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Effect of Inner and Outer Airflow Characteristics on High Liquid Pressure Prefilming Airblast Atomization

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The objective is to provide a better understanding of the hybrid atomization process to support the development of fuel injectors for future high-performance/low-emissions gas turbine combustors. In this type of fuel injector, both airblast forces and high liquid injection pressure are combined to achieve satisfactory performance over the entire range of combustor operation. The investigation involved conducting an experimental study using a fuel injector with the capability of reversing the direction of rotation of each of the two air swirlers used in the design, in addition to reducing the flow area of each swirler. The experimental investigation was supported by analytical calculations that provided information on the fuel injector flowfield characteristics and relative motion between the swirling air and liquid fuel film. The results demonstrated that a combination of corotating inner airstream and counterrotating outer airstream with respect to the rotational direction of the enclosed liquid film yields the finest sprays as compared to other swirler configurations. The least efficient atomization was achieved when both airstreams were swirling in opposite direction to that of the liquid film. The study showed that in addition to air/liquid relative motion, other important aspects such as liquid injection pressure, direction of rotation of swirling air, and droplet coalescence should be considered in the design of a successful hybrid fuel injector.

Introduction

THE key to the successful development of advanced high-temperature rise and/or low-emissions combustors is to achieve a uniform distribution of fuel/air ratio in the combustion zone with a relatively simple fuel injection configuration. The limitations of using typical prefilming airblast atomizer in such an application are attributed to the inability of the fuel to spread radially outwards under high combustor pressures due to the relatively small prefilming device used in the atomizer and to the low fuel injection pressure. In addition, the performance of the airblast atomizer rapidly deteriorates as the air pressure drop across the atomizer is reduced. On the other hand, the conventional pressure swirl atomization concept has demonstrated the capability to produce fine sprays under high fuel injection pressure. Thus, combining both atomization concepts in a single hybrid design presents an attractive approach for achieving satisfactory atomization over the entire combustor operating range.

Hybrid atomization can generally be achieved by either utilizing airblast forces in a pressure swirl atomizer or using a rather high fuel injection pressure in airblast atomizer. The performance of an airblast atomizer with high liquid injection pressure typically follows an almost flat mean drop size profile over a wide range of liquid flow rate. Such a profile is desirable in many applications. Moreover, for a low-emissions combustor, initial velocity of spray is an important parameter in achieving enhanced fuel/air mixing within a short distance, in particular when cross-stream penetration is used in design. High fuel injection pressure in prefilming airblast atomizer is also beneficial in producing a more uniform liquid film even under low fuel flow rate, or for short prefilming devices that are needed to minimize fuel deposition in atomizer.

In recent years, an investigation on hybrid atomization has been initiated by the present authors to evaluate the potential of using such an approach in advanced combustors, and to provide insight into the key parameters controlling this combined atomization mode of operation.[1,2] The actual role played by the air/liquid relative velocity and other important parameters in governing the atomization process has been investigated and reported in Ref. 1. Several liquid injection configurations were used to enable changing the magnitude and direction of air and liquid velocities and flow rates independently. The results indicated that, although the relative velocity effect is important in hybrid atomization, this effect is not the only parameter governing the spray quality. Also, better atomization was achieved under a high liquid injection pressure than that obtained under low pressures for the same level of relative velocity.

Reference 2 reports the results of the continued effort to understand the operation of the hybrid atomization. In this effort, a recently developed fuel injection model was employed to shed light on various atomization processes involved. The details of this model are described in Ref. 3. The predictions of the model were in good agreement with the measurements obtained for the pilot and main filming device of a hybrid atomizer. The results showed that the effect of the increase in liquid pressure of the pilot atomizer was more pronounced when the air pressure drop was significantly reduced. On the other hand, the most beneficial effect of using the atomizing air to assist the pressure atomization occurred when the fuel pressure was on the low side. The calculations demonstrated strong dependency of the spray characteristics on the design configuration of the hybrid atomizer.

The objective of the present study is, thus, to provide better understanding of the hybrid atomization process to support the development of advanced combustors for future engine applications. Based on such a study, enhanced design methods could be formulated and used to develop high-performance atomizers.

Experimental Configurations

The prefilmer was designed to have a large exit diameter of 0.041 m, which is more than double the size of conventional airblast atomizers, as shown in Fig. 1. The four tangential ports used to inject the fuel were selected in such a way to achieve a high exit velocity for the film. The diameter of the fuel hole and the flow number of the atomizer were 0.45 mm and 6.3×10^{-7} m^2 (11.5 lb/h/$\sqrt{\text{psig}}$), respectively. Fuel pressure differential across the atomizer up to 3000 kPa was used in the filming process. Under such high fuel pressure, the atomization process is not that of pure airblast type, but rather follows a hybrid atomization mode.

Although a single fuel injection configuration was employed in the atomizer design, a wide variation in air admission concepts was studied in the investigation. Air is admitted through inner and outer passages surrounding the filming device, with capability of

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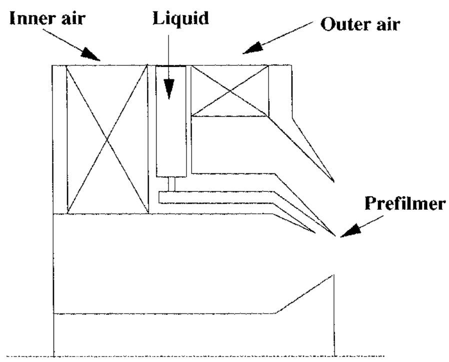

Fig. 1 Hybrid atomizer configuration used in tests.

providing swirling air through tangential slots and changing the flow area and direction of swirl rotation. The airflow splits between outer and inner passages were 60 and 40%, respectively, and several blocking bands were used to enable reducing the flow areas of the two passages simultaneously, so that the separate effect of air/liquid ratio on atomization could be examined.

The experimental setup consisted of the fuel injector mounted at the end of an air box spraying downward into a tank. A blower exhausted the vapor from the tank, and a static pressure inside the air box was measured with an electric capacitance gauge. Liquid flow through the atomizer was delivered using a positive displacement, dc-driven pump. The data were taken at room temperature and pressure, and the liquid used in all tests was a calibration fluid MIL-C-7024-B. The density, surface tension, and viscosity of this liquid at standard temperature of 298 K are 765 kg/m^3, 0.025 N/m, and 0.00092 kg/ms, respectively. A Malvern particle analyzer, model 2600, was employed to measure drop size distribution in the spray at a downstream distance of 0.051 m from the exit plane of the atomizer. The distribution was then used to calculate the Sauter mean diameter (SMD) of the spray. The tests were conducted over ranges of air pressure drop across the atomizer from 0.5 to 4.0%, air/liquid mass ratio from 0.5 to 9.0, and fuel injection pressure from 69 to 3000 kPa. Calibration of the Malvern instrument was conducted regularly and addressed mainly background signal and obscuration correction. Large number of data points were taken to enable the accurate detection of the atomizer performance trends.

Modeling of Hybrid Atomization

A recently developed fuel injection model has been used to provide information on the key parameters of the atomization process that are needed to support the evaluation of the atomizer performance. A brief description of the model elements is given in the following paragraphs.

In both airblast and pressure swirl atomization, the process involves forming a thin film of liquid as an important requirement for achieving fine sprays. In a typical long prefilming airblast atomizer, the formation of the liquid film is achieved by spreading the liquid onto the prefilmer under the effect of high-velocity air. The prefilmer geometry, fuel and air properties, and operating parameters are the main factors controlling the film thickness.[4] In some other designs, the filming surface is made so short that the actual film leaving the atomizer is controlled by the swirl chamber and atomizer lip geometry. The mechanism of film formation in this case is more or less similar to the one associated with pressure swirl atomization.[5]

In pressure atomizers, liquid film exits the final orifice as an expanding conical sheet. The sheet is normally disturbed by ambient effects. The balance with surface tension forces causes the formation of unstable waves with exponentially increasing amplitude, leading to liquid fragments breaking off the edge of the wavy sheet.[6,7] The fragments are assumed to immediately contract to ligaments, that in turn form spherical drops, with dimensions determined by wavelength of the sheet disturbance.

The breakup mechanism associated with fuel pressure atomization is considered in the calculation to dominate in the absence of air-assist or at low air pressure drop. At higher air pressure drop, the atomizer acts as an airblast type, and the liquid sheet disintegrates under the effect of the aerodynamic forces. The balance of the forces caused by gas pressure, surface tension, liquid inertia, and viscosity controls the sheet breakup mechanism.[8]

The formed drops may undergo secondary atomization if the Weber number experienced by each drop exceeds a critical value.[9] Secondary atomization due to the stripping breakup concept becomes important when sufficient relative velocity exists between air and droplet.[10] The two-phase flow simulation used in the model considers the effects of the instantaneous gas droplet relative velocity on the transfer quantities and the interaction of the mean and fluctuating motion between the two phases. The model consists of a fully coupled combination of Lagrangian droplet and Eulerian fluid calculations.

The model was used to calculate the velocity components in the atomizer flowfield and the relative velocity between the liquid and air at the atomizer exit under different test conditions. These results provide a useful tool in interpreting the hybrid atomizer performance trends obtained from the experiments, as described in the next section.

Experimental Results

The experiments were conducted, using the hybrid atomizer shown in Fig. 1, in such a way to address three distinctive aspects.

1) First is the performance of the baseline atomizer under the combined effect of airblast and fuel pressure functions. Both air-streams and injected liquid rotations are in same direction (corotating configuration).

2) Next is the effect of the rotational direction of the air swirlers with respect to the liquid swirl direction on the atomizer performance. (By reversing the position of the air tangential slot units, corotating or counterrotating airstreams with respect to the fuel rotation could be achieved).

3) Last is the separate effect of the air/liquid ratio on the hybrid atomization process. (By using a blocking band on the inlet section and changing the exit section component of each air passage, the air/liquid ratio could be varied while maintaining constant air pressure drop and fuel injection pressure).

To provide better understanding of the experimental observations, the fuel injection model was employed in the effort. The main objective was to calculate the effective relative velocity between the atomizing air and liquid stream at the atomizing edge under each test condition. The simulation of the internal passages of the atomizer and the atomizer flowfield was performed using the grid network shown in Fig. 2. A uniform airstream surrounding the fuel injector and flowing at 3 m/s was used to simulate the ambient effect on the injector flowfield. Examples of the calculated axial and swirl air velocity profiles at a number of downstream distances are shown in Fig. 3. The twin-peak axial velocity profiles resulting from the two separate airstreams rapidly join in a single continuous profile farther downstream of the atomizer exit. The rapid decay of the air swirl component with distance is also shown in Fig. 3. The strong

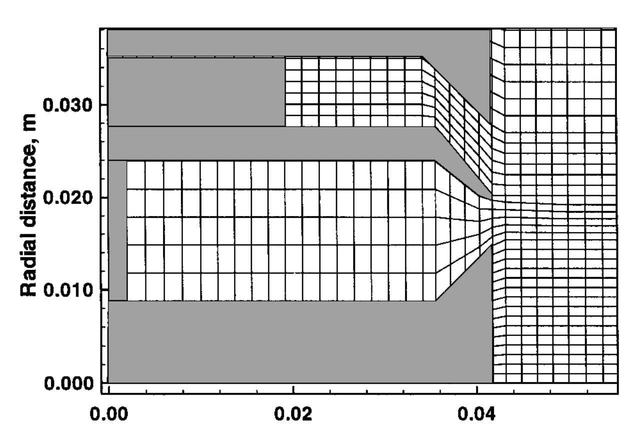

Fig. 2 Grid network used in analytical simulation.

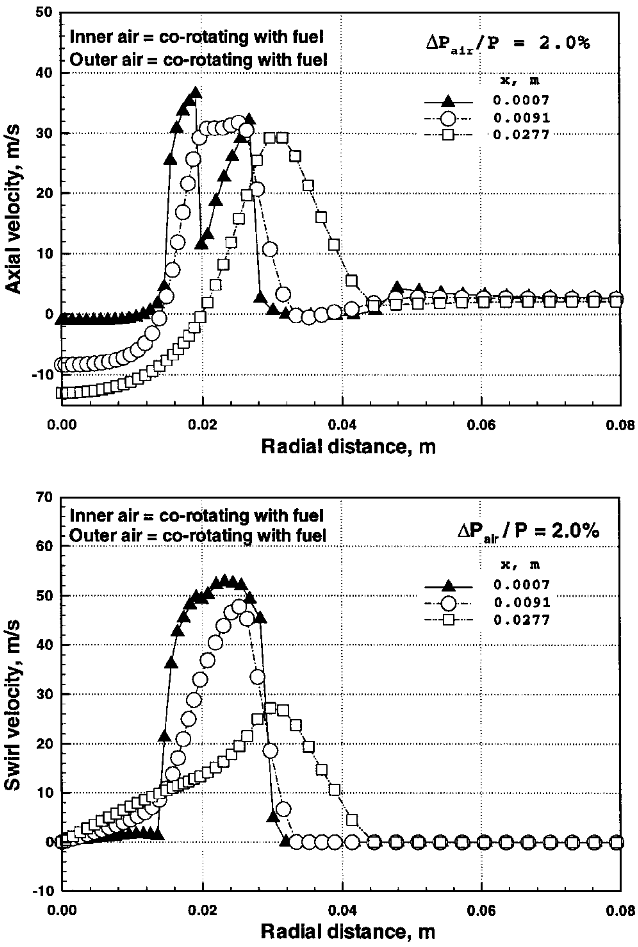

Fig. 3 Calculated air velocity profiles for inner and outer corotating air.

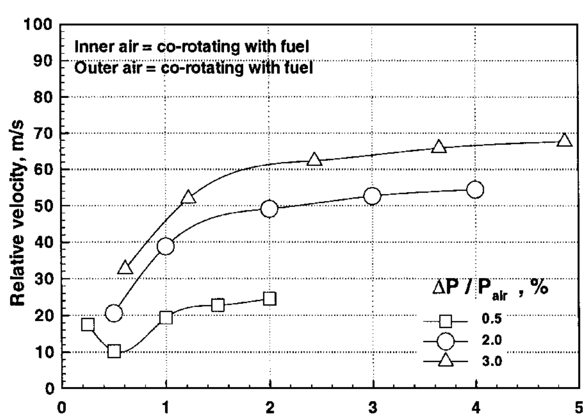

Fig. 4 Air/liquid relative velocities for corotating inner and outer airstreams.

swirling flowfield due to the two corotating airstreams results in the formation of a region of reversed flow downstream of the atomizer. The air/liquid relative velocity for each case was calculated at the location where the liquid film exits from the prefilming surface, and the relative motion in the three dimensions was considered. The definition of the relative velocity reflects the difference between the air velocity and the liquid injection velocity. A zero relative velocity indicates that both air- and liquid streams are flowing at same velocity and direction at the atomization point. The calculated relative velocities for the baseline atomizer configuration are plotted against air/liquid ratios in Fig. 4. The baseline configuration incorporates two corotating airstreams, with respect to liquid film rotation, and fully open flow areas for the two airstreams. Figure 4 shows that a

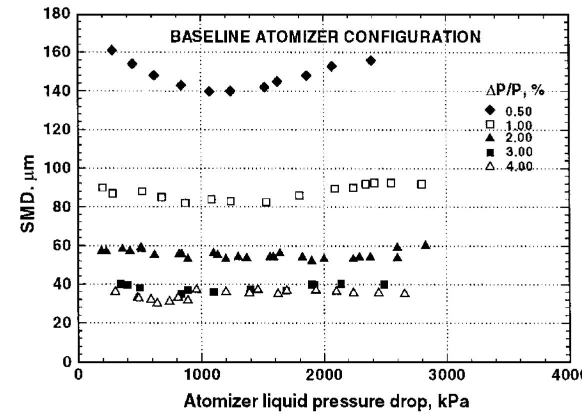

Fig. 5 Variation of SMD with liquid pressure for baseline configuration.

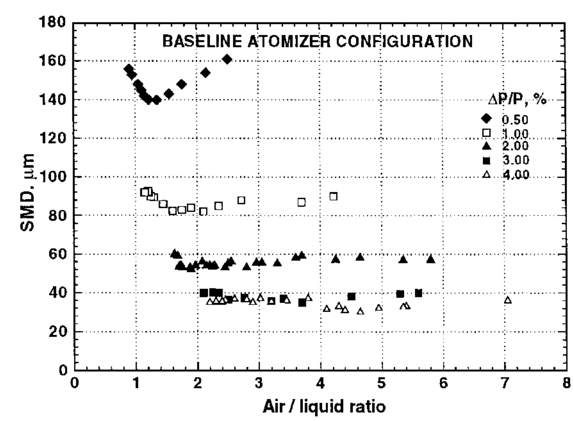

Fig. 6 Variation of SMD with ALR for baseline atomizer configuration.

reduction in air/liquid ratio results in a decrease in relative velocity. This is mainly due to the accompanied increase in liquid injection velocity. On the other hand, at a low air pressure drop of 0.5%, further reduction in air/liquid ratio (ALR) causes the liquid velocity to exceed the air velocity resulting in a reversed trend of increasing relative velocity under these conditions.

Figure 5 shows the SMD measurements obtained for the baseline atomizer over a wide ranges of air pressure drops and liquid injection pressures. The same results are plotted against the atomizer ALR in Fig. 6. Notice that a nearly flat SMD profile is obtained at air pressure drops greater than 1.0%, irrespective of the liquid injection pressure used in the test. The opposing effects of increasing the air/liquid relative velocity and reducing the liquid injection pressure on liquid filming and atomization tend to cancel each other as ALR increases. Using an air pressure drop greater than 3.0% results in no appreciable reduction in SMD.

At a low air pressure drop (0.5%), a reduction in ALR from 2.5 to about 1.2, which is accompanied by an increase in liquid injection pressure, results in an improvement in atomization quality. This is attributed to the enhancement of the fuel filming process due to the increase in fuel injection pressure that offsets the adverse effect of the modest reduction in the effective air/liquid relative velocity shown in Fig. 4. Further reduction in ALR below 1.2 causes a gradual increase in SMD due to the significant reduction in relative velocity, as shown in Fig. 4.

Another important aspect of hybrid atomization that requires further investigation is the interaction between the swirling airstreams and liquid stream to achieve optimum atomizer performance. The present experiments involved testing the atomizer with the capability of reversing the direction of rotation of each airstream separately. Thus, four different configurations could be reached: both airstreams corotating with swirling liquid sheet, both airstreams counterrotating with liquid sheet, or either inner or outer airstream corotating with liquid sheet.

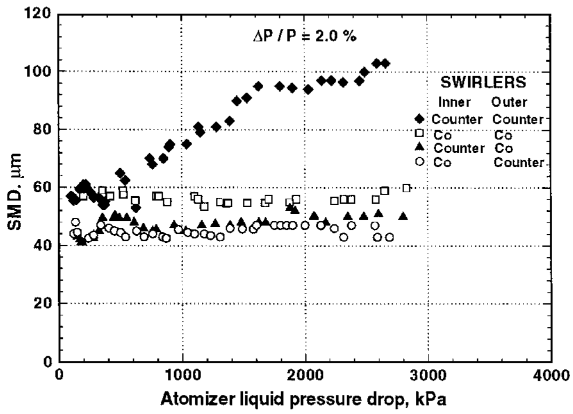

Fig. 7 Effect of swirler arrangement on SMD under different liquid pressures.

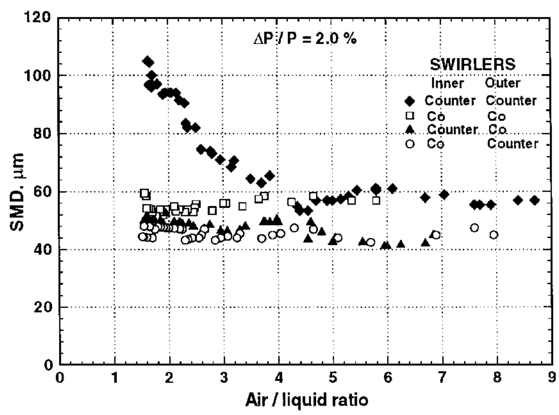

Fig. 8 Effect of swirler arrangement on SMD under different ALRs.

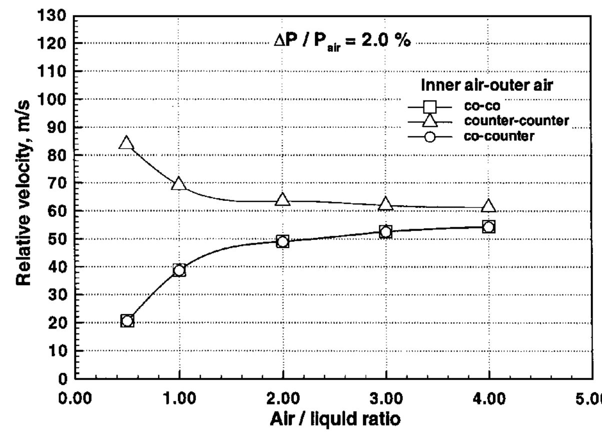

Fig. 9 Calculated relative velocities for a number of swirler arrangements.

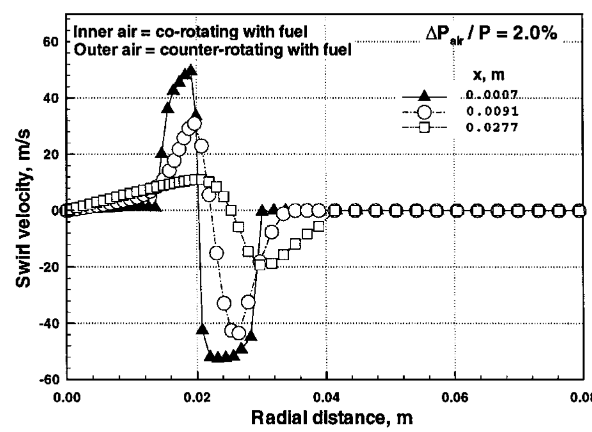

Fig. 10 Calculated swirl velocity profiles for corotating inner and counterrotating outer air configuration.

The results obtained for the different four combinations of inner and outer air rotation with respect to liquid rotation are shown in Figs. 7 and 8. The data are plotted against both liquid injection pressure and ALR to provide better picture of the effect of the key parameters on the atomization process. The results indicate that the least efficient atomizer configuration is the utilization of two counterrotating airstreams to atomize the liquid sheet. The difference between this approach and the other three configurations become more pronounced at higher levels of liquid flow rate (lower ALR) that are coupled with higher injection pressures. The lowest SMD levels measured for this atomizer were obtained when the inner airstream was corotating, and outer stream counterrotating with respect to fuel injection direction. Using the configuration in which the inner and outer airstreams are counterrotating and corotating, respectively, with liquid rotation, results in a small increase in SMD, as compared to the earlier case. The difference between these two configurations diminishes at larger ALR levels.

The fuel injection model was once again used to help understand the causes for the deterioration of the atomization quality when both airstreams were counterrotating with respect to liquid sheet rotation. The calculated relative velocities at atomizer exit are plotted in Fig. 9. Figure 9 shows that, the relative velocity actually increases as ALR decreases in the counter–counter swirler configuration due to the opposite direction of rotation of liquid and airstreams. The striking feature in Fig. 9 is that achieving highest air/liquid relative velocity through injecting liquid and air in opposite directions does not necessarily result in best atomization quality. The fine droplets produced under this configuration are compressed together due to the opposing swirling airstream, resulting in droplet coalescence or recombination and eventually producing sprays with larger SMD levels. For configurations with mixed corotating and counterrotating airstreams, the high shear forces exerted by the two opposing airstreams on the liquid film support efficient atomization, in addition to the very rapid decay of the air swirl component, that reduces the chances of droplet coalescence. Examples of rapid decay in the calculated air swirl velocity profiles for counterrotating outer passage and corotating inner passage, with respect to liquid rotation, are evident in Fig. 10. Thus, the results presented in Figs. 7–10 indicate that, with appropriate selection of the air admission configuration, further enhancement of spray quality over conventional corotating air and liquid arrangement could be achieved.

The limitation of using the data shown in Figs. 6 and 8 to establish the effect of ALR on atomization arises because changing ALR in the test is always coupled with changes in relative velocity and liquid injection pressure. To actually separate the effects of ALR on SMD in the present investigation, the effective flow areas of the two air passages were simultaneously reduced in increments by using a blocking band around the inlet section of each air passage and replacing the exit section component to achieve same reduction in corresponding exit area. Three different band sizes were used to reduce the open area of each air passage from 100 to 80, 60, and 30%, respectively. By this means, both air pressure drop and liquid injection pressure could be kept constant while changing the airflow rate and, consequently, the ALR.

The results obtained under constant air pressure drop and liquid injection pressure, but with different airflow areas, are plotted in Figs. 11 and 12. Figure 11 demonstrates the effect of increasing the ALR on the spray SMD under relatively high air pressure drop of 4.0% and for two levels of liquid injection pressure. The results for two atomizer configurations are given in Fig. 11. In one configuration, both airstreams were corotating with liquid, and in the other, inner air was corotating and outer air was counterrotating with respect to liquid rotation. It is obvious for both configurations that the effects of ALR on atomization quality are more pronounced than those shown earlier in Figs. 6 and 8. This is the direct result of separating the effect of ALR from those of the air/liquid relative

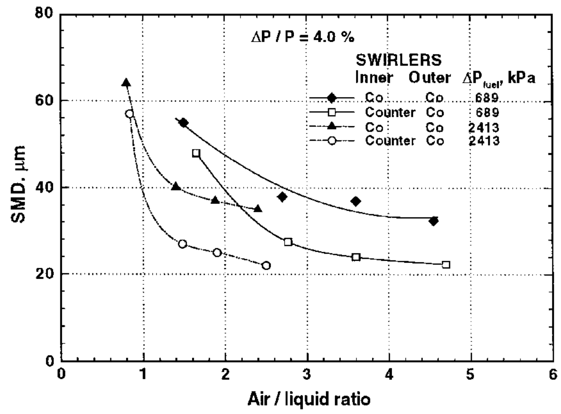

Fig. 11 Net effect of ALR on SMD at high air pressure drop.

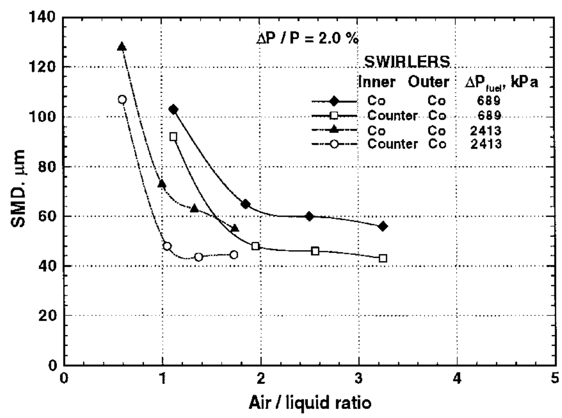

Fig. 12 Net effect of ALR on SMD at low air pressure drop.

velocity and liquid pressure in the latter group of results. Thus, the data shown in Fig. 11 represent the net effect of ALR on SMD.

The superior performance of the atomizer when employing a counterrotating outer air passage over the one using both airstreams corotating with liquid is evident in Fig. 11, in particular under higher ALRs. For example, a 50% reduction in SMD at ALR of 3.5 could be achieved by reversing the outer air swirler direction. This improvement in atomization can have a significant effects on the ignition characteristics and performance of the combustor using such a fuel injection approach. Figure 12 includes similar results, but at lower air pressure drop of 2.0% to provide a broader picture of the effects of ALR and atomizer swirling arrangement on the atomization process. The results demonstrate the same performance trends, but at much higher SMD levels that are caused by the lower airblast impact on the liquid film. It is, however, observed that under low liquid injection pressure the net effect of ALR on SMD becomes negligible once ALR exceeds a value of about 2.0. On the other hand, a continuous improvement in SMD with the increase in ALR is noticed under a high air pressure drop. The main conclusion reached from these observations is that the actual effect of ALR varies with such factors as air pressure drop, liquid injection pressure, and air swirler arrangement.

Summary and Conclusions

An experimental hybrid atomizer was used to provide better understanding of the atomization process under both airblast and high liquid pressure effects. The atomizer was designed in such a way that the direction of rotation of the two airstreams used in the atomizer could be reversed independently. Also, provisions were made to reduce the flow areas of the two airstreams in increments to allow evaluating the separate effects of the atomizer ALR on the atomization process. The experiments covered a wide range of operating conditions. A recently developed fuel injection model was utilized in the effort to provide sufficient information on the key parameters of the atomizer flowfield that are needed to support the experimental findings.

The main conclusions reached in the investigation are summarized as follows.

1) The performance of the baseline configuration of the hybrid atomizer followed that of conventional atomizers. The baseline atomizer incorporated two corotating airstreams and fully open flow areas. At a higher air pressure drop across the atomizer, almost a constant spray SMD was measured irrespective of ALR used in the tests. This is attributed to the opposing effects of increasing air/liquid relative velocity and reducing liquid injection pressure that cancel each other. Under a much lower air pressure drop, the variation of SMD with ALR demonstrated a minimum in SMD value.

2) The results obtained for different combinations of air swirler rotational directions indicated that the least efficient atomization was achieved when both airstreams were swirling in opposite direction to the liquid injection direction. This is believed to be resulting from better potential for having droplet coalescence due the formation of a dense spray region under the opposing swirling airflow against the droplet motion. Best performance was obtained for the configuration that utilized a corotating inner airstream and counterrotating outer airstream with respect to the liquid rotation.

3) The net effect of the ALR on the SMD was evaluated using different air passage open areas that enabled changing the airflow rate while maintaining constant levels of air pressure drop and liquid injection pressure. By this means, it was demonstrated that the actual effects of ALR were more pronounced than those observed with conventional experiments, where variation of ALR was achieved through changing liquid flow rate.

4) The investigation confirmed the conclusion that the air/liquid relative velocity effect, although a key parameter, cannot be used alone to interpret the performance of the hybrid atomizer. Other important aspects, such as the actual level of liquid injection pressure, direction of rotation of atomizer swirling air, and conditions favorable for droplet coalescence, must be considered in the design of a successful hybrid atomizer.

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