoted by:

$$Q_1 = Q_2 = Q_3 = Q_4 = Q_0$$

The pressure drop to determine equalized pressure across the network, to reduce flow pressure variation is determined by a selected target microchannel:

$$\Delta p_4 = Q_0 R_4$$

- Radiative / Convective heat interface transfer is defined by:

$$q_H = \dot{m}\, Cp \;\; \Delta\, t$$

q_H	Heat load
$\triangle\, t$	Temperature difference
$\dot{m}$	Mass flow rate
Cp	Heat Capacity

These parameters will give optimization of a thermally functional material in relationship to surface temperature fluctuations. The heating effect from a surface material pane is regulated by water uniform parabolic and laminar flow profile for transition temperature decrease. Management of thermal flow would progress building transparent façades internal and external surfaces, as the polymer device will act as a thermal flow bridge. Current transparent facades technologies considers a glass building to be one surface, notwithstanding this one surface is comprised of a number of assembly components, frames, mullions, waterproofing gaskets, drainage channels. The entire glass envelope in capillary flow glazing could not be treated as one entity, as the vascular network will have a resistance to flow , if treated as one interconnected network, and this would be considerable. Pumping pressures need to be controlled, as energy generation from active conductivity control of polymer/glass would be outweighed by the pumping energy demands with in the network. However the separation of the facade into multiple photoactive layers, figure 8.2, to work with gravity and reduce pumping pressure is the starting point of this control process through the surfaces of glazed buildings being formed from multiple level layering, figures 8.2.

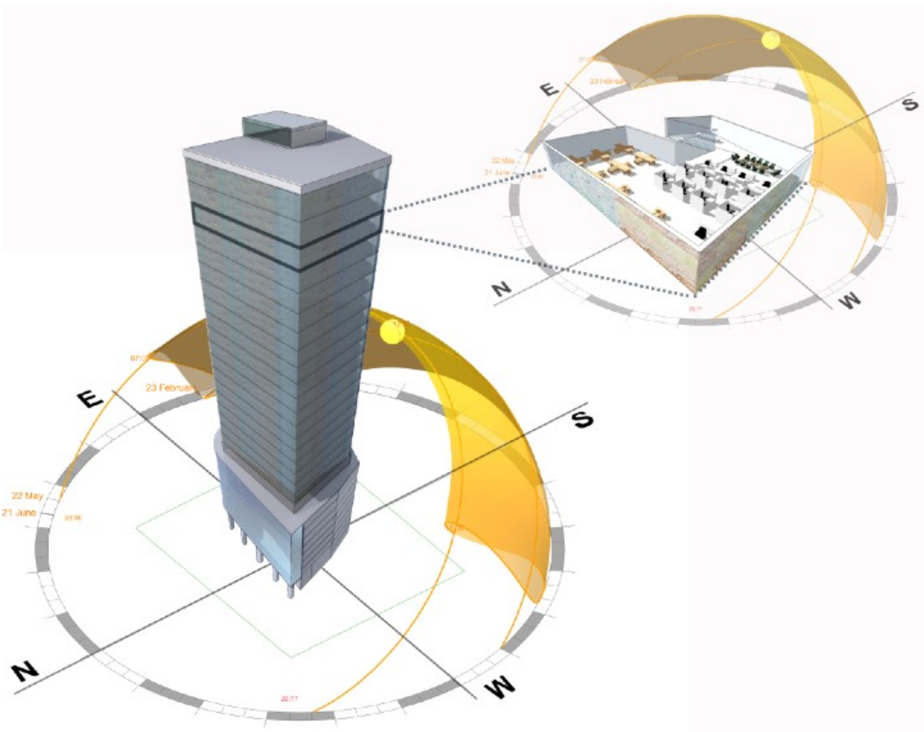


Figure 8.2 Layer-by-Layer approach to create Photoactive Layering.

Each level is acting as a photoactive layer interconnect, at a multiscale level to create a holistic glass facade. These are the mechanisms applied by trees, in the creation of a canopy to form the leaf area density of a tree as a multiple layering approach. Each leaf geometry and functionality is connected to orientation for the maximization of daylight capture. The formation of an envelope by a floor level layering approach gives regulation influence in dealing with orientation, temperature differentials and gravity effects, figure 8.3.

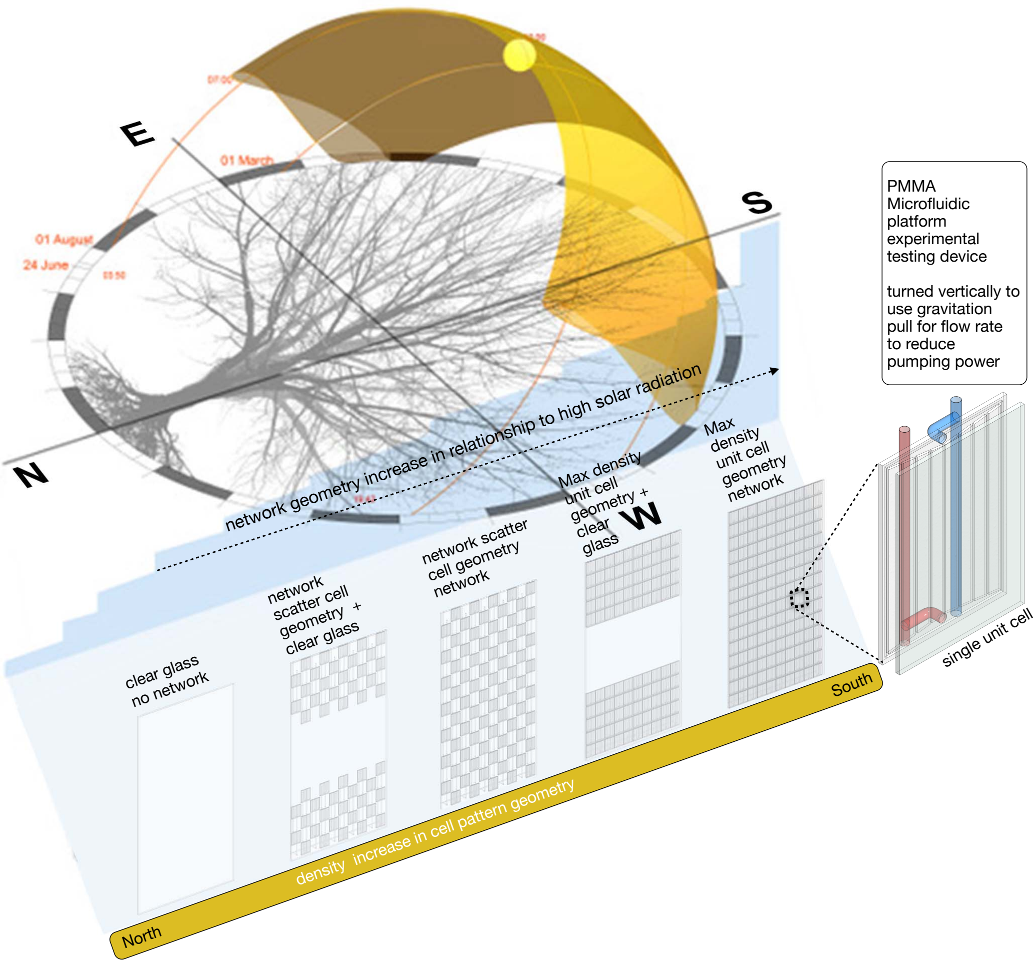


Figure 8.3 Cell Geometry Pattern Linked to Solar Radiation.

The layer-by-layer approach using gravitational pull to influence and manage fluidic flows, working with gravity feed will reduce pumping power. By glazed surfaces in manageable level modules to avoid pumping fluids through a continuous vertical surface in avoidance of multiple floor, vertical fluid transfer and consequential increased pumping pressures demands. The ramification of this is the creation of autonomous cellular floors zones that will have energy generation from glass / polymer photoactive surfaces to respond to energy floor zone demands. An intrinsic link of energy generation to consumer energy demand at a localized level.

The fluid flow that is now confined within a layer level will give and enhance real time adjustment to fluidic flow rates as a thermal recirculation cycle. By the liquid acting as a natural heat sink and energy storage capacity to regulate material conductivity by active flow rate manipulation requires management. This active management of heat transport flow will feed into tank reservoir for energy removal. Through sensors and actuators devices gives active measures by regulating flow rate and absorptivity in setting steady state energy capture and storage. Thermal management strategies are determined by thermal energy load – unload processes. This load shift to remove energy from the heat carrier fluid to revert back to steady state temperatures, as shown in Figure 8.4.

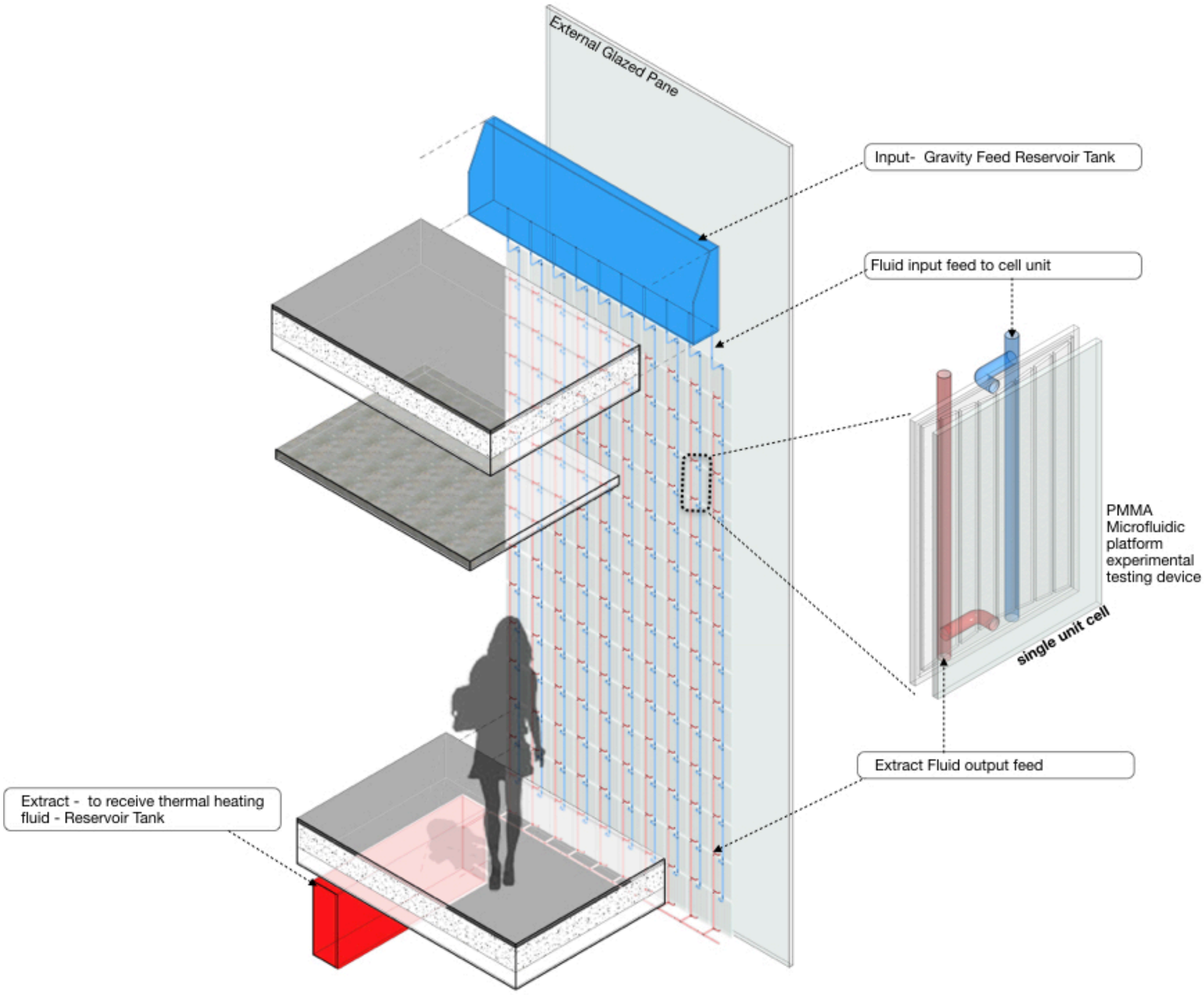


Figure 8.4 Localized Energy Load-Unload process

Energy load shift is a heat transfer capture / storage cycle. Thermal reservoir tanks located to each floor level can achieve this. This horizontal layering of a façade will create autonomous energy capture and storage, tailored to building levels. Each floor is acting as an independent unit within a multiscale of units in the formation of the envelope façade skin, illustrated in Figure 8.4.

The ability to store thermal energy in reservoirs can be converted into electrical energy by Peltier devices. This thermoelectric semiconducting engineering offers electricity conversion from thermal energy storage. This is active management in response to changing solar radiation patterns and absorptivity. The energy is generated at a localized level, served by microvascular capillary glazing in avoidance of extended distribution feeds. To provide optimization of pumping energy demand linked with hot water storage. The integration of multifunctional systems, including energy production, distribution and storage technologies, into a capillary glass envelope, are new methodologies.

8.9.1 Vascular Cell Density relationship to Solar Radiation

The disconnection of the glass façade into an autonomous floor levels is a movement away from current technological solutions and serves all approaches. This objective connects energy demands to a multifunction capillary glass envelope to reduce carbon emissions from reliance of one holistic approach to heating and cooling demands. The system functionality is, however, intrinsically linked to evaluation of fluidic flow, building orientation and climate. The optimization of integrated energy capture and storage objectives for glass capillary façades will enable energy generation and carbon footprint to sync with different geographical regions. The multi micro-channel geometry design addresses the need for controlled processing of a thermal functional material to advance a dynamic building surface skin. The network channel design has to be linked to solar radiation exposure in connection to building geographical climatic location, building orientation geometry and solar radiation G incident to a planar surface. The following facade images give an impression of absorptivity linked to solar radiation, figure 8.5, 8.6, 8.7

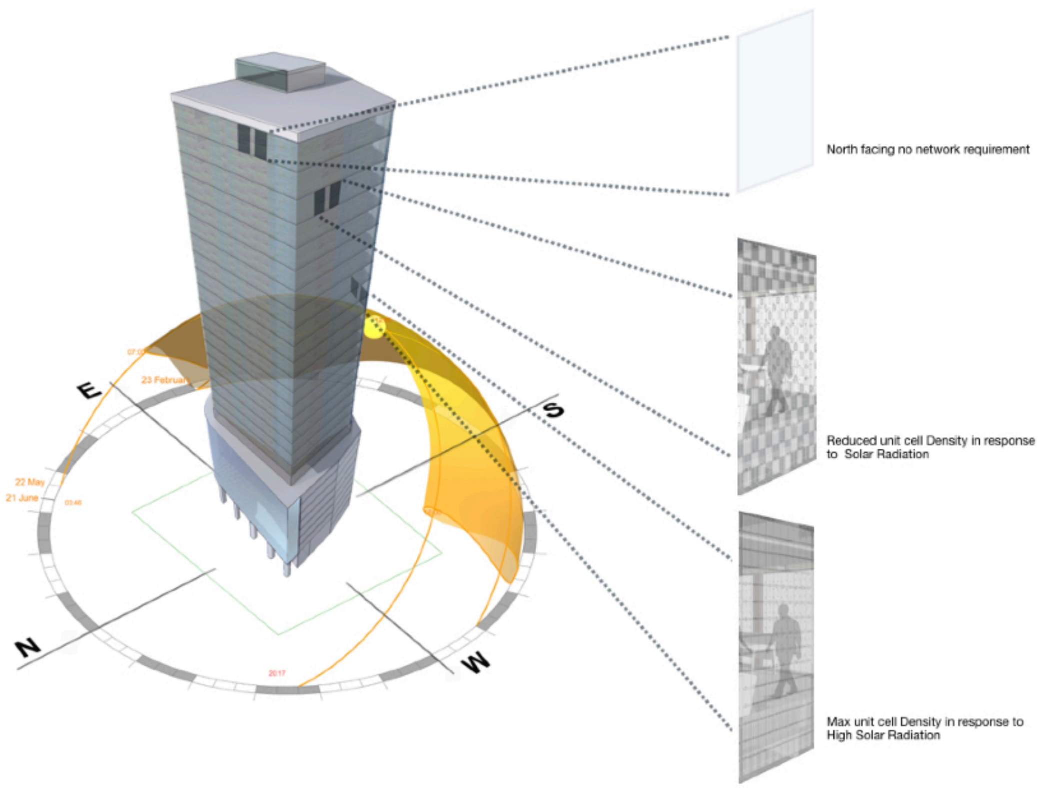


Figure 8.5 Absorptivity Connection to Solar Orientation, the intensity of the multi microchannel network increased as a direct relationship to higher solar radiation.

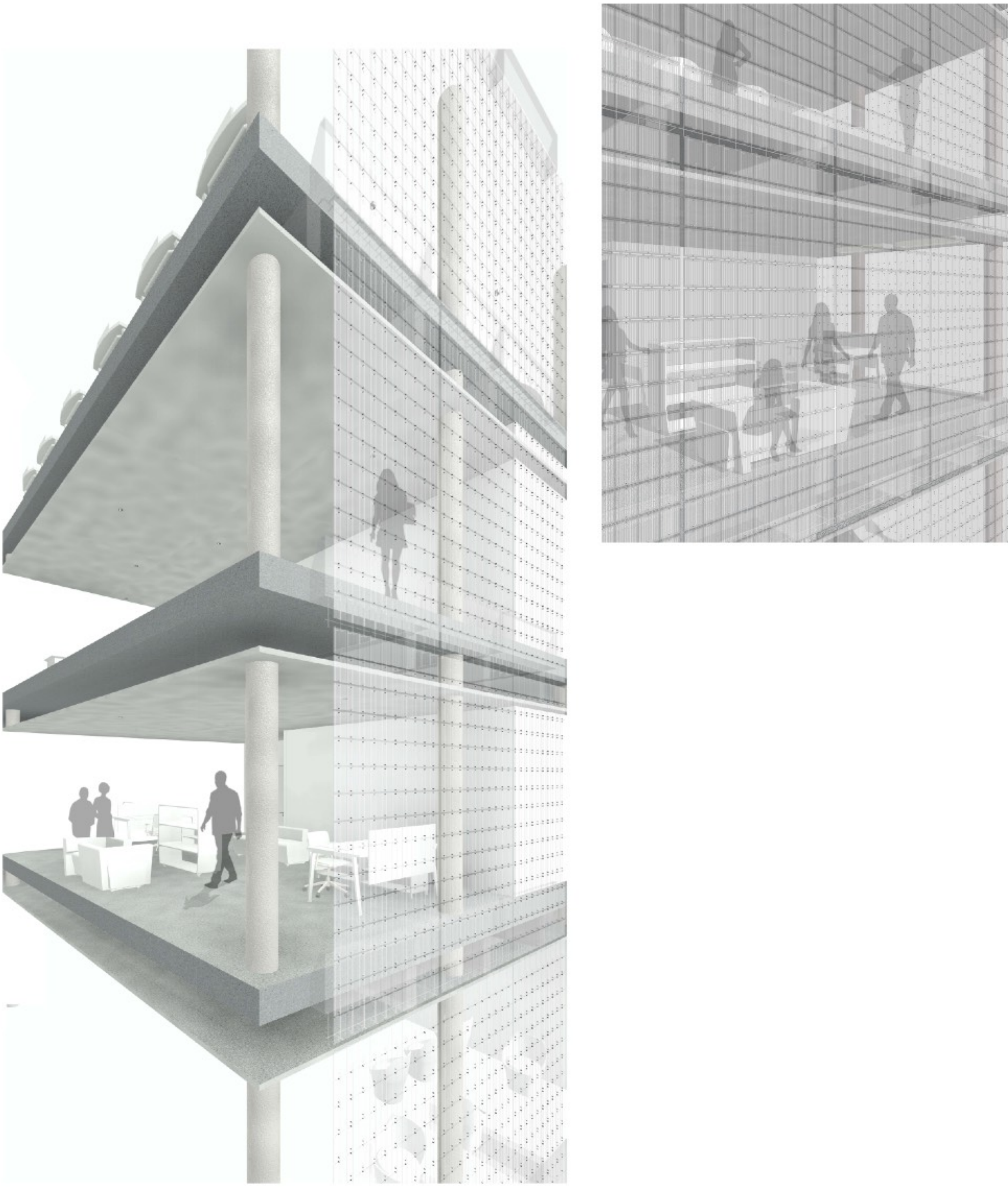


Figure 8.6 Maximum Absorptivity in relationship to High Solar Radiation.

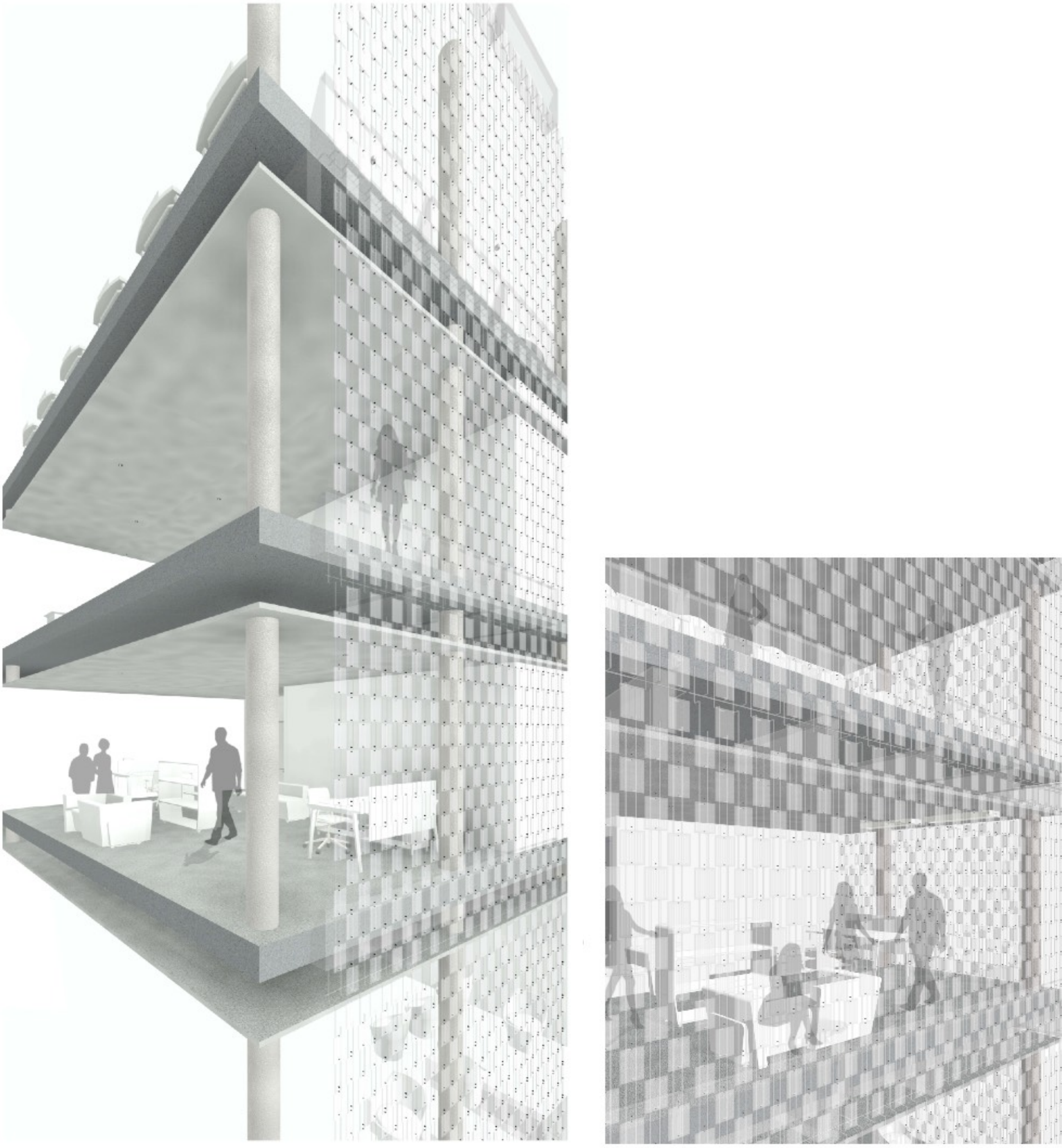
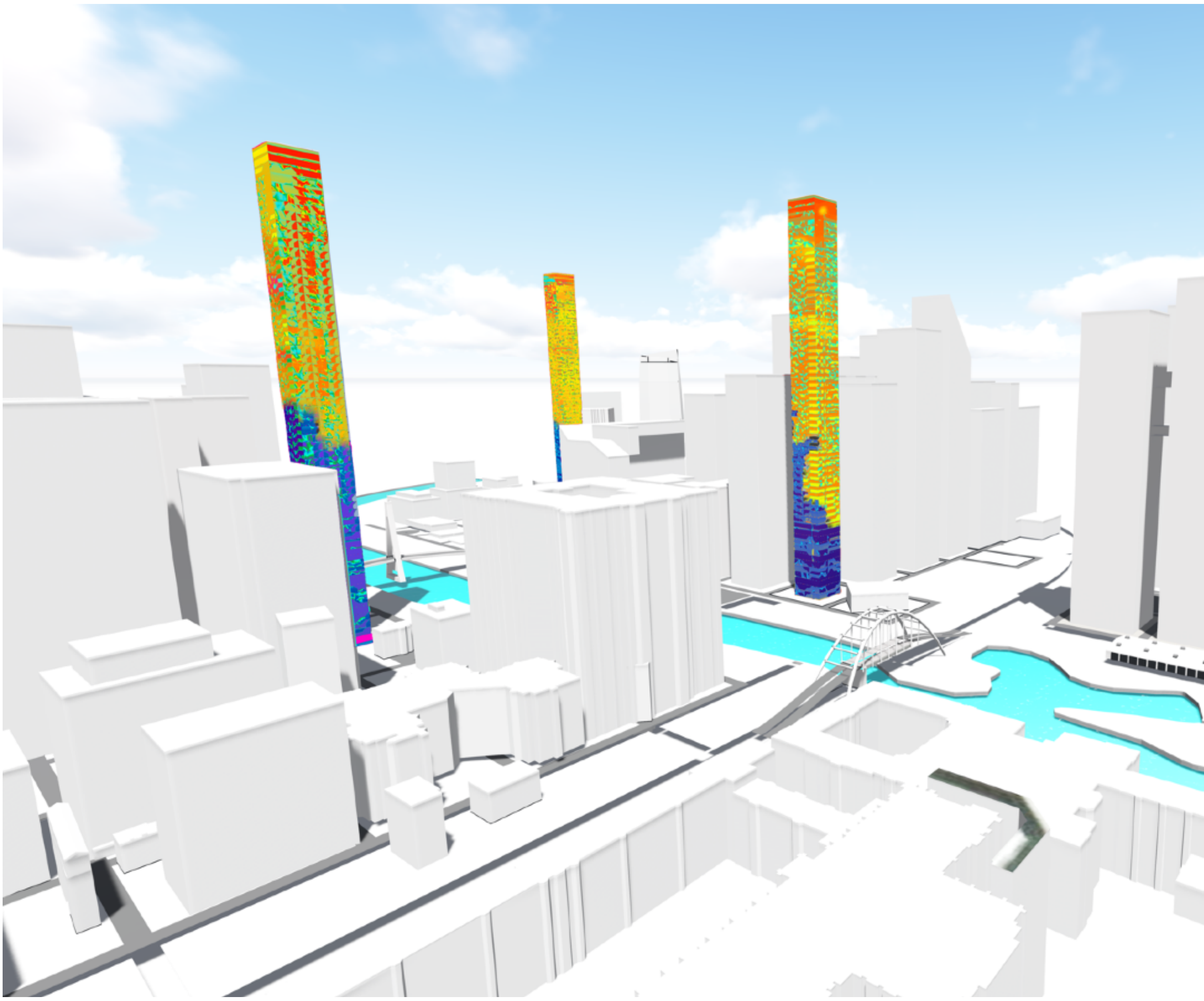


Figure 8.7 Geometry Density of the Network will change in relationship to Solar Radiation Intensity

Present envelope glazing systems depend on reducing the g-value with solar radiation shading, for minimizing internal thermal load transmission. However, these component systems cannot adapt to changing environmental conditions, as they are designed to static boundaries as determined by U-value. These performance modes must change their role from a static element to an dynamic façade. Climatic global warming requires performance change by the hour, season and weather conditions. Nature has developed functional materials of complex hierarchy to regulate thermal conductance by vasculature formations using chemical fluid for absorptivity.

8.10.2 Solar Absorbing Fluid

A designer fluid approach for a heat transport carrier fluid could create varying action and reaction chemical trigger in responses to NIR. If the heat carrier fluid chemical compounds contained photosensitive molecules, this would generate changing patterns of colour in response to interface heat transport within the microvascular network. Synthesizing a nanofluid with absorbing chemical dye pigments fluidics, enable chemical colour trigger response to NIR for the creation of a myriad of changing colour patterning. This visual effects of thermal conductance of interface heat transport will be displayed in colour, by the influence of irradiance, building surface geometry, orientation and city core temperatures, figure 8.8.



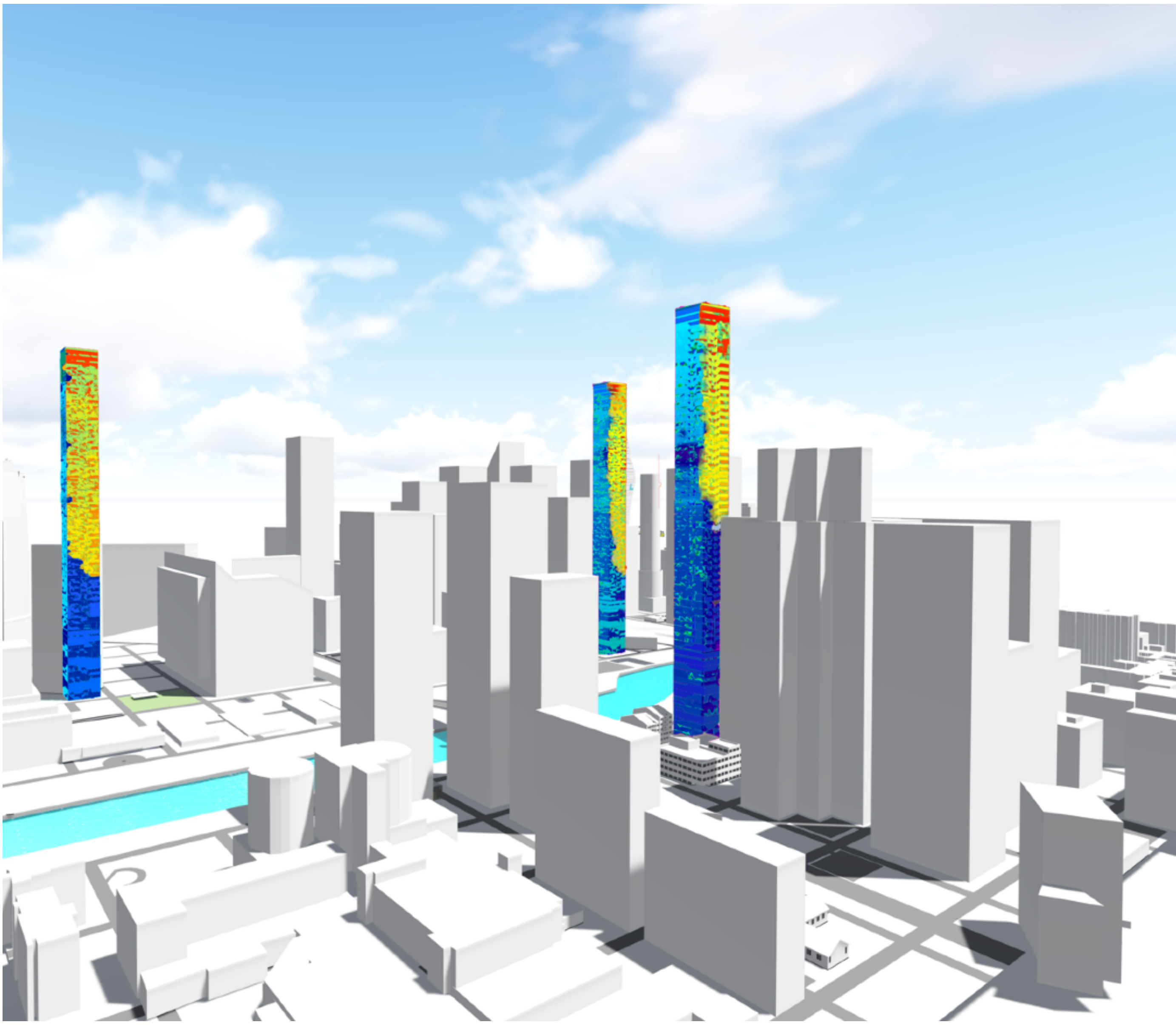


Figure 8.8 Photosynthetic Fluid Envelope

Greater demands have been placed to minimize operational building energy use by maximizing generated energy and day lighting that are integrated within the building envelope. A thermally functional polymer will advance these aims as a permanent IR absorber, to adapt to changing environmental conditions. To enable transition temperature decrease as a heat flow cycle, for regulation of thermal interface transport exchange to material regions. This thermal management may also enable dehumidification of transparent façades by convective cooling by air to external surfaces. This is a dynamic heat seeking system to progress current static façade to a thermally functional adaptive layer. The integration of artificial microfluidic networks of solar absorbing fluid in active flow is a new methodology.

8.10 Conclusion of Method

Reductions of greenhouse gas emissions are a pan global aim through minimized operational building energy use and maximization of generated energy. Building envelopes play a major role in operational energy consumption as they define the boundary conditions between climate and thermal comfort within buildings. Glazed façade performance is viewed as an uncontrolled load that sets the operational performance requirements for air cooling and heating mechanical plant that demands energy. These envelopes remain energetic weak to deliver higher U value and minimize effective power outputs.

This research presents a bridge to close the knowledge gap that is step change to advance transparent materials that is an energy capture and storage system. This characterization of a material to lower its phase transition temperature by thermal switching will enhance solar energy modulation. The morphogenesis of leaf vasculature sets an underlying process of flow distribution, pressure, fluidic transport and resistance. This notion of precise hydrodynamic control of microfluidics will progress thermal material characterization to advance a polymer device, into a switchable IR absorber. This is achieved by hierarchical succession of branching sequence patterns that conform to rules of minimum effective power flow rates in the transportation of fluidics within fractal networks. That is defined through pressure equalization in diminishing flow pressure variation and mass flow rate to enhance unified thermal load capture by fluidics.

The summary is considered the key learning and proof of principle results from the experiment as carried out, the heating effects of the two polymer panes as a thermal switchable solar IR absorber is defined by water flow. The abstract learning is, switchability IR absorber is achieved by switching of water flow by modulating volumetric flow rates, to manipulate energy capture and storage functions. These approaches will ultimately lead to the desired morphology of a dynamic thermal function polymer using precision hydrodynamic flows. A biological system of leaf vasculature sets an underlying process to advance heat seeking targeting transparent materials. Through planar extensional flow generated in cross sectional network matrix geometry to advance and develop a novel system for materials acting as an IR radiation stop-band with the ability in harvesting thermal energy. By the control processing of a functional transparent material to direct the structural assembly as a microfluidic platform for desired thermal flow characterizations. The discussion and findings that are presented in Chapters 5, 6,, 7 and 8, have been published in Nature Scientific Reports in 2016.

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