CFD model-based natural ventilation control – the possibility, strategies, and potential

Y. Zhang[1], Y. Ji [1]

[1]Institute of Energy and Sustainable Development, De Montfort University, The Gateway, Leicester, LE1 9BH, United Kingdom

Corresponding email: YiZhang@DMU.AC.UK

SUMMARY

This paper investigates the potential of CFD-based control strategies. The simple model of an open-plan office is used to demonstrate the case for buoyancy combined wind-driven natural ventilation. Three control strategies are compared: a feed-forward control based on the steady-state analysis of the ventilated space; a feedback control with arbitrary control rules; and a transient CFD model-based predictive control strategy. The simulation results show that: (1) owing to the non-linearity of the system, feed-forward control strategy that uses stead-state simulation results as references may lead to significant control errors; (2) Although even with simple arbitrary rules, the feedback control can deliver slightly better results than the feed-forward control, the scope of improvement is limited and would become more and more difficult to achieve with the increase of complexity of real buildings; (3) model-based control strategy is the preferred solution, especially when means are available for accurate wind speed prediction. The potentials and barriers for the application of online model-based control and the necessary future development are discussed in the final part of the paper.

INTRODUCTION

CFD has been widely used in the design of naturally ventilated buildings. Research on the behavior of both buoyancy-driven and wind-driven natural ventilation buildings have been reported [3][4][5][7]. Unlike mechanical ventilation systems, the behavior of natural ventilation systems is much less predictable. The air movement in the naturally ventilated space is significantly affected by the ambient and the internal conditions. The importance of dynamic thermal simulation with CFD has been stressed by many authors. Efforts have been put in integrating CFD with dynamic thermal modeling for buildings [6][10]. Novel efficient transient solution methods have been developed to enhance the computational performance of dynamic thermal CFD simulation [8] [10]. Such developments are critical to the advance of dynamic CFD applications in both design and operations of naturally ventilated buildings.

In both buoyancy-driven and wind-driven natural ventilation buildings, the driving forces are subject to stochastic fluctuations. Also, due to the generally lower air velocity, longer response time to a control action is expected. These make the naturally ventilated systems harder to control than the mechanical systems. A number of studies using CFD to validate the design of control strategies for the ventilation systems have been reported. Zerihun Desta and colleagues reported the off-line application of CFD in the development of the controller model for a mechanically ventilated space [9]. The study showed the potential of model-based control strategy in such application.

Model-based predictive control strategies has been developed and applied in building systems [11]. However, it is hard to find any on-line application of CFD models for the purpose of operation of the building system. The restraint has been obvious – the (lack of) computing power. In this paper, we use a much simplified CFD model for an open-plan office to evaluate the performance of traditional feed-forward and feedback controls and a model-based strategy. The aim is to demonstrate to potential benefit of online CFD model-based predictive control, and also discuss the requirement and restraints of such applications.

WIND-DRIVEN NATURAL VENTILATION

The case considered in this paper is buoyancy combined with wind driven airflow in a simple two-dimensional building structure (Figure 1). The ventilation openings are arranged to enable the wind driving force assisting the thermal buoyancy by locating the windward openings at low level and the leeward opening at high level. The test room is situated in a large field, which will perform the same way like a wind tunnel. The windward opening size can be updated automatically during the CFD calculation in order to justify the optimization of the control. Two obstructions with 1.2m heights in a row within the test room are used to represent office baffles. The heat input of the test room is from the floor except the part between the windward opening and the first obstruction.

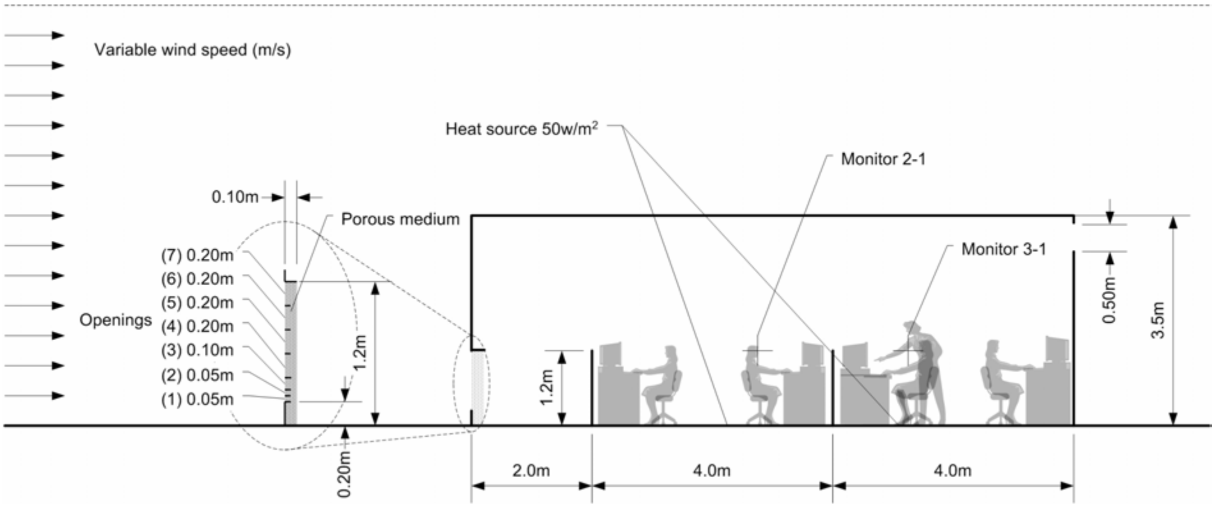

Figure 1. Simplified 2-D model of an open-plan office

The CFD modeling

The commercial CFD code CFX [1] was used to model airflow and heat transfer in this work. This package employs a coupled, multiple element (hex, tet, wedge and pyramid) and fully implicit solver using finite volume method. Primitive variables (velocity, pressure, enthalpy, etc) are defined at nodes at the corners of each element. Conservation equations are obtained by integration over the elements, creating arbitrary polyhedral control volumes about each node. The solver assembles one big matrix for the entire set of hydrodynamic equations (mass and momentum) and solves them simultaneously.

The airflow inside the test room is the combination of natural and forced convection, and the estimated Rayleigh number is above 1010. The nature of the airflow can be treated as turbulent therefore a turbulence model is needed. For natural ventilation modeling, two-equation RANS turbulence models are generally applicable because these models can compromise the accuracy and the computing cost compared with other sophisticated turbulence modeling such as large eddy simulation [2]. In this work the shear stress transport (SST) k-omega based model was used to conduct the CFD simulation. In SST model the turbulence shear stress is accounted by a transport equation, which offers high accuracy in the prediction of the flow separation under adverse pressure gradients.

The boundary conditions used are adiabatic walls, walls with a constant heat flux, openings, inlets and symmetries. The boundaries of the computing domain are the edges of the far field. At the air intake location of the testing room it is not possible to explicitly set a loss coefficient (f) to account the volume flow reduction due to sharp edges. Here, porous media were used to represent the losses. For a sharp-edged opening within a flow domain, the pressure losses ΔP across an opening due to airflow can be defined by the loss coefficient (f), density (ρ) and normal component of velocity (U_n) using the following form:

$$\Delta P = \frac{1}{2} f \rho U_n^2 , \qquad (1)$$

Where the loss coefficient f is related to the discharge coefficient of an opening as follows:

$$f = \frac{1}{C_d^2} , \qquad (2)$$

The specified losses in the porous media are the isotropic resistance K_s , which is a constant defined by the loss coefficient and the porous medium thickness δ :

$$K_s = f / \delta \ (\mathrm{m}^{-1}), \qquad (3)$$

Both steady and transient simulations were conducted. For steady state, physical timescale of 1s and high-resolution advection scheme were used to manage convergence; while for transient simulation, a timescale of 5s with 50 inner loop iterations were used. The timescale could be increased if the convergence criteria were achieved within 2 or 3 inner loop iterations. For both simulation types, the criteria used for judging convergence are: i) all the RMS Residuals are lower than 10^{-4}; and ii) the global domain imbalances for Energy equations in both fluid and solid domains are less than 0.5%.

Steady state simulation

Steady state simulations were carried out to study the impact of the ambient wind speed and the opening size on the indoor flow field. A matrix of 10 different opening settings by 10 wind speeds has been simulated, and the results are shown in Figure 2 and 3.

It is noticeable that when the ambient wind speed is lower than 3.0m/s, the temperatures measured at the monitor points in the two occupied zones divided by the baffles show little definitive correlation to the size of the opening. Also from Figure 3, the changes of the temperatures in the two zones follow different patterns. This is understood as a result of the switch of flow patterns in the entire indoor space.

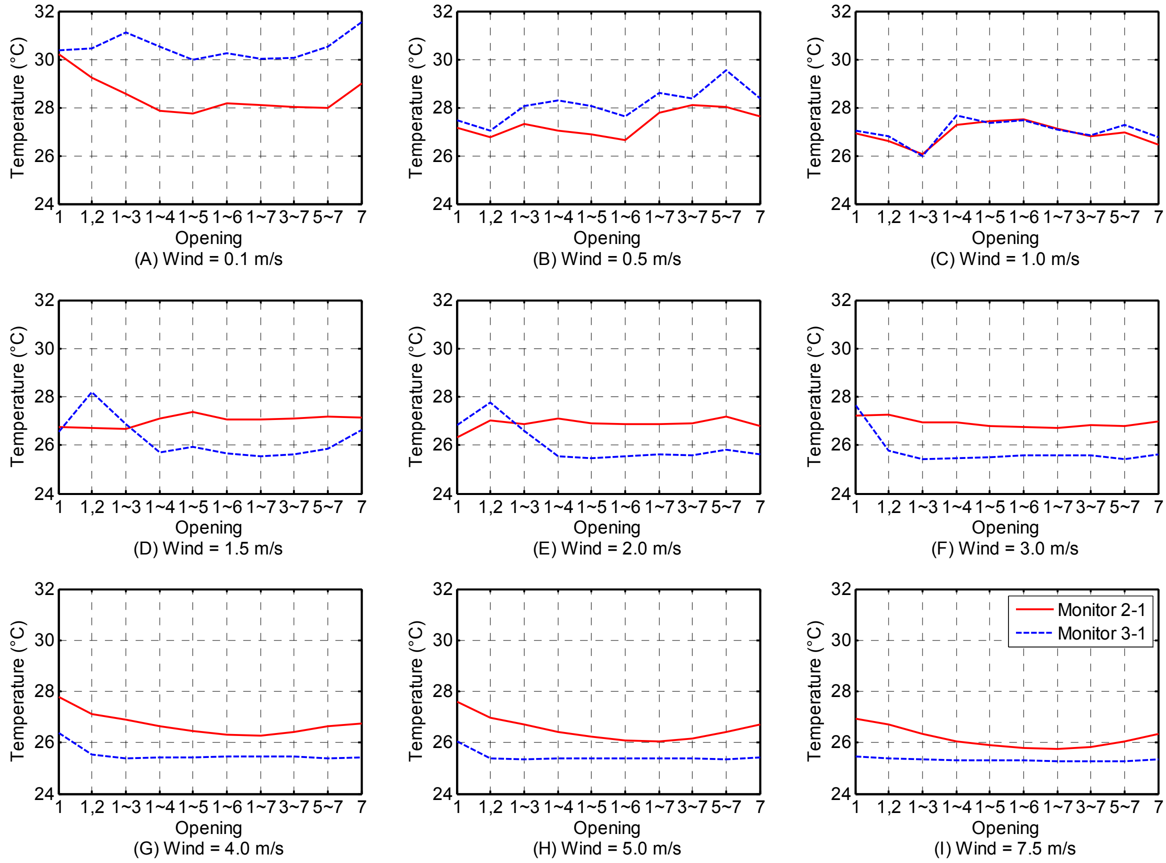

Figure 2. Temperature profiles at Monitors 2-1 and 3-1 with different openings

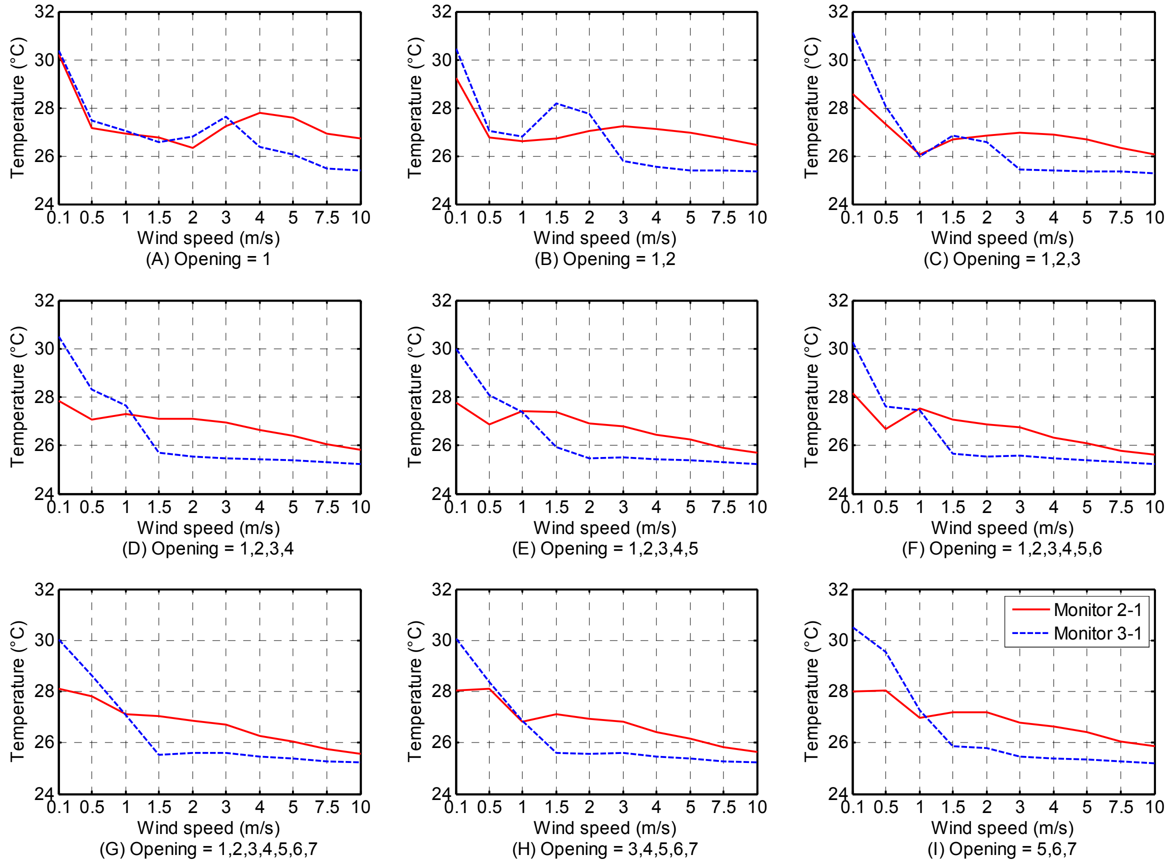

Figure 3. Temperature profiles at Monitors 2-1 and 3-1 with different wind speed

Thermal response to ambient wind speed

In order to demonstrate the non-linearity of the system, a transient simulation was conducted with a fixed opening of 1, 2 and 3 (0.2m wide). The ambient wind speed increased from 0.1 m/s to 6.1 m/s at a rate of 0.4 ms^{-1}/min. Instead of decreasing constantly, the temperature at Monitor 2-1 reached a low point when the wind speed was approximately 1.5m/s, before rebounded to a high level at over 28.3°C (see Figure 4). This signified the instability of the indoor flow field when the driving wind speed is less than 4m/s.

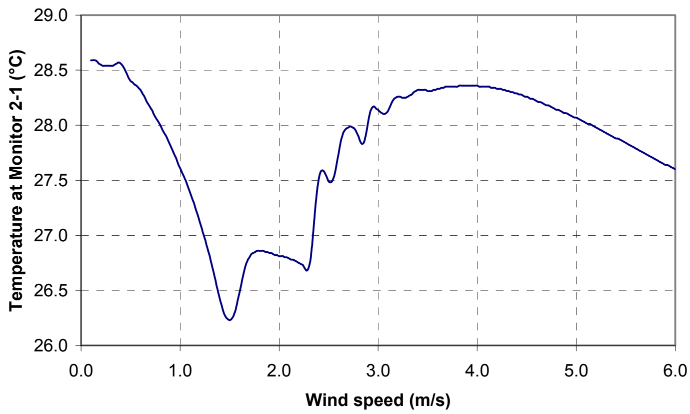

Figure 4. Temperature profile at Monitor 2-1 with steadily increasing wind speed

CONTROL STRATEGIES

The non-linear characteristics and instability of natural ventilation pose a significant challenge to the control and operation of such buildings. A number of control strategies are tested in this study. Firstly, the ventilation of the building with a fixed 0.2m wide opening is simulated with a realistic wind profile for 100 minutes. The temperature at Monitor 2-1 is recorded as a benchmark (see Figure 5).

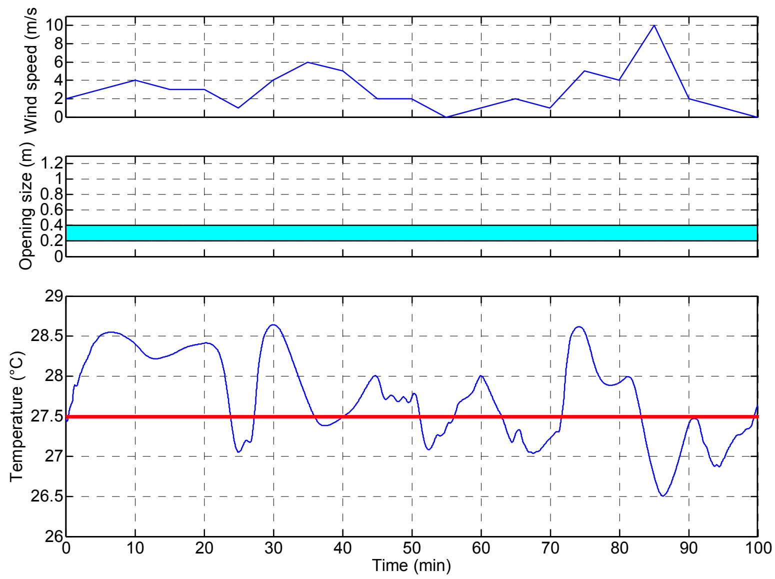

Figure 5. Monitor 2-1 temperatures with fixed opening

Three different control strategies are subsequently tested. These are:

(1) Feed-forward control, which uses the readings of wind speed and a control map derived from the steady state simulation to decide the opening size at each time step.
(2) Feedback control, which, in each control cycle, adjusts the opening size according to the present and historical temperatures at the monitor point.
(3) Model-based predictive control, which utilizes the CFD model, the present state of the system, and the present wind speed reading to evaluate the possible outcomes of control actions, and choose the best option according to the simulation results.

With all three strategies, a control target of maintaining the temperature at Monitor 2-1 at 27.5°C is defined. Also the control cycle is set at 5 minutes.

Feed-forward control

From Figure 2 and 3, it is possible to compose a control map (Table 1) that matches the desired opening sizes with different wind speeds. Such map is subsequently used in the feed-forward control strategy to determine the opening size in each control cycle. The simulation result is shown in Figure 6.

Table 1. Control map based on stead state simulation

Wind speed (m/s)	Openings	Size (m)
0.1	1,2,3,4,5	0.60
0.5	1,2,3	0.20
1	1,2,3,4,5,6	0.80
1.5	1,2,3,4,5	0.60
2	1,2,3,4	0.40
3	1,2	0.10
4	1	0.05
5	1	0.05
7.5	1	0.05
10	1	0.05

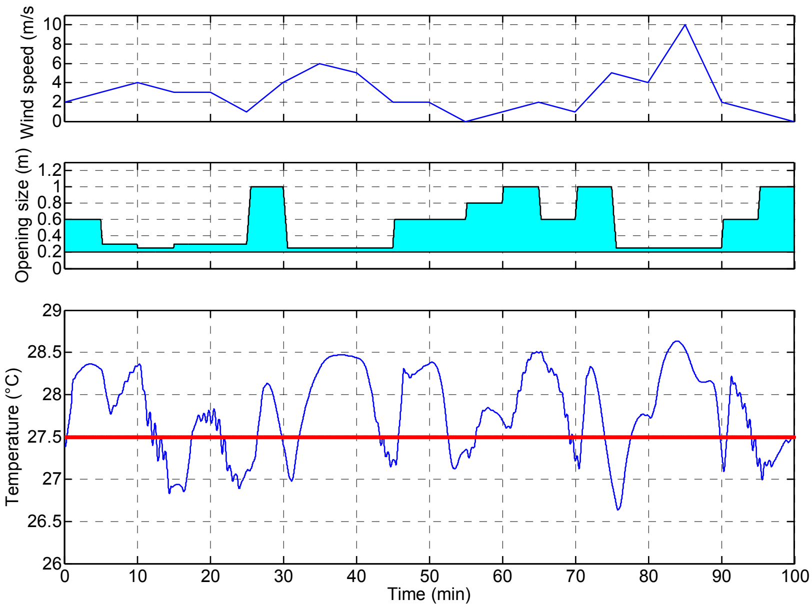

Figure 6. Monitor 2-1 temperature under feed-forward control

Feed-back control

A set of simple rules have been used to adjust the opening size according to the present temperature and the temperature from the previous control cycle at Monitor 2-1. The rules are described in List 1. Simulation results are presented in Figure 7.

List 1. Control rules

Let $Error_t = T_{2-1_t} - 27.5(°C)$ and $Error_{t-1} = T_{2-1_{t-1}} - 27.5(°C)$ to be the present control error and the error at the last time step,

If $Error_t > 0.5°C$ then

- If $Error_{t-1} > Error_t + 0.5°C$ (error decreases) then
  - Keep the present opening
- Else if $Error_{t-1} > Error_t - 0.5°C$ (error persists) then
  - Widen the opening by one step
- Else (error increases significantly) then
  - Widen the opening by two steps

Else if $Error_t < -0.5°C$ then

- If $Error_{t-1} < Error_t - 0.5°C$ (error decreases) then
  - Keep the present opening
- Else if $Error_{t-1} < Error_t + 0.5°C$ (error persists) then
  - Narrow the opening by one step
- Else (error increases significantly) then
  - Narrow the opening by two steps

Otherwise

- Keep the present opening

Done

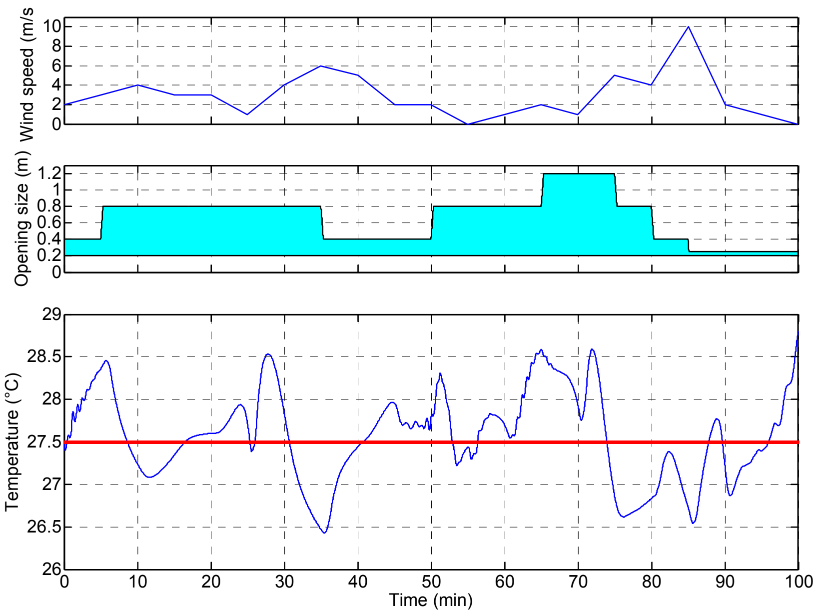

Figure 7. Monitor 2-1 temperature under feedback control

Model-based predictive control (MBPC)

The model-based predictive control strategy uses the model output to assist control decisions. The results of possible scenarios and control actions are simulated with the dynamic CFD model; and the most appropriate action is chosen based on the predefined the criteria – to maintain the temperature at Monitor 2-1 at 27.5°C in this case. It is assumed that, at the beginning of each control cycle, the controller knows the present state of the system, but is unable to predict the change of wind speed in the next 5 minutes. Instead, the controller assumes the wind speed would remain constant during the cycle. From the simulation results shown in Figure 8, it is clear to see that this would cause significant control error when wind speed is changing rapidly (see the time step at 80 min in Figure 8).

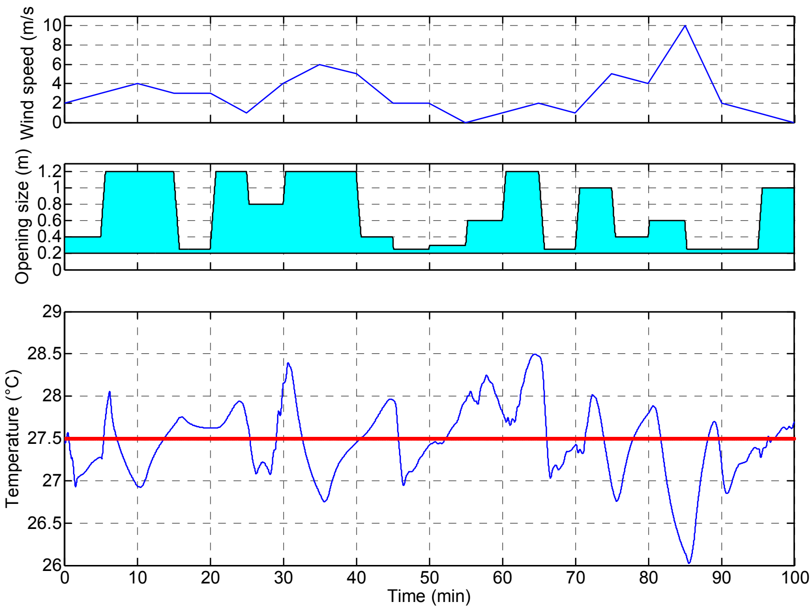

Figure 8. Monitor 2-1 temperature under model-based predictive control

Model-based predictive control with perfect wind speed prediction (Ideal MBPC)

An idealistic model-based predictive controller that is able to correctly predict the wind speed for the present control cycle is simulated. As shown in Figure 9, the performance of the idealistic controller is significantly better than other control strategies described in this paper. Table 3 summarizes the statistics of control errors as a result of different strategies.

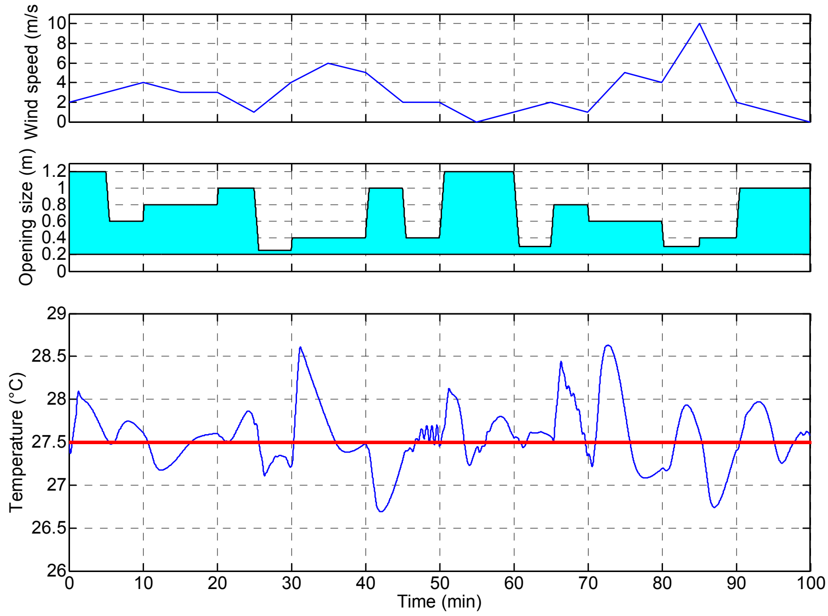

Figure 9. Monitor 2-1 temperature under model-based control and perfect wind speed prediction

Table 2. Summary of controller performance

Control error (°C)	Fixed	Feed-forward	Feed-back	MBPC	Ideal MBPC
$Error_{\mathrm{mean}}$	0.24	0.30	0.08	-0.04	0.07
$\lvert Error\rvert_{\mathrm{mean}}$	0.49	0.54	0.44	0.36	0.30
$Error_{\mathrm{RMS}}$	0.59	0.62	0.55	0.46	0.40
$\lvert Error\rvert_{\mathrm{max}}$	1.15	1.16	1.50	1.61	1.26

Comparing the root mean square errors of the results of different control strategies, it is obvious that the feed-forward control is the least effective option. This is because when the thermal process is involved, the time constant of the system is much larger than the control cycle; therefore the references from steady state analysis give poor accuracy in the estimation of the target flow field. The feedback control is slight better than the uncontrolled benchmark. Admittedly, the control rules applied in the feedback strategy was overly simple and can be further improved. It would be difficult, however, for a control engineer to fully understand the behavior of a realistic building system, (which could be much more complex than the example,) in order to invent the appropriate control logic. The model-based predictive control strategies, especially the one with means of accurate wind prediction, seem to be the better solution.

DISCUSSION

The study presented in this paper used a much simplified 2-D model to simulate the natural ventilation process in open-plan office. Admittedly the simplifications, such as the absence of thermal response of the building structure, contents and occupants, and the fluctuation of ambient temperature and wind direction and so forth, limit the generalization of the results. However, a few conclusions can be reliably drawn from the study.

Firstly, it is proved that the indoor airflow as a result of buoyancy combined with wind-driven natural ventilation is very complex. The dependency of the airflow pattern on the ambient condition, the internal geometry, and the internal thermal load is non-linear and unstable, therefore difficult to predict. This further proves the current approach of using steady state simulation to assist building natural ventilation design could be problematic in certain circumstances. Detailed models, dynamic thermal simulation combined with CFD, and parametric analysis are preferable.

Secondly, the effectiveness of the traditional controllers, such as feed-forward and feedback strategies, depends on the good understanding of the dynamics of the system. A conventional approach or experiences with traditional ventilation systems would unnecessarily deliver desired results. Further research should focus on the dynamics of naturally ventilated buildings. On the other hand, model-based predictive control strategy could be a plausible candidate.

And lastly, computing power has been the major restraint to the extensive application of (dynamic) CFD. With the advances of computing technology, however, this barrier has looked much lower than years before. Using the simple 2-D model, a transient simulation of 30s took proximately 5 minutes on an Intel E6600 processor. Real-time simulation would requite the processor to be 10 times faster, which, according to the Moore's Law, should be achieved with 5 years time. Online CFD-based control will "soon" be both desirable and feasible.

REFERENCES

1. Ansys CFX 2005 version 10, user manual http:// www.ansys.com/products/cfx.asp
2. Chen Q. 1995. "Comparison of different k- models for indoor air flow computations" Numerical Heat Transfer, Part B, 28; pp. 353-369
3. Cook, MJ. Ji, Y. Hunt, GR. 2003. "CFD modeling of natural ventilation: combine wind and buoyancy forces". International Journal of Ventilation, Vol.1(3):169-180
4. Hunt, GR. Linden PF. 2001. "Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind", J. Fluid Mech. Vol. 426:355-386
5. Ji, Y. Cook, MJ. 2007, "Numerical studies of displacement natural ventilation in multi-storey buildings connected to an atrium", Building services engineering Research, Vol.28(2):1-16
6. Li, L. Mak, CM. 2007. "The assessment of the performance of a wind catcher system using computational fluid dynamics" Building and Environment, Vol.42:1135-1141
7. Linden, PF. Lane-Serff, GF. Smeed, DA. 1990. "Emptying filling boxes: the fluid mechanics of natural ventilation", J. Fluid Mech. Vol.212:309-335
8. Somarathne, S. Seymour, M. Kolokotroni, M. 2005. "Dynamic thermal CFD simulation of a typical office by efficient transient solution methods", Building and Environment, Vol.40:887-896
9. Zerihun Desta, T. Janssens, K. Van Brecht, A. Meyers, J. Baelmans, M. Berckmans, D. 2004. "CFD for model-based controller development", Building and Environment, Vol.39:621-633
10. Zhai, Z. 2006. "Application of Computational Fluid Dynamics in Building Design: Aspects and Trends", Indoor and Built Environment, Vol.15(4):305-313
11. Zhang, Y. Hanby, VI. 2006. "Model-Based Control of Renewable Energy Systems in Buildings", HVAC&R Research, Vol.12(3a):577-598