A TWIN-FLUID INTERNALLY MIXED SWIRL ATOMIZER

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ABSTRACT

This paper describes a new atomizer in which the principles of a conventional pressure swirl atomizer and an internally mixed air-assisted atomizer are combined together. The resultant atomizer is different from both the pressure swirl and the air-assisted atomizer in the structure of the spray produced by it. The structure of the spray produced by the atomizer mentioned in this paper depends on the ratio of flow rates of liquid and atomizing gas flowing through the twin fluid atomizer. At low flow rates of atomizing gas, the atomizer produces a hollow cone spray without any tulip structures. Where as, at high flow rates of atomizing gas the spray is a solid cone. This unique feature of the spray structure, i.e. to have both the hollow cone and solid cone spray from the same atomizer, distinguishes this atomizer from the current state-of-art atomizers and can have various commercial applications.

INTRODUCTION

The transformation or break up of bulk liquid fuel into a spray is of great importance in liquid fuel combustion that is used in various propulsion systems and industrial 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 [1 –3]. There are many other issues in spray combustion that are directly related to the characteristics of the spray. For example, non-symmetrical spray flames and hot-streaks can cause serious damage to combustor liners and have serious impact on combustor exit temperature distributions (i.e., pattern factor) [4]. Therefore, flames must be kept well away from liner surfaces. Since the flame shape, flame location and pattern factor strongly depend on the characteristics of the fuel spray, controlling the spray properties has become an issue of major concern because of potential damages it can cause to the engine. Apart from combustion applications, atomizers are used widely in many industrial processes such as spray painting, spray dying, spray cooling, drug delivery, etc. They are also widely used in agriculture industry for spraying pesticides. In the present scientific scenario, atomizers are finding applications in formation of nano-particles, nano-tubes and manufacturing of MEMS devices. They are used in Combustion Vapour Deposition (CVD) methods [5] and in inkjet printers [6]. However, all these applications demand unique features of the spray and hence, various types of atomizers are being used for these applications. Most preferred atomizers for combustion applications are pressure-swirl atomizers due to their large spray angle and hollow cone structure of the spray to cover larger combustion volume. But, very fine spray with a solid cone structure is needed for synthesis of nano-particles to provide uniformity and hence, ultrasonic atomizers are preferred there. This paper describes a new atomizer, which combines the principles of pressure-swirl and air-assisted atomizers, having unique operating principle and spray structure. It is envisaged that this atomizer will be able to address some of the disadvantages of the state-of-the-art atomizers.

In simplex pressure swirl atomizer [1-3, 7, 8], the liquid is made to flow through a swirl inside the atomizer that provides a tangential motion to the flow. Upon exiting from the atomizer, this tangential motion leads to an increase in flow area owing to centrifugal forces. The liquid emerges from the atomizer as a hollow and thin liquid cone. This leads to subsequent thinning of the liquid cone resulting in breaking of cone into ligaments and atomization. Thus, the spray formed by such an atomizer will always have a hollow cone structure. Furthermore, the energy for atomization is provided solely by the kinetic energy of the liquid at the exit of the atomizer. Therefore, a large pressure difference has to be maintained across the atomizer for good atomization. These atomizers cannot be used for applications where a solid cone spray structure is needed, e.g., final surface finish in spray painting, drug delivery, inkjet printing, etc. Furthermore, the droplet penetration and size distribution cannot be controlled in such atomizer, because, for a fixed geometry, only controlling parameter is the liquid supply pressure.

The atomization characteristics can be controlled in an internally mixed air-assisted atomizer [9]. In an internally mixed air-assisted atomizer, a small amount of air is introduced into the liquid flow inside the atomizer. This atomizing air occupies some area inside the atomizer. This causes an increase in the liquid velocity and, hence, in liquid kinetic energy. Therefore, it can provide better atomization at lower liquid supply pressures. The atomization characteristics, e.g., the droplet size and the liquid flow rate, can be varied independent of each other by varying the liquid supply pressure and the amount of atomizing air simultaneously [9]. However, the liquid emerges from the atomizer axially, without any tangential velocity. Therefore, the spray thus formed has a solid cone structure and has a small spray angle.

In the atomizer discussed in this paper, a conventional swirl atomizer is modified to create a two-phase swirling flow. A small amount of air is added into the liquid inside the atomizer and the resulting two-phase mixer is made to flow through a helical passage imparting a swirl to the flow. At different Air-Liquid mass Ratios (ALR), different flow regimes are witnessed by the two-phase flow from a bubbly flow at low ALR to a dispersed flow at high ALR [10, 11, and 12]. Owing to the multi-dimensional nature of this two-phase swirling flow inside the atomizer, the spray behaves differently at different ALR giving unique features to the atomization process as discussed in this paper. Thus, the same atomizer, for same liquid flow rate, can provide both the hollow cone and solid cone spray by varying the operating parameters of liquid supply pressure and ALR. This feature can make this atomizer useful for a wide range of applications, starting form liquid combustion in gas turbine or IC engines to spray painting, spray cooling, drug delivery, agricultural sprays, etc.

EXPRIMENTAL DETAILS

Atomizer

The atomizer discussed in this paper is an internally mixed, air-assisted, swirl atomizer. It consists of a liquid inlet port, few air inlet holes, an air settling chamber, a helical passage, a spin chamber and the atomizer orifice, as shown in figure 1.

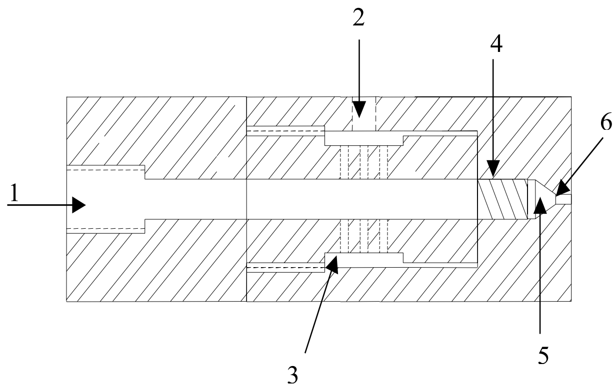

Figure 1: Schematic of the atomizer. ((1) Liquid inlet port, (2) Air inlet holes, (3) Air settling chamber, (4) Helical Passage, (5) Spin chamber, (6) Atomizer orifice)

Liquid water is introduced into the atomizer through the inlet port and it flows in the straight circular tube. A small amount of air is introduced into the atomizer through radially located holes on the tube walls. Before being introduced into the atomizer, the atomizing air settles in the settling chamber. This chamber allows for an equal distribution of air through all the air inlet holes of the atomizer. Also, the pressure of air in that chamber is total air pressure, which is higher than the static pressure present at the tip of air injection holes, and, thus, to certain extent prevents the back flow of liquid into the air passage. The atomizing air interacts with the liquid inside the atomizer and creates a two-phase air-liquid mixture. The air-liquid mixture flows through this helical passage before it goes to the spin chamber. This passage in created by press fitting a small screw element, having acme threads cut onto its surface, inside the atomizer tube. This passage converts the flow of the two-phase mixture from being purely axial to a rotating flow that has a tangential and an axial component by providing a swirling motion to it. This swirling two-phase flow, emerging from the helical passage, develops into a fully developed swirling flow. The pattern of the flow inside this chamber depends on the ratio of mass flow rates of the air and the liquid [10, 11, 12]. The swirling two-phase flow emerges from the atomizer at a very high velocity through the orifice leading to almost instantaneous atomization at the orifice exit.

Experimental Setup

The schematic of the experimental setup used to visualize the spray structure emerging from this atomizer is shown in Fig. 2.

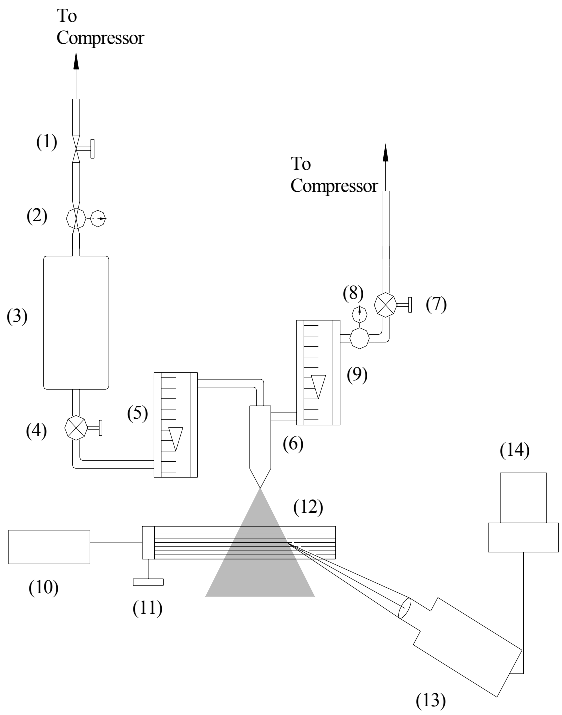

Figure 2: Schematic of the experimental setup. ((1, 7) Pressure regulating valve, (2, 8) Pressure gage, (3) Water storage tank, (4), Ball valve, (5,9) Rotameter, (6) Atomizer, (10) He-Ni Laser source, (11) Cylindrical lens, (12) Laser sheet, (13) CCD Camera, (14) PC.)

High-pressure air was introduced into a cast iron pressure vessel to drive water through a pressure regulating valve, a metering valve, and a flow meter and then through the atomizer. A pressure gage was used to measure the fluid injection pressure P, which was also equal to the pressure drop across the injector ΔP since the fluid was injected into the atmosphere. The injection pressure was varied using the pressure regulating value. This variation of pressure caused a change in the flow rate of water, which was measured using a calibrated rotameter. The atomizing airflow rate was controlled and measured using a pressure regulating valve and a calibrated rotameter respectively. The supply pressure of the atomizing air was monitored using a pressure gage to correct for the density variation. The spray produced by the atomization process was investigated visually by a CCD camera interfaced to a personal 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.

RESULTS AND DISCUSSIONS

Figure 3 shows an image of a water spray produced by the atomizer. In this case, the operating conditions (i.e., liquid supply pressure and air flow rate) were manipulated simultaneously to maintain a water flow rate of 0.3 LPM (5.59 g/s) with an air flow rate of 1.815 g/min ($3.025*10^{-2}$ g/s). That corresponded to an ALR of 0.005. A hollow cone spray structure is clearly visible in Fig. 3. The previous researches on swirl atomizers have reported [7, 8] the formation of a tulip shaped liquid structure at the exit of the atomizer at such low flow rates followed by atomization. However, the spray from the atomizer reported in this paper shows a fully developed air core inside the hollow conical spray at such low flow rates. This suggests the assistance provided by the atomizing air to the atomization process by de-stabilizing the liquid internally. The introduction of air forms a two-phase air-liquid mixture inside the atomizer, whose flow is governed by two-dimensional, two-phase fluid dynamics. When a very small amount of air (ALR less than 0.01) is introduced in the internally mixed atomizer, the mixture produced is a bubbly mixture with air bubbles imbedded inside the liquid flow [10]. This mixture flows through the helical passage and gets a swirling motion and comes out of the atomizer as a hollow cone spray, as shown in Fig. 3. Since the air bubbles occupy a finite area inside the atomizer, the liquid is squeezed to a smaller available area. This causes an increase in the liquid velocity or kinetic energy and helps in the atomization process. Secondly, the increase in air core, due to coalescence of air bubbles, reduces the sheet thickness of the hollow-cone spray and thus improves atomization. Thirdly, the air bubbles, which are at higher pressure than the ambient pressure, explode when they emerge from the atomizer. This bubble explosion introduces localized instabilities to the liquid jet and improves atomization. Furthermore, the presence of air bubbles in the bulk liquid greatly reduces the consolidating influence of surface forces and viscous forces by introducing local discontinuities. Therefore, the kinetic energy of liquid, enhanced by energy transfer from atomizing air, is sufficient to breakup the liquid into droplets. In this case the axial liquid velocity inside the atomizer is relatively low due to the low flow rate. Therefore, the predominant velocity component is the tangential velocity component. The centrifugal forces acting on the liquid, due to the tangential velocity introduced by the swirl, opens up the liquid into a conical shape and thus, produces a hollow cone spray.

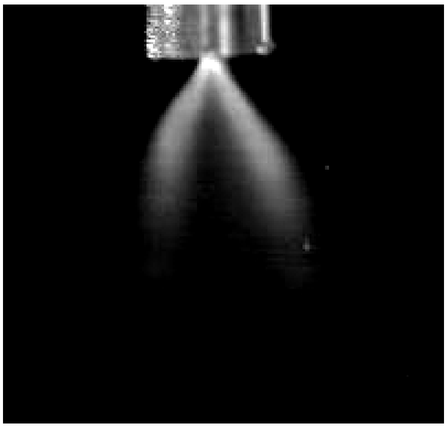

Figure 3: Hollow Cone Spray of water; Water flow rate = 0.3 LPM, Air flow rate = 1.815 g/min, ALR = 0.005

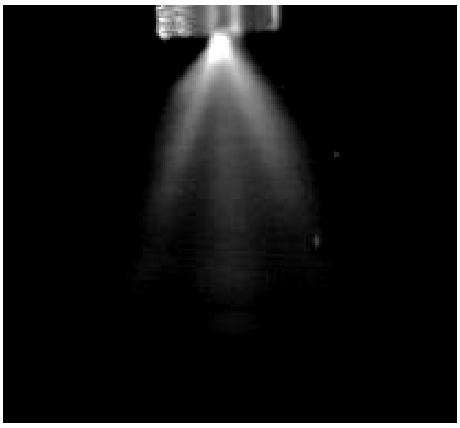

Figure 4: Solid Cone Spray of Water; Water flow rate = 0.3 LPM, Air flow rate = 8.82 g/min, ALR = 0.026

Next, the atomizing air flow rate was increased to 8.82 g/min (0.147 g/s) and the water supply pressure was increased accordingly, to compensate for the reduction in water flow rate due to reduced available flow area for the water, to maintain the water flow rate constant at 0.3 LPM. This corresponds to an ALR of 0.026, which belongs to the slug flow regime of the two-phase flows [12]. At these operating conditions it was observed that the spray produced by the atomizer takes a solid cone shape. An image of the spray at these conditions is shown in Fig. 4. The solid cone spray structure can be attributed to the fact that the reduction in liquid flow area as well as the increase in liquid supply pressure greatly increases the axial component of the liquid velocity in the atomizer tube. The internal swirl inside the atomizer, although much stronger than the swirl produced at low ALR, is not sufficient and strong enough to overcome this axial momentum of the liquid and, hence, the predominant velocity component of the liquid is axial velocity in this case. Therefore, the centrifugal force acting on the liquid is much weaker compared to the axial momentum, restricting the spread to the spray in the radial direction. However, air, being much lighter than water, experiences the strong influence of centrifugal acceleration inside the atomizer and is pushed radially outward towards the periphery of the flow. Therefore, the atomizing air shrouds the liquid cone when it emerges out of the atomizer and thus, further restricts the spread of the liquid in radial direction. The net effect is the formation of a solid cone spray as seen in Fig. 4.

The formation of both the hollow cone and solid cone spray by the same atomizer, for the same liquid flow rate, is a unique feature of the atomizer reported in this paper. The spray cone angle can also be varied by just controlling the ALR and, thus, different cone angles and spray structure can be obtained for the same flow rate of liquid. So far all the controllable atomizers reported in open literature have shown control over the droplet size distribution and spray penetration. This atomizer, for the first time, has shown control over the spray structure itself and can find far-reaching applications in many industrial and commercial applications.

CONCLUSIONS

This paper describes the development of a new atomizer that combines the principals of swirl atomization and internally mixed, air-assisted, twin fluid atomization. The mechanism of atomization obtained from this atomizer is distinctly different from both the swirl atomizer and air-assisted atomizer. The atomization in this atomizer is strongly influenced by the two-phase flow regime inside the atomizer and the multi-dimensional nature of the two-phase flow. This paper, for the first time, reports a strong control over the atomization process, providing a hollow cone spray and a solid cone spray for the same liquid flow rate and thus, can have wide range of applications.

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