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Influence of Ambient Air Pressure on Effervescent Atomization

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The influence of ambient air pressure on the drop-size distributions produced in effervescent atomization is examined in this article. Also investigated are the effects on spray characteristics of variations in air/liquid mass ratio, liquid-injection pressure, and atomizer discharge-orifice diameter at different levels of ambient air pressure. It is found that continuous increase in air pressure above the normal atmospheric value causes the mean drop-size to first increase up to a maximum value and then decline. An explanation for this characteristic is provided in terms of the various contributing factors to the overall atomization process. It is also observed that changes in atomizer geometry and operating conditions have little effect on the distribution of drop-sizes in the spray.

Nomenclature

ALR = air/liquid ratio by mass
a = speed-of-sound in two-phase flow
c_v = specific heat at constant volume
D_b = bubble diameter
d_0 = nozzle-exit orifice diameter
E_b = bubble energy
$\dot{m}$ = mass flow rate
p_a = atomizing air pressure
p_c = static pressure in air cavity
p_e = static pressure in exit orifice
q = Rosin-Rammler distribution parameter
R = gas constant
r = ratio of air-to-liquid volumetric flow rates
T = temperature
β = volume flow fraction
γ = ratio of specific heats
Δp = air-injection pressure $(p_c - p_A)$
μ = dynamic viscosity
ρ = density
σ = surface tension

Subscripts
A = ambient air
a = atomizing air
L = liquid
M = two-phase mixture

Introduction

CONVENTIONAL twin-fluid atomizers, e.g., air-assist and airblast atomizers, employ the kinetic energy of a flowing airstream to shatter the liquid jet or sheet into drops. Air-assist atomizers use a relatively small quantity of air flowing at a very high velocity. This is because the air is supplied from a compressor or a high-pressure cylinder and it is important to keep the airflow rate down to a minimum. In contrast, because the air velocity through an airblast atomizer is usually limited to a value corresponding to the available pressure differential across the liner-wall of a combustor, a much larger airflow rate is required to achieve good atomization.[1]

A number of recent publications[2–5] have described a method of atomization which is normally referred to as "aerated-liquid" or "effervescent" atomization. In effervescent atomization, air (or gas) is injected at low velocity into a flowing liquid at some point upstream of the exit orifice. The injected gas flows into a mixing cavity where it creates a bubbly two-phase flow. The basic atomization mechanism has not yet been studied in detail, however, it is believed[3] that since both liquid and atomizing air exit through the same orifice, the area available for the liquid flow is reduced, causing it to be discharged at a higher velocity. At the same time the liquid is "squeezed" by the gas bubbles into thin shreds and ligaments which are further shattered into small drops by the rapid expansion of gas bubbles which occurs immediately downstream of the discharge orifice.

The studies of Lefebvre et al.[2] and Wang et al.[3] showed that an effervescent atomizer can achieve good atomization at very low injection pressures and low air/liquid mass ratios. It was also found that the mean drop-size of a spray produced in effervescent atomization is virtually independent of the exit-orifice diameter. This could be an important advantage for combustion devices in which large holes and passages are desirable to minimize problems of plugging and blockage by contaminants in the fuel. Furthermore, it was found that atomization performance was fairly insensitive to variations in liquid viscosity. Further investigations have revealed that the normal adverse effect of an increase in liquid viscosity is greatly reduced if liquid breakup occurs rapidly, as it certainly does in effervescent atomization.[6] This explains why Buckner et al.[7] were successful in atomizing highly viscous non-Newtonian liquids using an atomizer of this type.

All previous investigations of effervescent atomization have been confined to measurements of spray characteristics under conditions where the air-liquid mixture is discharged into air at normal atmospheric pressure. It is considered desirable to determine whether the advantages offered by effervescent atomization are still present at higher levels of ambient pressure for the following reasons:

1) Before effervescent atomization can be accepted as a practical alternative to the more conventional methods of fuel injection employed in gas turbines, such as pressure-swirl and air-blast nozzles, it is necessary to demonstrate that good atomization can be achieved over wide ranges of combustion pressure.

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2) Information on drop-size distributions is an essential prerequisite for calculations on fuel evaporation rates and various aspects of combustion performance. Furthermore, drop-size data are needed for the successful application of the mathematical models now being developed for describing fuel evaporation and combustion processes.

The main objective of the present study is to investigate the effect of ambient pressure on the mean drop-size and drop-size distributions of sprays produced in effervescent atomization. The effects of variations in air/liquid mass ratio, liquid-injection pressure, and atomizer discharge-orifice diameter on the spray characteristics at different levels of ambient air pressure are also studied.

Experimental

The effervescent atomizer employed in this investigation is illustrated in Fig. 1. It features a single round-exit orifice of the type that has been thoroughly evaluated at normal atmospheric pressure by Whitlow.[8] Although there is little interest in this single-hole design for application to gas turbine combustors (because it produces a too-narrow spray-cone angle) the results obtained can be regarded as representative of multihole atomizers. It is impractical to test a multihole configuration at high pressures because the wide-angle spray that it produces tends to create droplet mists which remain in suspension around the spray and lower the accuracy of drop-size measurements. Moreover, the wide-angle spray tends to deposit liquid on the optical windows which further reduces the accuracy of the results obtained.

In operation, liquid enters at the top of the atomizer and flows downward towards the exit orifice. Air enters the annular space surrounding the mixing tube and passes through small injection holes into the mixing tube to create a two-phase air-liquid flow. This two-phase mixture then flows downward to the exit orifice and is ejected into the ambient air.

The mixing tube and the containment tube are made of clear acrylic to permit visual observation of the internal two-phase flow. The mixing tube has an internal diameter of 6.4 mm and a wall thickness of 1.6 mm. Six rows of four holes, used for injecting air into the mixing tube are drilled through the wall of the mixing tube perpendicular to its axis. Each row is spaced 6.4 mm apart along the length of the tube and rotated 45 deg from its neighbors. The diameter of each injection hole is 0.76 mm. The last row of injection holes is located 51 mm upstream of the exit orifice. The overall length of the atomizer is approximately 140 mm. The atomizer is designed to allow interchangeable exit orifices. Four different orifice diameters, 1.2, 1.6, 2.0, and 2.4 mm, are used in the present study. Each of the four orifices has a length/diameter ratio of 0.5.

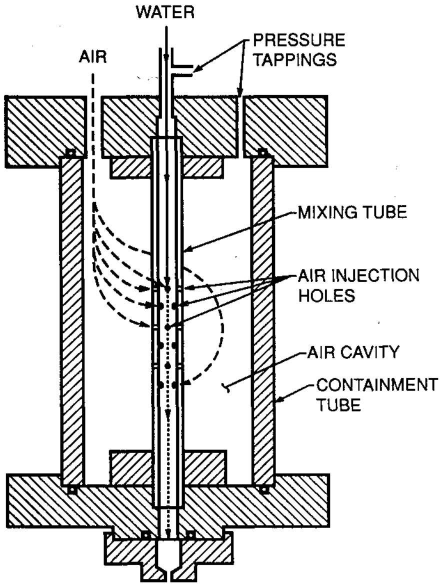

Fig. 1 Plain-orifice effervescent atomizer.

A new atomization test facility, shown schematically in Fig. 2, was constructed for the interrogation of sprays at elevated pressures. The main component is a cylindrical pressure tank which is mounted on a stand with its axis in the vertical position. This tank is made of 347 stainless steel and is rated for a working pressure of 2.2 MPa (315 psia). It is approximately 2.4 m in height and 600 mm in diameter. It is fitted with one pair of 75-mm-diam windows and one pair of 127-mm-diam windows. The 75-mm windows are designed to pass a Malvern laser beam, while the 127-mm ones are for observation purposes.

The atomizer is mounted at the top of the tank and sprays downward. In order for the whole spray to be contained within a distance of 330 mm from the Malvern receiver lens (which is required for accurate measurements by the Malvern instrument) the atomizer is located at a horizontal distance of 180 mm from the receiver window. The drops produced in atomization gravitate to the bottom of the tank, from where the liquid is disposed of through an exhaust system.

The recirculation of fine droplets is kept to a minimum by connecting one air line to a manifold located at the top of the tank which provides a gentle downdraft of air flowing at 0.4–0.6 m/s through the test section. A honeycomb flow straightener ensures a uniform flow velocity across the entire cross section of the tank. The amount of air employed in this manner is such that an increase in the airflow rate no longer changes the mean drop-size of the spray, as illustrated in Fig. 3. The recirculation of fine drops is further reduced by the installation of another honeycomb flow straightener which is located 300 mm downstream of the nozzle exit. In addition

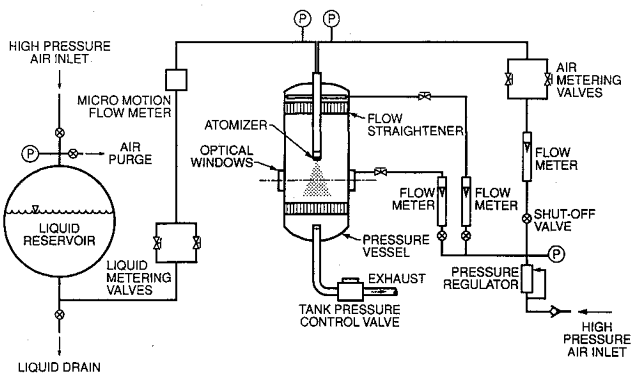

Fig. 2 Schematic diagram of test facility.

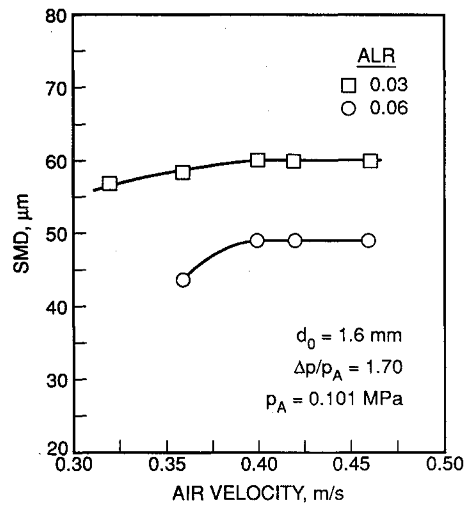

Fig. 3 Influence of downdraft air velocity on mean drop-size.

to the downdraft of air described above, separate flows of air are maintained over the optical and observation windows to further protect them from contamination by the accumulation of small droplets.

The air and liquid flow lines are shown in Fig. 2. High-pressure air is available at 13.8 MPa from storage tanks located near the laboratory. This air supply is regulated to the desired level and then used for atomization, tank pressurization, and window purging. The same supply also provides air to pressurize the liquid storage reservoir. The atomizing air, tank pressurization air, and window-purge air pass through separate air metering systems for each air flow. All three air flow rates are measured using Brooks rotameters, while air pressures are measured on Duragauge pressure gauges.

Liquid is stored in a 83-l stainless-steel pressure reservoir which is pressurized to the desired level using air. The liquid passes through a number of valves, pressure gauges, and flow meters to provide the desired nozzle operation conditions. Liquid flow rate is measured using a Micro-Motion mass flow meter (model D12-SS). This instrument directly measures the amount of mass flowing through the meter; variations in temperature, pressure, and viscosity do not affect its measurement. Liquid-injection pressure is measured just prior to entering the pressure tank using a Duragauge pressure gauge (0–2.2 MPa). The ambient air pressure within the tank is measured using a standard Bourdon-tube pressure gauge and is maintained constant using a pneumatic back-pressure valve located in the exhaust line.

A Malvern 2600 particle sizer fitted with a 300-mm lens is used for quantitative measurements of drop-size distributions. The principles of operation and limitations of this instrument are well established (e.g., Swithenbank et al.[9] and Dodge[10]). Drop-size distributions are characterized by the Sauter mean diameter (SMD) using the two-parameter Rosin-Rammler[11] model which is defined as

$$Q = 1 - \exp - (D/X)^q \qquad (1)$$

where Q is the fraction of the total volume contained in drops of diameter less than D, and X and q are constants for a given drop-size distribution. The exponent q in Eq. (1) provides a measure of the spread in drop-sizes. The higher the value of q, the narrower the size distribution. For pressure-swirl atomizers the value of q generally lies between 2–4 depending on the liquid used and the operating pressure. Airblast atomizers tend to have values of q ranging from 1.5 to 3.

Drop-size measurements are carried out at a distance of 150 mm downstream of the nozzle with the laser beam passing through the centerline of the spray.

Test Conditions

All tests are carried out using water having the following properties; $\mu = 0.001$ kg/ms, $\sigma = 0.0734$ kg/s^2, and $\rho = 1000$ kg/m^3. Water was selected for this study, partly for reasons of low-cost and convenience, but also because its viscosity is close to that of aviation kerosene. Therefore, the drop-size data acquired in this investigation may be regarded as representative of most jet fuels. The ranges of liquid-injection pressure, ambient air pressure, air/liquid mass ratio, and discharge-orifice diameter covered in this investigation are indicated in Table 1.

Table 1 Test conditions

Parameter	Range
Ambient pressure p_A	0.101–0.790 MPa (14.7–114.7 psia)
Injection pressure/ambient pressure ratio $\Delta p/p_A$	1.36, 1.70, 2.04
Air/liquid mass ratio ALR	0.01–0.12
Discharge orifice diameter d_0	1.2, 1.6, 2.0, 2.4 mm

Measurements of pressure were made in the exit plane of the final discharge orifice (p_e) and in the upstream air cavity (p_c) for several different air/liquid ratios, liquid-flow rates, and cavity pressures. It was found that, unlike a single-phase gas flow, the critical value of p_c/p_e above which the flow is choked varies with the flow conditions upstream of the discharge orifice, and the ratio of the air volumetric flow rate to the liquid volumetric flow rate. It was observed that the critical value of p_c/p_e is a unique function of the ratio a/r, where a is the speed-of-sound in the bubbly mixture and r is the ratio of the air volumetric flow rate to the liquid volumetric flow rate. We have

$$r = \text{ALR}\ \rho_L/\rho_a \qquad (2)$$

$$a^2 = (p/\rho_M)[(1/\beta) + (p/\rho_M c_{v_M} T)] \qquad (3)$$

where ρ_M is the density of the mixture which is given by

$$\rho_M = (1 - \beta)\rho_L + \beta\rho_a \qquad (4)$$

The specific heat of the mixture at constant volume is obtained as

$$c_{v_M} = (1 - k)c_{v_L} + kc_{v_a} \qquad (5)$$

where k is the ratio of the air mass flow rate to the total mass flow rate, i.e.

$$k = \frac{\dot{m}_a}{\dot{m}_a + \dot{m}_L} \qquad (6)$$

Equation (3) was derived under the following assumptions: 1) the liquid and the air have the same velocity and temperature; 2) the liquid may be considered as an incompressible fluid and the air as a perfect gas; 3) the mixture is homogeneous; and 4) the flow is one-dimensional, steady and adiabatic.

It may be noted that when no liquid is present in the atomizer, $\beta = 1$, $c_{v_M} = c_{v_a}$, and Eq. (3) reduces to the well-known expression for sonic velocity in a single-phase flow

$$a^2 = \gamma p/\rho \qquad (7)$$

The relationship between p_c/p_e and a/r is shown in Fig. 4. It can be expressed numerically as

$$p_c/p_e = 0.50(a/r) + 1.63 \qquad (8)$$

The above equation may be used to determine whether or not the discharge orifice is choked. If the value of p_e calculated from Eq. (8) exceeds the local ambient air pressure p_A, this

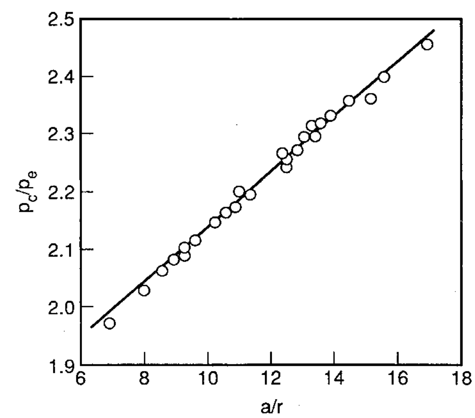

Fig. 4 Relationship between nozzle pressure ratio and upstream flow conditions.

is a sure indication that the atomizer is operating under choked exit-flow conditions.

The relationship between p_e and p_A is illustrated in Fig. 5 for four different values of ALR and a constant $\Delta p/p_A$ of 1.36. This figure shows that the ratio p_e/p_A declines with increase in p_A until it becomes unity. At this point the nozzle is no longer choked and p_e remains equal to p_A at all higher levels of ambient air pressure. Of special interest in Fig. 5 is that the value of p_A at which it becomes equal to p_e, increases with increase in air/liquid ratio. This result is important because it helps to explain the results obtained on the influence of ambient air pressure on mean drop-size, as illustrated in Fig. 6 for the same values of ALR and $\Delta p/p_A$ that were used in calculating the p_e/p_A ratios shown in Fig. 5. For most atomizers in which air is used to shatter the liquid into droplets, an increase in ambient air pressure usually leads to a reduction in mean drop-size. This in only to be expected since Weber number is directly proportional to air pressure. However, Fig. 6 shows SMD increasing with increase in ambient air pressure until a maximum value is reached beyond which any further increase in p_A causes the SMD to decline. This unusual relationship between SMD and p_A was also observed by Wang and Lefebvre[12] in their study on the effect of ambient air pressure on the mean drop-sizes produced by pressure-swirl atomizers. These workers linked the initial increase in SMD with increase in p_A to contraction of the spray-cone angle, as noted in previous studies on the effects of ambient pressure on spray characteristics by De Corso and Kemeny[13] and Ortman and Lefebvre.[14]

When a spray is formed at the outlet of a pressure-swirl atomizer, the larger drops penetrate farther radially than the smaller droplets. This causes the drops to be distributed radially from smaller drops at the center of the spray to larger drops at the edge. As the spray contracts with increase in ambient air pressure, the liquid volume fraction becomes distributed in a smaller circle. However, the diameter of the Malvern laser beam remains constant at 9 mm, with the result that a reduction in spray-cone angle increases the proportion of large drops in the sampling volume and the instrument indicates an increase in SMD even if, in fact, the SMD is unaffected by change in cone angle.

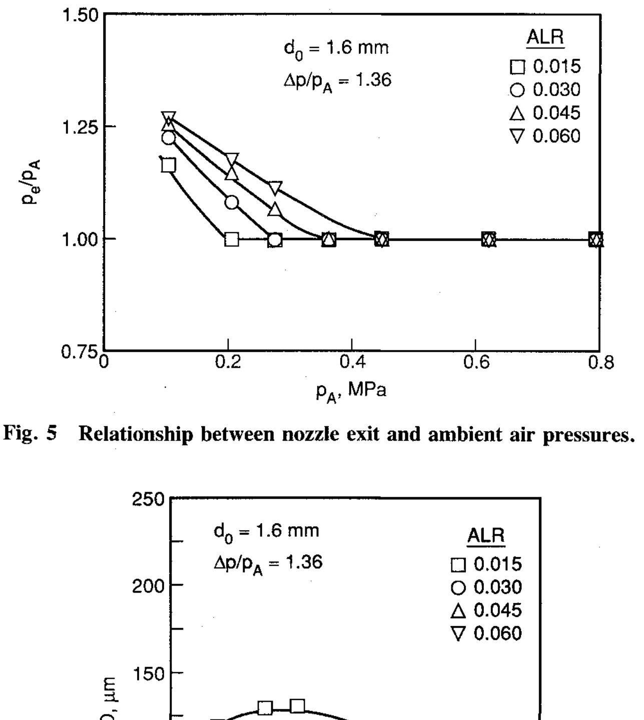

Fig. 5 Relationship between nozzle exit and ambient air pressures.

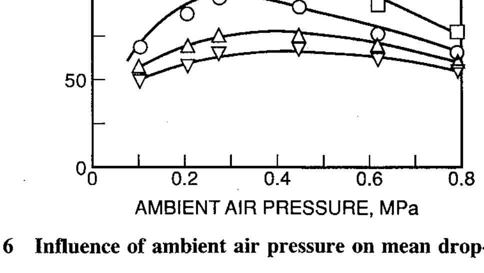

Fig. 6 Influence of ambient air pressure on mean drop-size.

Thus, the results obtained with pressure-swirl nozzles, which show that increase in ambient air pressure above the normal atmospheric value causes the SMD to rise initially before declining with further increase in pressure, could be due in part to the reduction in spray-cone angle which accompanies an increase in ambient air pressure. Only at high ambient air pressures, where a change in air pressure has no effect on spray angle, is it possible to determine the true effect of p_A on SMD.

Although this explanation for the characteristic shape of SMD vs p_A curves is feasible for pressure-swirl nozzles, it has no bearing on the present study. In a separate series of tests on the effects of ambient air pressure on spray structure, it was found that variations in ambient air pressure have little effect on the spray-cone angles produced in effervescent atomization.

A possible explanation for the initial increase in SMD with increase in p_A, as shown in Fig. 6, lies in the contribution made by bubble energy to the total atomization process. This bubble energy is defined as

$$E_b = [1/(\gamma - 1)]p_e(\pi/6)D_b^3[1 - (p_A/p_e)^{(\gamma-1)/\gamma}] \quad (9)$$

where $\gamma = 1.4$ for an isentropic expansion.

In order to understand the role played by bubble energy in producing the results shown in Fig. 6, it is necessary to examine this figure alongside the curves drawn in Fig. 5 showing the variation of the ratio p_e/p_A with ambient pressure. Note that according to Eq. (9) the bubble energy is zero when this ratio is unity.

As the ambient air pressure is increased from its normal atmospheric value, E_b is initially quite high since p_e/p_A is significantly greater than unity, as shown in Fig. 5. This figure also shows that with an increase in p_A the ratio p_e/p_A declines, and the bubble energy diminishes correspondingly, causing SMD to increase. Eventually, a critical ambient pressure is reached, its actual value depending on the ALR, at which $p_e = p_A$ and E_b becomes zero. At this and all higher levels of pressure, the bubble energy makes no contribution to atomization and the SMD gradually declines as Weber number increases with pressure, as mentioned above.

Another interesting feature of Fig. 6 is that the influence of ambient air pressure on mean drop-size declines with increase in air/liquid ratio. This result, which is characterisic of all atomizers in which air is used as the driving force for atomization, is brought out more clearly in Fig. 7, in which some of the results contained in Fig. 6 are extended to higher values of air/liquid ratio.

The effect of variations in nozzle discharge orifice diameter on mean drop-size was measured over a wide range of ambient air pressures. Figure 8 is typical of the results obtained. It shows SMD plotted against ambient air pressure for constant values of $\Delta p/p_A$ and air/liquid ratio. The four sets of data points correspond to discharge orifice diameters of 1.2, 1.6, 2.0, and 2.4 mm. Figure 8 demonstrates that variations in discharge orifice diameter have little or no effect on mean drop-size, thus confirming the results of previous investigations carried out at normal atmospheric pressure.[3,5]

Figure 9 illustrates the effect of variations in air-injection pressure on mean drop-size. It shows that the beneficial effect on atomization quality of an increase in air-injection pressure, as noted in all previous investigations on effervescent atomization carried out at normal atmospheric pressure, is main-

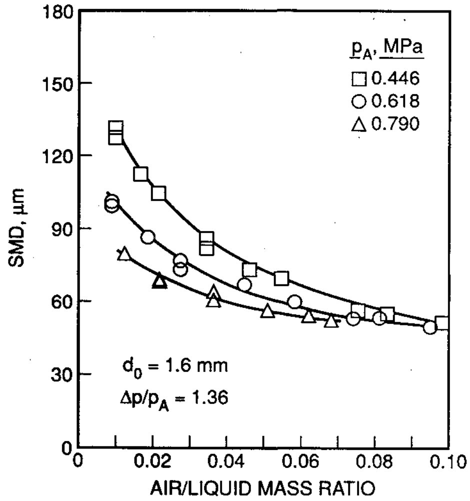

Fig. 7 Influence of air/liquid ratio on mean drop-size.

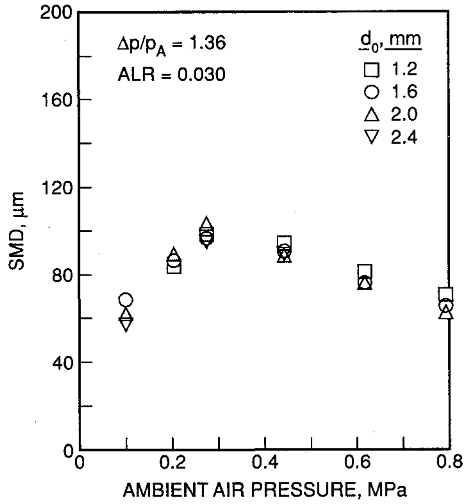

Fig. 8 Influence of exit-orifice diameter on mean drop-size.

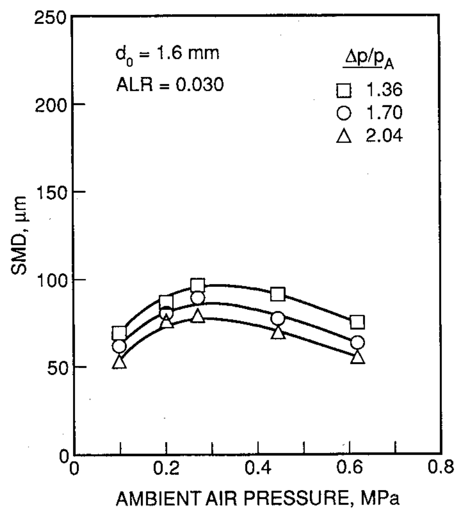

Fig. 9 Influence of air-injection pressure on mean drop-size.

tained at the higher levels of ambient air pressure employed in this investigation.

The drop-size distributions of the sprays produced in effervescent atomization are represented satisfactorily by the Rosin-Rammler q parameter. Figure 10 shows q as a function of p_A for three different values of $\Delta p/p_A$. The q values shown in this figure correspond to the SMD data plotted in Fig. 9. Figure 10 shows that variations in ambient air pressure have

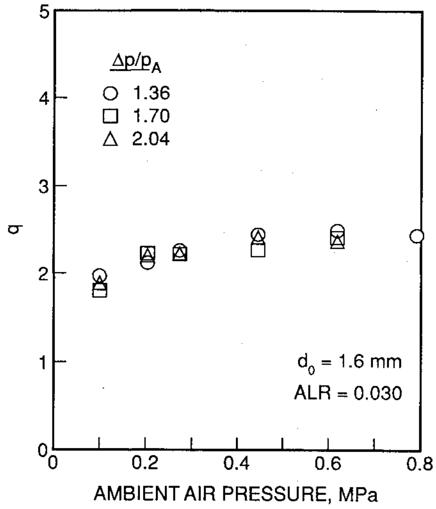

Fig. 10 Influence of ambient air pressure on Rosin-Rammler drop-size distribution parameter.

only a small effect on q which increases from around 1.9 at normal atmospheric pressure to around 2.3 at a pressure of 0.8 MPa (116 psia). Measurements of q carried out at ALR's varying from 0.015 to 0.060 show that over this range the influence of air/liquid ratio on drop-size distribution is also quite small.

Conclusions

From measurements of drop-size distribution carried out on a plain orifice effervescent atomizer over wide ranges of air/liquid ratio and ambient air pressure, the following conclusions are drawn:

1) All the experimental data obtained on the influence of ambient air pressure on mean drop-size show that a continuous increase in p_A above the normal atmospheric value causes the SMD to first increase up to a maximum value and then gradually decline.

2) The characteristic shape of the plots of SMD vs p_A are attributed to the combined effects of two different processes. The basic effect of an increase in ambient air pressure is to improve atomization quality by raising the Weber number. However, at low ambient air pressures, the atomization process is enhanced by the release of energy contained in the air bubbles. This additional source of energy is dependent on the ratio of the static pressure in the exit orifice to the ambient air pressure, p_e/p_A. Increase in ambient air pressure above the normal atmospheric value causes this ratio to decline until eventually $p_e = p_A$ and the contribution made by bubble energy to atomization becomes zero. At this condition the SMD attains its maximum value.

3) An increase in air/liquid ratio causes SMD_{max} to occur at a higher value of ambient air pressure.

4) Variations in ambient air pressure, air-injection pressure, and air/liquid ratio have little effect on drop-size distribution, with the values of the Rosin-Rammler distribution parameter generally lying between 1.9–2.3.

5) Mean drop-sizes and drop-size distributions are largely independent of the discharge-orifice diameter.

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