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# Internally Mixed Liquid Injector for Active Control of Atomization Process

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**This paper presents the results of an experimental study of an internally mixed liquid injector. In this type of injector, atomization is attained by injecting a small amount of air (i.e., of the order of 20% of the mass flow rate of liquid) into a liquid stream within the injector. Since most of the energy for atomization is supplied to the liquid by the atomizing air, a significantly small pressure drop can produce very fine spray with a small amount of atomizing air. The results presented in this paper suggest that the investigated injector could be used to control the flow rate and spray characteristics independent of each other by simultaneously varying the supply pressure of the liquid and the atomizing airflow rate. The effect of elevated backpressure on the injector's performance was also studied. It was found that the range of droplet sizes that could be obtained by the atomizer did not change when the pressure at the injector exit was increased. The preliminary results obtained in this paper suggest that a controlled version of the investigated injector may find applications in modern gas turbine engines.**

## Introduction

THE quality of combustion processes (e.g. ignition, flame stability, efficiency, and emissions) in liquid-fueled engines strongly depends on the atomization quality.[1] There is evidence that the performance of the combustion process under given operating conditions may be optimized by a specific droplet size, which may not be the minimum size that could be generated by the injector. For example, Rink and Lefebvre[2] reported that fine atomization caused substantial reductions in the production of unburned hydrocarbons because it reduces the droplet's evaporation time and thus increases the time available to attain complete combustion of the reactants. On the other hand, they have also reported that the reduction in mean droplet size increases $NO_x$ emissions, which was attributed to reduction in evaporation time and consequent increase in the time available for NO reactions to proceed toward equilibrium. Such results strongly suggest that the combustion processes could be optimized by using atomizers that could be controlled to produce sprays with desired properties, for example, droplet sizes and velocities.

To date, gas turbines have employed pressure and/or air-blast atomizers or a combination of these injectors.[3] Pressure atomizers have a poor turndown ratio[3] because at low flow rates, when the pressure drop across the injector is small, the atomization is very poor. This problem has been partially resolved in some engines by the use of dual-orifice atomizers. The drive to improve the quality of the generated sprays has resulted in increased use of air-blast atomizers in recent engines. Such atomizers employ the interaction of high-pressure air from the compressor with liquid sheets and ligaments to produce fine sprays. However, air-blast atomizers require large quantities of air to attain satisfactory atomization.[3] Such large quantities of air are not available at startup, idling, and for high-altitude relight, resulting in very poor performance of the atomizers at those operating conditions of the engine.

These observations suggest that there exists a need for new atomizers that could produce sprays with controlled properties over wide ranges of operating conditions using a relatively small amount of air. This paper presents the results of an investigation of an internally mixed liquid atomizer that may potentially overcome some of the limitations of state-of-the-art atomizers. In contrast to air-blast atomizers, where the air blast impinges upon the liquid streams after they emerge from injector's flow passage, the air and liquid fuel interact inside the injector in an internally mixed atomizer.[4–8] Conceptually, these atomizers are similar to effervescent injectors, which require a small amount of air to produce a very fine spray.[3,9–11] Good operation of an effervescent injector requires the formation of a mixture of air and liquid in a mixing chamber whose characteristics correspond to a bubbly two-phase flow.[12] However, when operating in this mode, effervescent injectors are sensitive to acceleration and thus cannot be safely employed in airborne applications.

The injector investigated in this study attempts to overcome the shortcomings of effervescent atomizers. Instead of forming a bubbly air–liquid mixture inside the injector, a low flow rate of pressurized air is impinged upon the flowing liquid, a short distance upstream of the injector's exit plane, in an effort to atomize the liquid. Because the interactions between air and liquid occur over a very short distance, the resulting atomization process may be less sensitive to acceleration.

The investigated injector appears attractive because it requires a very small amount of air to produce fine atomization with only a small pressure drop across the injector. It is envisioned that in engine applications, this injector will obtain its air from a small, electrically driven, auxiliary compressor that will increase the pressure of a very small fraction of the main compressor air, say 0.1%, by, for example, 40 psi (275 kpa). The results presented in this paper show that if the supply pressures of both the fuel and air are controlled independently, the atomization of the spray can be controlled over a wide range of fuel flow rates. Consequently, employing such injectors in engines with small, auxiliary fuel and air pumps will enable engineers to independently control the characteristics of the generated sprays. Another potential advantage of the internally mixed injector is that the fuel flow rate is relatively insensitive to variations in the combustion chamber pressure,[7,8] thus the fuel flow rate is not likely to respond to combustor disturbances, which will reduce the likelihood of combustion instabilities.

The main objective of this study is to investigate the performance of an internally mixed injector suitable for airborne gas turbine engines. Specifically, this study investigated the dependence of the atomization process upon the amount of atomizing air, the fuel supply pressure, and the backpressure. Furthermore, this study sought to determine the mode of operation that would permit control of the characteristics of the generated sprays.

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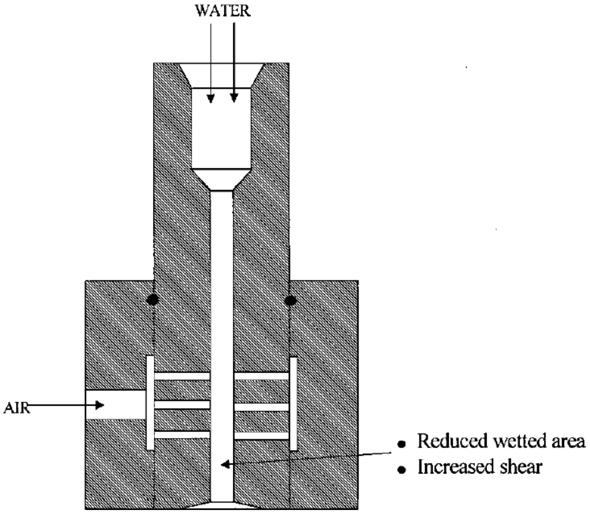


Fig. 1 Cross-sectional view of the Investigated Internal Mixing Air-Assisted Injector.

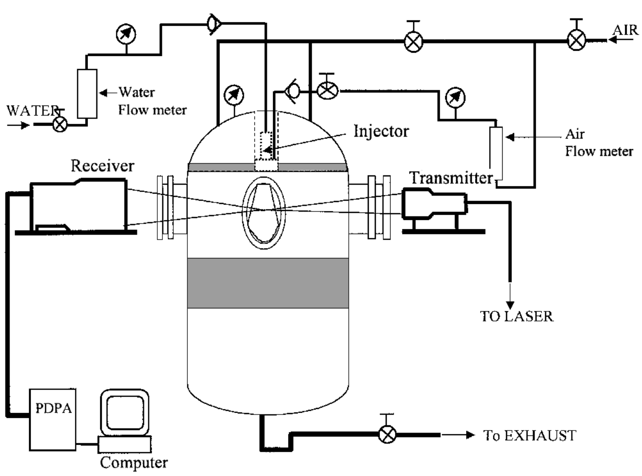


Fig. 2 Schematic of the Experimental Setup.

## Experimental Efforts

### Experimental Setup

A cross-sectional view of the investigated injector is shown in Fig. 1. Liquid enters through the wide opening of a tube that narrows down into a 0.8 mm–diam, 13.4 mm–long tube. Air is radially injected into the liquid flow through six 0.5 mm–diam holes just upstream of the injector's exit.

Figure 2 shows a schematic of the experimental setup that had been developed to investigate the performance of the internally mixed injector. The injector was installed at the top of a cylindrical chamber, which was 3 ft (0.91 m) high and had a diameter of 8 in. (0.2 m). High-pressure air was supplied into the chamber to pressurize it, and the pressure inside the chamber was varied by throttling a valve in its exhaust line. The chamber was designed to withstand pressures up to 200 psi (1.37 MPa) and included a relief valve that opened at 150 psi (1.03 MPa) to ensure adequate safety.

The chamber had three windows that provided optical access to the spray. Two of the side windows on the chamber were at an angle of 30 deg with respect to one another to provide optical access for the transmitter and receiver of the Phase Doppler Particle Analyzer (PDPA) system that was used to characterize the spray. The third window, which was at the same elevation as the other two, provided visual access to the spray. All the windows were circular and 5 in. (12.7 cm) in diameter. The chamber was mounted on a traversing mechanism and could be moved along three mutually perpendicular directions with 0.025 mm resolution. Downward

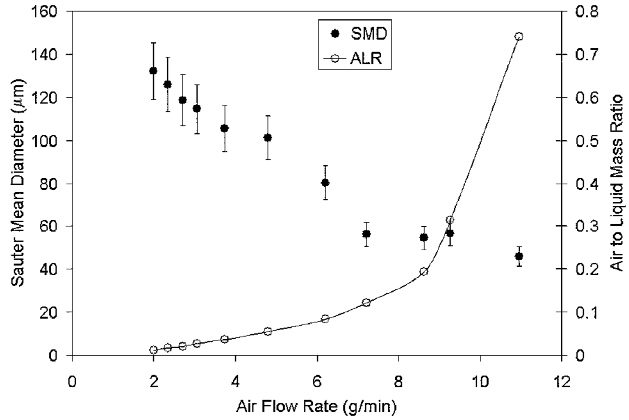


Fig. 3 Dependence of droplet SMD and ALR upon the air flow rate, for a constant water supply pressure of 20 psi (137.41 kPa) and atmospheric back-pressure, at the center of the spray. Error bars indicate 10% measurement errors.

flowing, low-velocity air (i.e., $v \approx 1$–2 m/s) was introduced into the chamber through a honeycomb structure at the top of the test section to prevent misting of the windows by recirculating liquid droplets. This air left the system through another honeycomb structure just downstream of the test section.

Droplet sizes and velocities were measured downstream of the injector exit, at a distance of 2.5 in. (6.35 cm), using an Aerometrics PDPA system. An argon-ion laser that provided a 2 W–power green light (i.e., 514.5 $\mu$m) and 1.5 W–power blue light (i.e., 488 $\mu$m) was used by the PDPA. A transmitting lens with a focal length of 300 mm and a receiving lens with a focal length of 750 mm were used in the optical path of the PDPA. The receiver was oriented at a 30 deg forward scatter position with respect to the transmitter to gather light scattered by the droplets. Both the transmitter and receiver were mounted on stationary, rigid platforms, and the injector, along with the test chamber, was moved by the traversing mechanism. This ensured that any point in the spray could be brought to the intersection of the laser beams. The PDPA could measure droplet sizes in the 0.7 $\mu$m to 220 $\mu$m** range. The droplet size and velocity data were collected and analyzed using DSA™ software from Aerometrics on a personal computer with a 486 processor. On the average, the percentage of valid data ranged from 70 to 98%, depending on the spray density and droplet sizes. Each data point was obtained using at least 1000 valid measurements.

The mass flow rates and supply pressures of both liquid and air were monitored using standard flow meters and pressure gauges (see Fig. 2). The liquid and air supplies were controlled with a pressure-regulating valve and a needle valve, respectively.

All the results presented in this paper were obtained with water and room-temperature compressed air from a laboratory compressor.

### Results and Discussion

Initially, the performance of the injector when the test chamber was maintained at atmospheric pressure was investigated, and the results are presented in Figs. 3–9. Figures 3–5 describe the variations in the spray characteristics when the water-supply pressure was kept constant at 20 psi (137.41 kPa) while the amount of atomizing air was varied. It should be noted that although the water-supply pressure was kept constant in these experiments, the flow rate of the water was not constant. In fact, the water flow rate decreases

**This range of measurement cannot be achieved with one set of measurement parameters for the PDPA. Rather, it expresses the measurement capabilities for monosized droplets when the maximum droplet size to be detected is set close to the actual droplet size. In a realistic situation, when the maximum of the detecting range is set to, say, 220 $\mu$m, the minimum size that can be detected is no less than $\frac{1}{35}$ of the maximum, which is 6.3 $\mu$m.

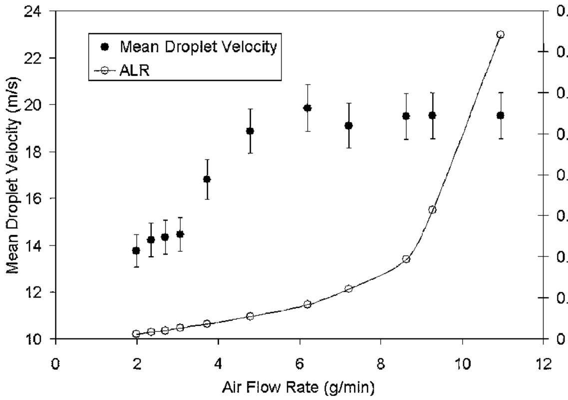


**Fig. 4 Dependence of mean droplet velocity and ALR upon the variations in air flow rate, at a constant water supply pressure of 20 psi (137.41 kPa) and atmospheric back pressure, at the center of the spray. Error bars indicate 10% measurement errors.**

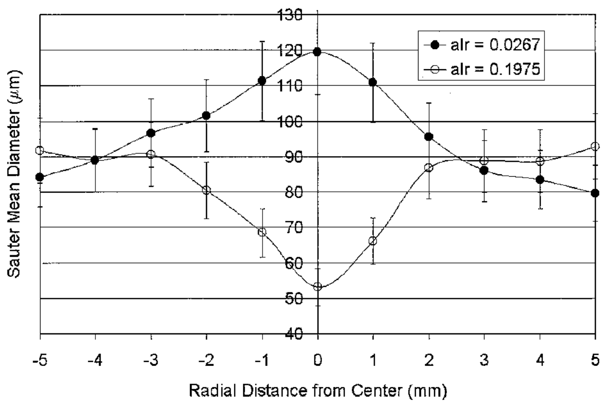


**Fig. 5 Radial distribution of SMD of the droplets for low and high ALR, with atmospheric conditions inside the test chamber. Water supply pressure was kept constant at 20 psi (137.41 kPa). Error bars indicate 10% measurement errors.**

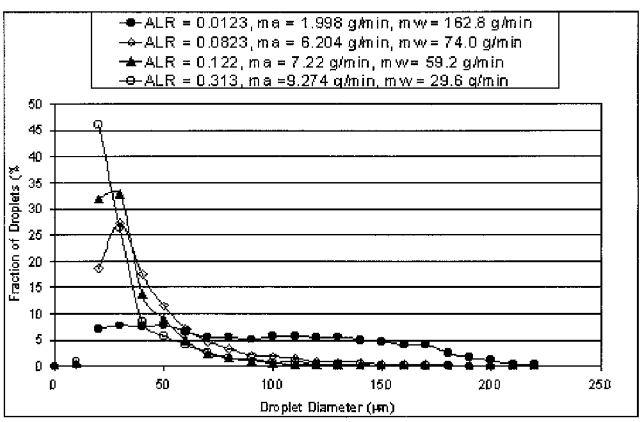


**Fig. 6 Fractional distribution of droplet sizes for different ALR at a constant water supply pressure of 20 psi (137.41 kPa), at the center of the spray. Each data point describes the sizes within an interval of ± 5 $\mu$m around the indicated size.**

as the airflow rate increases, which is evident from the nonlinear relationship between the air–liquid ratio (ALR) and the airflow rate in Figs. 3 and 4. This occurs because the pressure inside the atomizer increases as the airflow rate increases, thus reducing the water flow rate through the injector. Consequently, when the flow rate of air was varied from 1.998 to 10.96 g/min, the ALR increased from 0.0123 to 0.741, which corresponds to a decrease from 162.8 to 14.8 g/min in the water flow rate.

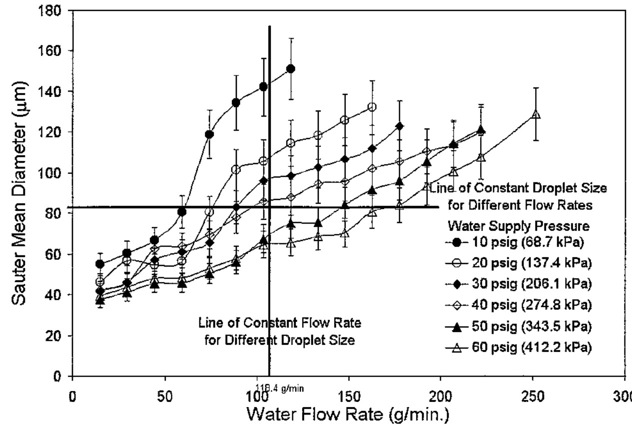


**Fig. 7 Performance map of the injector showing the dependence of centerline SMD upon water flow rate at different water supply pressures and for zero back pressure. Water flow rate was varied by changing the amount of atomizing air. Error bars indicate 10% measurement errors.**

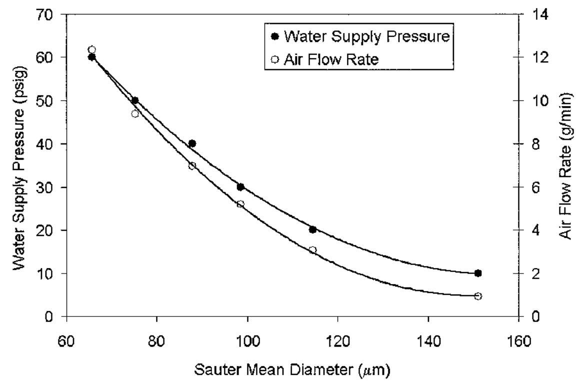


**Fig. 8 Required variations in water supply pressure and air flow rate to obtain variable droplet SMD's for a constant water flow rate of 118.4 g/min.**

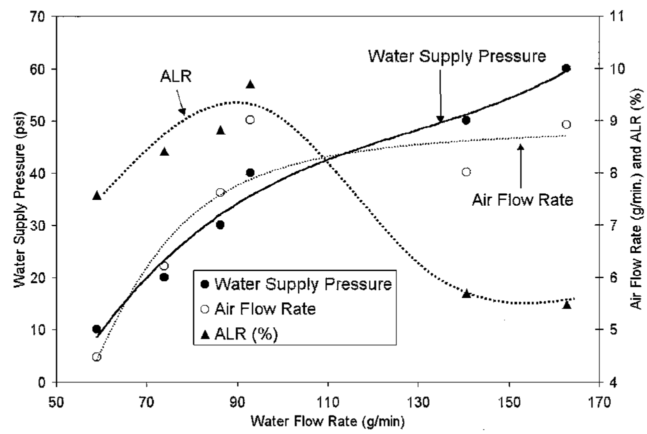


**Fig. 9 Required variations in water supply pressure, air flow rate and ALR to obtain a constant SMD of 80 $\mu$m for different water flow rates.**

Figure 3 shows that the Sauter mean diameter (SMD) of the spray droplets decreases from 132 to 45 $\mu$m as the airflow rate increases from 1.998 to 10.96 g/min. It is believed that atomization in the investigated injector is induced by two effects. First, the increase in airflow rate is accompanied by increased restriction on the water passage, thus accelerating the water flow. This, in turn, increases the kinetic energy of the water, resulting in improved atomization. Second, the increase in airflow rate is accompanied by an increase of the air velocity and thus the shear force that it exerts upon the water. Consequently, the number of droplets being stripped from the water filaments increases, resulting in finer atomization. The acceleration of the water due to the introduction of air is evident in Fig. 4. It shows that the mean droplet velocity at the center of the spray, 2.5 in. (6.35 cm) downstream of the injector exit, increased from 13.5 to 20 m/s as the ALR increases from 1.2 to 10%. Correlating the ALR with the SMD and mean droplet velocity in Figs. 3 and 4 reveals that significant variations in the spray's SMD and velocity occur as the ALR increases from 1 to 10%. However, further increase in the ALR (up to 74%) has almost no effect on the spray's SMD and velocity. Thus, the data in Figs. 3 and 4 suggest that when the investigated injector is operated with an atmospheric backpressure, its ALR need not exceed 10%. Although the reasons for the limited effect of increased ALR (beyond 10%) upon the droplet SMD and average velocity remain unknown, it is speculated that it is related to the different characteristics of the two-phase flow within the injector at low and high ALRs.[12]

Figure 5 shows the radial distribution of the spray's SMD. It shows that at low ALR, the largest droplets are at the center of the spray and the SMD decreases monotonically toward the edge of the spray. The opposite behavior is exhibited at high ALR. Moreover, Fig. 5 indicates that the droplets at the edge of the spray are larger at high ALR than at low ALR. It is speculated that at low ALR, the injected air is confined to an annular region near the wall, where it shears the liquid to form smaller droplets near the spray's edge, as shown in Fig. 5. In contrast, at high ALR, the air penetrates through the water flow all the way to the center of the injector, where it shears the water flow to form smaller droplets in the center of the spray while producing larger droplets at the periphery of the spray. Furthermore, it is evident from Fig. 5 that the droplet sizes decrease almost everywhere in the spray with an increase in ALR. Therefore, the reduction in droplet size with increase in ALR is not a local phenomenon at the center of the spray, but a global event occurring everywhere in the spray.

Figure 6 describes the dependence of the droplet size distribution upon the ALR. Each data point describes the percentage of droplets within an interval of $\pm 5 \mu$m around the indicated size. Droplet sizes below 20 $\mu$m could not be accurately measured because of limitations of the PDPA system (see footnote**). At a very low ALR, the distribution is fairly flat up to 150 $\mu$m. As the ALR increases, a distinct peak appears around 30 $\mu$m. This peak becomes sharper as the ALR increases, indicating more uniformity of droplet sizes. It should be noted that at high ALR, the peak occurs at 20 $\mu$m, which is also the very close to the smallest detectable droplet size, suggesting that the diameters of a large fraction of the spray's droplets are below 20 $\mu$m.

Next, the results of a study of the effect of varying the liquid supply pressure and airflow rate (with a needle valve, while keeping its supply pressure constant) upon the resulting spray are presented. As the results of the initial tests suggest, simultaneous variation of these quantities could be used to control the spray characteristics.

A performance map for the investigated injector was obtained by repeating the described tests with water-supply pressures between 10 psi (68.70 kPa) and 60 psi (412.24 kPa), and the results are presented in Fig. 7. For low water flow rates, the lines in Fig. 7 coalesce around 40 $\mu$m, thus suggesting that this is the smallest obtainable SMD with the investigated injector. It is realized that the droplet sizes produced by the investigated injector are larger than that produced by effervescent atomizers[9–11] and conventional swirl or air-blast injectors.[3] However, because no efforts were made to optimize the performance of the injector (Rather, it was designed to have a simple geometry for easy manufacturing and to simplify flow modeling.), it is plausible that varying the injector's design or operating conditions would yield even smaller SMDs. It is noteworthy that when hot (i.e., low-density) air was supplied to the injector directly from a compressor rather than room-temperature air from an accumulator, an SMD of 15 $\mu$m was easily obtained.

The data in Fig. 7 indicate that in contrast to the behavior exhibited by pressure and air-blast atomizers, the investigated injector can atomize very small water flow rates into very fine sprays. This observation suggests that the investigated atomizer can be effectively used to obtain good atomization during engine startup and idling.

The performance map in Fig. 7 shows that varying the water-supply pressure while keeping the water flow rate fixed (which requires varying the airflow rate, as shown in Fig. 3), provides means for controlling the spray's SMD. This can be achieved by moving along a vertical line in Fig. 7. Similarly, changing the water-supply pressure along, for example, the horizontal line in Fig. 7 provides means for changing the water flow rate while keeping the spray SMD constant.

Figure 8 describes the manner in which the water-supply pressure and airflow rate vary as one moves along the vertical line in Fig. 7. It shows that these two independent parameters can be varied to obtain any desired SMD in the 65–155 $\mu$m range while keeping a constant water flow rate of 118.4 g/min. The data plotted in Fig. 8 were obtained by interpolating between the results shown in Fig. 7. Figure 8 indicates that both the water-supply pressure and the airflow rate should be decreased monotonically to increase the SMD of the spray. As the airflow rate decreases, the pressure inside the atomizer also decreases, as less volume is occupied by the air, thus allowing more water to flow into the injector. To compensate for this increase in water flow rate, the water-supply pressure must be decreased as well.

Figure 9 shows how the water-supply pressure and airflow rate should be varied to obtain a constant SMD of 80 $\mu$m at different water flow rates. This set of data is also obtained by interpolation of data presented in Fig. 7. For convenience, the ALR is also presented, although it is not an independent variable. The data in Fig. 9 were curve fitted. These data show that although the water supply pressure must increase monotonically to obtain higher water flow rates, the airflow rate reaches a plateau and should be kept nearly constant for water flow rates above 100 g/min. Moreover, Fig. 9 indicates that the corresponding ALR drops significantly with increase in water flow rate, from the 10% required at 100 g/min to 5.5% at 160 g/min. Arguably, as the water-supply pressure increases to provide a higher water flow rate, the kinetic energy of the water increases as well and the atomization process needs less "assistance" from air. Consequently, less air per unit mass of water (i.e. ALR) is required.

In all the described experiments, the test chamber was maintained at ambient pressure. However, in a real engine, the spray is injected into a high-pressure combustion chamber. When the pressure downstream of the injector increases, the pressure drop across the injector decreases, thus increasing the air density within the injector. Because atomization by the internally mixed injector is induced by the transfer of kinetic energy from air to water, and because the kinetic energy of the air is a function of its density, it is expected that the performance of the injector will be influenced by variation of the backpressure. Furthermore, at a given airflow rate, the air kinetic energy is inversely proportional to its density. Consequently, it is expected that at elevated backpressures, and thus higher air densities, the performance of the atomizer will deteriorate.

A set of experiments was performed to evaluate the effect of the chamber pressure upon the investigated injector's performance. In these experiments, the test chamber pressure was increased in steps from atmospheric to 40 psig (274.80 kPa) and the water-supply pressure was adjusted to maintain 20 psi (137.41 kPa) pressure drop across the injector, which is the pressure drop used in the first set of experiments with atmospheric backpressure. The results of these experiments are shown in Fig. 10, which is an expanded version of Fig. 3 but without ALR curves. It should be noted that the data for atmosphericback pressure presented in Fig. 10 is not the same dataset presented in Fig. 3 (tests with atmospheric backpressure were performed again as part of the last set of experiments). Thus, the zero backpressure data points in Fig. 10 are very similar but not identical to those in Fig. 3.

As noted in the analysis of the data in Figs. 3 and 7, which dealt with atmospheric backpressure data, the SMD cannot be decreased below a certain threshold magnitude even with large quantities of airflow rate. Interestingly, Fig. 10 shows that this limit remains the same for all of the investigated backpressures as all the curves converge to the gray strip between 40 and 50 $\mu$m. Figure 10 further shows that as the backpressure increases, a higher ALR is required to reach SMDs in the gray zone. The fact that more ALR is needed

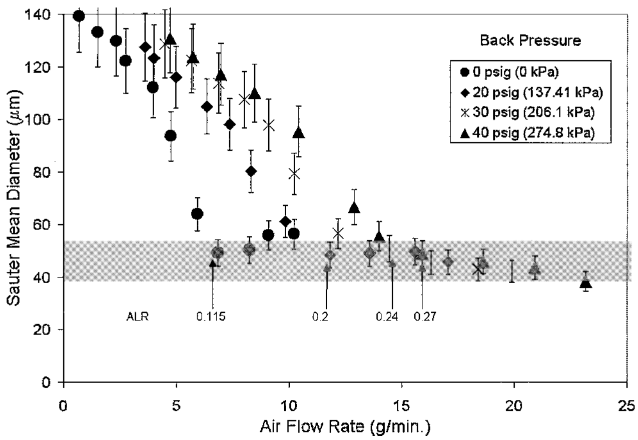


**Fig. 10 Dependence of SMD upon air flow rate for various back pressures, at the center line of the spray, for a constant pressure drop of 20 psi (137.41 kPa) across the injector. Error bars indicate 10% measurement errors.**

to obtain a given SMD at elevated backpressure was expected, as explained earlier, as a result of increase in the air density. Figure 10 indicates that with zero backpressure, an ALR of about 12% is required to obtain an SMD between 40 and 50 $\mu$m (in the gray strip), but at elevated backpressure of 40 psig, an ALR of 27% is required for the same SMD. Thus, although the density of the air increased by a factor of 3.7, the required ALR and thus the amount of required air increased only by a factor of 2.25. Significantly, these findings suggest that the achievable range of SMD of the internally mixed injector will not decrease as the combustor pressure increases. Rather, a moderate increase of airflow rate will be required to obtain SMDs in the low limit of this range.

## Summary and Conclusions

An internally mixed, air-assisted atomizer that can potentially be used in airborne gas turbine engines was experimentally investigated. The investigated injector provided droplets with SMDs in the 40–140 $\mu$m range. The measured data suggest that such injectors can be employed to control the atomization process by simultaneously varying the liquid-supply pressure and airflow rate. Tests at elevated backpressures showed that the range of droplet sizes that can be obtained by the atomizer does not decrease when the chamber pressure increases, although the injector requires more air at elevated backpressures.

## Acknowledgment

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