

Next Generation of Consumer Aerosol Valve Design Using Inert Gases

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Abstract

The current global consumer aerosol products such as deodorants, hairsprays, air-fresheners, polish, insecticide, disinfectant are primarily utilised unfriendly environmental propellant of liquefied petroleum gas (LPG) for over three decades. The advantages of the new innovative technology described in this paper are:

- i. no butane or other liquefied hydrocarbon gas;
- ii. compressed air, nitrogen or other safe gas propellant;
- iii. customer acceptable spray quality and consistency during can lifetime;
- iv. conventional cans and filling technology.

Volatile organic compounds and greenhouse gases must be avoided but there are no flashing propellants replacements that would provide the good atomisation and spray reach. On the basis of the energy source for atomising, the only feasible source is inert gas (i.e. compressed air), which improves atomisation by gas bubbles and turbulence inside the atomiser insert of the actuator. This research concentrates on using ‘bubbly flow’ in the valve stem, with injection of compressed gas into the passing flow, thus also generating turbulence. Using a vapour phase tap in conventional aerosol valves allows the propellant gas into the liquid flow upstream of the valve. However, forcing bubbly flow through a valve is not ideal. The novel valves designed here, using compressed gas, thus achieved the following objectives when the correct combination of gas and liquid inlets to the valve, and the type and size of atomiser ‘insert’ were derived:

1. Produced a consistent flow rate and drop size of spray throughout the life of the can, compatible with the current conventional aerosols that use LPG: a new ‘constancy’ parameter is defined and used to this end.
2. Obtained a discharge flow rate suited to the product to be sprayed; typically, between 0.4g/s and 2.5g/s.
3. Attained the spray droplets size suited to the product to be sprayed; typically, between 40mm and 120mm.

Keywords

Aerosol valve, compressed gas, bubbly flow, effervescent, continuous spray

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Introduction

In the field of consumer aerosol can, the replacement of conventional propellants (such as butane) with safe gases such as air and nitrogen (so called compressed gas aerosols) offers a number of technical challenges that have limited their application in the market, despite their environmental advantages:

- i. Insufficient atomisation power, leading to the spray having a large droplet size and inferior spray pattern.
- ii. This becomes noticeable to the consumer, as a ‘wet’ spray, rather than the fine mist that the consumers expect.
- iii. Significant drop off in spray ‘power’ as the can is depleted due to the reduced volume of liquid in the can to be sprayed causing a corresponding decrease in pressure.
- iv. Consumers notice a further reduction in spray performance as well as not having full recovery of the product.

The valve to be designed in this investigation should ideally overcome or reduce both of these problems and this is done by exploiting a phenomenon known as effervescence or ‘bubbly flow’. Bubbly flow comes about when a small proportion of compressed gas within the can is injected directly into the passing flow of product within the valve assembly. Effervescence is the process of various actively introducing gas bubbles into a liquid flow, immediately upstream of the exit orifice, thereby forming a two-phase flow. These are of interest due to their potential for using a small flow of atomising gas to produce a very fine spray [1,2].

Researchers and engineers have studied their use for application including household aerosols [3,4]. The technique has not been applied in commercial aerosols because even at the low value of gas/liquid mass ratio (GLR) (around 1%), can pressures drop too quickly causing the compressed gas in the can to atomise. Also dispensing the gas and liquid simultaneously and producing the required flow, is itself complex. In addition, effervescent atomising prediction for modelling drop size was recently made by researchers on high viscosity material such as gelatinised starch suspension [5–7].

Moreover, Asmuin [6] designed atomiser inserts using inert gases for domestic aerosols, which will be discussed in detail in the next section. All the consumer aerosol valves designed in this investigation can also be used with conventional butane propellants, which were also tested, that were also shown to offer improved performance with regard to their spray characteristics. The word ‘domestic’ and ‘consumer’ has been used throughout this paper interchangeably as normal practice which provides a same connotation. The inventive steps of the corresponding valve designs were initially filed with a number of the interlocking patents [8–12]. The overall aims of this study are to design consumer aerosol valves using inert gas propellants (i.e. compressed gas, nitrogen, etc.) using the concept of ‘bubbly flow’ generated in the conduit in the flow passage upstream of the exit orifices.

Thus, by providing the correct geometry of orifices and mixing chamber, the flow becomes highly energised and turbulent. Specifically, the prime objectives of this investigation are as follows:

- To produce sprays that look, feel, spray and perform like current consumer aerosols
- No use of butane or other liquefied gas propellants (LPG)
- Safe compressed gas propellants (i.e. air, nitrogen, etc.)
- Step-change in performance over current compressed gas technology

- Cover all aerosol formats including bag-on-valve aerosol
- No cost or manufacturing penalties
- Utilised standard components or standard component sizes
- Easy filling and no requirement for vapour phase tap (VPT)
- Constant discharge flow rate through the life of the can
- Drop size constancy through the life of the can
- Good penetration up to 1000mm, through the first pulse of the spray
- Lower dropout through the can life

The novel consumer aerosol valves designed and demonstrated in this study [13] using inert gas such as compressed air, carbon dioxide (CO₂) or nitrogen (N₂) propellants, have been applied to a wide variety of aerosol valve applications so as to be widely applicable in the market. Continuous valves are used in products such as deodorants (e.g. Lynx), hairspray, air-freshener (e.g. Febreze), insecticide and polish and also applicable to high viscosity formulations such as hair removal cream (Veet).

Previous works

There are few and limited published works that are currently available dealing with domestic aerosols using inert gases. However, this section intends to highlight these findings which are related to the atomiser insert design [6,7] and the previous study of Dunne and Weston [14] with respect to the design of continuous valve. In relation to a new atomiser insert design for domestic aerosol valves working with inert gases, Asmuin [6] and Bruby et al. [7] divided the work into two different phases namely, ‘liquid phase’ and ‘two-fluid phase’.

Figure-1 shows the enlarged scale of the atomiser insert that was designed. As it is shown, the atomiser insert includes an expansion chamber which is open at the lower end of the atomiser insert and a orifice channel, which has less diameter than expansion chamber and it extends vertically and facing upward which is parallel therewith to open at the upper end of atomiser insert. There is a right-angled (sharp) edge providing an immediate transition between expansion chamber and orifice channel. Between partitions, there are a number of throttling holes which provides connection within flow channel and the expansion chamber of atomiser insert.

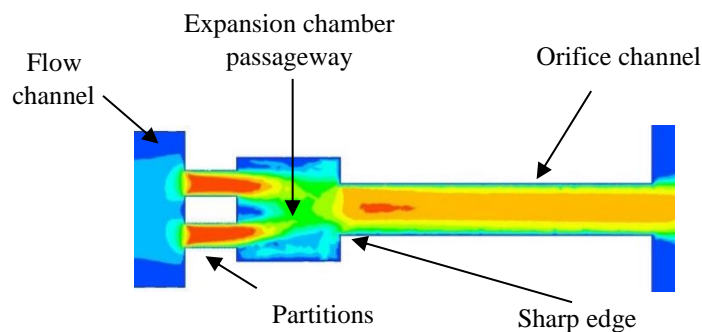


Figure-1: A new atomiser insert

Figure-2 shows the schematic design of valve assembly and the atomiser insert. As shown in this figure, when the actuator is depressed, the stem moves down and compresses the springs. Therefore, the gas inlet is open with respect to displacement from the gasket and the

compressed gas from head space can bleed into the flow channel. At the same time, the liquid inlets are opened by bending the lower gasket so that the liquid can flow into the liquid channel.

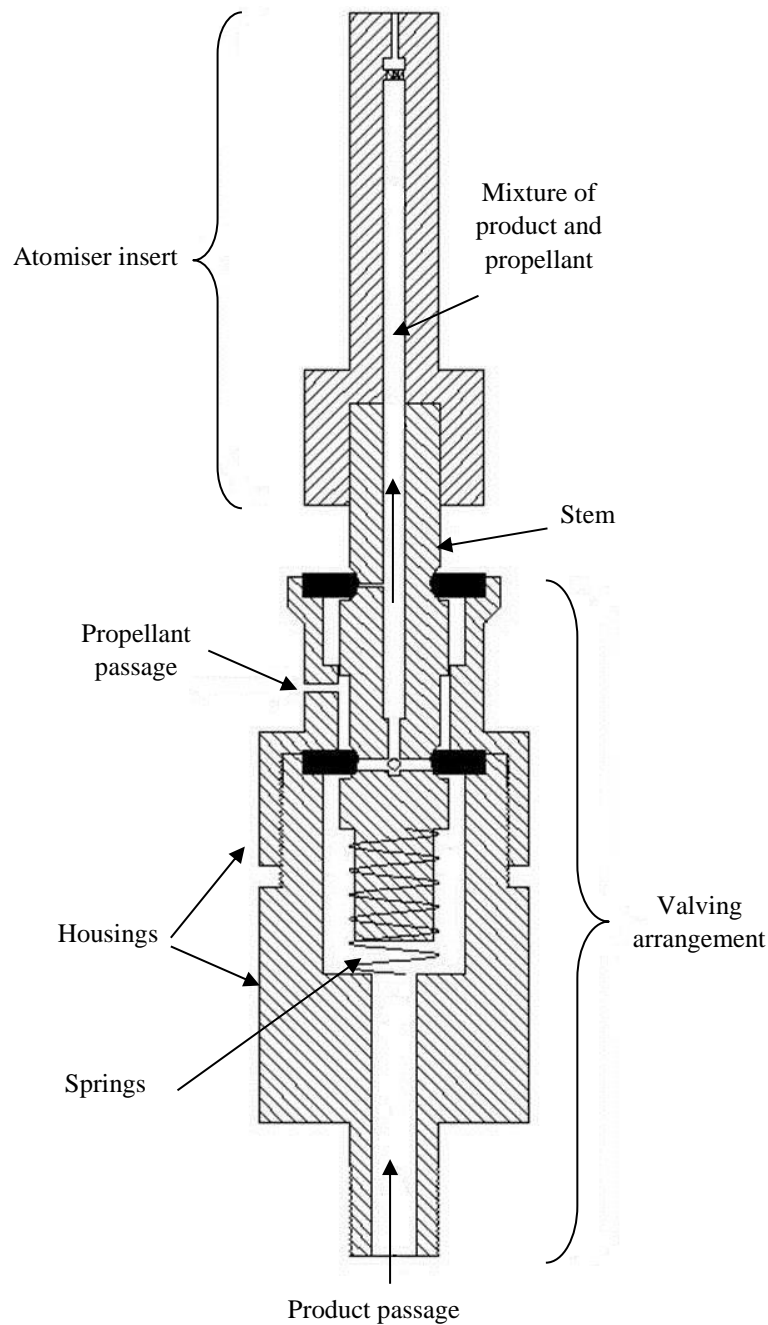


Figure-2: Operation of new atomiser insert

Figure-3 shows the geometry of the atomiser insert and the characteristics of the bubbly flow at the downstream end of the flow channel combine to give a number of turbulent bubble-laden jets impacting the sharp edges. Therefore, when the jets are developed, it makes the fluid (liquid and gas) to travel along the orifice channel and form flow separation from the wall of the first part of orifice. The length of orifice channel is such that the flow re-attaches to the wall at a downstream region thereof. The separation and re-attachment are a highly fluctuating

phenomenon, which is very beneficial to the atomisation into droplets of the jet emerging from the exit of orifice channel.

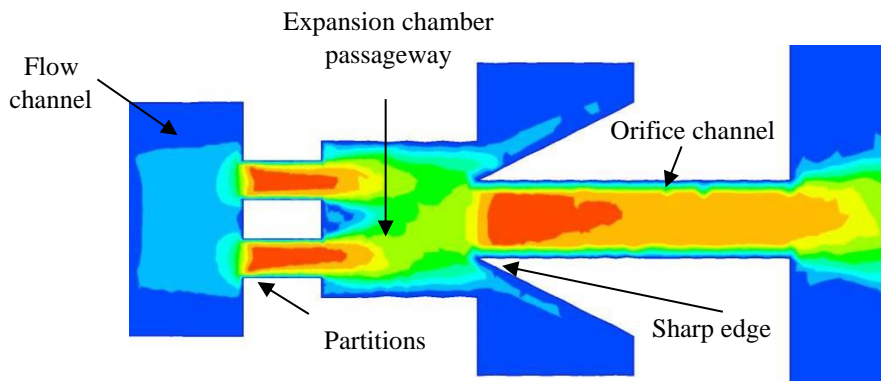


Figure-3: Illustration of modified constructions of spray-generating atomiser inserts

The result from the device is a fine liquid spray. Furthermore, the fluctuations at the exit of expansion chamber passageway provide a different hissing sound, which is considered as ‘attractive’ to users of aerosols since such a sound is expected from current liquefied gas propellant aerosols.

There was also a study on the design of continuous valve using inert gases [14] in 1990 in which the valve was attempted to improve the fineness of sprays generated by an inert gas. The main objective of this design was to bleed the gas into the liquid achieving two-fluid atomisation and thus ‘bubbly flow’ resulting in the increase in liquid breakup and provide fine sprays. Figure-4 shows the ‘flow discharge valve’ which was designed by Dunne et al. in 1990. This valve regulates the flow of a liquid product from an aerosol canister (24), which is pressurised by a permanent gas propellant comprising a tubular valve stem (34) formed with a liquid orifice (36) and a gas orifice (42) leading into a mixing chamber (54).

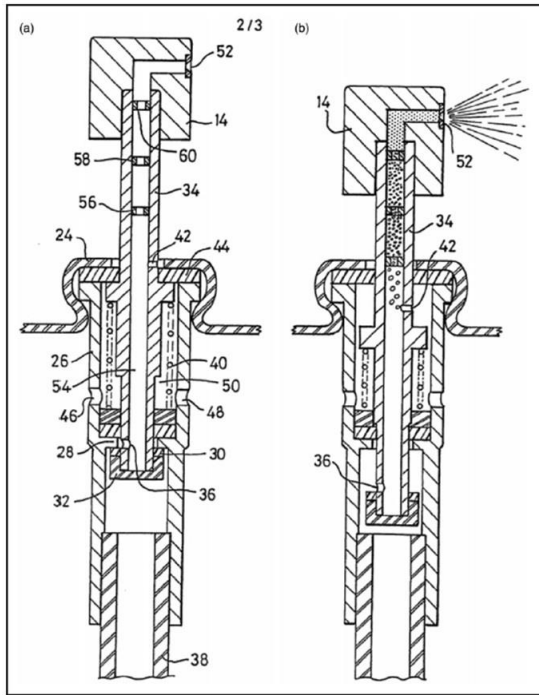


Figure-4: Schematic design of 'flow discharge valve'. (a) closed position and (b) open position

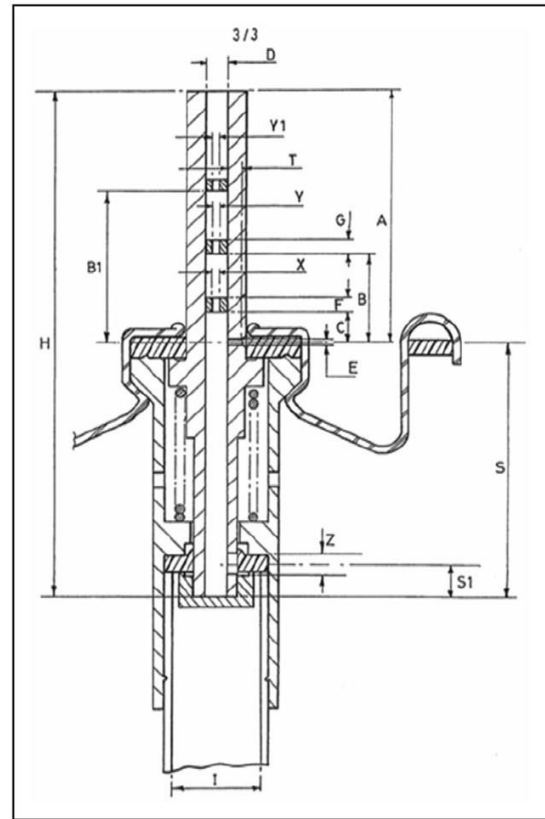


Figure-5: 'Flow discharge valve' with reference character for the dimensions of major parts

Downstream of the chamber is at least one restrictor (56) through which the mixture is forced to pass to produce a choked or sonic flow, which results in the mixture expanding to form a foamy mixture. Although there might be similarity at first sight between the design of Dunne et al. with 'bi-valve' designs (see next Section) used in this investigation, this design is complicated in nature with different dimensions and operating parameters (see Figure-5). Table-1 summarises the design dimensions of this valve.

Table-1: Dimension sizes of major parts of 'flow discharge valve' [14]

Dimensions (mm)	Dunne et al.'s 'flow discharge valve' range
B	8 – 25
B1	12 – 25
C	0 – 25 (preferred size)
D	1 – 3
E	0.10 – 0.25
F	0.5 – 4
G	0.5 – 4
S	10 – 30
S1	3 – 6
T	0.5 – 2
X, Y, Y1	(0.1 x D) – (0.75 x D)
Z	1 – 3

Novel aerosol valve designs

There are various types of domestic aerosol product around the world. Most of these products use continuous flow valves for low viscous products such as water or ethanol. In continuous flow valves as soon as the actuator is depressed, the spray comes out continuously until the actuator is released. In this investigation, two different domestic continuous flow aerosol valves are developed: the ‘bi-valve’ and the ‘single gasket’ [8,9]. The ‘bi-valve’ and ‘single gasket’ are developed to be mainly applicable for use on products such as deodorant, hairspray, air-freshener, insecticide and polish which are normally water or ethanol based with up to 1 cP viscosity. Therefore, in this investigation, most of the tests for proof of concepts were done with ethanol or water as liquid products.

Before discussing the new designs, it is appropriate to highlight the previous work carried by Dunne and Weston in 1990 as described above. As shown in Figure-4, their valve was aimed at producing a bubbly flow and then passing the flow through a series of choked orifices, with the objective of producing finer bubbles and, it was argued, finer sprays. In the following section, some comparisons are given between the present ‘bi-valve’ geometry and their designs. In particular, it was considered that the severe flow blockage introduced by Dunne et al.’s [14] designs would provide unacceptable low flow rates unless greater can pressures than those in current use are used and, so, the first valves designed and tested had similarities with the Dunne et al.’s valves but without the choked orifices. Moreover, their design has some restrictors in the liquid channel to provide:

- i. Conveying the liquid (first passage) under gas pressure to a mixing region
- ii. Conveying the pressurised gas (second passage) separately from the liquid into the mixing region
- iii. At least one restrictor is located between the mixing region and the exit orifice to force the mixture of liquid and gas to pass.

‘Bi-valve’

This section provides the various novel designs of the next generation of domestic aerosol valves using inert gases as a propellant. Figure-6 shows the initial design of the new domestic aerosol valve known as the ‘bivalve’. As is shown, with depressing the stem downward, the two identical gaskets, which are located in the grooves on the stem, bend because of the actuator force.

Therefore, the liquid hole and gas hole are revealed and the fluids mix in the mixing chamber to generate ‘bubbly flow’. Liquid comes through the dip tube, which is located at the upstream end of the housing and therefore the housing is always filled with liquid. When the stem is depressed, the liquid inside the housing can pass through the liquid holes on the stem. Gas enters the housing space through the gas hole which is drilled into the housing. When the stem is in an open position, gas is injected into the fluid flow through the gas hole on the stem. In this development design, the housing has two separate parts which are assembled together to hold the bottom gasket in place and seal the liquid holes when the stem is in rest position, as shown in Figure-6.

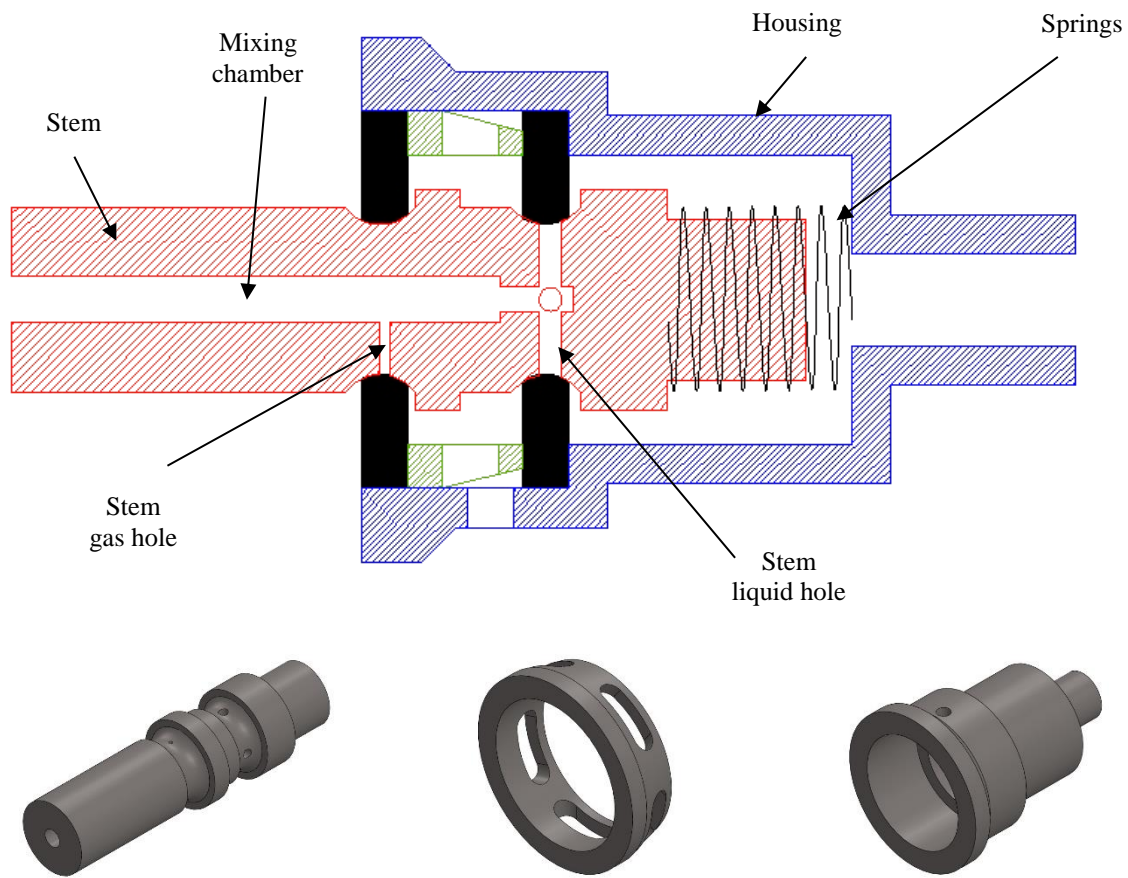


Figure-6: Prototype design of new domestic aerosol valve called ‘bi-valve’

The gaskets used are those available commercially for existing conventional aerosol valves and the upper outside shape of the housing was designed for crimping within the ‘one inch’ metal cups that are most common for conventional consumer aerosol valves. There might be similarity at first glance between the design of Dunne et al.’s shown in Figure-5 and the ‘bivalve’ design which were used in present investigation, but their design is more complicated with regards to the different dimensions and the operating parameters when compared to the ‘bi-valve’. Table-2 summarises and compares the design dimensions of these valves. It is noted that the geometrical parameter range indicated in this table was extended further for the further valve developments described earlier in previous works. As shown in Figure-5, the Dunne et al. design has at least one restrictor in the liquid channel to provide orifices as sonic conditions were proposed for the bubbly flow with the aim of reducing bubble size, thus reducing drop size.

Table-2: Dimension sizes of major parts of ‘flow discharge valve’ [14]

Dimensions (mm)	Dunne et al.’s ‘flow discharge valve’ range	New domestic aerosol valve ‘bi-valve’ range
B	8 – 25	N/A
B1	12 – 25	N/A
C	0 – 25 (preferred size)	N/A
D (mixing chamber)	1 – 3	1
E (gas inlet)	0.10 – 0.25	0.20 – 0.40
F	0.5 – 4	N/A
G	0.5 – 4	N/A
I	1 – 7	2
S	10 – 30	15 – 31
S1	3 – 6	11.5 – 22
T	0.5 – 2	1.5
X, Y, Y1	(0.1 x D) – (0.75 x D)	N/A
Z (liquid inlet)	1 – 3	0.3 – 0.7

The author, as described previously (see ‘previous work’ section), observed that interfering with the bubbly flow in a chamber once set up gave excessive pressure drop worsening the drop size and greatly reducing the flow rate. Thus, the ‘bi-valve’ design was developed to minimise interference with the bubbly flow once set up. Also, the valve designed by Dunne et al. works with 5:1 volumetric ratio of gas to liquid, but the new domestic aerosol valve presented in this investigation is developed to operate with around 3:1 volumetric ratio of gas to liquid, or less, to avoid excessive reduction of can pressure during aerosol lifetime. Although up to 9:1 volumetric ratio has been achieved. By adopting the design process noted at the beginning of this section, a number of design iterations were conducted as the experimental measurement programme described in the next section progressed. These were machined and subsequently tested with the aim of achieving the following prime objectives:

- i. Liquid product flow rates and drop sizes commensurate with those acceptable for a representative range of products, e.g. deodorants, airfresheners and polishes
- ii. Low pressure drop through the pack life of the can (i.e. controlling bleeding of atomising gas to the necessary minimum for satisfactory atomisation and ensuring sufficient gas to completely evacuate the can of product)
- iii. Relatively constant discharge flow rate through the pack life of the can (compared with current compressed gas consumer aerosols)
- iv. Relatively constant drop size through the pack life of the can

Super single gasket

The developed form of the ‘bi-valve’ assembly as described in the previous section has overall five different parts namely, stem, housing, two identical gaskets, spacer (which separates the gaskets). This is apart from the springs, dip tube, mounting valve cup and mounting cup gasket, which are common to all aerosol valves. However, the simplest conventional domestic aerosol valve has three parts which are stem, housing and gasket where the manufacturing cost of the ‘bi-valve’ is more expensive. Therefore, new design referred to as ‘super single gasket (SSG)’ valve designs were developed to give the required ‘bubbly flow’ generation whilst reducing the manufacturing cost. Figure-7 shows the SSG valve assembly which has only one gasket, and when the stem is moved downward to produce spray, the liquid hole should pass the ridge whilst the gas hole is still above the ridge. It is noted that the ridge does not need to be a perfect

tight seal but rather is a sliding fit. This is because the gas pressure above and the liquid pressure below the ridge are nearly equal.

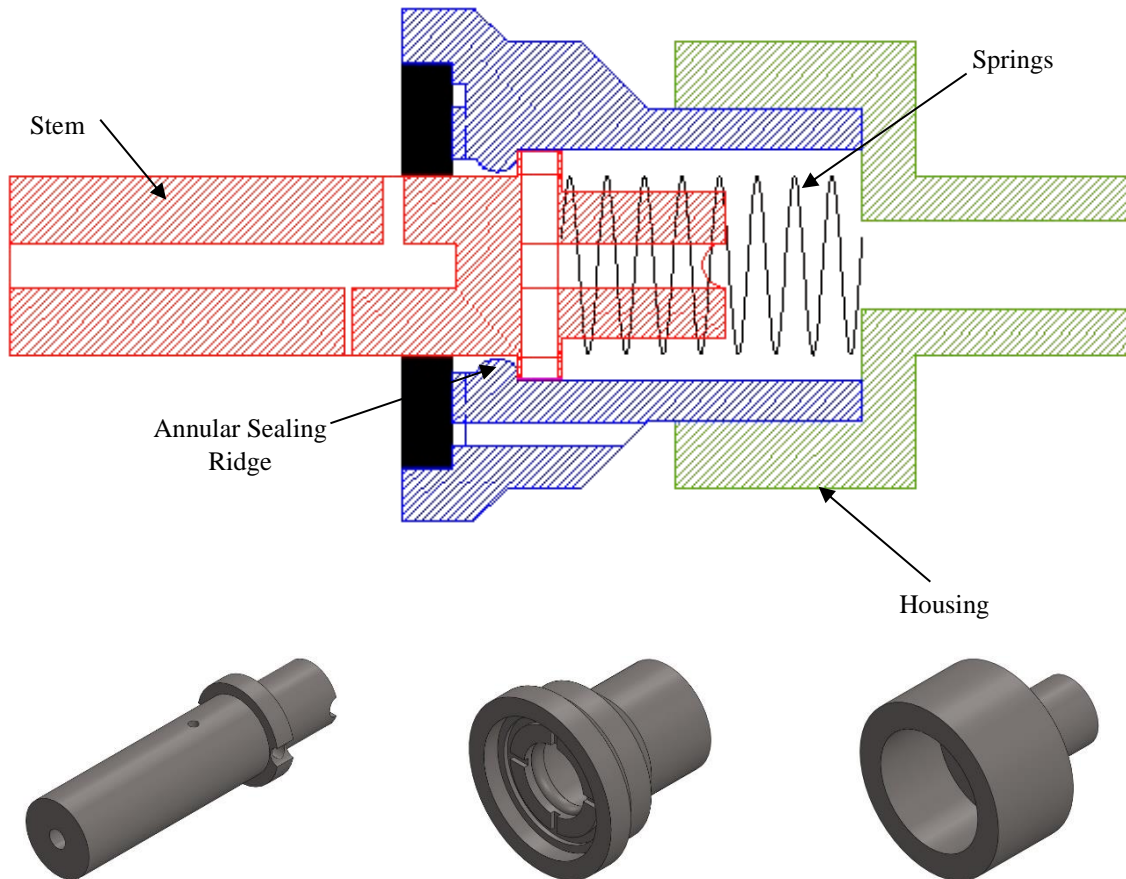


Figure-7: Schematic diagram of prototype design of 'super single gasket'

Apparatus and methods of data processing

This section generally discusses all experimental apparatus used and the test procedures that they were used in. In this section, there is also a short overview of the previous journal paper [7] in the author's laboratory that was related to designing and selecting the inserts for inert gases (i.e. compressed air). The apparatus and methodology were divided into that for studying steady flow sprays and that for studying realistic spray 'pulses' from cans or reservoirs representing cans. The author's work used almost entirely unsteady sprays from conventional metal aerosol cans, a special commercially available glass pressurised reservoir and also a specially constructed brass reservoir (or 'brass can'). However, the steady spray flow control system, first developed and described by Burby et al. [7] was also used for some tests and it was also a convenient means for filling the cans with both gas and liquid.

Steady flow control board

The steady spray experimental apparatus was designed to investigate a variety of aerosol atomiser insert designs [7] both for 'liquid only' and 'two-fluid' atomisation using a flow control board, which could independently control both gas and liquid pressures and flow rates

to the atomiser insert designs. Compressed air and water were generally used, and the following data were acquired:

- i. Droplet size
- ii. Mass flow rate
- iii. Cone angle

In designing the steady spray experimental apparatus, the following was taken into consideration:

- i. A sufficient supply of compressed air to provide the required mass flow rate through the atomiser insert;
- ii. An ability to control the water and air supplies independently to the atomiser insert;
- iii. A suitable mounting for the aerosol console and associated apparatus;
- iv. The laser machine was chosen for measuring the droplet size and distribution as it is a nonintrusive technique that is generally used in the consumer aerosol industry

The most promising designs found using the steady flow system were then characterised using the ‘brass can’, described to simulate real transient can conditions (see next Section). And as described below, ‘real’ aerosol cans were then used with the valves and inserts crimped into them.

Flow control system: Figure-8 shows the flow control system which comprises: a reservoir (2) partly filled with deionised water and pressurised to 12bar (maximum) by using the regulator on a standard 200bar compressed air in gas bottle (1) through 4mm bore nylon tube (11). The pressurised liquid is supplied to the can or atomiser insert (3) via 4mm bore nylon tube (12). A rotameter was used for liquid flow rate and an electronic pressure gauge (4) was used to measure supply pressure while two rotameters (5) were used to measure and control flow rate via a needle valve (6). An electronic pressure gauge (gas) (7) and pressure gauge (gas) (8) were used to measure supply pressure. An electronic flow meter (gas) (9) and rotameter for gas (10) were used to measure supply gas flow rate to the atomiser insert.

Experimental apparatus for unsteady flow Valve mounting. There were three different types of reservoir for mounting valves, which were used in this investigation. First of all, a ‘brass can’ was used to do most of the initial test trials to find out the valve performances. The brass can could be used either with valves crimped in standard aerosol cups, or with uncrimped valves in some cases. This system could be conveniently utilised at relatively high pressure (up to 14 bar) but was inconvenient to handle and could not be used for measuring liquid flow rate, versus can emptying, by using the technique of weighting the can at intervals.

Figure-9 shows the ‘brass can’ which was used for mounting the inserts and valves to run some test trials. This was made in the lab to simulate as a real can within 475mL capacity. It can be pressurised up to 14bar maximum from top when the inserts or valve were put into the can. A commercially available glass aerosol research container (the ‘glass can’) then became available for more trials with those valves upholding the interest.

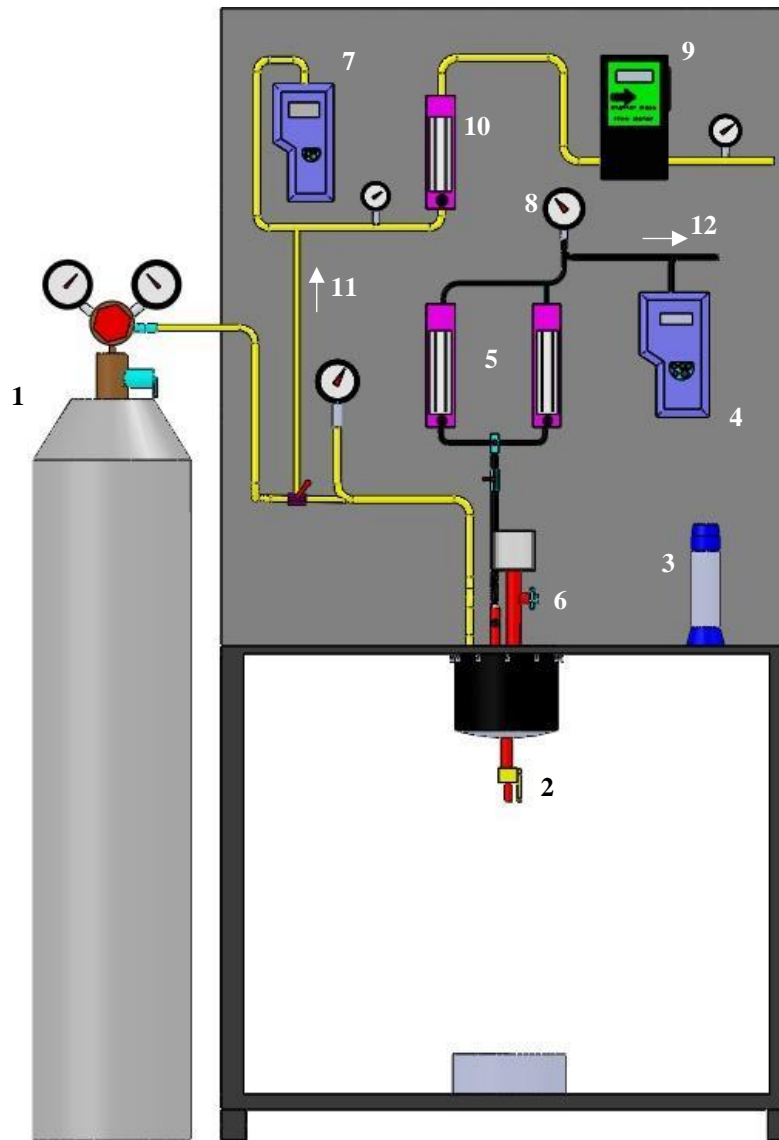


Figure-8: Schematic diagram of the flow control system

This was convenient to use and could be used to measure liquid flow rate by the weighting method. The ‘glass can’ has 100mL volume capacity and it was used to model as a conventional can with pressure up to 10 bar. For the ‘brass can’ and ‘glass can’ many crimped inserts and cup assemblies could easily be used again and again with easy refilling and re-pressurising. In the later stages, commercial aluminium and tinfoil cans (see Figure-9), of various volumes and pressure ratings, were used for testing the valves in real conditions. In these cases, it was found that once a valve was crimped in a cup and onto a can, the valve could not be dismantled for maintenance and cleaning.

Crimping method: To attach aerosol valve components together and into cups, and subsequently into the cans in some cases, a crimping method is used. Collets used in crimping machine expand to push the metal of the valve cup under the curl of the can. The machine comprised filling chamber for propellant and collets for crimping and ‘swaging’ the assembled

valve into a can. Collets move into the mounting cup and spread to a specific diameter and depth.

Filling method: One of the major methods in aerosol filling is the ‘gasser shaker’ in which the can is vacuumed, and the assembled valve is crimped to the can and then the propellant is injected into the can with plain shakes [15,16]. This method was used to fill the can with an inert gas when the assembled valve was used in the aluminium can or tinfoil can, in this investigation. Figure-9 shows the method of filling in this research. The sample can is vacuumed and there is no liquid in the can. The ‘brass can’ is filled with required liquid and is pressurised. When the valve is opened, the liquid into the brass can is pushed into the trial can till the required ratio is gained. Then the valve is closed. Subsequently, the can is pressurised as shown in Figure-9 with an inert gas. Then, the pressure is checked with the pressure gauge.

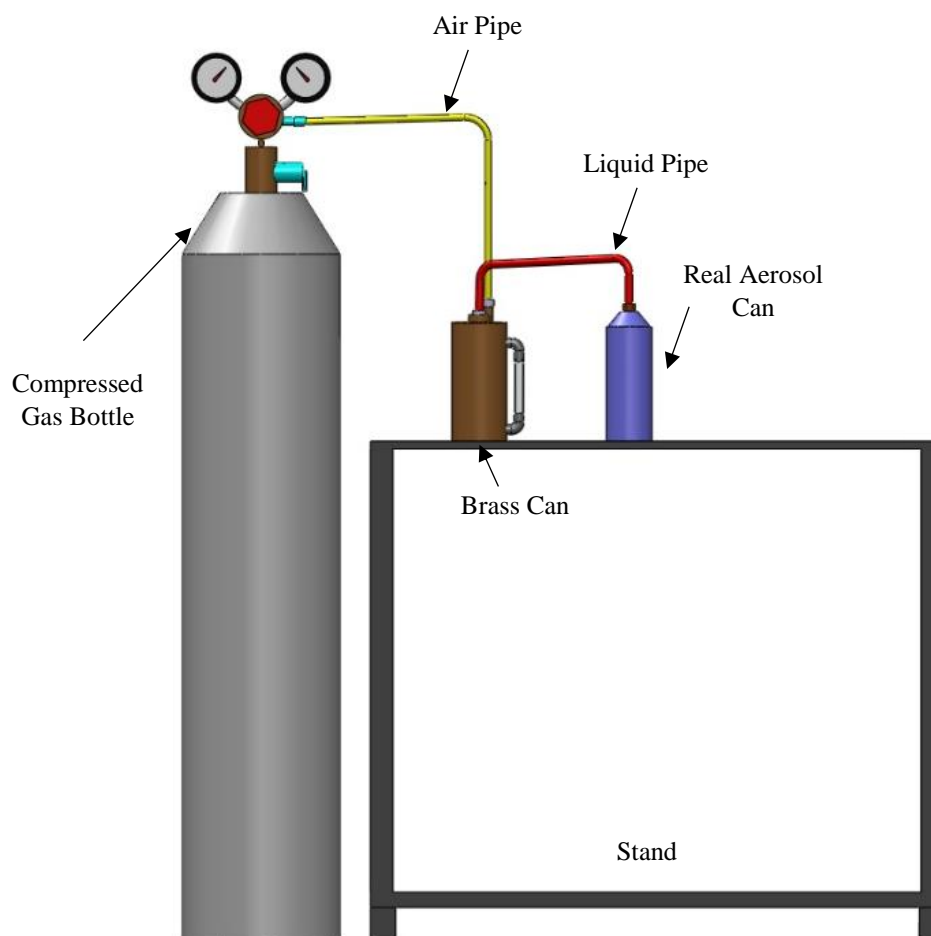


Figure-9: Filling method

Conceptual theory of data processing (liquid and gas content of can)

As shown in Figure 10, the initial fill ratio F (%) or brimful capacity (BFC) is defined as:

$$\text{Fill Ratio, } F(\%) = \frac{V_{\text{Liq}}}{V_{\text{Can}}} \times 100 = \frac{V_{\text{Liq}}}{V_{\text{Liq}} + V_{\text{Gas}}} \times 100 \quad (1)$$

Fill ratio varies for different commercial aerosol products and it can be chosen by the manufacturer. Also, the initial pressure of the can, P_1 , is chosen by companies and it is limited according to the type of the can. When a liquefied gas propellant is used, the total liquid in the can is the sum of the liquid product and the liquid phase of the propellant. When the can is emptied of all liquid, in order to have acceptable spraying occurring, the pressure P_2 must be a certain value, which depends upon the propellant and insert type, as well as the initial fill ratio.

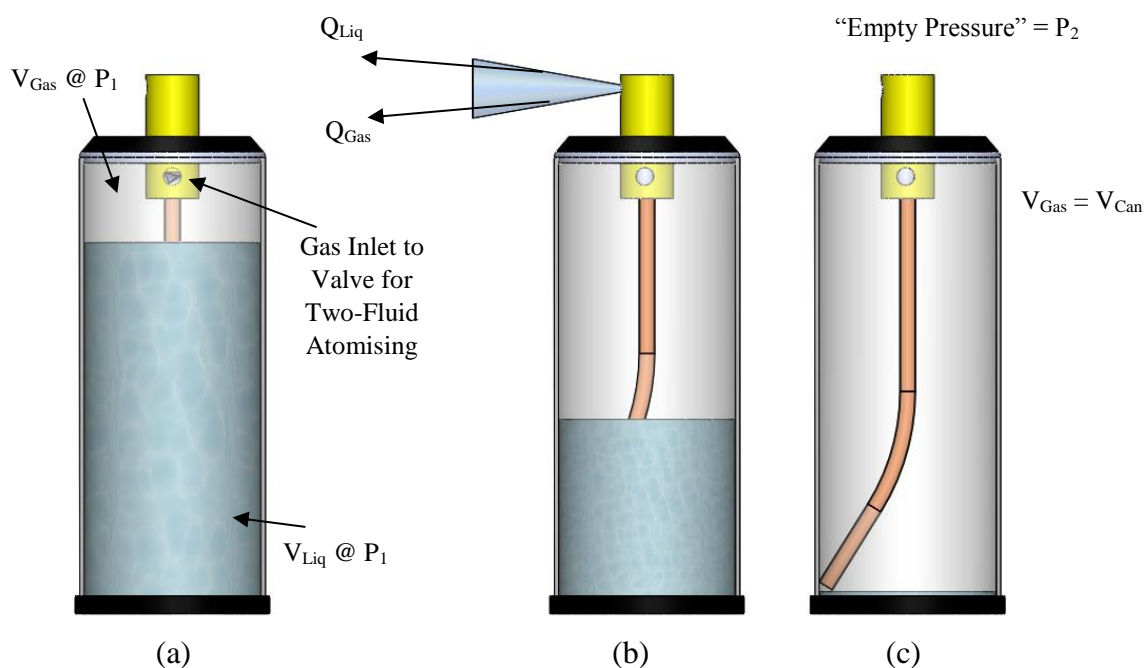


Figure-10: A can's spraying performances: (a) can is full; (b) during spraying; (c) can is empty

In the description below, the case of compressed (inert) gas propellants is considered for the general case when some of the gas is bled from the can to aid atomisation. The gas volume which is ejected from the can in the spray is calculated at atmospheric conditions. At the initial gas pressure, P_1 , the atmospheric equivalent is calculated from the initial gas volume from the following equation that assumes the ideal gas law with isothermal expansion of the gas.

$$\text{Initial Gas Volume (atmospheric equivalent)} = V_{\text{Gas}} \times \frac{(P_1 + 1)}{P_{\text{atm}}} \quad (2)$$

where convenience pressure is measured in 'bar' and noting that P_1 is a gauge pressure. Similarly, when the can is emptied of all liquid, the atmospheric equivalent volume of gas remaining in the can is calculated from following equation:

$$\text{Final Gas Volume (atmospheric equivalent)} = V_{\text{Can}} \times \frac{(P_2 + 1)}{P_{\text{atm}}} \quad (3)$$

From these two equations, the total volume of ‘atomising gas’ at atmospheric pressure is:

$$V_{\text{atom}} = V_{\text{Gas}} \times \frac{(P_1 + 1)}{P_{\text{atm}}} - V_{\text{Can}} \times \frac{(P_2 + 1)}{P_{\text{atm}}} \quad (4)$$

Where:

$$V_{\text{Can}} = V_{\text{Gas}} + V_{\text{Liq}}$$

So that equation (4) can be written as:

$$\begin{aligned} \frac{V_{\text{atom}}}{V_{\text{Liq}}} &= \left(\frac{V_{\text{Gas}}}{V_{\text{Liq}}} \times \frac{P_1 + 1}{P_{\text{atm}}} \right) - \left(\frac{V_{\text{Can}}}{V_{\text{Liq}}} \times \frac{P_2 + 1}{P_{\text{atm}}} \right) \text{ or} \\ \frac{V_{\text{atom}}}{V_{\text{Liq}}} &= \left(\frac{V_{\text{Can}}}{V_{\text{Liq}}} - 1 \right) \left(\frac{P_1 + 1}{P_{\text{atm}}} \right) - \left(\frac{V_{\text{Can}}}{V_{\text{Liq}}} \times \frac{P_2 + 1}{P_{\text{atm}}} \right) \end{aligned}$$

With substitution of fill ratio from equation (1):

$$\frac{V_{\text{atom}}}{V_{\text{Liq}}} = \left[\left(\frac{100}{F} - 1 \right) \left(\frac{P_1 + 1}{P_{\text{atm}}} \right) \right] - \left[\frac{100}{F} \times \frac{P_2 + 1}{P_{\text{atm}}} \right] \quad (5)$$

This represents the average atomising gas/liquid volume flow rate ratio during spraying of a compressed gas propellant when some of the gas is bled off from the can.

$$\frac{V_{\text{atom}}}{V_{\text{Liq}}} = \frac{Q_{\text{Gas}}}{Q_{\text{Liq}}} \quad (6)$$

Table-3 shows the calculation of different initial fill ratios and pressures and the final can pressure based on the equations (5) and (6). This table shows that arbitrarily at this stage if one specific a final can pressure of at least $P_2 = 3\text{bar}$ being required for acceptable atomisation, then for an initial can pressure of 9 bar and fill ratio 50% an atomising gas/liquid volume ratio of 3 would be available. Taking an air density of 1.2 kg/m^3 and water at 1000 kg/m^3 this indicates a mass ratio for atomising air/liquid flow rate of 0.0036, or a mass ratio of up to approximately 0.4%. A number of published works on two-fluid atomisation, e.g. combustion, shows that this is a relatively small ratio.

Aerosol manufacturers and consumer product companies are not keen on reducing fill ratio below 50%, nor on using the higher pressure 12 bar cans; however, doing either of these would greatly reduce design challenges and ensure better spraying through can life if the gas bleeding method is used to improve atomisation. Minimising the pressure value P_2 at which the insert still atomises well, is also seen to be very important.

Table-3: Parameters for ‘two-fluid atomisation’

Case number	Fill ratio F%	Initial can pressure P ₁ (bar)	Final can pressure P ₂ (bar)	Available Q _G /Q _L for atomising	Notes	Comments
1	40	9.0	2.5	6.25	9bar can with low fill ratio.	
2	50	9.0	2.5	3.0	9bar can with acceptable fill ratio.	
3	40	9.0	3.5	3.75	9bar can with low fill ratio and increasing the required value of final pressure.	available Q _G /Q _L for atomising is remarkably less than case (1) and slightly higher than case (2)
4	50	9.0	3.5	1.0	9bar can with acceptable fill ratio and increasing the required value of final pressure.	too small Q _G /Q _L available for atomising.
5	50	12.0	2.5	6.0	12bar can with acceptable fill ratio.	doubled available Q _G /Q _L for atomising compare with case (2)

In the previous work related to this investigation [6,7] in which a novel atomiser inserts were designed, the work was concentrated on using the novel two-fluid atomisers’ inserts in a controlled manner and measured the flow rates of the liquid and of the atomising gas (Figure-11).

Because the steady flow control board was used during these investigations, the supply pressure values of gas and liquid were independently varied to get the required flow rates; however, in the real aerosol can situation studied here, when the atomiser is an insert attached via the actuator cap to a valve, with the gas and liquid supplied into the bottom of the valve from the can, the supply pressures for gas and liquid will be (almost) exactly the same. Also, there is an unknown pressure P_C which is needed in the gas-liquid mixing chamber in order to push a bubbly flow through the insert at certain gas and liquid flow rates, Q_G and Q_L, respectively. The pressure P_C cannot be simply calculated because the pressure drops of bubbly flows through the orifices and chamber of the atomiser insert is very complex. A gas supply pressure P_G must have a value above P_C, and (P_G – P_C) depends on the injection orifice diameter (e.g. 0.20 mm) and the required gas flow rate, Q_G. The liquid injection does not occur through an orifice but rather via a step down from the bore of the supply pipes to the bore of the mixing chamber.

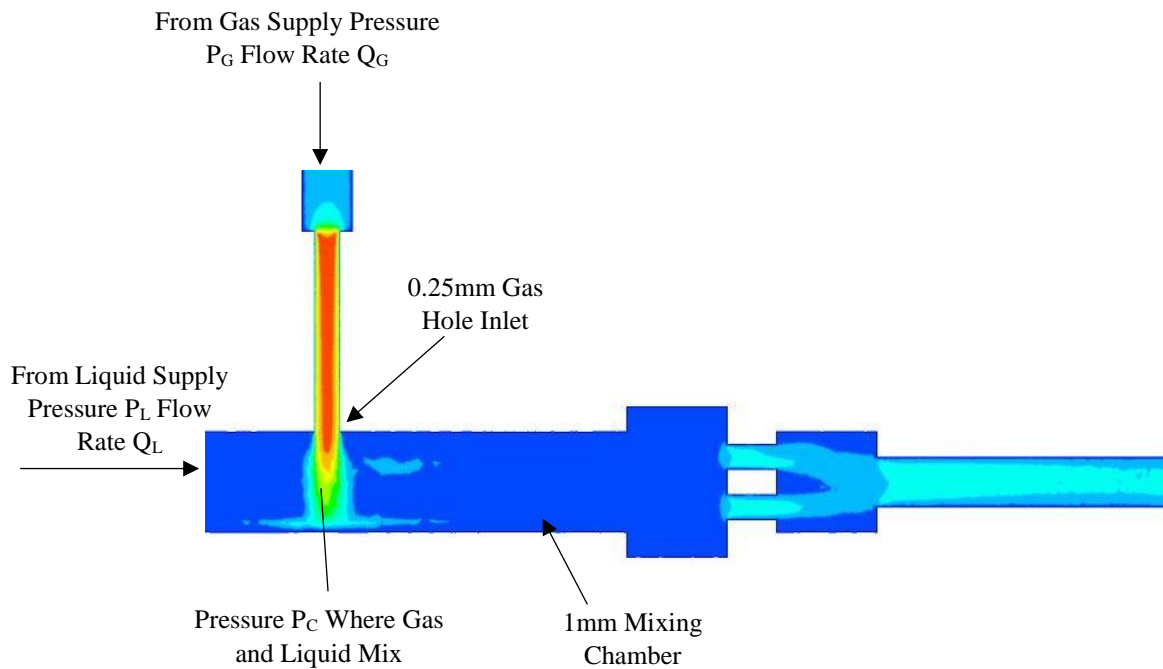


Figure-11: Schematic of setup for steady flow two fluid atomiser insert testing

The value required for P_L is greater than the value of P_C , due to this reduction in bore, and by an amount depending upon the value set for Q_L . It would be purely a coincidence if $P_G = P_L$ for a given required combination of Q_G and Q_L . It would be useful to measure Q_G and Q_L for conditions where P_G and P_L are fixed to be equal, because this is the true situation if the atomiser insert is being supplied from an aerosol can. For example, measure Q_G and Q_L , for $P_G = P_L = 2\text{bar}, 3\text{bar}, 4\text{bar}, \text{etc.}$

This would provide information on the sizes of liquid and gas orifices needed with the mixing chamber, in order that the flow rates and flow rate ratios needed for good sprays are produced as a can empties. However, this would be background design information because the true practical set up when using the can, would use a different chamber than shown in Figure-12 and there is the complication that the bubbly flow must pass through the valve before reaching the atomiser inserts (for this reason the orifices in the valve stem should have as large an area as possible so that the valve has minimum effect on the bubble flow and its pressure drop).

As sketched in Figure-12, the next testing (using the can) must concentrate on using different combinations of gas and liquid injection orifices into the mixing chamber. For a given atomiser insert attached, there should be one combination of these gas and liquid inlets that optimises spraying during lifetime of a can, i.e. as the pressure in the can reduces, with the proviso that the can must be empty when spraying stops (i.e. no liquid left in a zero pressure can). The first testing gives guidance on the flow rates and flow ratios needed in the research and the minimum pressures needed for atomising, and thus the fill ratios that are to be used.

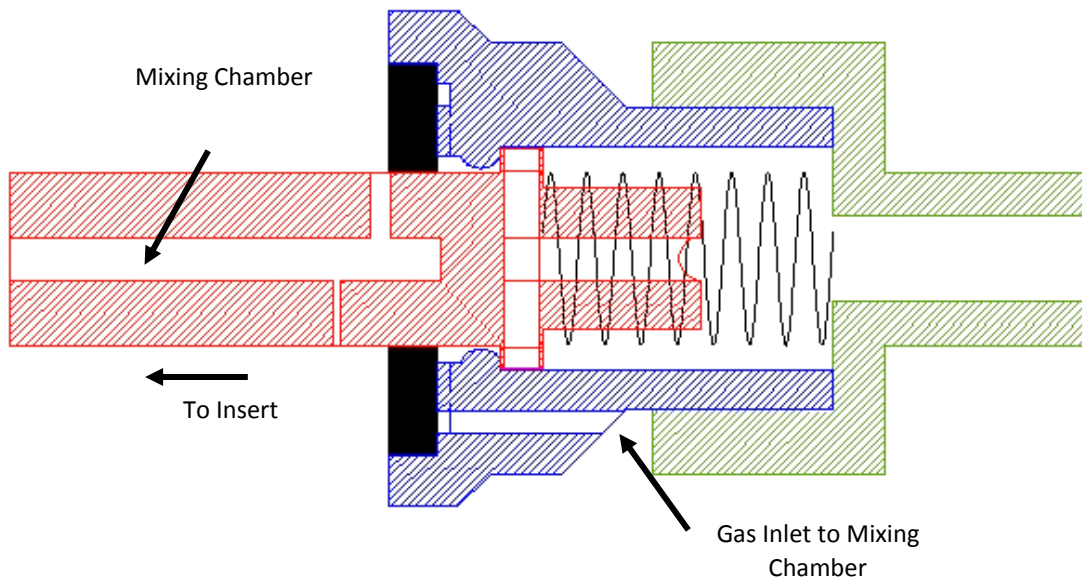


Figure-12: Set-up for can tests

Experimental errors

Droplet size: The laser family and its family of light scattering instruments are accepted as benchmark particle sizing devices and usually an accuracy of $\pm 1.0 \mu\text{m}$ for $D_{(v,50)}$ is reasonably assumed, provided that the spray meets certain conditions which include:

- Obscuration of laser beam to be between 5% and 60% approximately: this was the case for the current measurements;
- Beam steering effects of vapour are either negligible or, as in the case of ethanol sprays in the current experiments, can be obviated by the 'kill data' routine that removes its effects.

Liquid flow rate: Apart from when using the 'brass can' reservoir, the liquid flow rate during spraying is measured by using a stopwatch to spray for periods of, usually, 10s or 20s, and weighing the can and its contents before and after this period. Error contributions are:

- Time duration is measured to within $\pm 0.5\text{s}$ approximately. In addition, there are unknown transient effects because spraying start up and shut down when pressing and releasing the actuator to activate the valve, cannot be truly instantaneous.
- The weight is measured to be within $\pm 0.1\text{g}$, a typical sprayed mass being 5 – 10g in 10s.
- The measured liquid flow rate is estimated to be accurate to within $\pm 10\%$ at the worse.

Atomising gas flow: When presenting the results, values are quoted of the percentage of the can gas that has been bled off to aid atomisation. These are calculated by using equation (5), which compares the actual can pressure at the time when the liquid product has been completely evacuated, with the pressure that should exist if no gas had been bled from the can. This assumes isothermal gas expansion in the can and the ideal gas law, both of which are reasonable

assumptions. The can pressure is measured to be within ± 0.1 bar approximately. However, another error source is due to possibly measuring the ‘empty’ pressure either when the can is not quite empty or slightly after it is empty, i.e. by keeping the valve open after emptying all the liquid so that can gas escapes through the dip tube. Finally, there is a possible error source from the accuracy of determining the initial fill ratio i.e. the accuracy of knowing the ‘brim full’ volume of the can and of the initial volume of liquid in the can. From the above, it is considered that if $X\%$ is the measured percentage of gas bled off, then the true value is within the bounds $(X \pm 2)\%$. The results provided in the next section are related to the volume flow rate of the (bled off) atomising gas Q_G at each time step, and the ratio of gas and liquid volume flow rates, Q_G/Q_L is based on the estimation of Q_G to be at NTP, i.e. 1atm and 293 K. The spreadsheet column calculates Q_G using the ideal gas law and the assumption of isothermal expansion of the gas remaining in the can at each time step. The calculation makes use of measurements including the changes in weight and pressure of the can during the time step. As both these have error sources, the expected error is significant, and it is estimated that with a typical average value of Q_G/Q_L being around 5, individual values may have an accuracy of ± 2 .

Other error sources: The above errors should usually be random and would manifest themselves as scatter in data. When measurements were taken, there were other potential sources of error that were more systematic for a given set of data. For example, if the spray is positioned so that it does not project centrally across the laser beam of the laser instrument, there would be systematic errors as the can is evacuated with it remaining in the same position. During the experiments, the development device nature of some of the valves led to slight jamming of the stem and, as mentioned in the appropriate sections, this can affect the spray and the measured flow rate.

Results and discussions

Ideally, the new consumer aerosol valve designs should be capable of performing in a similar way to current conventional (liquefied gas propellant) aerosol valves, and certainly have better spraying performance than current commercial inert (compressed) gas aerosols and for a wide range of products. From the consideration in the preceding sections of this paper, the performance can be best described by characteristics describing drop size, liquid flow rate, constancy of drop size and flow rate during can lifetime, and the capability of fully evacuating the can of liquid. Other application-dependent characteristics include spray penetration (‘throw’), fraction of inhalable drops and spray angle. The required performance should be achievable using existing commercially available cans and ideally using 12 bar cans (which would be filled at 9 to 10 bar) but possibly using the higher pressure cans that are also available but with cost penalties (e.g. 18 bar cans).

This section first presents the spray performance for some of the representative ‘off-the-shelf’ products that use conventional aerosol valves such as airfreshener, polish, deodorant, hair spray and insecticide using butane propellant and also the relatively few current products using inert gas are covered. These data confirm the benchmark performances that are of interest and then, in ‘bi-valve’ results and ‘super single gasket’ valve results, the prototype design of the new consumer aerosol valve designs described in novel aerosol valve design are tested using water and ethanol simulating the product. Furthermore, this section shows the results of using these prototype designs and compared the results with a conventional aerosol valve result which is called here as the ‘control valve’. This conventional valve is designed for using an inert gas propellant in which the gas inlet is located on the housing of the valve, similar to that of VPT. Also, one to four liquid holes are machined on the stem, which is sealed by a conventional gasket. Thus, when the valve is pushed down, and it is in the open position, the gasket will

bend, and the liquid hole(s) is revealed. This supposedly allows the mixture of the product and gas from the housing to pass through the liquid holes towards the actuator. The results for this valve were provided from one of the major companies in the consumer aerosol market and because of the strict confidentiality imposed, the author cannot mention its name.

The sprays were characterised using the laser instrument. The downstream distance between the atomiser insert and the laser beam was kept at 15cm. This downstream distance was selected as being the furthest downstream that could be used without the risk of the spray impingement on the lens. All images were also captured using a digital still camera, which provided qualitative information and also data on cone angle.

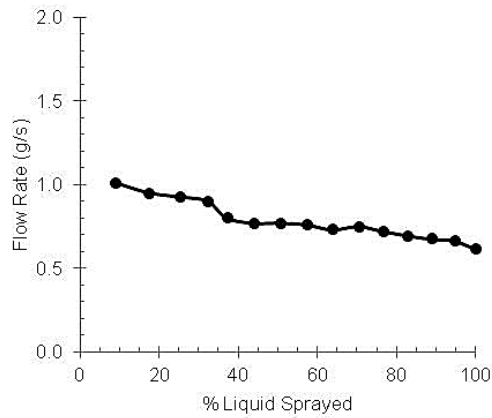
At this stage, it is apparent that some consistent definition is required in order to quantify the ‘constancy’ of liquid flow rate and droplet size in order to give meaningful comparisons between various aerosols (by aerosols the combination of can-product-valve-insert is means). It was apparent that simply taking the difference between the first measured value of liquid flow rate (full can) and last value (empty can), and dividing by the first value, although seemingly the obvious definition for consistency, was not ideal because the initial value could occasionally suffer from effects such as the initial priming of the valve and, more importantly, the final value often included ‘spluttering’ effects as the can emptied. Thus, here it is proposed to use the 90% and 10% points in the can emptying results: these are arbitrary choices made by examining many sets of results. Thus, the definition of flow rate constancy (C_Q) and drop size constancy (C_D) is:

$$C_Q\% = \left(\frac{\text{Flow rate @10\% liq. sprayed} - \text{Flow rate @90\% liq. sprayed}}{\text{Flow rate @10\% liq. sprayed}} \right) \times 100 \quad (7)$$

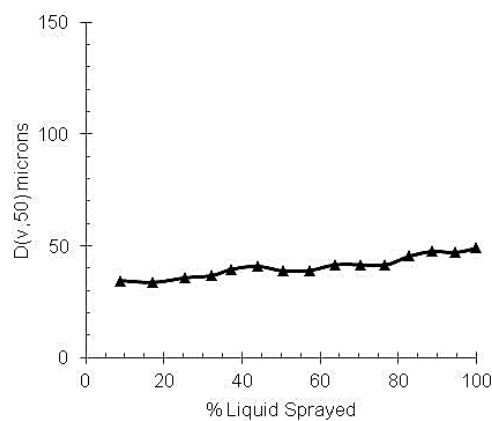
$$C_D\% = \left(\frac{\text{Drop size @90\% liq. sprayed} - \text{Drop size @10\% liq. sprayed}}{\text{Drop size @10\% liq. sprayed}} \right) \times 100 \quad (8)$$

Spray characterisation and performances of current consumer aerosols using conventional consumer aerosol valves

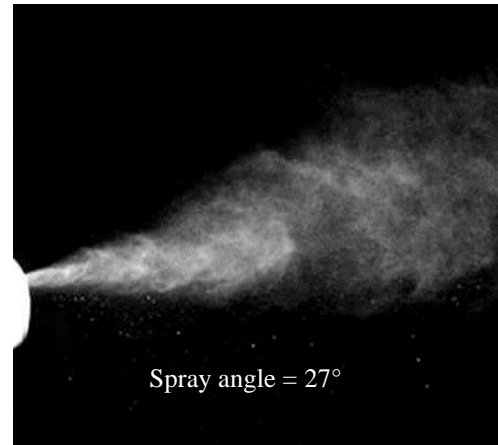
Figure-13 shows the spray performance of one of the most common air-freshener in the market, which uses butane as a propellant in its product. As is shown, the discharge flow rate decreased smoothly from 1g/s to 0.6g/s at the end of the can with constancy of $C_Q = 30\%$. There is a very steady increase in particle size $D_{(v,50)}$ (ignoring the pick which is an experimental error) with $C_D = 38\%$. Figure-14 shows the images of spray performance at the beginning and the end of pack life.



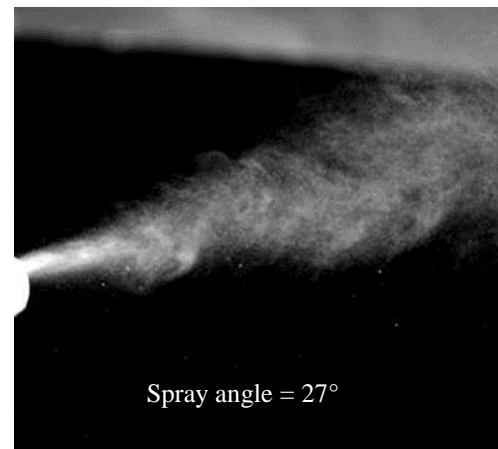
(a)



(b)



(a)

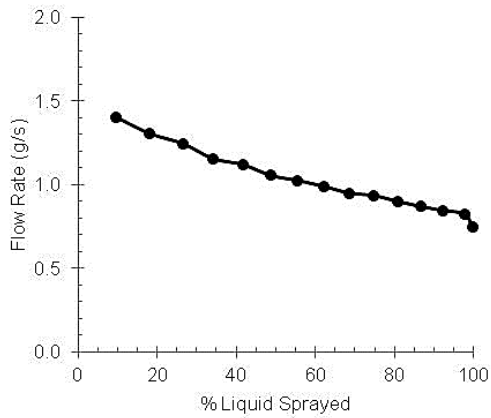


(b)

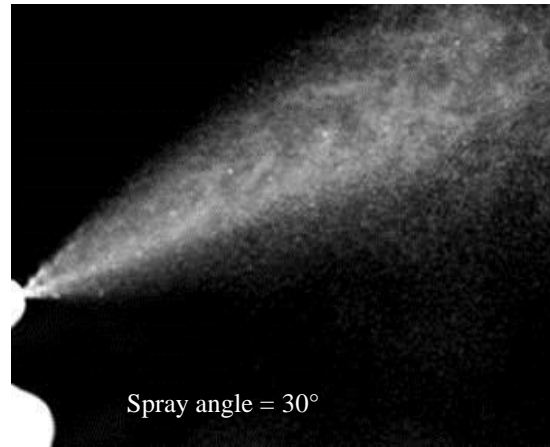
Figure-13: Spray performance of current air-freshener using LPG propellant. (a) discharge flow rate and (b) particle size

Figure-14: Spray image of current air-freshener using LPG propellant. (a) beginning of the can and (b) end of the pack life

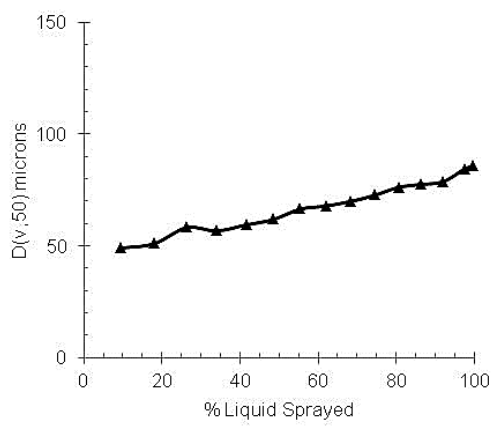
However, air-fresheners are a product area that has been recently addressed by major filler companies using compressed gas products and these should provide the benchmarks in the field. Figure-15 shows the result for spray performance of one of the most popular air-fresheners in the UK market at the time of this research. The cans have about 60% fill ratio with initial pressure of 9 bar at 20°C. As is shown, the discharge flow rate decreased smoothly from 1.4g/s to 0.8g/s at the end of the can with a constancy of $C_Q = 43\%$. There is a very steady increase in particle size $D_{(v,50)}$ with $C_D = 60\%$. Figure-16 shows images at the beginning and at the end of the pack life, and a clear reduction of spray angle is seen. The performance of this conventional air-freshener is surprisingly poor in terms of constancy and particularly at high initial flow rate, when compared with butane propellant cans.



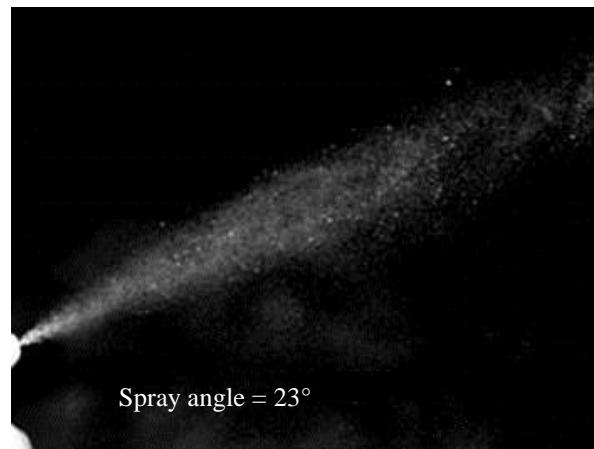
(a)



(a)



(b)

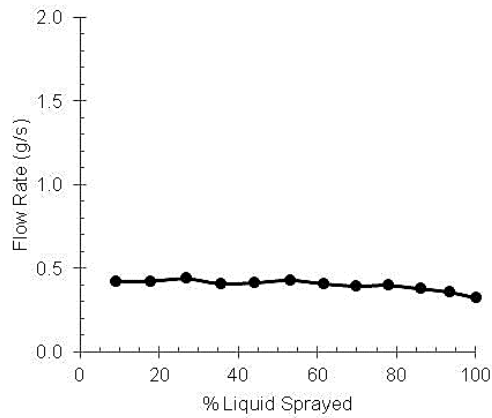


(b)

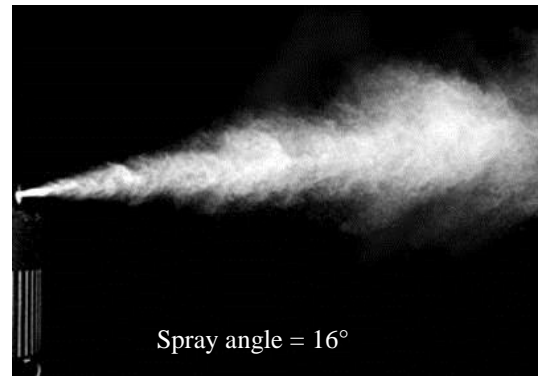
Figure-15: Spray performance of current air-freshener using inert gas propellant. (a) discharge flow rate and (b) particle size

Figure-16: Spray image of current air-freshener using inert gas propellant. (a) beginning of the can and (b) end of the pack life

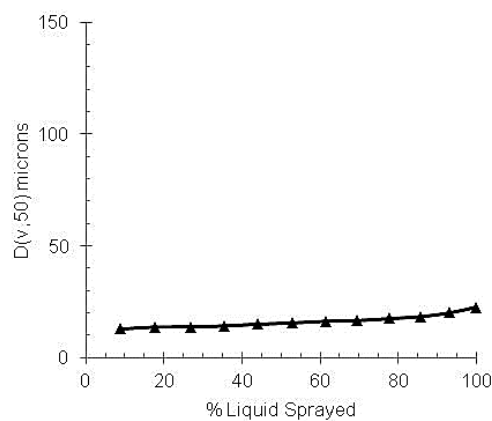
The properties of deodorants are similar to antiperspirants except that the cooling effect is more important to convey freshness in the latter and the former are more heavily seeded with powder to absorb perspiration. This usually means that deodorant has a relatively wetter spray and is ethanol based. Figure-17 shows the spray performance of a popular ‘off-the-shelf’ deodorant. As is shown, there is a relatively constant discharge flow rate around 0.4g/s through the can life, with constancy of $C_Q = 1\%$, such good constancy is typical when using liquefied gas propellant. The particle size is in a very low range between $13\mu\text{m}$ at the beginning to $22\mu\text{m}$ at the end, with a constancy of $C_D = 46\%$. Figure-18 shows the images of spray performance at the beginning and the end of pack life.



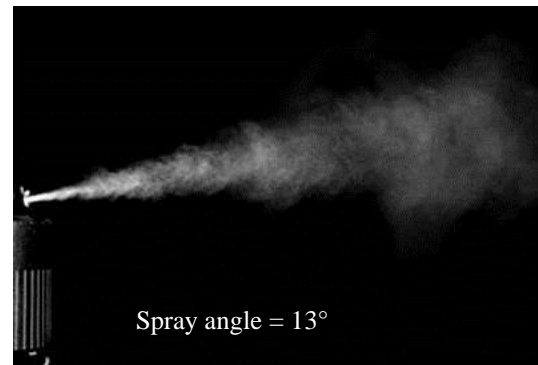
(a)



(a)



(b)

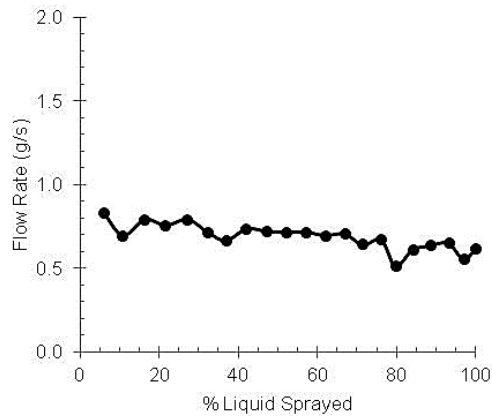


(b)

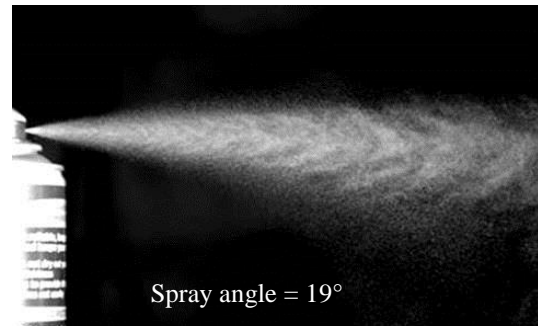
Figure-17: Spray performance of current deodorant using LPG propellant. (a) discharge flow rate and (b) particle size

Figure-18: Spray image of current deodorant using LPG propellant. (a) beginning of the can and (b) end of the pack life

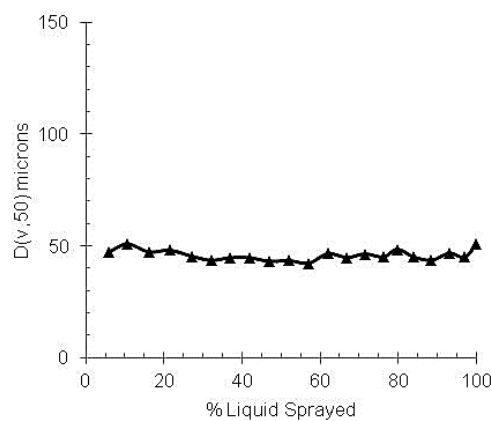
Hair spray products need a soft wide spray with fine or medium-sized particles. It must not drench the hair, but it needs to spray wet until it reaches the hairs so that the resin can flow along the shaft of the hair to a joint where the solvent evaporates to produce a 'weld'. The new hair spray products have changed their formulation and there is about 80% ethanol and the rest are 20% water added with resin, neutraliser, plasticiser and fragrance. Figure-19 shows the spray performance result for a conventional hairspray. As is shown, the discharge flow rate drops to 0.8g/s at beginning and 0.5g/s at the end of the pack life with constancy of $C_Q = 25\%$. Also, the particle size is quite steady through the can life at around $D_{(v,50)} = 45\mu\text{m}$ with constancy of $C_D = 3\%$. Figure-20 shows the images of hair spray performance at the beginning and the end of pack life.



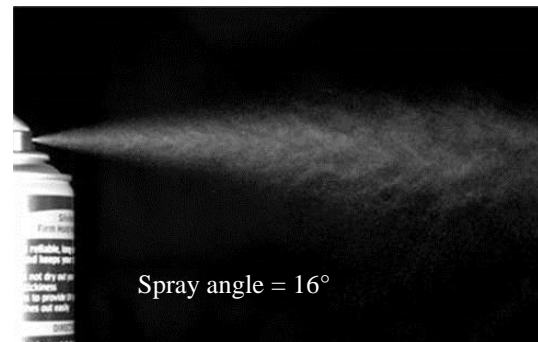
(a)



(a)



(b)



(b)

Figure-19: Spray performance of current hair spray using LPG propellant. (a) discharge flow rate and (b) particle size

Figure-20: Spray image of current hair spray using LPG propellant. (a) beginning of the can and (b) end of the pack life

In addition to tests of available current aerosols for various uses, the author has held communications with several major companies in the aerosol field to have guidance on acceptable performance for inert gases products. Thus, e.g. although current deodorant has very fine sprays with drop size around $20\mu\text{m}$ or less, the achievement of values of $D_{(v,50)}$ around $40\text{--}45\mu\text{m}$, when using compressed gas, was considered to be of interest. Table-4 shows the summary of benchmark performances to be achieved for different products when using the new types of inert gases valves. It is noted that the base liquid product for most of the conventional aerosol valves are water, ethanol or mixture of ethanol/water and also the initial pressure is between 8 bar and 12 bar with fill ratio of 50% to 70%. Furthermore, current inert gas products achieve ‘constancy’ of performance around $C_Q = 40\%$ and $C_D = 30\%$, so that the new valves must significantly improve on these values.

Table-4: Benchmark performance of the conventional aerosol products

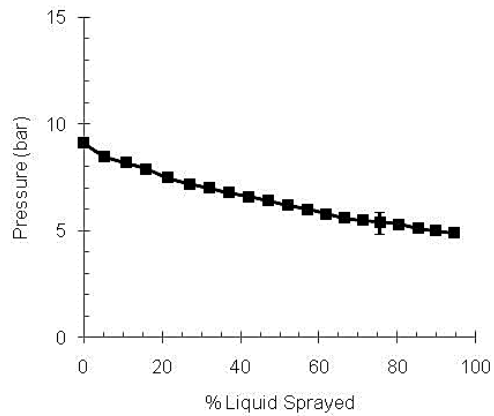
Product	Drop size $D_{(v,50)}$ (μm)	Flow rate (g/s)	Reach (mm)	Spray angle	Estimated constancy	
					$C_Q\%$	$C_D\%$
Deodorant	30 – 40	0.4+	500+	15+	1 – 5	20 – 30
Air care	40 – 50	1.2±	800+	20 – 40	20 – 35	40 – 50
Hair spray	35 – 50+	0.4 – 0.8	300	15+	30 – 40	5 – 10
Insecticide	50 – 80+	1.5+	2000+	10 – 20	20 – 30	5 – 10
Disinfectant	85	1.1 – 1.6	150+	30 – 50	20 – 30	5 – 10
Furniture polish	150+	0.8 – 1.6+	500	25 – 30	30 – 40	30 – 40

‘Bi-valve’ results

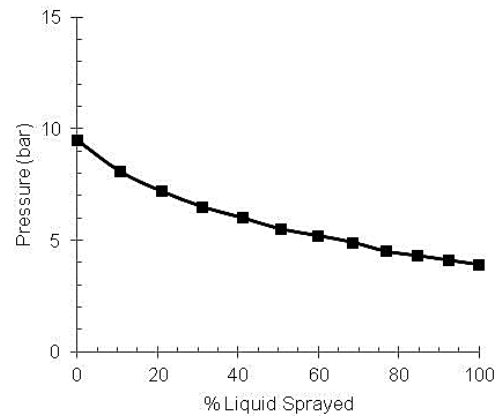
There were various designs of the ‘bi-valve’ which were manufactured as a proof of concept (PoC) designs with different combination of the central liquid feed, main liquid holes and gas holes. All of them were tested in this investigation to find those valve-insert combinations with satisfactory constant pressure drop, discharge flow rate and the constant drop size.

However, the first stage of this investigation was to select the valves that worked through pack life of the can without bleeding off too much gas, and the pressure drop, and discharge flow rate were measured first, without drop size data. In this stage, one of the PoC designs which is called ‘bi-valve #2-7’ was chosen as a prototype design to be used for further investigation in terms of functionality and repeatability.

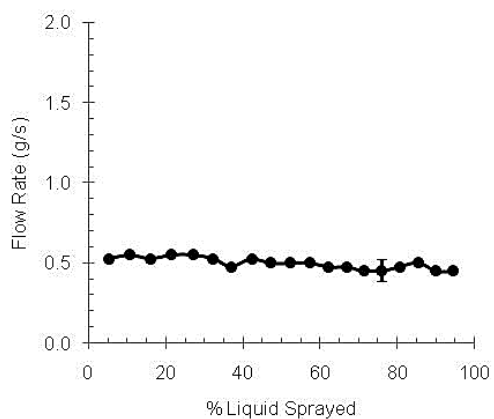
Figure-21 shows the spray performance result of the ‘bi-valve #2-7’ filled with 40% fill ratio of ethanol into the 100mL glass can and pressurised to 10 bar and using 0.23mm aqua insert. As shown in this figure, the discharge flow rate is remarkably steady with $C_Q = 18\%$ and the particle size is increasing smooth with very small values (for ethanol spraying) rising from 40.96 μm to 47.49 μm with an excellent constancy of $C_D = 20\%$. Figure-22 shows the result for ethanol with 50% fill ratio of the 100mL glass can and 10 bar pressure with compressed air using 0.23mm aqua insert.



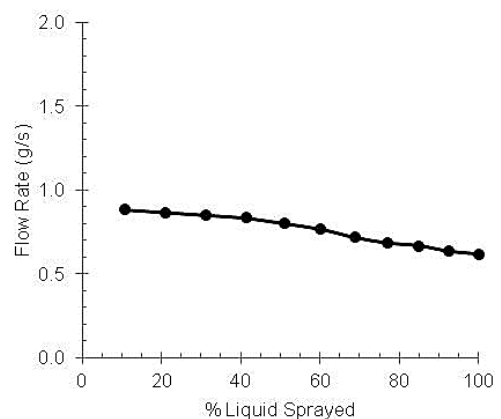
(a)



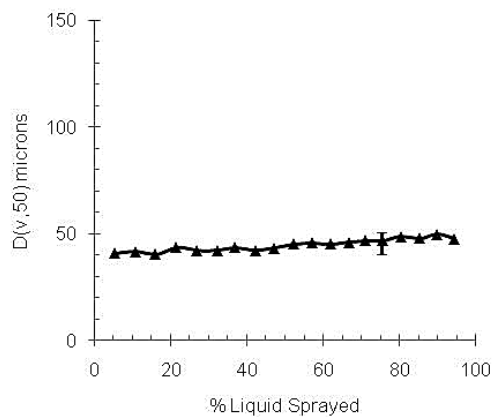
(a)



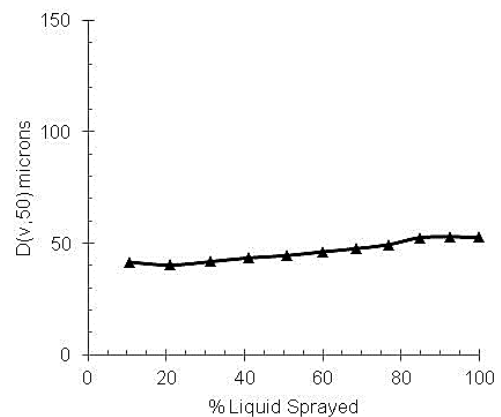
(b)



(b)



(c)



(c)

Figure-21: ‘Bi-valve #2-7’ with 40% fill ratio of water; glass can (100 mL) pressurised with compressed air up to 10bar, using 0.23mm aqua insert. (a) pressure drop, (b) discharge flow rate and (c) particle size

Figure-22: ‘Bi-valve #2-7’ with 50% fill ratio of ethanol; glass can (100 mL) pressurised with compressed air up to 10bar, using 0.23mm aqua insert. (a) pressure drop, (b) discharge flow rate and (c) particle size

As shown, there is a drop-in discharge flow rate with good constancy ($C_Q = 24\%$) but not as good as in the case of ethanol. The flow rate was also higher for water than for ethanol which was not always the case for the various valves. Also, the particle size increased slowly from

41.78 μm to 52.67 μm with a good constancy ($C_D = 24\%$). Clearly, this valve was very good for achieving constancy in flow rate and drop size. Figure-23 shows the qualitative images of spray performance using a ‘bivalve #2-7’ with 60% fill ratio of ethanol and water in two different cans.

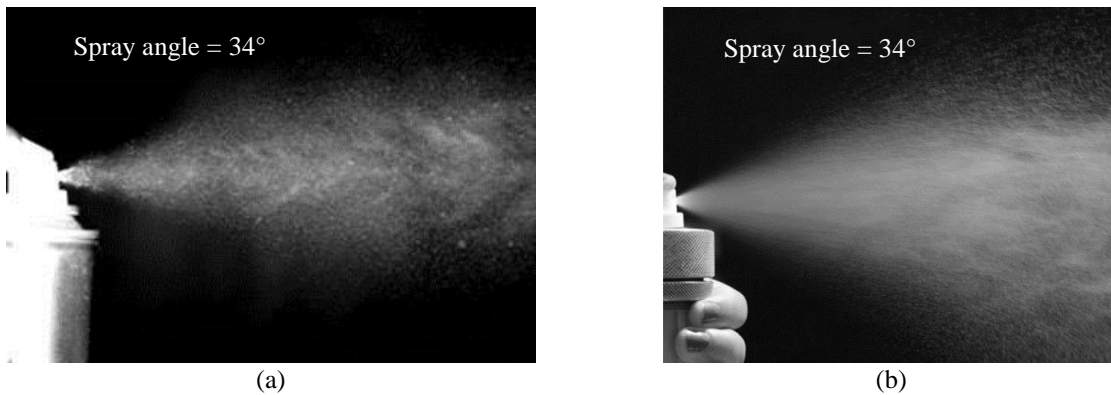


Figure-23: ‘Bi-valve #2-7’ spray image pressurised to 10bar using 0.33mm MBU CO₂ insert. (a) 60% Fill ratio of water in 200ml can and (b) 60% Fill ratio of ethanol in 100 ml can.

The next stage of this investigation will discuss the spray performances of ‘bi-valve #2-7’ with a conventional domestic aerosol valve which is here called as ‘control valve’. In this stage, ethanol was used as a liquid product with using a 0.33mm insert with three different inside geometry (Aqua, MBU and MBU CO₂). Figures-24 to 26 show the comparison of spray performance results of the ‘bi-valve #2-7’ and ‘control valve’ using ethanol with 60% fill ratio and 10 bar pressure with nitrogen using 0.33mm insert with three different inside geometries.

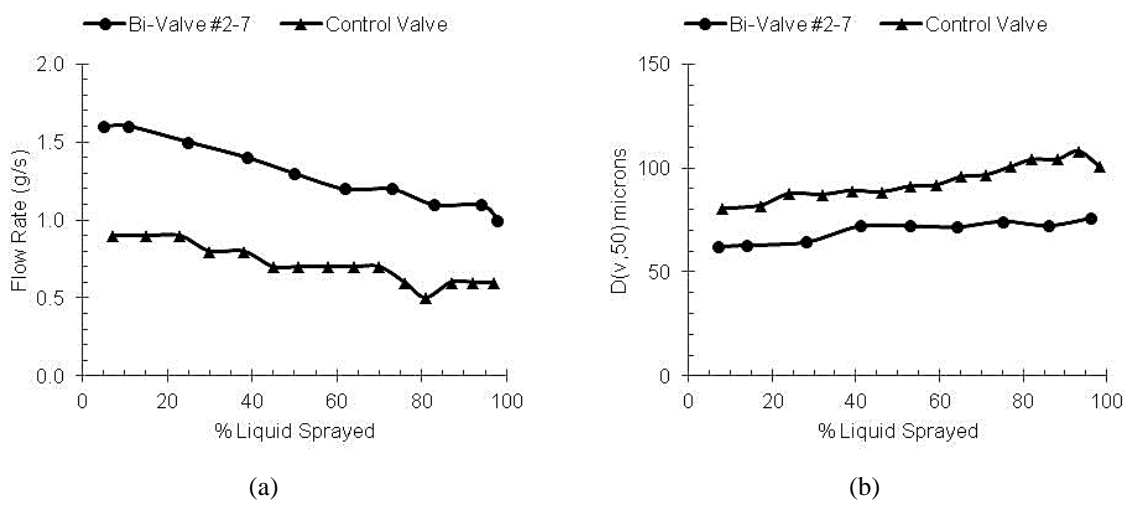
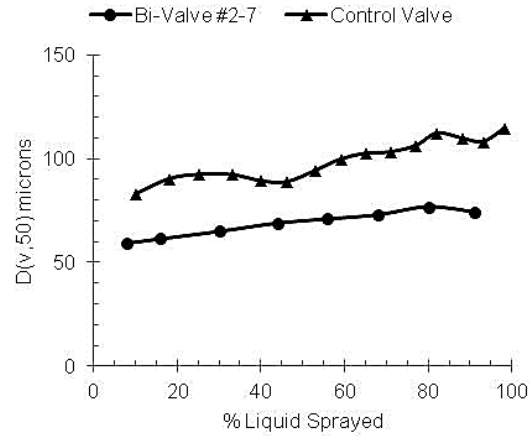
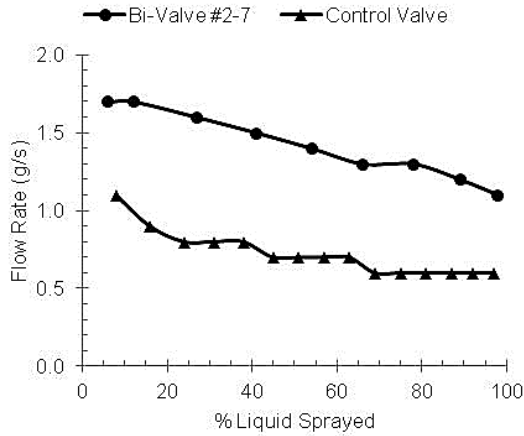


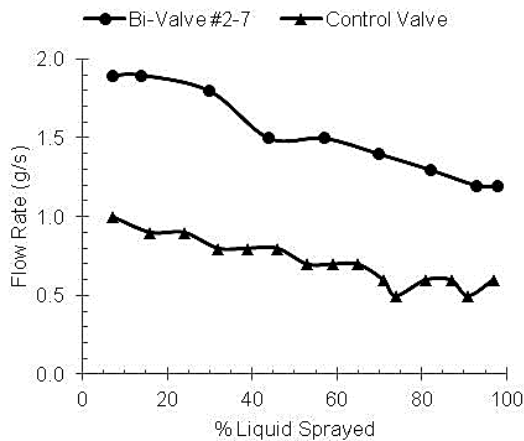
Figure-24: Comparison of spray performance result between ‘bi-valve #2-7’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm MBU CO₂ insert. (a) discharge flow rate and (b) particle size



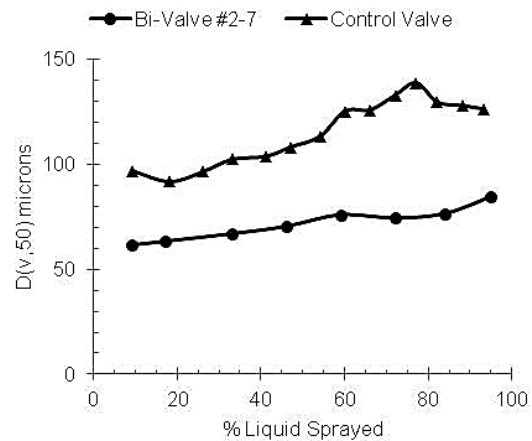
(a)

(b)

Figure-25: Comparison of spray performance result between ‘bi-valve #2-7’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm MBU insert. (a) discharge flow rate and (b) particle size



(a)



(b)

Figure-26: Comparison of spray performance result between ‘bi-valve #2-7’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm aqua insert. (a) discharge flow rate and (b) particle size

As shown in these figures, discharge flow rate for ‘bi-valve’ is higher than using ‘control valve’ but it has a remarkably better constancy (see Table 5). Moreover, as can be seen in these figures, particle sizes are lower for ‘bivalve’ than those obtained from ‘control valve’. Also, as shown in Table 6, the ‘bi-valve’ can provide much better constancy than the ‘control valve’. Tables-5 and 6 summarises the spray performance results of ‘bi-valve #2-7’ and the ‘control valve’ with using three different inserts.

Table-5: Summary of spray performance results for ‘bi-valve #2-7’ filled with 60% of ethanol and pressurised to 10bar

Insert type	Discharge flow rate (g/s)			Particle size (μm)		
	Beginning of the can	End of the can	C _Q %	Beginning of the can	End of the can	C _D %
MBU CO2	1.6	1.0	31	62.2	75.9	18
MBU	1.7	1.1	29	59.2	74.2	25
Aqua	1.9	1.2	37	61.5	84.5	34

Table-6: Summary of spray performance results for ‘control valve’ filled with 60% of ethanol and pressurised to 10bar

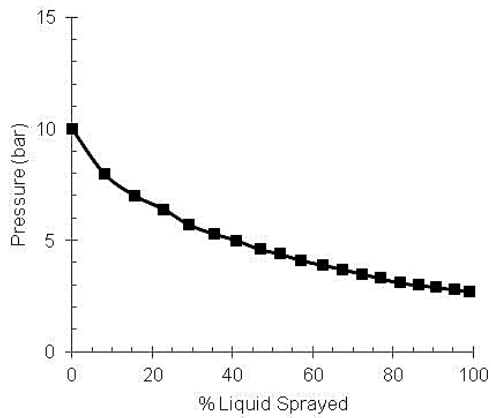
Insert type	Discharge flow rate (g/s)			Particle size (μm)		
	Beginning of the can	End of the can	C _Q %	Beginning of the can	End of the can	C _D %
MBU CO2	0.9	0.6	42	80.7	101.1	32
MBU	1.1	0.6	43	83.1	114.7	38
Aqua	1.0	0.6	50	97.1	126.4	68

‘Super single gasket’ valve results

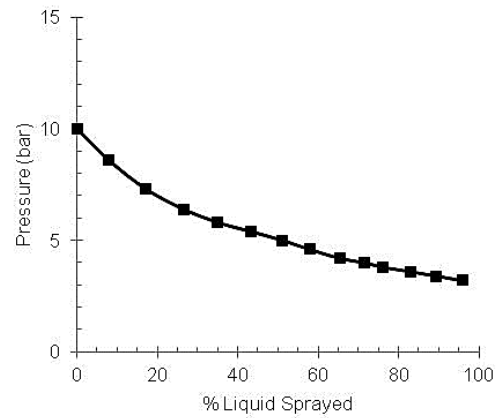
This section provides the spray performance results for the new consumer aerosol valve designs called ‘super single gasket’ valves. The basic reason for moving to this design was that it was envisaged that there were savings to be made in complexity and, thus, manufacturing costs for the ‘bi-valve’ designs. The aim was to simplify the design without sacrificing the basic fluid mechanical arrangement of a mixing chamber with liquid and gas added separately to the chamber. As shown in Figure-7, this valve has a housing with an annular ridge inside which has a sliding fit with the stem and acts sufficiently as a seal for the purpose of segregating gas and liquid inlet flows into the stem.

The selected results showed in this section are first the prototype design of ‘super single gasket’ which was crimped into a valve cup and the ‘glass’ reservoir was used to measure the spray performance of this valve with different products such as water and ethanol.

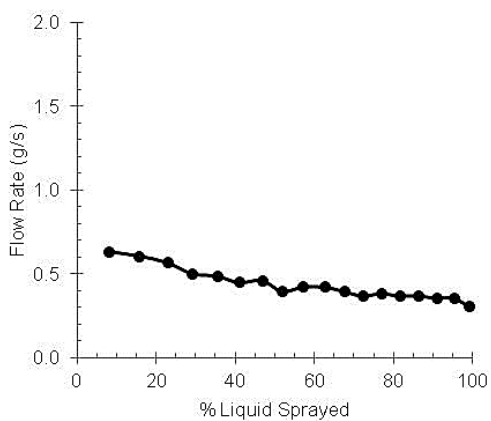
Figures-27 shows the results for 60% fill ratio of ethanol and 10 bar pressure with nitrogen using 0.30mm aqua insert. Also, Figure-28 shows the results using 60% fill ratio of water and 10 bar pressure with nitrogen using 0.33mm MBU CO2 insert. As is shown in these figures, there is a complete evacuation of the can through the pack life of the can and with about 8% of the can gas bleeding into the mixing chamber. Discharge flow rate with using ethanol and 0.30mm aqua insert is from 0.63g/s at the beginning to 0.3g/s at the end of the pack life with a constancy of C_Q = 25%. However, using water and 0.33mm MBU CO2 shows that the discharge flow rate is from 1.4g/s to 0.8g/s with a constancy of C_Q = 30%. In addition, the particle size measurements for ethanol (see Figure-27) shows a smooth increase from 39.24 μm to 67.82 μm with a constancy of C_D = 22%. Whereas for water the particle size commences from 73.3 μm to 96.5 μm with a constancy of C_D = 28% (see Figure-28).



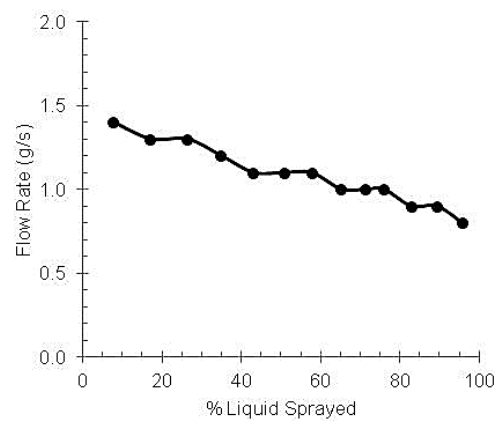
(a)



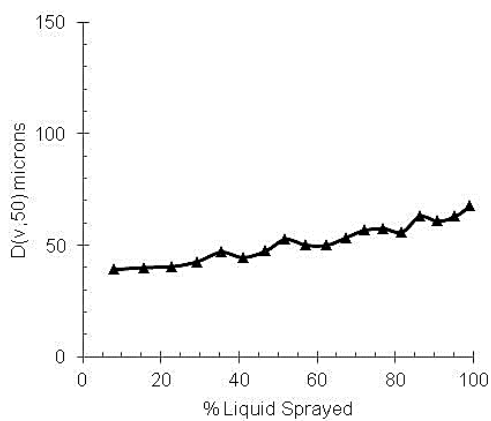
(a)



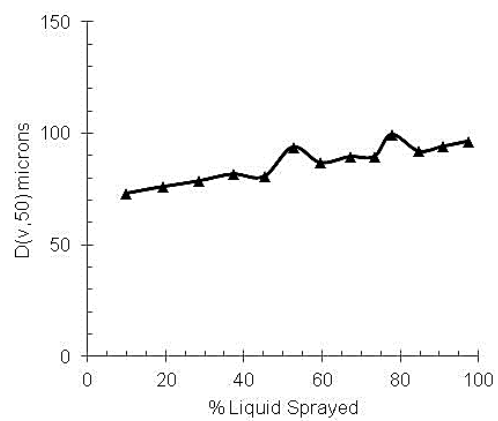
(b)



(b)



(c)

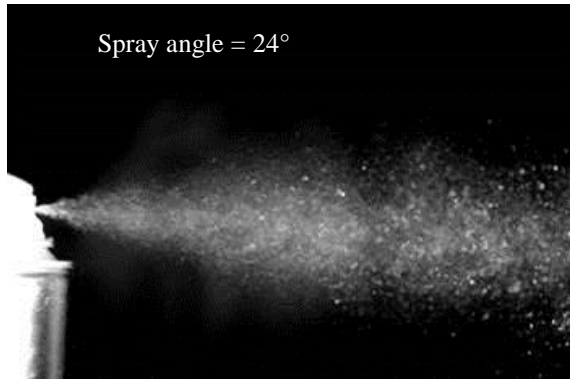


(c)

Figure-27: ‘Super single gasket’ with 60% fill ratio of ethanol, pressurised with nitrogen up to 10bar using 0.30mm aqua insert. (a) pressure drop, (b) discharge flow rate and (c) particle size

Figure-28: ‘Super single gasket’ with 60% fill ratio of ethanol, pressurised with nitrogen up to 10bar using 0.33mm MBU CO₂ insert. (a) pressure drop, (b) discharge flow rate and (c) particle size

Figure-29 shows the qualitative images of spray performance using a ‘super single gasket’ with 60% fill ratio of ethanol and water in two different cans.



(a)



(b)

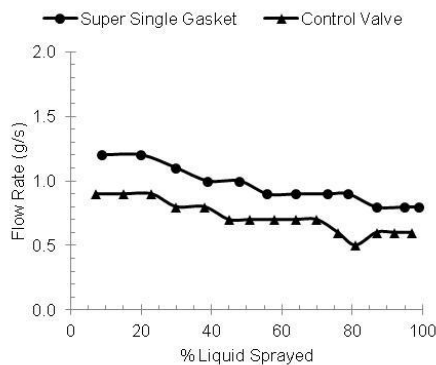
Figure-29: ‘Super single gasket’ spray image using 0.33mm MBU CO₂ insert. (a) 60% Fill ratio of water in 250 ml can and (b) 60% Fill ratio of ethanol in 100 ml can

Furthermore, comparison was also made in relation to the spray performance of the ‘control valve’ with ‘super single gasket’ valve. Table-7 shows a summary of the results of ‘super single gasket’ using ethanol with 60% fill ratio and 10 bar pressure with nitrogen using three different 0.33mm inserts.

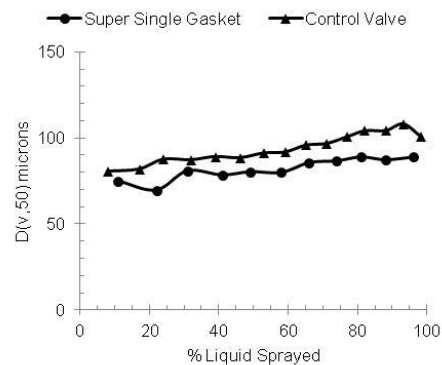
Table-7: Summary of spray performance results for ‘super single gasket’ filled with 60% of ethanol and pressurised to 10bar

Insert type	Discharge flow rate (g/s)			Particle size (µm)		
	Beginning of the can	End of the can	C _Q %	Beginning of the can	End of the can	C _D %
MBU CO ₂	1.2	0.7	33	75.0	88.9	17
MBU	1.2	0.8	33	82.0	95.2	13
Aqua	1.2	0.7	41	75.8	115.2	50

On comparison, it is shown that discharge flow rate of ‘super single gasket’ is slightly higher than ‘control valve’ but with better constancy. Moreover, the particle size of ‘super single gasket’ is remarkably lower than the ‘control valve’ and with extremely better constancy (Figures-30 to 32).



(a)



(b)

Figure-30: Comparison of spray performance result between ‘super single gasket’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm MBU CO2 insert. (a) discharge flow rate and (b) particle size

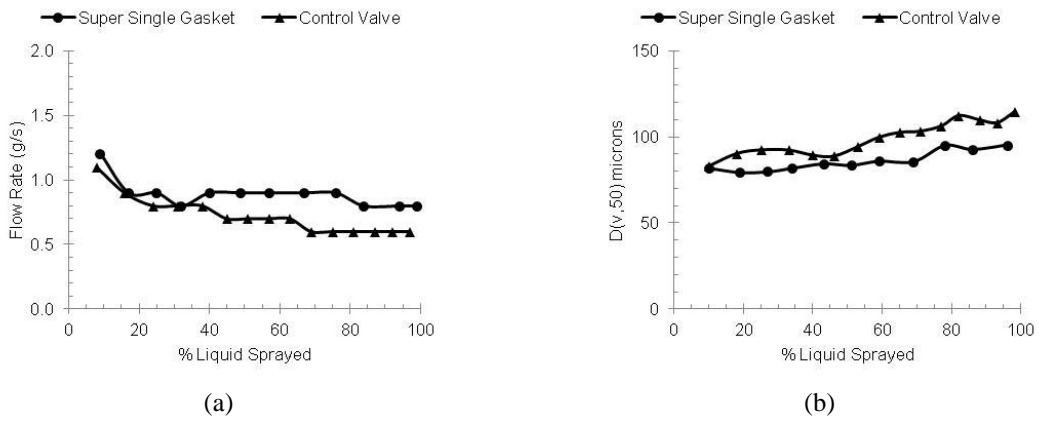


Figure-31: Comparison of spray performance result between ‘super single gasket’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm MBU insert. (a) discharge flow rate and (b) particle size

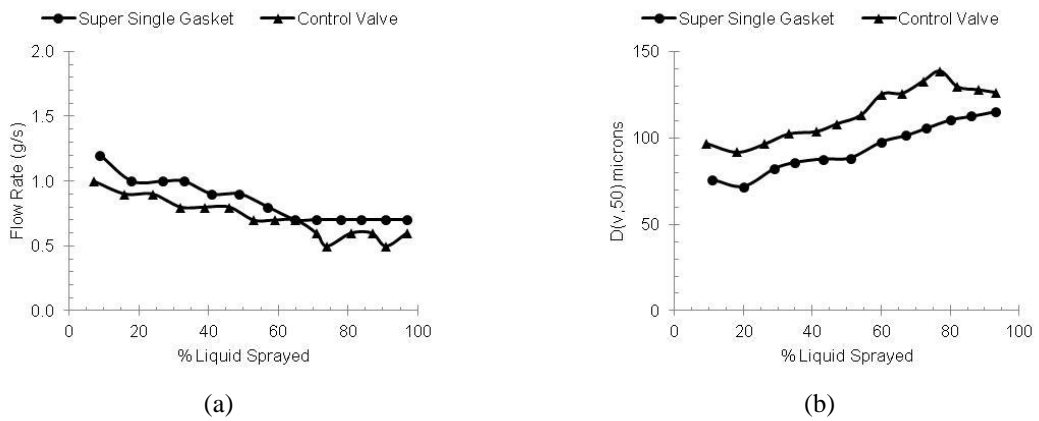


Figure-32: Comparison of spray performance result between ‘super single gasket’ and ‘control valve’ filled with 60% of ethanol, pressurised to 10bar using 0.33mm aqua insert. (a) discharge flow rate and (b) particle size

Conclusion and future work

1. Consumer aerosol valves design has not changed significantly for 50 years and new designs will be required if inert (compressed) gas propellants are to fully replace liquefied gas propellants. The latter release tremendous energy when they flash-vaporise on leaving the aerosol, whilst can pressure is maintained almost steady and fine atomisation is easily achieved, as is producing a near constant product flow rate and drop size during pack life.
 - a) However, all liquefied gases are either VOCs or greenhouse gases; they are increasingly ‘undesirable’.
 - b) Safe compressed gas propellant (e.g. air or nitrogen) provide relatively little atomising energy and the power available reduces as the can empties.
 - i. This makes obtaining fine sprays relatively very difficult.
 - ii. In addition, flow rate and drop size may vary unacceptably during can lifetime when current conventional valves are used.
2. The bleed-off of compressed gas from the can, to assist atomisation and modify flow rate, has been successfully addressed in this investigation by proposing, constructing and testing a range of novel valves and using them with a range of insert sizes and designs.
3. The philosophy behind the valve designs is to separately control the liquid product and bleed-off gas by their own valve arrangements before they combine as a ‘bubbly flow’ in a mixing chamber upstream of the actuator cap and insert. This differs from conventional valves where a VPT may be used upstream of a single conventional gasket valve so that a ‘bubbly flow’ is forced to pass through a single valve.
 - a) The conventional VPT arrangement passes a two-phase flow through small valve stem orifices and a conventional path, which causes pressure losses upstream of the insert and thus reduces flow rate and gives non-optimal atomisation.
 - b) The new valve arrangements do not suffer from the above restrictions.
4. During this study, several new designs of valve with gas injection into a mixing chamber upstream of the actuator and insert have been tested.
 - a) It has been found that these valves spray well, using water, ethanol and a range of ‘real’ liquid products, and when using conventional commercially available swirl-type atomiser inserts.
 - b) The new valves fit into standard valve cups using standard gaskets and crimping methods.
5. The requirement for as steady flow rate and drop size as possible, during the pack life of an aerosol, has been quantified successfully using the new definitions of ‘constancy’ parameters for liquid flow rate, C_Q , and volume median drop size, C_D . Use of these parameters permits quantifying the performances of valve-insert combinations and comparing performances with conventional valves and products.

6. In addition, measurements of several off-the-shelf aerosols and discussions with major consumer aerosol companies has led to chart detailing the desired benchmark performances of compressed gas aerosols for a range of product types.
7. The spraying performance data for the various new valves have shown that the mixing of gas and liquid upstream of the insert has certain benefits during the evacuation of an aerosol can:
 - a) For a given flow rate and gas pressure, drop size achievable is lower than for conventional compressed gas aerosols.
 - b) Constancy values of flow rate and drop size can be made remarkably low (i.e. good), with values achieved at around 10% for both parameters compared with 25–35% for conventional cases.
8. The reason for the achievement of such good constancy is not fully understood and requires a thorough fundamental study:
 - a) It involves complex interactions as the bubbly mixing chamber flow passes through the insert and results in changes of pressure differences set up between mixing chamber, internal can volume and external atmosphere, as a can is emptied.
 - b) For this reason, the combinations of valve design and insert to achieve good constancy at given values of drop size and flow rate, require experimentation and the present study has derived satisfactory combinations for water-based air-fresheners and ethanol-based deodorants.
9. Both size and design of atomiser insert are very important for flow rate and drop size, and for their constancy values.
 - a) In a particular example, a 0.33mm exit orifice ‘MBU CO₂’ type insert gave better performance than a 0.33, ‘aqua’ type inserts, where the former has relatively abrupt internal corners and no swirl chamber before the exit and the latter is more contoured internally and has a swirl chamber.
10. The different valves for compressed gas aerosols are as follows, with their pros and cons given in each case:
 - a) ‘Bi-valves’ have separate gasket valves for allowing gas and liquid into a mixing chamber.
 - i. They are easy to construct in the laboratory but relatively complex and bulky, and thus relatively costly, if injection moulded.
 - ii. They offer full flexibility in the numbers, positions and size of liquid and gas inlet sizes and thus a relatively large number have been made and tested thus exploring a wide range of flow rates and drop size.

- b) ‘Super single gasket’ (SSG) valve which has a single conventional gasket and the liquid and gas holes of the stem slide past the gasket and into separate liquid and gas feed zones where the zones are separated by an annular ridge on the internal wall of the valve housing.
 - i. The design is simple and easily mass manufactured by injection moulding.
 - ii. One additional component is required compared with conventional valves (a bottom part of the valve housing); however, this may be solvable by further design effort.

Future works

Fundamental study of the formation and properties of the ‘bubbly flow’ systems possibly including the use of ‘scale up’ experiments could be part of the future study. In addition, the application of computational fluid dynamics to the flow in the can-valve-insert system needs further investigation. Moreover, further work could include the understanding of how the properties of the two-phase flow leaving an insert affects atomisation quality and also how the internal insert geometry affects the spray. Exploring the use of the valves in bag-in-can or bag-on-valve systems could also provide wide applicability of the new valve presented throughout this paper.

Declaration of Conflicting Interests

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References

1. Swithenbank J. *Characterisation and evaluation of a CFD model of effervescent atomisation*. Swithenbank J, GR/L74460/01.
2. Catlin CA and Swithenbank J. Physical processes influencing effervescent atomiser performance in the slug and annular flow regimes. *Atom Sprays* 2001; 11: 575.
3. Kuta TJ, Plesniak MW and Sojka PE. Entrainment control for ligament controlled effervescent atomiser sprays. *Atom Sprays* 2003; 13: 561.
4. Bush SG and Sojka PE. Entrainment by conventional effervescent sprays. *Atom Sprays* 2003; 13: 605.
5. Lefebvre AH. *Atomisation and sprays*. New York: Taylor & Francis, 1989.
6. Asmuin. *Investigation into novel matched valve-actuator atomiser insert design for compressed gas aerosol*. PhD Thesis, University of Salford, Manchester, January 2011.
7. Burby ML, Nasr GG, Hawthorne G, et al. Novel aerosol insert design utilising inert compressed gas. *Atom Sprays*, 2014.
8. Nasr GG, Yule AJ and Burby ML. *Spray discharge assembly*. Patent no. WO2011/061531, April 2011.
9. Nasr GG, Yule AJ and Burby ML. *Aerosol spray device*. Patent no. WO2011/128607, April 2011.

10. Nasr GG, Yule AJ and Burby ML. *Low loss valve*. Patent no. WO2011/061481, April 2011.
11. Nasr GG, Yule AJ and Burby ML. *Liquid dispensing apparatus*. Patent no. WO2011/042751, April 2011.
12. Nasr GG, Yule AJ and Burby ML. *Liquid dispensing apparatus*. Patent no. WO2011/042752, April 2011.
13. Nourian A. *Next generation of consumer aerosol valves using inert gases*. PhD Thesis, University of Salford, Manchester, March 2013.
14. Weston TE, Willow BL, Dunne ST, et al. *Flow discharge valve*. Patent no. PCT/WO 90/05580, 1989.
15. British Aerosol Manufacturer's Association (BAMA). *Aerosol the inside history*. Hertfordshire, UK: BAMA, 2001.
16. http://www.bama.co.uk/the_history_of_aerosols/ (accessed 20 April 2012).
17. Yerby T. *Aerosol valves*. Precision Valve Corporation, Aerosol 101, March 2012.

Notation

C_D	particle size constancy (%)
C_Q	discharge flow rate constancy (%)
$D_{(v,50)}$	mean median diameter (μm)
F	fill ratio (%)
P	pressure (bar)
P_{atm}	atmospheric pressure (bar)
P_C	mixing chamber pressure (bar)
P_G	gas pressure (bar)
P_L	liquid pressure (bar)
Q_G	volume flow rate of gas during spraying (m^3/s)
Q_L	volume flow rate of liquid during spraying (m^3/s)
V_{atom}	total volume of atomising gas
V_{Can}	total volume of the can
V_{Gas}	total volume of gas during spraying
V_{Liq}	total volume of liquid during spraying