NOVEL AEROSOL INSERT DESIGN UTILIZING INERT COMPRESSED GAS

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Original Manuscript Submitted: 6/12/2013; Final Draft Received: 5/20/2014

Household aerosols are self-contained handheld devices for spraying products such as air fresheners, hairspray, surface cleaners, polishes, and deodorants. Industrial aerosols are similar devices for spraying: cleaners, lubricants, paints, and adhesives. They also have hospital and specific medical uses for spraying coagulants and disinfectants. Worldwide around 20 billion devices are manufactured annually and the UK has a major share of this market, manufacturing 5 billion units, second only to the USA. Led by the Californian Air Resources Board (CARB) in 2001, there is mounting pressure for the use of liquefied gas propellants (volatile organic compounds) in aerosol cans to be banned. This paper addresses the challenges of creating a fine spray using a pressurized inert gas (non-VOC) as the propellant for household aerosols. The spray produced has to achieve a relative performance to that of a traditional fine spray VOC propellant aerosol with regard to droplet size, reach, cone angle, and flow rate. The findings of this work have demonstrated that to achieve a sub-50-µm (Dv,50) spray is extremely challenging when using compressed inert gas and single fluid alone. However, by bleeding air into the insert arrangement, a spray of 24 µm (Dv,50) can be obtained and this is comparable in droplet size to that produced by a traditional fine spray VOC aerosol.

KEY WORDS: aerosol, insert, Malvern, two-fluid atomizer, non-VOC

1. INTRODUCTION

One of the major contributing factors to world pollution today is the use of hydrofluorocarbons (HFCs), which are commonly used as a propellant in domestic household aerosols. Globally, there are around 20 billion devices manufactured annually and the UK has a foremost share of this market (BAMA Report, 2006), manufacturing 5 billion units, which is second only to the United States.
1.1 Aerosol Propellants

Propellants used in aerosol cans be divided into two categories, a liquefied propellant, such as a volatile organic compound or a compressed gas (which this paper addresses), such as nitrogen, air, or carbon dioxide. The propellant ingredients in an aerosol can also differ for each product and are dependent on the function of the product being sprayed, for example, hairspray, deodorant, air freshener, etc.

One of the first popular volatile organic compound (VOCs) aerosol propellant used in aerosol sprays was chlorofluorocarbons (CFCs), such as trichlorofluoromethane (F11), dichlorofluoromethane (F12), and dichlorotetrafluoroethane (F14). CFCs were initially used as an aerosol propellant because they are nonflammable, stable, low in toxicity, and extremely safe under normal conditions of use. This same stability means that they are not destroyed in the troposphere, but instead, drift upwards to the stratosphere where they are broken down by the strong sunlight. This releases chlorine (Cl), which adds to the natural depletion cycle of ozone.

In the mid-1970s there was concern over the use of fluorocarbons, as it was found to adversely affect the ozone layer. In 1997 the Montreal Protocol called for the elimination of CFCs and today, almost all aerosol cans contain alternative propellants, such as HFCs. Some of the propellants used are butane, methylene chloride, nitrous oxide, o-phenyl phenol, propane, trichloroethane, or trichloroethylene.

HFCs (volatile organic compounds) were a replacement for CFCs, as they do not contain any chlorine and so do not deplete ozone. However, HFCs do release hydrocarbons, which ultimately contribute to the greenhouse effect. With continued environmental pressures to lower the quantity of greenhouse gases, the use of HFCs in aerosol cans will also be banned eventually and alternative nonvolatile organic (non-VOC) propellants will have to be used.

The predicted move to non-VOC propellants presents a number of challenges to the industry, as non-VOC sources, such as compressed air, have limited energy when compared to HFCs. Therefore to ensure comparable atomization quality to that of traditional propellants over the life of the can, novel insert and valve arrangements will have to be designed for the aerosol industry. It is in this paper that three types of aerosol insert designs will be discussed:

1. a single-piece atomizer insert, swirled and nonswirled (liquid only);
2. a multiple atomizer insert with flow features (liquid only);
3. and a multiple atomizer insert with air injection (two fluid).

1.2 Challenges

Figure 1 compares how can pressure varies over the duration of the can life for a conventional HFC can and a non-VOC can utilizing compressed air. As shown in Fig. 1, for the
FIG. 1: Can pressure bar against time.

can filled with butane, a relatively constant gas pressure, typically 4–5 bar, is maintained through the life of the can, thus being able to provide a relatively constant energy source and thus flow rate throughout the can life (Nasr et al., 2002). The other benefit that arises from using HFC as a propellant is the energy content through the flash vaporization of the liquid propellant as it is exposed to atmospheric pressure as it exits the nozzle. This immediate release of energy through vaporization aids in atomizing the product that is carried with the propellant.

For a non-VOC propellant, such as compressed air, the pressure within the can drops significantly through the life of the can. This is due to the air volume within the can increasing as the product is consumed and thus reducing the pressure within the can. This results in a reduction in the energy and ultimately the atomization quality of the spray.

The challenges in designing a compressed aerosol can using a non-VOC propellant, such as compressed air, is to maintain adequate pressure within the can for as long as possible. Typically the pressure in the can must remain above 3.5 bar to ensure a suitable atomization quality over the life of the spray and to also ensure that there is sufficient gas pressure to empty the can of product.

Additionally, depending on the application of an aerosol spray, as shown in Table 1 there are a number of performance criteria to be met, these being (i) flow rate through the life of the can, (ii) droplet size through the life of the can, (iii) penetration (throw), and
TABLE 1: Performance targets for a range of aerosol products

<table>
<thead>
<tr>
<th>Product</th>
<th>Usual base liquid</th>
<th>Liquid flow rate full can (mL/s)</th>
<th>Volume median diameter $D_{v,0.5}$ (full can, µm)</th>
<th>Reach (mm)</th>
<th>Spray angle (degrees) &amp; patternation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deodorants (body sprays)</td>
<td>Water or ethanol</td>
<td>0.4+</td>
<td>30–40</td>
<td>500+</td>
<td>20+ Full or hollow cone</td>
</tr>
<tr>
<td>Air care (air fresheners)</td>
<td>Water</td>
<td>1.2+/– or 0.6+</td>
<td>40–50+</td>
<td>800+</td>
<td>20–30? Full cone preferable</td>
</tr>
<tr>
<td>Hairspray</td>
<td>Ethanol</td>
<td>0.3–0.4</td>
<td>35–45</td>
<td>300</td>
<td>20+</td>
</tr>
<tr>
<td>Insecticide (pest control)</td>
<td>Water</td>
<td>3.0+ or 1.5+</td>
<td>25–30 or 40–60</td>
<td>2000+</td>
<td>20–30 Full cone preferable</td>
</tr>
<tr>
<td>Disinfectant (surface treatment)</td>
<td>Water</td>
<td>1.10–1.60</td>
<td>85</td>
<td>150+</td>
<td>30–50 Full cone preferable</td>
</tr>
<tr>
<td>Polish (furniture)</td>
<td>Water (but emulsified giving high viscosity)</td>
<td>0.86–1.15</td>
<td>150+?</td>
<td>500</td>
<td>25–30 Full or hollow cone</td>
</tr>
</tbody>
</table>

(iv) cone angle. For the work presented within this paper, the product flow rates used in the investigation primarily concentrated around the hairspray, air freshener, and polish range.

2. TRADITIONAL AEROSOL CAN DESIGN

2.1 Fine Spray

An aerosol spray is categorized as a fine spray when the mass median diameter $D_{v,50}$ is less than 70 µm. This is satisfactory for water mist fire suppression, some coating applications, and for oil burners, while for humidification applications a fine spray would be defined as $D_{v,50} < 35$ µm and in medical inhalation applications a $D_{v,50} < 15$ µm and ideally $D_{v,50} < 10$ µm. It is also defined in a number of applications such as materials synthesis, drugs, nuclear reactor safety, multiphase combustion processes, pollution formation, and flue gas cleaning (Nasr et al., 2002).

Until recently it has been generally thought that when an atomizing gas cannot be used to produce a fine spray, swirl “hollow cone” atomizer inserts are the choice for giving good atomization. However, evidence (Asmuin, 2011) now indicates that at low flow rates (<6 mL/s) using small orifices (between 0.3 and 0.5 mm), very fine sprays
can be produced at least as well via turbulence generated in the atomizer, and also by bubble generation by cavitation. This is of fundamental interest for applications that are striving for fine atomization with low energy costs, such as gasoline direct injection and, of principal interest here, household aerosols.

In recent projects (Nasr et al., 2011; Asmuin, 2011; Nourian, 2013; Yule, 2003) have studied methods of replacing VOC propellants in aerosol cans while maintaining spray quality. Some of the results have demonstrated the future capability of providing VOC-free aerosols using inert gas propellant through appropriate design of the internal nozzle and valve.

3. INSERT DESIGN

Pressure atomizer inserts are often used in aerosol can and trigger pump sprays and also in the small number of current inert (compressed) gas propellant products (typically polish, sprays that do not required good spray quality).

As shown in Fig. 2, the insert is located in the actuator cap. The insert has channels, which can be nonswirled or swirled, molded into the insert body or in the boss of the actuator. Liquid is fed into the outer parts of these vanes before entering the swirl chamber. This imparts a vortex flow, leading to a conical liquid sheet at the exit of the orifice, therefore giving a spray.

In spite of considerable unpublished work by aerosol manufacturers (Yule, 2003; Dumouchel, 1992), it has not been found possible to produce a MMD (mass median diameter) much less than 65 µm at the flow rates required for household aerosol products using liquid only (single fluid). The problem is caused by the reduction in Reynolds number when scaling a swirl atomizer insert down. The conical sheet that breaks up into drops becomes thicker, giving larger drops when falling below a certain value of Reynolds number. Although swirl may be added to other atomization techniques in order to change spray angle, the “classical” swirl atomizer insert is not a solution to the present problem.

It is noted that microswirl atomizer insert arrays, made using microelectromechanical system (MEMS) technology, have been successfully introduced (Yule et al., 1997) in gas turbine combustion, but the use of around 100 bar liquid pressure maintains the Re number at high enough values to give thin liquid sheets.

Atomizer inserts disintegrate a bulk of liquid with different viscosities and flow rates. This can be achieved with “liquid only” or by introducing air into the fluid, “two-fluid atomizer.” There are three main inserts designs that can be used to produce breakup:

1. plain orifice atomizer insert;
2. pressure swirl atomizer insert;
3. effervescent atomizer insert.
3.1 Plain Orifice Atomizer Insert

A plain orifice atomizer insert (no swirl) comprises a small exit hole orifice that passes fluid under a certain pressure. If the liquid velocity is low, the spray produced will be a thin distorted pencil. When the liquid pressure exceeds the ambient gas pressure by about 1.5 bar, a liquid jet is formed into an atomized spray (Singh et al., 1998). A major consideration in the design of a plain and swirl atomizer insert is pressure losses, as this will affect the discharge coefficient. Excessive losses will decrease the effective pressure drop across the atomizer insert and will wastefully dissipate the atomization energy of the can. In this research, plain orifice atomizer insert diameters of between 0.3 and 0.5 mm and with hole depths between 1.5 and 10 mm were tested.
3.2 Pressure Swirl Atomizer Insert

Pressure swirl atomizer inserts are used for high-viscosity liquid sprays and household aerosol sprays. They convert the pressure energy of the liquid into kinetic energy and increased liquid velocity. As shown in Fig. 2 and Table 2, the swirl atomizer designs consist of tangential passageways that feed a central exit orifice in a disk compartment of the atomizer insert. The tangential velocity component of the liquid velocity gives

**TABLE 2: Singlefluid inlet arrangements**

<table>
<thead>
<tr>
<th>Inlet Arrangement</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two inlets (nonswirled)</td>
<td>![Diagram of Two inlets (nonswirled)]</td>
</tr>
<tr>
<td>Three inlets (nonswirled)</td>
<td>![Diagram of Three inlets (nonswirled)]</td>
</tr>
<tr>
<td>Two inlets (swirled)</td>
<td>![Diagram of Two inlets (swirled)]</td>
</tr>
<tr>
<td>Three inlets (swirled)</td>
<td>![Diagram of Three inlets (swirled)]</td>
</tr>
</tbody>
</table>
the possibility of pumping pulsating energy into the turbulent flow (Lefebvre, 1989). This occurs when the air core within the atomizer fluctuates due to the interaction of the helical waves set up by the tangential inlet water and the precessing air core. These localized pulsations of the air core result in variations in the local film thickness profile along the sheet, which ultimately affects droplet breakup. It is generally accepted that the pressure swirl atomizer insert is the most efficient method of producing a fine and well-dispersed spray using pressurized liquid for a given flow rate.

3.3 Effervescent Atomizer Insert (Two Fluid)

Effervescent atomization is the process of introducing gas bubbles into a liquid flow immediately upstream of the exit orifice, thereby forming a two-phase flow. One form of effervescence is in the form of supercritical injection, whereby the gas is dissolved in the bulk fluid, thus creating a flashing fluid. The other method is to introduce low-velocity gas, like air into the flow, which then creates bubbles within the atomizer. As the pressure decreases toward the exit of the orifice the bubbles grow, thus squeezing the liquid into thin sheets and ligaments. At the orifice exit the bubbles then explode, thus helping to shatter the thin sheet and ligaments into a well-atomized spray (Yule et al., 2000; Babitskill, 1974).

Researchers and engineers have studied the use of effervescence to reduce droplet sizes in applications such as diesel engines (Koivula, 2000; Soteriou et al., 1995) and aerosol devices (Yule et al., 1998; Rashkovan et al., 2004). For aerosol products a number of valve designs (located inside the can, upstream of the orifice) (Weston et al., 1989) have been developed that are comprised of a series of choked orifices to produce a bubbly flow. However, these blockages may have the effect of producing excessive pressure drops and thus result in an inefficient use of can pressure.

One of the main reasons why effervescent atomization has not been widely adopted in aerosol cans is that the bleed-off of the compressed air in the can has been too great, thus depleting the gas pressure that is used to atomize the product within the can. Also, dispensing the gas and liquid simultaneously and producing the required flow can be complex.

4. EXPERIMENTAL ATOMIZER INSERT DESIGN

The novelty of the work (Asmuin, 2011) presented in this paper is to describe how the use of internal insert geometry can be used to produce a good microspray. The aforementioned atomization methods were used in the design of three insert types:

1. single-piece atomizer insert, swirled and nonswirled (liquid only);
2. multiple atomizer insert with flow features (liquid only);
3. multiple atomizer insert with air injection (two fluid).
All of the designs were tested using high-pressure water (pressurized by air), up to 10 bar, which is the typical can starting pressure for a non-VOC can. For the case of the two-fluid-flow insert, compressed air was injected upstream of the insert.

4.1 Single-Piece Insert Design

The “single-piece” atomizer inserts were made from clear acrylic and were divided into two main categories, swirl and nonswirl, as shown in Fig. 3. This was based upon the liquid inlet arrangement to the swirl chamber. The number of liquid inlet ports were varied during the testing to include two and three for both the swirled and nonswirled designs. The inlets for all the cases were equally spaced circumferentially around the swirl chamber.

The passage length from the swirl chamber was varied from 1.5 to 7.5 mm, and the exit orifice diameter was fixed at 0.25 mm for all cases. The exit orifice diameter was chosen because it is at the lower limit of orifice size that can be used on a commercial aerosol can in order to reduce the chance of blockage (particularly when used for hairspray) and provide the conditions conducive to produce a fine spray.

FIG. 3: Single-insert assembly (liquid only).
4.2 Multiple Insert Design

The second generation of multiple stage inserts were designed for liquid only. The individual disk inserts included a series of internal flow features to alter the turbulent structure within the atomizer design, thus aiding atomization. The inserts were assembled in varying combinations, as shown in Fig. 4, and droplet size measurements were taken over a range of flow rates and pressures. These insert flow features, as shown in Table 3, will be discussed as follows:

4.2.1 Approach Chamber (Part A)

Part A (Table 3) is called upper cylinder (UC) or approach cylinder. It is positioned just after the mixing chamber. It is made from a brass plate with a 25 mm diameter and a
Table 3: Multiple-insert flow modification features

<table>
<thead>
<tr>
<th>Part A</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5mm diameter</td>
<td></td>
</tr>
</tbody>
</table>

Part B

- Straight cylinder, 0.25mm diameter
- 3.8mm diameter

Part C1 & C2

- 1.3mm diameter

Part D

- 2mm diameter

Part E & E3

- Flow Direction
- Star shaped
- Conical protrusion

Part E6

- Conical protrusion
- External disc diameter not shown

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thickness of 1.0 mm. The plate has a hole at the center, with different part A’s having sizes ranging from 0.9 to 1.5 mm.

4.2.2 Throttling Hole (Part B)

Part B (Table 3) is the throttling hole, which is used to reduce the effective flow area within the channel and so accelerate the flow. Two types of throttling hole were used in the designs tested: (i) straight throttling hole and (ii) a throttling hole with divergence.

The throttling hole was made from a brass plate with a 25 mm diameter and 0.5 mm wall thickness. It is labeled a throttling hole because of the position after part A (or upper cylinder). The designs for a range of part B’s consisted of a number of small holes with varying diameters.

4.2.3 Expansion Chamber (Part C)

Part C (Table 3) is known as the expansion chamber and is made from a 25-mm-diameter brass plate. This part was usually located after part B, the throttling hole.

4.2.4 Turbulator Chamber (Part D)

Part D (Table 3) is known as the turbulator, and it is made from a brass plate and is similar to part C. The length of the turbulator is twice that of the expansion chamber. It has a 2 mm diameter hole drilled in the center with a 1 mm depth.

4.2.5 Orifice Channel (Part E)

The final component, part E (Table 3), is the orifice channel. It combines a conical protrusion and a final orifice channel. This part is also called an exit orifice or extension orifice. It is located between the aforementioned chamber and the final orifice. There are five different sizes of orifice channels, part E, E1, E2, E3, and E4, and these are described in the following:

1. Part E has a conical protrusion with a divergence angle of 26°, a hole of 1 mm depth and 0.5 mm diameter, and is drilled through the disk. Part E6 is a reverse of part E, a conical protrusion, and acts as the final orifice.

2. Part E1 has one hole drilled to a depth of 1.0 mm and 0.3 mm in diameter with a conical protrusion inclined at 26° tangentially. The hole continues with a straight hole, 0.3 mm in diameter and 1.0 mm depth. Part E7 is a reverse of part E1.

3. Part E2 has the same characteristics as Part E. The hole is 0.5 mm in diameter and to a depth of 0.5 mm.
4. Part E3 has a conical protrusion inclined at 26° tangentially, with the inlet to the conical protrusion being profiled in the shape of a star. The hole was drilled to a depth of 1.0 mm and 0.3 mm in diameter and then continues with a straight hole, 0.3 mm diameter and to a depth of 1.0 mm.

5. Part E4 has an inclined conical protrusion of 26° and a hole of 0.5 mm in diameter and a hole depth of 0.6 mm.

6. Part E10 is the reverse form of part E4, with a conical protrusion acting as the final orifice.

4.3 Two-Fluid Atomizer Design

For the two-fluid atomizer insert designs the multiple-insert arrangements, as described in Section 4.2, were used along with an additional channel for the injection of compressed air into the mixing chamber. As shown in Fig. 5, the gas was injected perpendicular to the liquid flow and the number of injection ports was also varied during the investigation.

5. EXPERIMENTAL APPARATUS

5.1 Control Board

The steady spray experimental apparatus enabled the liquid, and in the case of the two-fluid insert designs, the gas supply to be independently regulated to the insert. As shown by the schematic in Fig. 6, the control system was comprised of the following: There is a reservoir (1) filled with deionized water and pressurized to 12 bar (maximum) using the regulator on a standard 200 bar compressed air bottle (2). The pressurized liquid is supplied to the insert (4) via 4-mm bore nylon tubes. A rotameter for the liquid (6) and an electronic pressure gauge (liquid) (5) were used to measure the flow rate and supply pressure to the insert, and the flow rate was regulated via a needle valve (7).

For the two-fluid atomizer designs, bourdon pressure gauge (gas) (8) and an electronic pressure gauge (gas) (11) were used to measure the supply pressure. In addition, there was also an electronic flow meter (gas) (9) and rotameter (10) used to measure the supply gas flow rate to the atomizer insert. A needle valve on the gas rotameter was used to control the flow rate of gas.

5.2 Quantitative Measurements

To analyze the spray structure for the insert designs, a number of quantitative measurements were used. A Malvern Mastersizer-X was used to measure the droplet size of the spray produced at a stand-off distance of 200 mm.
FIG. 5: (a) Multiple inserts for “two-fluid atomization” with each device made of brass and (b) an assembled device.

It should be noted that $D_{v,50}$ has been used in this investigation to compare the droplet size data, as it is readily used in the aerosol industry to assess spray quality. The $D_{v,10}$ and $D_{v,90}$ values are also of importance as a percentage of $D_{v,10}$ less than 10 μm represents the potential for inhalables, which has health implications. The $D_{v,90}$ would also be considered, as a greater percentage of larger droplets in the spray will result in “overwetting” due to the longer evaporation times, and this is not considered desirable for most consumer applications. The work presented within this paper is primarily concerned in achieving a $D_{v,50}$ that could be used for fine aerosol spray applications.

The cone angle for the spray was measured from still images of the spray, and the flow rate for the designs was measured directly from the rotameters on the control board. (Timed collection techniques were also used.)

*Atomization and Sprays*
6. DISCUSSION OF RESULTS

The droplet size and cone angles for a range of pressure insert bodies, as described in Section 4, were tested at 9 bar. The insert types tested were:

1. single insert, liquid only (Section 4.1);

2. multiple insert arrangement, liquid only (Section 4.2);

3. multiple insert arrangement, liquid and compressed air (Section 4.3).
6.1 Single Insert

For both the single-insert and multiple-insert, liquid-only designs, the Reynolds numbers, based upon the exit diameter, were in the region of 5000–7000, and so are well above the critical Weber number of 2320, so disturbances should not be damped out, even with an increase in chamber length.

For the single-insert design, a range of exit orifice and chamber lengths were used during the tests, along with flow rates ranging from 1.2 to 3.0 mL/s (at 9 bar). For the single-insert, liquid-only designs, the results showed that the various arrangements primarily produced highly collimated jets, as shown in Fig. 7(a), with narrow cone angles.

**FIG. 7:** Single insert (liquid only).
of around 5°, especially with the two-inlet-port arrangement. By increasing the number of port inlets, the spray cone angle was increased to around 15° [Fig. 7(b)], especially at the lower length-to-diameter ratios.

As shown in Fig. 8 (100 mL/min), it was found that by reducing the length/diameter ratio for the three-inlet-port arrangement, the droplet size decreased, with breakup occurring closer to the nozzle exit. At increased passageway length-to-diameter ratios, the droplet size did increase and this could be attributed to an increase in frictional losses due to increased passageway length, thus reducing the amount of swirl and increasing the film thickness.

At the reduced length-to-diameter ratio for the two-inlet port arrangement, the droplet size is larger when compared with that of the equivalent three-inlet port arrangement. This could be attributed to the larger pressure drop across the two-inlet port into the swirl chamber, thus resulting in a reduced pressure drop across the exit office and a reduction in energy for atomization. At increased chamber lengths the droplet size reduces, which is contrary to the three-inlet port case. This is probably due the frictional losses due to the extra length being offset by the initial higher inlet velocity into the swirl chamber and the film being stretched and thinned through the chamber. For all the designs tested, the droplet sizes were above 100 µm, $D_{v,50}$. Though this may be acceptable for products like polish, the droplet size produced using single inserts cannot be considered to be within the category of a fine aerosol device.

![FIG. 8: Single insert (liquid only).](image)
6.2 Multiple Insert, Liquid Only

A number of multiple-insert geometry arrangements, as described in Section 4.2, were tested using liquid only at 9 bar and at a range of liquid flow rates that spanned the aerosol product market. As can be seen from Fig. 9, which shows liquid flow rate against droplet size, the size of droplets varies from 62 to 170 µm, $D_{v,50}$.

With the inclusion of multiple flow features, the droplet size has been significantly reduced when compared with the single-insert arrangement. The designs produced full cone sprays, as shown in Fig. 10, with narrow spray angles of between 25° and 40°. These narrow cone angles are typically not achievable with swirl mechanical breakup units (MBUs).

With the inclusion of swirl inserts, as expected, the cone angle was increased from around 25° to 40° for a number of the designs; this also aided in reducing the droplet size. It should be noted that even at the relatively high flow rate of 4 mL/s it was still possible to produce a 62-µm $D_{v,50}$ droplet size. Even though the droplet size has been improved, the droplet size is still too high for most fine aerosol products.

6.3 Multiple Insert, Two Fluid

6.3.1 Flow Features

As demonstrated for the liquid-only case, flow features within the insert can improve atomization. However, to create a fine spray it was deemed necessary to inject air (which

![FIG. 9: Multiple insert (liquid only).](image-url)
would be bled from the aerosol can) into the liquid flow, upstream of the multiple-insert arrangement. The Reynolds numbers for the liquid and gas designs were above 5000, thus high enough to create conditions for bubbly flow, whereby the turbulent forces in the liquid phase overcome the gas–liquid interfacial tension, thus creating a bubbly flow.

It should be noted that the nature of the bubbly flow within the stem and the insert has yet to be quantified with regard to the two-phase regime that is being experienced in the valve assembly. Understanding the flow regime is further complicated by the fact that the air is injected into a vertical valve arrangement and then passes through 90° prior to being discharged from an insert. Future work will explore the nature of this two-phase flow regime within the valve.

The design rationale behind the geometrical insert arrangement is to enhance the two-phase flow in the following ways. As shown in Fig. 11, liquid would flow through the liquid inlet (a) into the flow channel (b). It is then mixed with gas coming from the compressed air (c) at the mixing chamber. The gas inlet is perpendicular (90°) to the liquid inlet. The mixing of the gas with the liquid in the mixing chamber creates bubbly flow, which passes through a jetting orifice from which the bubbly flow passes through an outlet expansion chamber (d). This produces turbulent bubble-laden jets, which impact on the sharp edges (e) at the outlet of the expansion chamber (d). The throttling hole can be offset away from the center line rather than might be expected by simply protecting the throttling hole in the orifice channel.

The combination of the bubble-laden jets and their impact on the sharp edge together give flow separation from the interior surface of the orifice channel (f). The length of the orifice channel is such that the flow reattaches to the wall in the downstream region (g), so that a new bubble starts to form before the jet finally discharges at the exit orifice.
FIG. 11: Operation of bubbly flow jets from the throttling hole in the atomizer insert.

The size and distribution of the bubbles will vary as they progress downstream toward the exit orifice. The size of the bubbles is likely to increase due to a reduction in pressure downstream; however, the increased level of turbulence produced by the flow features will increase the inertial forces of the turbulent eddies, thus overcoming the surface tension of the bubble, resulting in a reduction in bubble size.

It should be noted that the jets from the throttling hole (h) also provide the following phenomena:

1. They produce localized high velocity at the inlet edge, which increases the size of the separated flow region inside the orifice channel (f).

2. They also increase the turbulence level of the bubbly flow, which increases the unsteady separation and reattachment of the separation zone in the orifice channel.

3. They cause further breakup of the bubbles.

The pressure for this bubbly flow approach should be between 1 and 20 bar, but for a selected consumer aerosol can, the pressure should be between 4 and 12 bar. The
quantity of gas bled through gas inlet (c) is around 4–8 times the liquid volume (using atmospheric conditions). The higher the amount of gas that is bled will cause the can pressure to reduce quickly, resulting in only liquid remaining in the can after the entire can pressure has been depleted.

Figure 11 illustrates the throttling hole (h), which extends parallel to the axes of expansion chamber (d) and flow channel (f). However, the throttling hole bends at a small angle (e.g., up to 30°) with respect to the axial direction. This feature could be used to increase the “cone angle” of the spray, especially the angle between the boundaries of the spray, near the exit orifice. This “cone angle” will increase when the angle of inclination of throttling hole (h) is increased but in an unpredictable way.

6.3.2 Gas Liquid Ratio
The multiple-insert combinations were tested at a range of liquid and air flow rates and the corresponding droplet sizes were measured. From this, the results were inputted into D-plot (a 3D analysis package) to produce isocontours of droplet size for a range of fluid flow rate and gas/liquid ratios (volume basis). By plotting the results in this format, it provides a useful tool to enable the gas/liquid ratio to be chosen to achieve a particular flow rate and or droplet size combination.

For the devices a wide range of gas/liquid ratios were chosen, from 2/1 up to 235/1, in order to establish the envelope for the various insert arrangements. As shown in Fig. 12, as expected the droplet size does decrease with an increase in gas/liquid ratio. Though the results illustrate droplet sizes of 18–48 µm ($D_{v,50}$), which covers a range of aerosol applications (Table 1), the gas/liquid ratios are too high and unrealistic for aerosol can applications. At these gas flow rates, the gas pressure would be depleted prior to the product being exhausted from the can. This therefore raises the question of the ideal gas/liquid ratio and is discussed in the next section.

6.3.3 Fill Ratio
The limitation on the amount of air that can be bled from the can is based upon the fill ratio (volume of liquid product to volume of the can) and the pressure rating of the can. For most manufacturers a ratio of 40% is the minimum when using compressed air. Therefore the maximum volume available for compressed air is 60%. The second limitation is the maximum pressure rating for the can. For compressible aerosol devices, a 12-bar-rated can would be used. This would enable the gas to be pressurized to 9–10 bar. Higher pressure rated cans are available, such as 18 bar, but most aerosol manufacturers are reluctant on going to these high pressures because of cost implications.

The amount of gas available for atomization can be calculated by considering a typical aerosol can with a start pressure of 9 bar. If an average liquid flow rate is assumed and an average atomizing gas flow rate, where the gas is bled from the can during spraying, a fill ratio $F$ (%) (liquid to can volume) can be defined as
FIG. 12: $D_{v,50}$ of liquid flow rate against (high) gas-to-liquid ratios.

\[ F = \frac{V_{liq}}{V_{can}} \times 100 = \frac{V_{liq}}{(V_{gas} + V_{liq})} \times 100 \]  

(1)

The value of $F$ can be chosen by the manufacturer; typically it is around 50\%. The initial can pressure $P_1$ can also be chosen, being limited according to the type of can. The pressure $P_2$ when the can has just been emptied of all liquid must be at least a certain order (typically 2.5–4 bar) to achieve acceptable spray performance toward the end of the product. This also depends upon the atomizer insert design. It is important to recall that the gas volume used for atomizing is calculated at atmospheric conditions.

The initial gas volume in the can $V_{gas}$ is defined at the initial gas pressure $P_1$ (gauge), so that this gas volume, if it were at atmospheric pressure, would be equal to $V_{gas}[\{(P_1 + 1)/P_{atm}\}]$. Similarly, the volume of gas in the can when the can has just been emptied of liquid, at atmospheric pressure, equals $V_{can}[\{(P_2 + 1)/P_{atm}\}]$.

So the volume of gas, at atmospheric pressure, that has been bled off for atomizing is

\[ V_{atom} = V_{gas} \left( \frac{P_1 + 1}{P_{atm}} \right) - V_{can} \left( \frac{P_2 + 1}{P_{atm}} \right) \]  

(2)

where $V_{can} = V_{gas} + V_{liq}$. 

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By dividing both sides of Eq. (2) by $V_{\text{liq}}$ and using Eq. (1) to substitute for $V_{\text{gas}}$ in Eq. (2), the following expression can be obtained:

$$\frac{V_{\text{atom}}}{V_{\text{liq}}} = \frac{100 - F}{F} \left( \frac{P_1 + 1}{P_{\text{atm}}} \right) - \frac{100}{F} \left( \frac{P_2 + 1}{P_{\text{atm}}} \right)$$

(3)

But this ratio of total volumes sprayed is exactly the same as the ratio of gas and liquid volume flow rates, i.e.,

$$\frac{Q_{\text{gas}}}{Q_{\text{liq}}} = \frac{V_{\text{atom}}}{V_{\text{liq}}}$$

(4)

From Eqs. (3) and (4), a calculation can be made with the available average atomizing gas/liquid volume flow ratio for different initial fill ratio and can pressure, $F$ and $P_1$, respectively, and the final can pressure $P_2$.

By using this analysis on a traditional aerosol can with an initial start pressure of 9 bar and a final can pressure of 2.5 bar, a gas/liquid ratio of 3 is obtained. Manufacturers and consumer products companies are not keen on reducing fill ratios below 50%, nor on using the higher pressure 12 bar cans; however, doing either of these would greatly reduce the design challenges and ensure better spraying through the can life.

Minimizing the pressure value $P_2$ at which the insert still atomizes well is a very important challenge. From the tests conducted, the lowest $P_2$ that can be achieved and still produce a reasonable spray is around 3.5 bar. At pressures below 3.5 bar, the droplet size does increase significantly and if the air bleed is too great, the worst-case scenario is that there is insufficient energy left to expel the entire product. Ideally, there would be little variation in flow rate and droplet size over the life of the can. However, in reality with compressed air cans, droplet size does increase and flow rate drops over the life of the can as the pressure is reduced. Therefore there is a tradeoff between air bleed and the droplet size at the start and the end of the can life.

As shown by the isocontour plots of $D_{v,50}$ in Figs. 12 and 13, to achieve a 3/1 ratio (by volume) of air to liquid while obtaining a droplet size comparable with a VOC propellant is extremely difficult to achieve; therefore higher gas/liquid ratios are required.

As shown in Fig. 14, a typical sample of the numerous geometrical combinations tested at 9 bar has been plotted. The best device produced a $D_{v,0.5}$ spray of 24 µm, which falls within the category of a fine spray. The geometrical arrangement that achieved this droplet size is shown in Fig. 5. The rest of the devices produced droplet sizes which are more suited to larger droplet applications, such as disinfectant surface treatment and air fresheners. The gas/liquid ratio that was used to achieve the droplet size was 4/1. It should be noted that at this ratio there would still be sufficient air pressure remaining to atomize the product at the end of the can life.

At typical flow rates, for products such as body sprays and air care, it was found that without inclining the throttling hole (h), the “cone angle” that was reached was around 20°, as shown in Fig. 15(a), whereas inclining the throttling hole (h) to an angle of 25°
**FIG. 13:** $D_{v,50}$ of liquid flow rate against (realistic gas/liquid ratios) can gas-to-liquid ratios.

**FIG. 14:** Multiple insert (liquid and gas).
produced a “cone angle” of around 30° [Fig. 15(b)] and removed a tendency to a denser spray zone at the center of the spray, especially at lower pressures.

When the throttling hole is set to an angle of 25°–30° to the axial direction, the liquid gains a small amount of swirl through an increase in turbulence of the exiting liquid, thus giving a full cone spray and significantly improving atomization. Basically, this process is different from the “swirl atomizer insert MBU”, which is used in many consumer aerosols.
6.3.4 Can Conditions

The aforementioned tests have concentrated on using the two-fluid atomizer inserts in a way which controls and measures the flow rates of the liquid and of the atomizing gas, as shown in Fig. 16. These pressure values are similar but not exactly the same, as they have been varied using the control board in order to achieve the required flow rates. However, in practice, when the atomizer forms part of the insert in an aerosol can actuator, with the gas and liquid supplied into the bottom of the valve from the can, the supply pressures for the gas and liquid will be (almost) exactly the same.

In the testing so far, a certain (unknown) pressure \( P_c \) is needed in the gas–liquid mixing chamber (internal diameter 1.0 mm) in order to induce a bubbly flow through the insert at certain gas and liquid flow rates, \( Q_g \) and \( Q_w \).

The pressure \( P_c \) cannot be calculated because the pressure drops of bubbly flows through the orifices and chamber of the atomizer insert are too 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 (0.25 mm) and the required gas flow rate \( Q_g \). The liquid (water) injection does not occur through an orifice but rather via a step down from the bore of the supply pipes (3 mm) to the bore of the mixing chamber (1.0 mm). The value required for \( P_w \) is greater than the value of \( P_c \), due to this reduction in bore, and by an amount depending upon the value set for \( Q_w \).

It would be purely a coincidence if \( P_g = P_w \) for a given required combination of \( Q_g \) and \( Q_w \). Therefore it would be useful to measure \( Q_g \) and \( Q_w \) for conditions where \( P_g \) and \( P_w \) are fixed to be equal, because this is the true situation if the atomizer insert is being supplied from an aerosol can, e.g., measure \( Q_g \) and \( Q_w \), for \( P_g = P_w = 2 \) bar, 3 bar, 4 bar, 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 atomization and sprays.

FIG. 16: Schematic of setup for atomizer insert testing.
sprays are produced as a can empties. However, the true practical setup is more complicated, as the bubbly flow must pass through the valve before reaching the atomizer insert. For this reason the orifices in the valve stem should have as large an area as possible so that the valve has a minimum effect on the bubble flow and its pressure drop.

7. CONCLUSIONS

It is generally recognized that the use of compressed air aerosol cans produce significantly inferior sprays over the life of the can when compared with conventional HFC aerosols. In this investigation the spray characteristics of a number of insert arrangements: single insert (nonswirled and swirled), multiple-insert, and two-fluid multiple-insert designs—have been investigated to establish their potential for producing a fine aerosol spray using compressed air as the propellant. The main findings of the investigation highlight that

1. The single-insert arrangement, using liquid only, with a can starting pressure of 9 bar was insufficient in producing a fine spray from using swirl features alone.

2. By suitable arrangement of multiple-insert geometries (liquid only), the turbulence and flow structure produced from the insert can significantly reduce the droplet size to around $60\ \mu m \ D_{v,50}$.

3. By using multiple inserts and injecting air upstream of the internal flow features, bubbly flow further reduces the droplet size to that of a fine spray, to between $24$ and $48\ \mu m \ D_{v,50}$.

4. For a 50% can fill ratio and a starting pressure of 9 bar, a gas/liquid ratio of between 3/1 and 8/1 will ensure that there is sufficient gas pressure to sufficiently atomize the majority of the product over the life of the can and to ensure an empty can. However, it should be noted at the higher gas ratios that the final droplet size at the end of the can, once the pressure drops below 3.5 bar, will significantly increase. Therefore there is a tradeoff between the droplet size at the beginning of the can and the final droplet size at the end of the can.

5. The use of isocontour plots can aid in the design process and selection of gas/liquid ratio and or product flow rates to achieve a certain droplet size.

6. The droplet sizes produced by the two-fluid insert arrangement illustrates that most consumer product aerosol droplet sizes that are currently produced using HFCs can be achieved by using compressed air, yet still expel the entire contents of a 50% full can.
8. FURTHER WORK

This work has highlighted the types of insert arrangements that are conducive to producing a well-atomized spray at typical can pressures for a non-VOC propellant. Further work will involve analyzing the two-phase flow structure within the inserts by using computational fluid dynamics and experimental measurement. The interaction of the valve and insert will also be investigated and the optimized designs will undergo can trials.

REFERENCES


