STUDY OF PRIMARY ATOMIZATION IN A HELICAL PASSAGE PRESSURE-SWIRL ATOMIZER

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ABSTRACT
In the present study, an attempt has been made to investigate the primary atomization process of a simplex pressure-swirl atomizer and the effect of various forces on conical liquid sheet disintegration. This paper describes the effect of liquid flow Reynolds number on the liquid jet breakup length and the spray cone angle. This study also examines qualitatively the effect of destructive and consolidating forces on the liquid sheet break up and concludes that the ratio of kinetic energy causing spray breakup and consolidating energy plays a critical role in the transformation of the tulip shaped liquid bulb at low Reynolds number into a fully developed hollow cone spray structure at high Reynolds number. With the increase in the kinetic energy, i.e., the inertial forces, the consolidating influence becomes weaker and weaker causing early breakup of the jet. This paper also proposes the use of a new non-dimensional parameter, designated by the ratio of the kinetic energy and consolidating energy, to represent the primary atomization process instead of the often used parameters like Reynolds number, Weber number and Ohnesorge number.

INTRODUCTION

The transformation or break up of liquid fuel into a spray is of great importance in liquid fuel combustion that is used in various propulsion systems and industrials processes. The spray, comprising of a multitude of droplets, provides a much larger surface area compared to the bulk liquid, thus greatly enhancing the liquid evaporation rate. Numerous spraying devices, which operate on different principles and are broadly designated as atomizers or injectors, have been developed over the years. The liquid atomization process contains two stages, primary atomization and secondary atomization. Primary atomization refers to droplet disintegration from a continuous liquid body. Secondary atomization refers to further droplet break up or coalescence during the transport process. Most studies in the past have been combined these two processes and treated them as one global process. For example, Rizk and Lefebvre [1], Suyari and Lefebvre [2], Chung and Presser [3] and others have illustrated the influence of liquid properties of viscosity, surface tension and density on atomization quality. However, to better understand the atomization mechanism, it is important to examine separately the two above mentioned atomization processes. This investigation is focused on the primary atomization stage of a simplex pressure – swirl spray.

In a pressure-swirl atomizer, a tangential velocity is provided to the liquid flow by introducing a swirling motion into the flow. The centrifugal force, due to the tangential motion of the liquid, spreads the liquid to a conical shape when it emerges out of the atomizer. This liquid cone breaks up into droplets due to the influence of various forces acting on it. The literature on the atomization in swirl atomizers is quite extensive. The classic work of Taylor [4] on water bells has identified the surface tension forces to be the force responsible for the shape acquired by the swirling liquid column. Parlange [5] has identified the importance of inertial forces also on the formation and breakup of bell type shapes under the influence of swirling motion. Ramamurthi and Tharakan [6, 7] have reported extensive works on coaxial swirl atomizers. They have mentioned different shapes of swirled liquid sheets, e.g., multiple tulip shape, single tulip shape, disintegration of tulip-shaped sheet, transition to conical shape and straight diverging conical sheet under different operating conditions [6]. Their efforts have revealed the influence of injection parameters and ambient pressure on the atomization process in a swirl atomizer. It was mentioned that the transition of the tulip bell shape to a wavy conical sheet occurs at a liquid phase Weber number of 150 [7]. Using a linear stability analysis of the swirling liquid, Ramamurthi and Tharakan [7] have also identified the importance of drag coefficient, ambient gas densities, thickness of liquid sheet, swirl intensities and radius of orifice on the sheet stability.

The literatures sighted in the previous paragraph have clearly identified two distinct groups of forces that take part in the atomization process. The first group of forces tries to consolidate the liquid and prevent its atomization. These are the retarding forces, which reduce the kinetic energy of the liquid. These forces are the internal and external viscous forces acting on the liquid and the surface tension forces. The second group of forces is the destructive forces represented by the centrifugal and axial forces acting on the liquid as well as the internal turbulence present in the liquid flow. When the destructive forces are dominant in the flow, the liquid cannot consolidate itself and breaks up into drops. This increases the overall surface area of the liquid, causing better evaporation and mixing. This initial break up of the liquid sheet or column into a multitude of droplets is the primary atomization. The atomization continues till equilibrium is attained between the consolidating and the destructive forces through the secondary atomization process. This paper describes an effort to better understand the primary atomization in a swirl atomizer by measuring the spray cone angle and the sheet breakup length over a range of flow Reynolds number. Particular emphasis was given to the sheet breakup and its dependence on the destructive and consolidating forces and an attempt was made to elucidate their importance on the atomization process.

EXPERIMENTAL DETAILS

A cross-sectional view of the helical passage swirl type atomizer tested in this study is shown in Fig. 1. Liquid enters through the threaded opening of a tube of 1.5 mm radius that extends up to spin chamber shown in Fig. 1. Between the spin chamber and entrance section a screwed element is pressed fit, leaving a settling chamber between the end of screwed element and the spin chamber. A double threaded screwed element having Acme thread of 0.455 mm^2 cross sectional area has been used. This screw element provides the helical passage to the liquid flow. The liquid attains a swirling motion when it traverses through this helical passage under the influence of the higher pressure driving the flow. The spin chamber is of conical shape of 46^0 in order to avoid the formation of vena-contracta in the orifice, which is of 0.8 mm diameter.

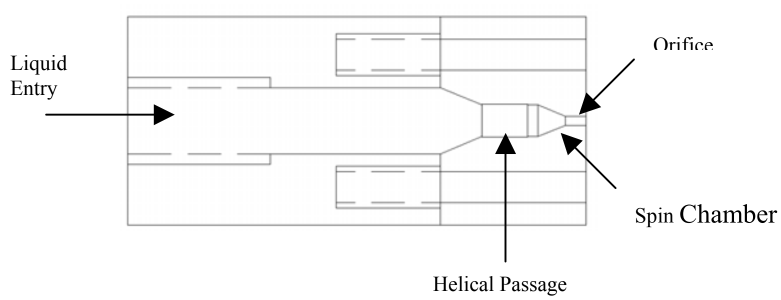

Figure 1: Schematic of the atomizer

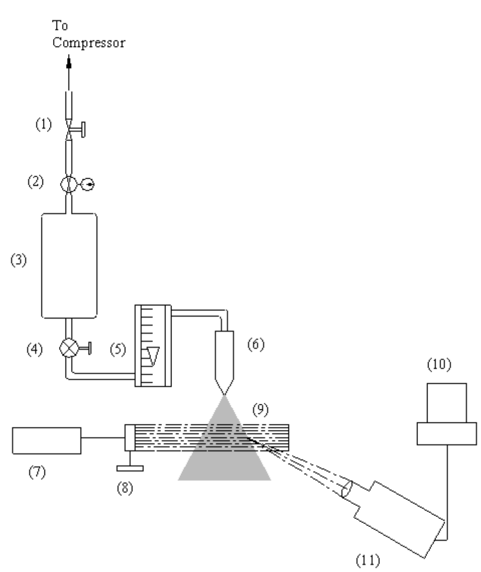

Figure 2: Schematic of the test setup ((1) Pressure regulating valve, (2) Pressure gage, (3) Water storage tank, (4), Ball valve, (5) Rotameter, (6) Atomizer, (7) He-Ni Laser source, (8) Cylindrical lens, (9) Laser sheet, (10) PC, (11) CCD Camera.)

The primary atomization of water (μ = 0.001 Nm/s, σ = 0.073 N/m) in still air was studied in a setup specifically developed for this purpose. The experimental set up used in this study is shown schematically in Fig. 2. High-pressure air is introduced into a cast iron pressure vessel to drive water through a pressure regulating valve, a metering valve, a flow meter and then through the helical passage pressure –swirl atomizer. A pressure gage is used to measure the fluid injection pressure P, which is also equal to the pressure drop across the injector ΔP since the fluid is injected into the atmosphere. The injection pressure was varied from 28 KPa to 850 KPa using the pressure regulating value. This variation of pressure caused a change in the flow rate of water from 0.05 LPM ($8.33*10^{-4}$ Kg/s) to 0.24 LPM ($4*10^{-3}$ Kg/s), which was measured using a calibrated rotameter.

The atomization process formed a hollow –cone spray and was investigated visually by a CCD camera interfaced to a computer. A 5mw diode LASER source of 632 nm wavelength was used to illuminate the spray. The LASER beam was converted into a sheet by using a cylindrical lens. The laser sheet was passed through the centerline of the spray. The CCD camera was focused perpendicular to LASER sheet and the images were captured in the computer. Suitable exposure time was maintained to see the break up length and movies were taken at different flow rates. These movies were analyzed and average break-up lengths and spray angle were estimated. The measured data were then analyzed to gain insight into the physics of the atomization process.

RESULTS AND DISCUSSIONS

In order to identify various parameters that affect the performance of helical passage pressure-swirl atomizer, an experimental study of the injector was carried out. The experimental investigation included studies of the effects of the flow Reynolds number on the performance parameters of the injector. The liquid flow rate was measured and the axial velocity at the exit plane of the atomizer was estimated using the continuity equation. The spray cone angle (α) was estimated by analyzing the images of the spray and the resultant velocity of the liquid along the cone surface was calculated. The *Re* was calculated based on the resultant velocity. In this study the flow *Re* was varied from 1250 to 7400. It was observed that at low *Re* values, which lies in the laminar flow regime, a very small bulb is formed at the exit of the atomizer followed by a liquid cone that breaks up into droplets, as seen in Fig. 3 (a). At these Reynolds numbers, the viscous forces are dominant and play a very important role in consolidating the liquid into a compact form. The collapsing of the rotating liquid bulb to a singular point introduces enough instability into the flow to break it up into droplets. With an increase in *Re*, a well-defined liquid bulb of tulip shape is formed due to the combined effect of consolidating energy (i.e. surface tension and viscosity) and the effect of kinetic energy (or destructive forces). The kinetic energy, manifested by the centrifugal forces and axial forces, tries to spread the liquid into a conical shape. As the liquid cone spreads out in the ambient, the kinetic energy decreases due to viscous forces and the surface forces. At one point the consolidating energy overcomes the effect of destructive energy and the liquid cone collapses again to form a bulb, as shown in Fig. 3 (b). However, with further increase in *Re*, the kinetic energy of the flow keeps on increasing causing an increase in the spray angle. At a certain Re, the consolidating energy is not sufficient to balance the effects of destructive energy, causing an opening up of the liquid bulb seen in Fig. 3 (c). Air now starts to diffuse into the liquid bulb and with an increase in *Re*, a fully developed air core is formed inside the liquid cone giving rise to the formation of a fully developed hollow cone spray as seen in Fig. 3 (d). The destructive energy in that case is such higher than the consolidating energy and the liquid cone can no longer sustain itself beyond a point and breaks up into ligaments and droplets.

(a) *Re* = 1835 (b) *Re* = 3869 (c) *Re* = 5610 (d) *Re* = 7094

Figure 3: Spray images at different flow Reynolds numbers

Figure 4 shows the effect of *Re* on the spray angle. It is seen that the spray angle increases almost linearly with an increase in *Re* through the laminar flow and bulb-cone regimes, the rate of increase of the angle decreases through the transition zone and it attains a constant value of about 80^0 in the fully developed hollow cone regime. With an increase in

Re, the overall velocity of the flow increases causing an increase in the tangential velocity as well. Due to the increased tangential velocity, the spray angle also increases. However, the magnitude of the frictional forces starts to increase with an increase in *Re*, and hence more and more of the kinetic energy is spent in overcoming the effect of friction, causing a reduction in the tangential forces. At lower *Re*, the breakup is due to the instability introduced by the collapsing cone and, hence, no kinetic energy is required for atomization. Therefore, the kinetic energy spreads the cone further out and hence the spray angle increases. However, at higher *Re*, during transition and atomization, a fraction of flow kinetic energy is spend in atomization, leaving less energy for cone spreading. Therefore, at higher *Re*, when we have fully developed hollow cone spray with surface atomization, the spray angle remains constant.

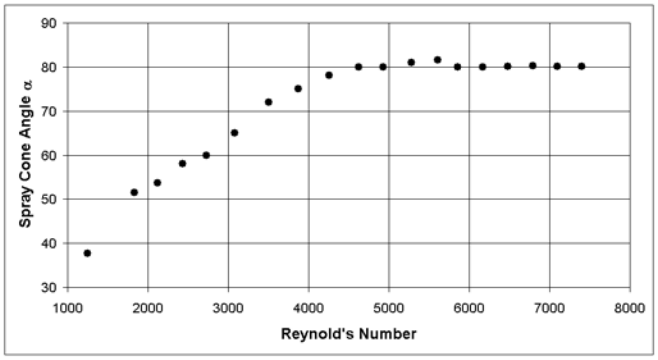

Figure 4: Variation in spray cone angle with flow *Re*

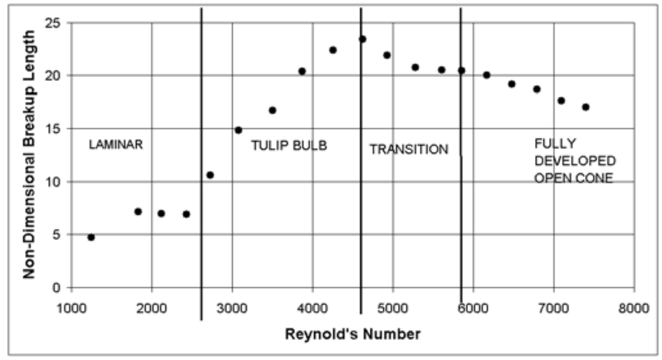

Figure 5: Variation in breakup length with *Re*

Figure 5 shows the variation of jet breakup length, non-dimensionalized by the atomizer exit diameter, with the flow *Re*. The data presented in Fig. 5 shows that in the laminar and tulip bulb regimes, the breakup length increases with an increase in *Re*. This can be attributed to the fact that the breakup in these regimes is primarily due to the collapsing of the swirling liquid flow and hence, is dominated by the consolidating effects that try to close the spray cone into a tulip shape. The increase in *Re* increases the kinetic energy causing more spread of the liquid cone. Due to the increase in kinetic energy, the liquid particles move faster with an increase in *Re* and hence, the magnitude of instability due to the collapse of the shape also increases. Therefore, the liquid requires less assistance from the kinetic energy for breakup. So, the liquid bulb, having larger kinetic energy, increases in size and penetrates deeper into the ambient, causing an increase in breakup length. But, the consolidating shear stresses acting on the liquid also increases with an increase in *Re* due to increased relative velocity between the liquid and the ambient. As the liquid penetrates more as a bulb, the surface area of the bulb increases and hence the surface tension forces decrease due to increased stretching. The data presented in Fig. 6 show an overall decrease in the requirement of consolidating energy (up to the breakup location) in this regime. However, a decrease in consolidating forces should lead to earlier breakup of the liquid. The fact that the breakup length increases in this regime points to the fact that the consolidating forces are predominant in this regime and the kinetic energy of the jet is used primarily to spread out the jet, which, when folded again by the consolidating energy, occupying more area. Also, some amount of consolidating energy is lost in the process. This process cannot be termed as atomization in its classical sense because neither kinetic energy nor the surface energy takes an active role in this process.

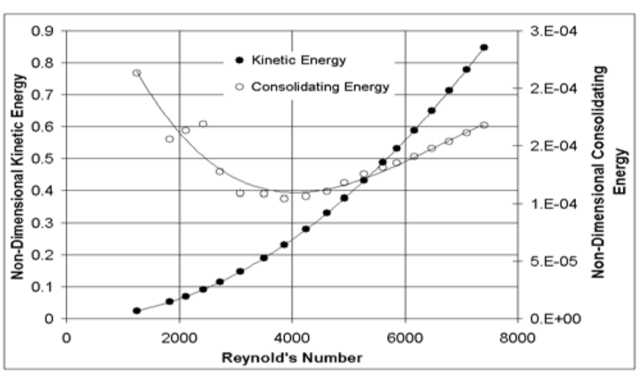

Figure 6: Variation of energies with *Re*

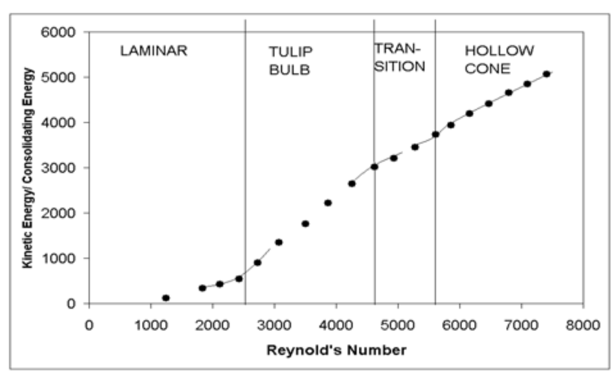

Figure 7: Ratio of energies vs. *Re*

As the *Re* is increased beyond a critical value (4600 in this study), the kinetic energy starts to come into play and it disrupts the liquid sheets to break it into ligaments and droplets. Beyond this point the effect of kinetic energy becomes predominant and the tulip shape of the liquid bulb starts to open up due to surface breakup, as seen in Fig. 3 (c). That causes a reduction in breakup length, clearly seen in Fig. 5. At this point the net destructive effects of the kinetic energy overcomes the combined consolidating effect of friction and surface forces causing the bulb rapture at a higher value of consolidating energy as shown in Fig. 6. Beyond this point, the available surface forces, upto the breakup point, increase due to a reduction in length, but it is not strong enough to prevent the breakup. The kinetic energy keeps on increasing with *Re* and the bulb starts to open up with surface breakup, establishing an air core inside the liquid cone. When the spray takes a fully developed hollow cone shape, seen in Fig. 3 (d), the consolidating forces are completely overwhelmed by the kinetic energy. That occurs at a *Re* of 5800 in this study. When the spray is fully developed hollow cone, the breakup length depends solely on the kinetic energy and hence, it decreases almost linearly with the *Re*.

The data presented in figures 4 through 6 are summarized in Fig.7, where the ratio of kinetic energy and consolidating energy is plotted against the flow *Re*. Figure 7 shows an increase in the ratio of these two energies suggesting a faster increase in kinetic energy than the consolidating energy. The results presented in Fig. 7 show a point of inflection at the boundary between every two adjacent regimes confirming the hypothesis of different regimes encountered by the flow. This observation from the data in Fig. 7 also suggest a crucial role played by this ratio in the transformation of the spray through the discussed regimes and, hence, on the atomization process. The present study shows that when the kinetic energy is more than 4000 times larger than the consolidating energy, the kinetic or inertial forces have an overwhelming dominance in the atomization process and they dictate the spray characteristics.

CONCLUSIONS

This paper describes an experimental study of the primary atomization process in a helical-swirl atomizer. The results presented in this paper show that at low flow Reynolds number the liquid acquires a tulip-bulb shape due to the dominance of the consolidating influence of viscous and surface forces that closes the liquid fan profile generated by the swirling flow emerging from the atomizer due to the centrifugal forces. In this regime the main function of the kinetic energy is just to open up the fan causing an increase in spray angle. The atomization in this regime is due to the instabilities created by the collapsing of the fan. At higher *Re* kinetic energy becomes predominant and breaks the liquid bulb into ligaments and droplets by overpowering the consolidating forces. This causes a reduction in the jet breakup length but the spray angle becomes constant in this regime. When the kinetic energy is about 4000 times the consolidating energy, the spray takes a fully developed hollow cone shape and thus, atomization is initiated by surface breakup causing a reduction in breakup length with an increase in *Re*. Over the entire range of flow *Re* studied in this effort, the ratio of the kinetic energy and consolidating energy was increasing accompanied by a qualitative improvement in atomization. The plot of this ratio versus the flow *Re* showed a point of inflection at the boundary of each regime suggesting a crucial role played by this ratio in the transformation of the spray through the discussed regimes and, hence, on the atomization process.

NOMENCLATURE

A	Exit area (m^2)
d	Orifice diameter (m)
E_C	Consolidating Energy per unit volume (N/m^2)
E_K	Kinetic Energy per unit volume (N/m^2)
E_S	Surface Energy per unit volume (N/m^2)
E_V	Viscous Energy per unit volume (N/m^2)
L	Breakup length (m)
$\dot{m}$	Mass flow rate (Kg/s)
Re	Flow Reynolds number
U	Axial Velocity (m/s)
V	Absolute Velocity (m/s)
α	Spray cone angle (Degrees)
ρ	Liquid Density (Kg/m^3)
μ	Coefficient of Viscosity (Nm/s)
σ	Coefficient of Surface Tension (N/m)

APPENDIX

Following equations were used to calculate various parameters for this study

$$U = \frac{\dot{m}}{\rho A} \tag{1}$$

$$V = \frac{U}{Cos\left(\frac{\alpha}{2}\right)} \tag{2}$$

$$\mathrm{Re} = \frac{\rho V d}{\mu} \tag{3}$$

$$E_K \propto \rho V^2 \tag{4}$$

$$E_V \propto \frac{\mu V}{d} \tag{5}$$

$$E_S \propto \frac{\sigma}{L} \tag{6}$$

$$E_C \propto \left(E_V + E_S\right) \tag{7}$$

All the length parameters were non-dimensionalized using the orifice diameter as the reference length.
All the energy parameters were non-dimensionalized with respect to the ambient pressure.

ACKNOWLEDMENT

This project is funded by Indian Space Research Organization through the Space Technology Cell at Indian Institute of Technology, Kanpur. Dr. K. Ramamurthi is the contact monitor.

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