Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46162

BEHAVIOR OF SPRAY IN A TWIN- FLUID ATOMIZER

N.P.Yadav
Dept. of Mechanical Engg.
Bundelkhand Institute of Engg. & Technology
Jhansi, Utter Pradesh, India
npy_biet@rediffmail.com

Abhijit Kushari
Dept. of Aerospace Engg.
Indian Institute of Technology
Kanpur, Utter Pradesh, India
akushari@iitk.ac.in

ABSTRACT

This paper describes an experimental study of the behaviour of spray structure in an internally mixed, twin– fluid atomizer in which air was introduced tangentially into the liquid stream inside the atomizer. The atomization in such atomizers is perceived to be strongly influenced by the mass flow ratio of atomizing gas (air) and the liquid (water). The order of magnitude of the ALR (Air-liquid mass flow ratio), for which the study was conducted, ranged from 0.0277 to 0.623. A PDPA (Phase Doppler Particle Analyzer) was used to study the spray formation process. The behaviour of the spray was studied by velocity and Sauter Mean Diameter (SMD) variations at a plane normal to the spray axis as well as along the flow direction of the atomizer. It was observed that the mass flow rate of the liquid deceases with an increase in air pressure while it increases with liquid pressure. The droplet diameter decreases with an increase in ALR for a given liquid supply pressure but sprays having droplet SMD of less than 60 μm at the centerline of the spray was produced at relatively lower ALR (i.e., 0.1). The variation demonstrated by the atomizer in this study makes it flexible to be used for various commercial applications, as the atomizer is capable of providing a wide range of spray patterns depending upon the application requirement.

Keywords: Atomizer, spray, twin-fluid, pressure

INTRODUCTION

The procedure of atomization or breaking of the liquid fuel into tiny droplets in form of fine spray plays a very important role in various industrial and propulsion applications. The droplets provide better mixing and increases the time available for complete combustion in liquid fueled combustion systems due to the reduction in liquid vaporization time by enhanced surface area than the bulk liquid itself [1]. The influence of spray quality on combustion/ignition performance and efficiency is well depicted in Reeves and Lefebvre [2], Lefebvre [3]. Various spray combustion issues in gas turbine engines are directly influenced by the characteristics of the spray. For example, non-symmetric spray flames and hot streaks can cause serious harm to the combustor liners and have serious impact on the combustion exit temperature distribution [4]. Thus major improvements in the performance of the liquid fueled combustors can be achieved by understanding the evolution process of the spray and by having the capability to control the spray characteristics. Various spraying devices operating on different principles and varied geometry have been developed with time [5, 6]. To date, most of the industrial/ combustion application of atomizers uses either pressure atomizers or pressure-swirl atomizers or air-blast atomizers [7–10]. The range of operating flow in pressure atomizers is bounded by poor spray quality at low flows and excessive pressure at high flows [7-10]. In simplex or pressure swirl atomizers, a swirling motion is imparted to the liquid so that under the action of the centrifugal force, it spreads out in the form of a conical sheet as it leaves the atomizer. This sheet then breaks up into liquid droplets under the influence of internal and external forces [7- 12].

Recently, air-assisted atomizers are gaining popularity because of the controllability over the atomization process and the improved quality of atomization provided by them [5, 6, 9, 13-30]. One class of air–assisted atomizers is effervescent atomizers, which are finding wide applications in experimental ramjet and scramjet combustors [18]. The quality of atomization in such an atomizer is good but their design procedure is quite difficult because of the requirement to produce a complex bubbly flow inside the atomizer and a possibility of bubbly explosion inside the atomizer, causing intermittent and inherently unsteady spray.

In an internally mixed, air assisted atomizer, the atomizing air interacts with the liquid inside the injector and assists in the atomization process [15, 16 and 17]. The potential advantage of such an atomizer is choking of the two-phase flow of the liquid and the air as it passes through the injector, due to the low sonic velocity of the two-phase liquid mixture [16]. Therefore, for gas turbine applications, the liquid fuel flow rate is relatively insensitive to variations in combustion chamber pressure and thus, the fuel flow rate is not likely to respond to combustor disturbances reducing the chances of coupling of combustor pressure and fuel flow oscillations [18]. Furthermore, the characteristics of the spray produced by such atomizers can be controlled [17, 19].

Since the use of internally mixed atomizers requires compressed air to assist in the atomization process, reducing the amount of atomizing air is important for its application in gas turbine engines. It has been pointed out in various previous studies that the atomization quality can be improved by allowing longer interaction between the air and water inside the atomizer [6, 26, 27] and that was achieved by providing a mixing chamber by Ferrira et al [27] and Lal et al. [30]. However, the design of the mixing chamber is not trivial as has been discussed by Ferriera et al [27]. Another possible variation in the design can be to introduce the atomizing air tangentially into the atomizer, thus, reducing the axial velocity of the incoming air for the same air supply pressure. This is expected to allow longer interaction between the air and liquid and, thus, improve the atomization quality at lower values of ALR's. The new atomizer investigated in this paper has features of internally mixed air assisted atomizer, but air was introduced tangentially into the liquid stream as opposed to radial [17] or axial [15] introduction in previous studies. Therefore, as seen in the presented study, the atomizer is able to provide fine sprays at lower ALRs.

NOMENCLATURE

ALR	Ratio of Mass flow rates of the air to that of the liquid.
m_w	Mass flow rate of liquid (water) (kg/s)
P_{air}	Air pressure (kPa)
PDPA	Phase Doppler Particle Analyzer
P_w	Liquid (water) pressure (kPa)
SMD	Sauter Mean Diameter (μm)

EXPERIMENTAL DETAILS

Injector Design

The schematic cross-sectional view of the atomizer discussed in this paper is shown in Fig. 1. The liquid, i.e., water, is supplied to the atomizer from the liquid inlet port of 8 mm diameter. A small amount of air is introduced into the liquid stream through four tangential holes, each of 1.0 mm in diameter on the circular wall of the tube in which the liquid flows. Before interacting with the liquid the air is allowed to settle in the settling chamber. This chamber ascertains uniform distribution of air through the holes in the circular tube.

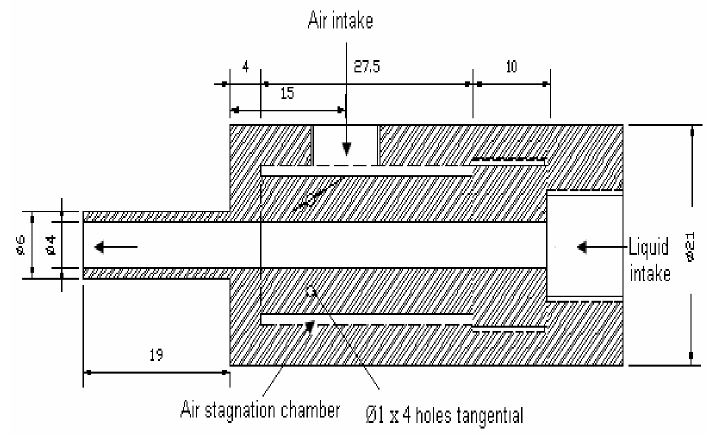

Figure 1. Schematic of the twin-fluid internally mixed atomizer

The air coming out of the air inlet holes interacts with the water flow and creates a two-phase air water mixture. This two-phase flow finally comes out of the orifice (4 mm in diameter) of the atomizer at velocity and spray characteristics are obtained depending upon the ALR and the liquid and air supply pressures.

Experimental Set Up

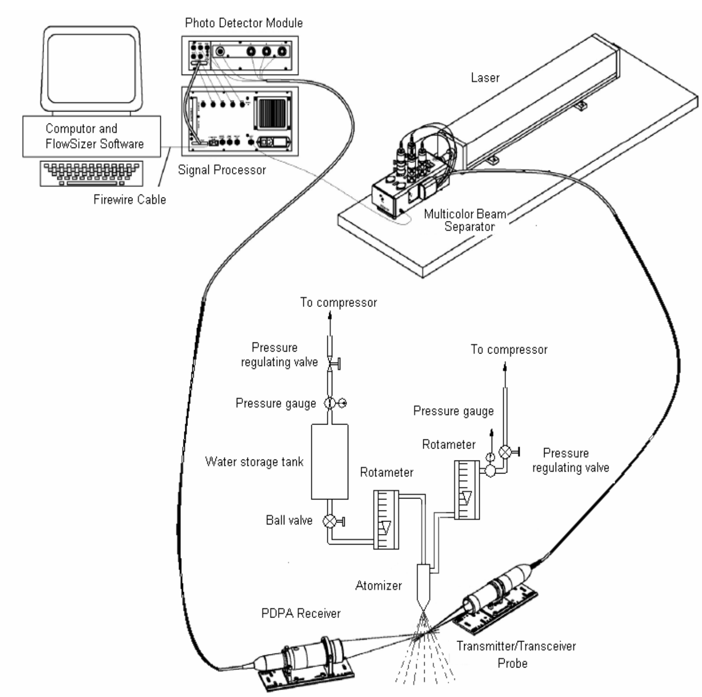

Figure 2. Schematic of the experimental set up and components of the PDPA system

Figure 2 shows the schematic of the experimental setup used in this study. For the purpose of water supply to the atomizer, water was first stored in a cast iron vessel.

Pressurized air was introduced into this vessel to drive the water through the pressure regulating valve, a metering valve and a flow meter to the atomizer at the required pressure conditions. The liquid injection pressure was measured using a dial pressure gage (accuracy ±1% of full scale) and could be varied using a regulating valve. The flow rate of liquid was controlled and measured using the liquid pressure regulating valve and a calibrated rotameter (having ±2% accuracy and ±0.25% repeatability) respectively. The flow rate of the atomizing air was controlled and measured using the air pressure regulating valve and a calibrated rotameter (having ±2% accuracy and ±0.25% repeatability) respectively. For the sake of corrections in density variation, the supply pressure of the atomizing air was closely monitored using a dial pressure gage of accuracy ±1% of full scale. It should be noted that all the pressure values reported in this paper are gage pressures relative to the ambient pressure of 100 kPa.

In the present study TSI® Inc. PDPA (Phase Doppler Particle Analyzer) [31] system was used to characterize the spray at ambient conditions (pressure = 100 kPa, temperature = 300 K). The atomizer was kept stationary in this study and the transmitter and receiver of the PDPA system were traversed along all the three orthogonal axes. An Ar-Ion laser was used in the PDPA system. A multicolor beam separator was used to separate the laser beam to 514.5 nm (green) and 488 nm (blue) wavelengths for the axial and tangential component of the velocity measurement respectively. The laser power was typically set at 1W during the experiment that provided an average laser power of 100 mW in the measurement volume. The fringe spacing was equal to 4.67 μm and 4.43 μm for the green and the blue fringes respectively. The scattered light was collected by the PDPA receiver probe of 512 mm focal length. The receiver was kept at 30^{o} with respect to the transmitted beam to measure the refracted light from the spray. The measurement error for velocity was estimated to be around 1%, the uncertainty of the drop size measurements is about ±5%, which is due to errors in the photomultiplier voltage setting and possible misalignments of optics [32]. The high voltage for the photomultiplier was adjusted for every measurement in such a way that the burst efficiency was maintained above 90%.

The PDPA measurements of drop sizes and velocities were performed at different planes downstream of the atomizer tip, starting from 50 mm below the atomizer tip. Therefore, z=0 represents the plane 50 mm downstream of the atomizer tip and the measurements were conducted up to z = - 80 mm (i.e., 130 mm downstream of the atomizer tip). At each z location, measurements were carried out at several points (x=0 to ±20mm, y=0 to ±20mm). Each measurement has been conducted by acquiring 20000 samples.

It should be noted that since the temperature of both the liquid as well as atomizing air was equal to the ambient temperature and the tests were conducted at atmospheric conditions, any evaporation of the droplets resulting in a change in the spray structure and droplet statistics is quite improbable.

RESULT AND DISCUSSIONS

This section discusses the results of the experimental study of the spray evolution from the twin fluid atomizer. For the sake of understanding the evolution pattern, variations of droplet velocities and Sauter Mean Diameter (SMD) at different locations with respect to air pressure (138 kPa to 552 kPa) were studied for different water supply pressures (ranging from 68.9 kPa to 206.8 kPa). The counter plots for SMD and velocity distribution were obtained in x-y (plane normal to the axis of atomizer) and y-z (plane along the axis of atomizer) to understand the spray nature. It has been reported earlier [6, 17,20, 21, 26, 29] that the mass flow rate of the liquid is also a function of air and liquid supply pressures for this type of atomizers, and, therefore, the variation of water flow rate over the range of operating conditions were also studied and are reported in this section.

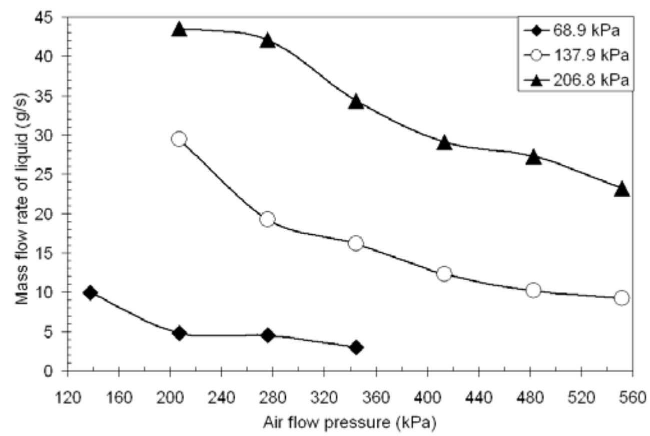

Figure 3. Variation in mass flow rate of liquid with air pressure at constant pressure of liquid

Figure 3 shows the variation in the mass flow rate of liquid (water) with air pressure at different water supply pressures. It can be seen that with the increase in air pressure, the mass flow rate of water decreases monotonically. For a constant liquid supply pressure of 68.9 kPa, the water flow rate decreased from 9.9 g/s to 3.02 g/s with an increase in the air pressure from 137.8 kPa to 344.73 kPa. The reason for this decrease in water flow rate can be attributed to the increase in the area occupied by air inside the atomizer, which reduces the available flow area for water and thus, reduces its flow rate. The data in Fig. 3 also shows that the water flow rate increases with an increase in the supply pressure of liquid, which results in an increase in the velocity of the liquid. The air liquid mass flow rate (ALR) decreases with the increase in supply pressure of the liquid, as in Fig.4, which is due to the increase in flow velocity at an enhanced pressure differential across the atomizer. The ALR for the atomizer increases from 0.0277 to 0.623 with increase in air pressure from 137.8 to 551.5 kPa and liquid pressure from 68.9 to 206.8 kPa.

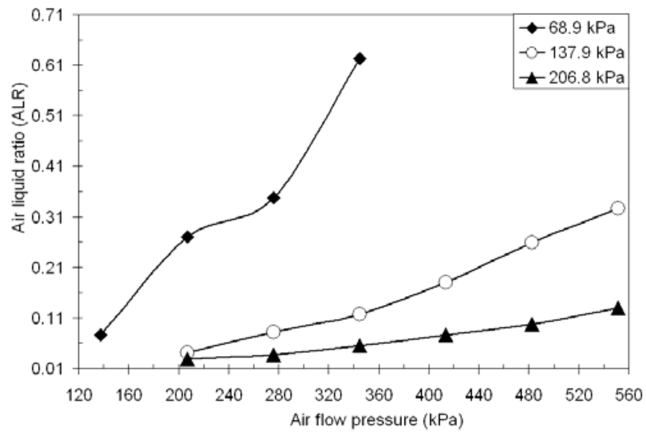

Figure 4. Variation in air liquid mass ratio (ALR) with air pressure at different supply pressures of liquid

The contour plot for the magnitude of resultant velocity (magnitude of the vector sum of two velocity components) distribution along the x-y plane normal to the axis of atomizer (at z = -40 mm) and y-z plane along the axis of the atomizer at ALR=0.269, air pressure (P_{air}) =206.8 kPa and liquid supply (P_w) =68.9 kPa are shown in Figs. 5 and 6 respectively. A higher velocity (above 14 m/s) was observed between x = ± 5mm, y = ± 5mm, as shown in Fig. 5 at z=-40mm. The variation in the velocity is symmetrical about x = 0 and y = -5 mm, which is due to the circular shape of the exit orifice. Ideally the spray should be symmetric about its axis and the discrepancy can be attributed to the misalignment of the atomizer on the test rig. Furthermore, the mean velocity of the spray decreases symmetrically from 14 m/s to 6 m/s when one moves towards the outer edge (x = ± 20mm, y = ± 20mm) of the spray.

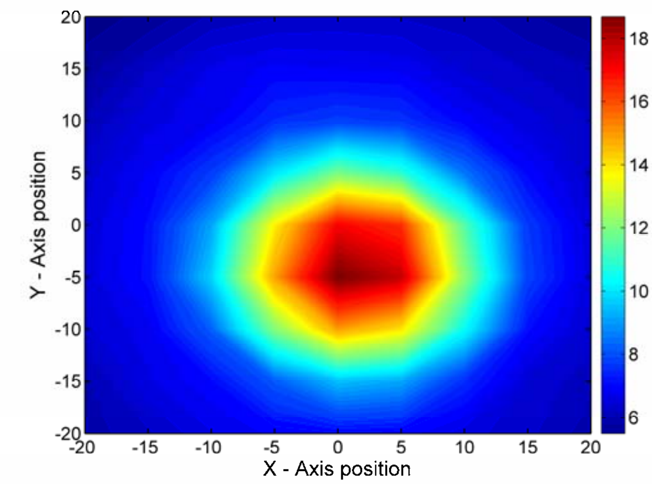

Figure 5. Contour of velocity magnitude (in m/s) distribution along the plane normal to the axis of atomizer at z=-40mm for m_w =4.75 g/s, ALR =0.269, P_{air}=206.8 kPa, P_w=68.9 kPa

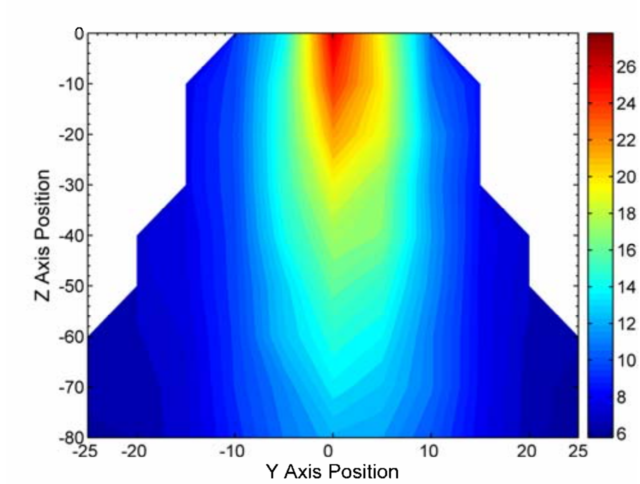

Figure 6. Contour of velocity magnitude (in m/s) distribution along the axis of atomizer for m_w =4.75 g/s, ALR =0.269, P_{air}=206.8 kPa, P_w=68.9 kPa

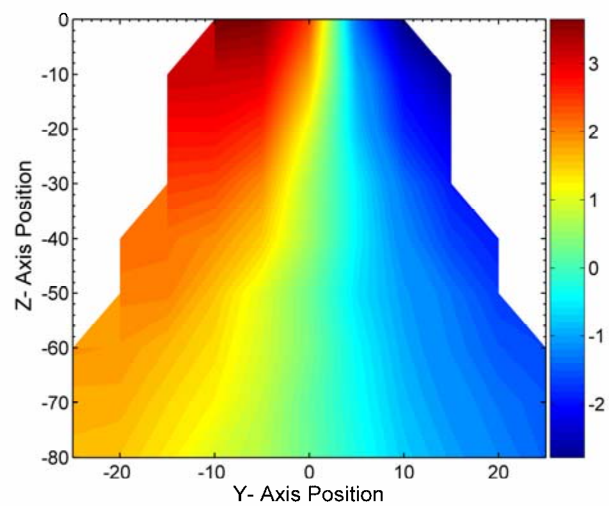

Figure 7. Contour of tangential velocity (in m/s) distribution along the atomizer axis for m_w =4.75 g/s, ALR =0.269, P_{air}=206.8 kPa, P_w=68.9 kPa

The variation of the velocity in z-y plane for x=0 at different locations from the tip of the atomizer (z=0 to 70 mm) are shown in Fig. 6. Since the measurement were started 50 mm below the tip of the atomizer, z = 0.0 was at that plane and the negative sign of z coordinate represents the direction of the jet. The mean velocity of the droplets is about 26 m/s at z= 0.0. This velocity decreases from 26 m/s to 14 m/s along the spray axis from z=0 to -40mm and beyond that it remain almost constant, suggesting that the critical velocity of the droplets is 14 m/s for these operating conditions. The velocity remains fairly high between y= 0 to ±5mm. Beyond, y = ±5mm velocity decreases upto 6.0 m/s.

The variation in the tangential component of velocity in z-y plane at x =0 at different locations from the tip of the atomizer are shown in Fig. 7. It can be seen that the tangential velocity is almost zero at the centre of the spray and it increases to a maximum value of only 3.5 m/s at the edges of the spray. Comparing the data presented in Figs. 6 and 7, one can conclude that the tangential component of velocity is quite small compared to the axial component of velocity. This explains the formation of a solid cone spray at the given operating conditions. One can argue that as the air holes in the atomizer are tangential holes there is swirling flow with centrifugal forces resulting in higher tangential velocities. But, the amount of atomizing air is less than that of the liquid (ALR = 0.269) which reduces the tangential velocity of liquid and the primary function of the air entering through the tangential holes is the increase the time of interaction between the phases.

The contour plot for Sauter Mean Diameter (SMD) distribution along x-y and y-z planes for ALR=0.269, air pressure (P_{air}) =206.8 kPa and liquid supply (P_w) =68.9 kPa are shown in Figs. 8 and 9. In Fig. 8, the SMD is lower at the central region of the spray (diameter ranging between 60 to 120 µm for x=0 to ± 10mm and y =0 to ± 10mm) and much larger droplets are present at the edges of the spray. This can be attributed to lower velocities at the edges of the spray as shown in Figs. 5 and 6. The smaller droplet sizes at the central region of the spray can be attributed to the penetration of atomizing air all the way to the core of the liquid column at the operating ALR, 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.

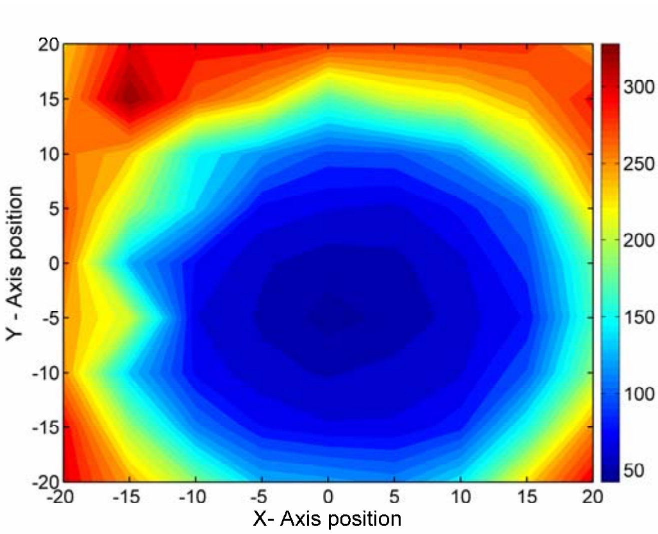

Figure 8. Contour of SMD (in µm) distributions along the plane normal to the axis of atomizer at z=-40mm for m_w =4.75 g/s, ALR =0.269, P_{air}=206.8 kPa, P_w=68.9 kPa

The variation of SMD in y-z plan axis is shown in Fig. 9. The SMD is observed to be almost constant at about 55 µm along the axis from z= -20 mm to -70 mm for y = 0 to ± 10 mm. This behavior suggests that both the primary and secondary atomization in this region is complete by z = 0.0 and, therefore, confirms the conclusion that the spray attains the critical velocity in the measurement domain as shown in Fig. 6. Beyond y = ± 10 mm, the SMD increases from 60 to 260 µm and the droplet sizes continue to decrease as one moves away from the tip of the atomizer suggesting secondary atomization at the edges of the spray to continue much longer than that at the central region of the spray due to lower velocity and larger sizes of the droplets.

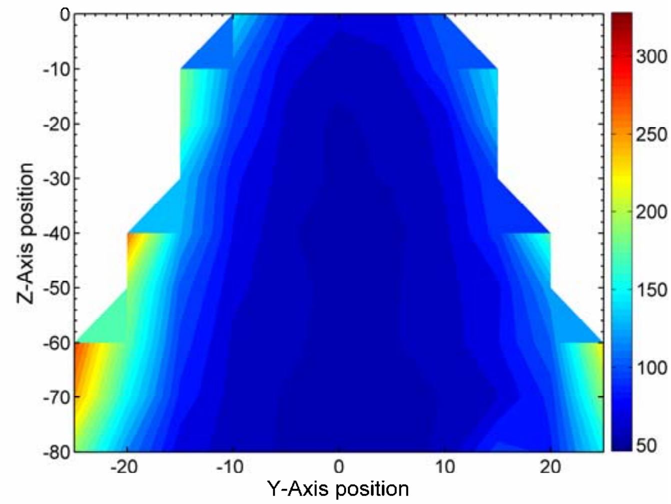

Figure 9. Contour of SMD (in µm) distributions at a the plane along the axis of atomizer for m_w =4.75 g/s, ALR =0.269, P_{air}=206.8 kPa, P_w=68.9 kPa

The variation of SMD with air pressure along the axis (z=0 to -80 mm) at x=y=0 for constant liquid pressure (68.9 kPa) is shown in Fig. 10. It should be noted that the location x = y = 0 is taken as the representative location for the spray as the droplet size is seen to be minimum at the centre of the spray. The mean diameter (i.e. SMD) of the spray decreases from 158.5 to 49.9 µm with an increase in air pressure from 137.8 kPa to 344.73 kPa at z=0. Similar trend is observed at all other axial locations, i.e., the droplet diameters decreases with an increase in the air supply pressure. This can be attributed to the increase in ALR with an increase in air supply pressure as shown in Fig. 4, which results in the increase in kinetic energy of the liquid owing to increased interfacial force between the two phases. Furthermore, beyond z = -20mm, the droplet size variation is almost independent of the measurement location, which can be attributed to the complete atomization as shown in Fig. 9 and discussed in the previous paragraph.

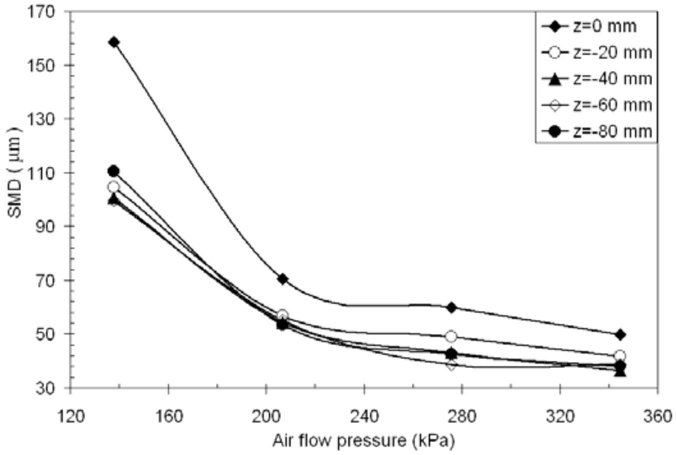

Figure 10. Variation in SMD with air pressure at constant liquid pressure (68.9 kPa) for different locations on the axis of atomizer

Figure 11 shows the variation in SMD with air pressure at z=-40 for different liquid supply pressures. The SMD decreases from 106.5 to 36.32 μm for a liquid supply pressure of 68.9 kPa with the increase in air pressure from 137.9 to 344.7 kPa because of increase in kinetic energy of the liquid and, hence, relative velocity of the liquid with respect to the ambient air, resulting in improved atomization. Furthermore, SMD increases with increase in liquid pressure at constant air pressure. This is due to an increase in liquid flow rate at higher liquid supply pressure resulting in a decrease in ALR (shown in Figs. 3 and 4), causing a reduction in interfacial shearing force by allowing less amount of atomizing air to enter the atomizer.

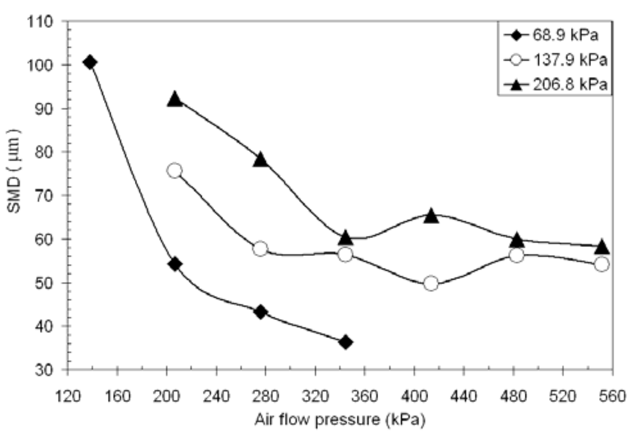

Figure 11. Variation in SMD with air pressure at the axis (z=-40mm) for different liquid pressure

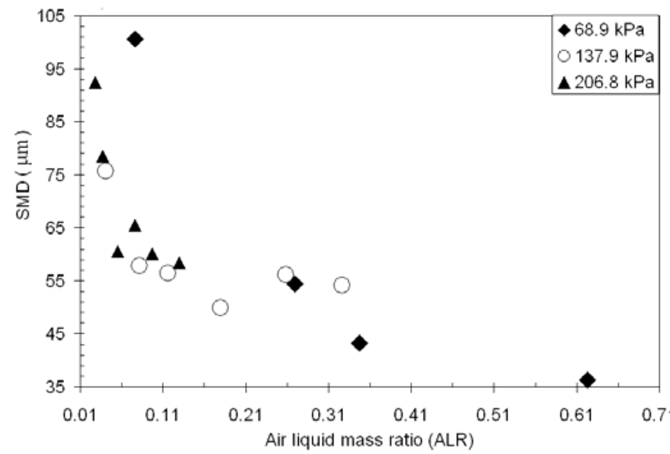

Figure 12. Variation in SMD with ALR at the axis (z=-40mm) for different liquid pressure

The variation of spray quality, i.e., SMD, with ALR for different liquid supply pressures is shown in Fig.12. The data in Fig. 12 show a decrease in the droplet size with the increase in the ALR for a given liquid supply pressure. The observation that all the points collapse onto one curve, independent of the pressure, is a strong indication that the ALR drives the droplet size. It can be speculated that this decrease in the droplet diameter value is due to the increase in airflow rate accompanied by the increase in the air velocity and, thus, the shear force that it exerts upon the liquid. This increased shear force "strips" smaller droplets from the bulk liquid flow, resulting in improved atomization.

It should be noted that the atomizer studied in this paper was able to produce droplets having SMD in the range of 60 μm at an ALR less than 0.1, which is a marked improvement over the data reported for an atomizer with radial air injection [17], which required an ALR of 0.3 to produce 60 μm droplet SMD. The reason for this improvement can be attributed to the tangential injection of air into the liquid flow. This results in a decrease in axial velocity of air inside the atomizer and introduces a tangential component to the air flow. Therefore, the air, due to its spiraling motion inside the atomizer, spends more time inside the atomizer than it spends in previous designs [15, 17]. Thus, the duration of interaction between the liquid and atomizing air increases resulting in improved atomization as has been reported by Kushari [6] for atomizers with longer length.

The results presented in this paper suggest that the investigated atomizer can be used to produce sprays with various spray characteristics at a lower ALR than conventional twin-fluid atomizers. Therefore, this atomizer can be used for various applications over a range of operating conditions and will be more economical.

CONCLUSIONS

This paper illustrates the spray evolution from a twin-fluid swirl atomizer by studying the effect of operating conditions (e.g., different air pressure and liquid pressure) on droplet velocity and droplet diameter and their variation with the quantity of atomizing air. It can be seen that by adjusting the parameters like ALR and liquid supply pressure, this atomizer can produce varying characteristics depending upon the ALR, air and liquid pressure conditions. The mass flow rate of liquid decreases with air pressure while increases with liquid pressure. The velocity distribution was symmetrical and large variation is observed from the center of the atomizer. The mean diameter of the spray changed with location as well as ALR and supply pressures of the liquid and air. As the atomizer is capable of giving sprays with varied properties, it is flexible to be used for different spray condition requirements depending upon the application at a lower ALR compared to other reported studies which makes its operation more economical.

REFERENCES

[1] Rink, K. K. and Lefebvre, A. H., 1987, "Pollutant Formation in Heterogeneous Mixtures of Fuel Drops and Air," *AIAA J. propulsion*, **3** (1), pp. 5-10.

[2] Reeves, C. M. and Lefebvre, A. H., 1986, "Fuel Effects on Aircraft Combustor Emissions," *ASME paper* 86-GT-212.

[3] Lefebvre, A. H., 1985, "Fuel Effects on Gas Turbine Combustion-Ignition, Stability, and Combustion Efficiency," *ASME J. Engg. Gas Turbines Power*, **107**, pp. 24-37.

[4] Chigier, N., 1993, "Spray Science and Technology," *Fluid Mechanics and Heat Transfer in Sprays*, *ASME Fluid Eng. Div. Publ. FED*, *ASME New York, NY* , **178**, pp. 1-18,

[5] Wang, X. F., Chin, J. S. and Lefebvre, A. H., 1987, "Influence of Gas Injector Geometry on Atomization Performance of Aerated-Liquid Nozzles," *ASME National Heat Transfer Conference*, Pittsburgh.

[6] Kushari, A., 2010, "Effect of Injector Geometry on the Performance of an Internally Mixed Liquid Atomizer," *Fuel Processing Technology*, **91**(11), pp. 1650 – 1954.

[7] Lefebvre, A. H., 1983, "Gas Turbine Combustion," *Hemisphere,* New York.

[8] Giffen, E. and Muraszew, A., 1953, "The Atomization of liquid Fuels," *Chapman & Hall Ltd.,* London.

[9] Lefebvre, A. H., 1989, "Atomization and Spray, *Hemisphere Publishing Corporation*.

[10] Bayvel, L. and Orzechowski, Z., 1993, "Liquid Atomization, Taylor & Francis.

[11] Mandal, B., Barman P. and Kushari, A., 2004, "Study of Primary Atomization in a Helical Passage Pressure- Swirl Atomizer," *ILASS-Europe, 6-8 September 2004*, Nottingham, U.K.

[12] Ramamurthi, K. and Tharakan, T. J., 1998, "Flow Transition in Swirled Liquid Sheets," *AIAA Journal*, **36** (3), pp. 420-427.

[13] Roesler, T. C. and Lefebvre, A. H., 1989, "Studies on Aerated Liquid Atomization," *Int. J. of Turbo and Jet Engines*, **6** (3-4), pp.221-230.

[14] Chin, J. S., 1995, "Effervescent Atomization and Internal Mixing Air Assisted Atomization," *Int. J. of Turbo and Jet Engines*, **12**, pp.119-127.

[15] Mullinger, P. J. and Chigier, N. A., 1974, "The Design and Performance of Internal-Mixing Multijet Twin-Fluid Atomizers," *J. Inst. Fuels*, **47**, pp.251-261.

[16] Biswas, M. N., 1982, "Atomization in Two-Phase Critical Flows," *Proceedings of the 2nd International Conference on Liquid Atomization and Sprays*, pp. 145-15.

[17] Kushari, A., Neumeier, Y., Israeli, O., Lubarsky, E. and Zinn, B.T., 2001, "Internally Mixed Liquid Injector for Active Control of Atomization Process," *Journal of Propulsion and Power*, **17**(4), pp. 878-882.

[18] Levy Y. and Lubarsky, E., 1996, "Oscillating Control Spray for the Suppression of the Low Frequency Combustion Instabilities," *Proceedings of 36th Israel Annual Conference on Aerospace Sciences*, February 21-22, 1996.

[19] Lee, J. Y., Kushari, A., Lubarsky, E., Zinn, B. T., Rozenberg, S. and Levy, Y., 2002, "Control of combustion instabilities and emissions using an internally mixed liquid atomizer with a vaporizer,"*40th AIAA Aerospace Sciences Meeting & Exhibit,* Reno, NV, Jan. 14-17, 2002. AIAA 2002-0617

[20] Karnawat, J. and Kushari, A., 2008, "Spray Evolution in a Twin-Fluid Swirl Atomizer," *Atomization Sprays* **18**(5), pp. 449-470.

[21] Karnawat, J. and Kushari, A., 2006, "Controlled Atomization using a Twin-Fluid Swirl Atomizer," *Expt. Fluids,* **41**, pp. 649-663.

[22] Kufferath, A., Wende, B. and Leuckel, W., 1999, "Influence of Liquid Flow Conditions on Spray Characteristics of Internal-Mixing Twin-Fluid Atomizers," *Int. J. Heat Fluid Flow,* **20**, pp. 513-519.

[23] Sovani, S. D., Sojka, P. E., and Lefebvre, A. H., 2001, "Effervescent Atomization," *Prog. Energy Combust. Sci*., **27**(4), pp. 483-521.

[24] Li, J., Lefebvre, A. H. and Rollbuhler, J. R., 1994, Effervescent Atomizers for Small Gas Turbines, *ASME (paper)*, 94-GT-495.

[25] Ramamurthi, K., Sarkar, U. K. and Raghunandan, B. N., 2009, "Performance Characteristics of Effervescent Atomizers is Different Flow Regimes," *Atomization Sprays,* **19**(1), pp. 41 – 56.

[26] Ferreira, G.., Barreras, F., Lozano, A., Garcia, J. A. and Lincheta, E., 2009, "Effect of Inner Two- Phase Flow on the Performance of an Industrial Twin-Fluid Nozzle with an Internal Mixing Chamber," *Atomization Sprays,* **19**(9), pp.873-884.

[27] Ferreira, G, Garcia, J. A., Barreras, F., Lozano, A. and Lincheta, E., 2009, "Design Optimization of Twin-Fluid Atomizers with an Internal Mixing Chamber for Heavy Fuel Oils," *Fuel Processing Technol*., **90**, pp. 270 -278.
[28] Broniarz-Press, L., Ochowiak, M., Rozanski, J. and Woziwodzki, S., 2009, "The Atomization of Water–Oil Emulsions, *Expt. Therm. Fluid Sci.* **33**, pp. 955–962.
[29] Jedelsky, J., Jicha, M., Slama, J., and Otahal, J., 2009, "Development of an Effervescent Atomizer for Industrial Burners, *Energy Fuels*, **23**(12), pp. 6121-6120.
[30] Lal, S, Kushari, A., Gupta, M., Kapoor J. C. and Maji, S.,2010, "Experimental Study of an Air Assisted Mist Generator," *Experimental Thermal and Fluid Science*, **34**, pp. 1029-1035.
[31] FlowSizer, Version: 2.0.4.0, 2001-2007,copyright©TSI Inc., *http://www.tsi.com*
[32] Zhang, Z., and Ziada, S., 2000, "PDA Measurements of Droplet Size and Mass Flux in the Three-Dimensional Atomization Region of Water Jet in Air-Cross Flow," *Experiments in Fluids*, **28**(1), pp. 29-35