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Breakup processes of pressure swirl spray in gaseous cross-flow

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ABSTRACT

Injection of liquid fuel in cross flowing air has been a strategy for future aircraft engines in order to control the emissions. In this context, breakup of a pressure swirl spray in gaseous cross-flow is investigated experimentally. The atomizer discharges a conical swirling sheet of liquid that interacts with cross-flowing air. This complex interaction and the resulting spray structures at various flow conditions are studied through flow visualization using still as well as high speed photography. Experiments are performed over a wide range of aerodynamic Weber number (2–300) and liquid-to-air momentum flux ratio (5–150). Various breakup regimes exhibiting different breakup processes are mapped on a parameter space based on flow conditions. This map shows significant variations from breakup regime map for a plain liquid jet in cross-flow. It is observed that the breakup of leeward side of the sheet is dominated by bag breakup and the windward side of the sheet undergoes breakup through surface waves. Similarities and differences between bag breakup present in plain liquid jet in cross-flow and swirl spray in cross-flow are explained. Multimodal drop size distribution from bag breakup, frequency of bag breakup, wavelength of surface waves and trajectory of spray in cross-flow are measured by analyzing the spray images and parametric study of their variations is also presented.

Introduction

Combustors of the next generation gas turbine engines are being designed to reduce pollutant formation while maintaining efficient performance. One of the ways to achieve this goal is to operate these combustors under fuel-lean conditions to avoid high temperatures associated with stoichiometric combustion that promotes the formation of pollutants such as NO_x. To ensure efficient combustion at fuel-lean conditions it is necessary to mix fuel and air thoroughly in both spatial and temporal domains (Lyons, 1981; Fric, 1993). This requirement has given rise to the concept of lean, premixed, prevaporized (LPP) combustor, which is studied with great interest in recent years for clean gas turbine engines.

In LPP configuration, the concept is to inject the jet of a liquid fuel into the high velocity cross-flow of air. The liquid column breaks up into ligaments that further undergo secondary atomization due to the aerodynamic interaction with the cross-flowing stream. The dynamics of a liquid jet in cross-flow is well understood and different aspects of this phenomenon such as breakup regimes (Mazallon et al., 1999; Sallam et al., 2004), penetration (Wu et al., 1998), drop size distribution (Tambe et al., 2005), mass flux distribution (Rachner et al., 2002) and numerical simulations (Herrmann, 2010; Pai et al., 2009) have been investigated extensively in past.

Another important strategy for the future, low NO_x engines is the injection of fuel spray instead of fuel jet into the cross-flow. The fuel spray may be created using one of the known spray formation techniques. The spray in this case may consist of a liquid sheet, ligaments or atomized droplets. Such a spray aided by its intrinsic breakup mechanism is expected to atomize and mix more efficiently in cross-flow compared to a plain liquid jet. Such a strategy needs to be explored further.

There have been a few attempts to study different types of sprays in gaseous cross-flows. Lin et al. (1999, 2001) studied effervescent sprays in subsonic and supersonic cross-flows. It is reported that the spray penetration in cross-flowing stream is more in case of an effervescent atomizer compared to a plain liquid jet. Also, the penetration height is seen to increase monotonically with increase in atomizing gas fraction. It was observed that as the amount of aerating gas increases, the droplet distribution transits from highly multi-dispersed to nearly mono-dispersed state. Ghenai et al. (2009) also carried out similar experiments in supersonic cross-flow with similar results. Better atomization and penetration were reported when the pure liquid jet was replaced by aerated jet. Seay et al. (1995) investigated atomization and dispersion of airblast spray in subsonic cross-flow. Leong et al. (2001)

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studied the airblast spray in cross-flow at elevated pressures. The observation was that an increase in atomizing air would result in higher penetration and better dispersion. Lee et al. (2010) investigated dynamics of pressure swirl spray in low speed cross-flow. They measured breakup lengths and SMD distribution downstream of injection. Dispersion of swirl spray in cross-flow was studied numerically by Salewski and Fuchs (2005) for a few cases. Lynch et al. (2011) recently observed a large spatial variation in SMD of swirl spray in cross-flow. Apart from these there are not many studies involving sprays in cross-flows.

In this paper, we attempt to characterize the pressure swirl spray in the presence of cross-flow over a wide range of operating parameters. This objective is set because of the fact that the fuel flow rate is significantly altered by the engine loading (no load to full load condition) giving rise to different spray structures having complex interaction with air flow. In this experimental study, water is used as an injection fluid in a cross-flow of air. The advantage of using pressure swirl spray is that it does not require secondary atomizing air as in twin-fluid atomizers and hence is simple in implementation similar to a plain liquid jet. Pressure swirl spray, being a hollow cone spray, is expected to give a better dispersion and penetration in lateral direction as compared to a plain liquid jet. Moreover the swirl spray is inherently three dimensional and may exhibit relatively complex interaction with cross-flow. As a starting point of understanding this complex mechanism, different breakup regimes are first identified based on flow visualization experiments and mapped with transition regions. The intention here is to understand the physics of different breakup processes when such a spray interacts with gaseous cross-flow. Temporal evolution of atomization of swirling liquid sheet is also investigated and the characteristic features such as spray trajectory, surface waves and drop sizes are quantified.

Experimental setup

Cross-flow and spray generation facility

A dedicated test facility is built in the laboratory to study the behavior of sprays in air cross-flow. The primary requirement of the present study is to have a uniform air flow in confinement. This is achieved in a blow-down tunnel arrangement shown schematically in Fig. 1. The setup consists of a settling chamber smoothly transitioning into the test section. The settling chamber helps in reducing flow fluctuations and maintaining steady air flow. The test section has a facility to attach the injector under investigation. Air is supplied to the settling chamber from compressed air storage (5 m^3 capacity, stored at maximum pressure of 35 bar) through a high-mass-flow pressure regulator (1800 scfm at 10 bar upstream pressure) and a diffusing rectangular piping section. The test section has a square cross-section with each side measuring 8 cm. Test section has transparent glass windows for optical access, measuring 15 cm by 7 cm, on all sides except at the bottom. The cross-flowing air velocity in the test section is varied from 8 to 90 m/s and the pressure in the test section is ambient pressure. The injector is positioned at the centerline of the bottom plate with an arrangement to move it along the centerline in direction of air stream. The liquid used for injection is also pressurized using the same compressed air source.

Though this is a blow-down type of arrangement, uniform airflow at steady velocities can be achieved for a minimum duration of 55 s continuously at maximum flow rates, which is found to be sufficient to conduct the designed experiments. It is measured and verified with the aid of a Pitot tube that uniform air-flow at constant velocity is achieved across the entire test section. Hence, boundary layer effects may be considered as negligible on account of the dimensions of the test section and the characteristic lengths observed in primary breakup. The coordinate system is shown for reference in Fig. 1. The cross-flow is along *x*-direction and the spray injection is along *z*-direction.

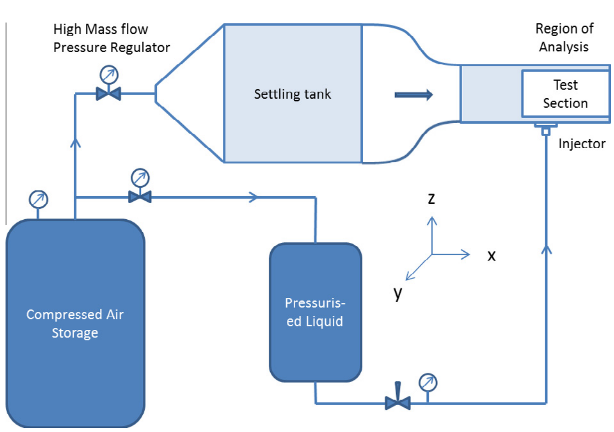

Fig. 1. Schematic of experimental setup.

Atomizer details

The pressure swirl atomizer (fabricated from brass) used in the current study is of hollow cone type. The swirl is generated by having a swirler inside the injector main body before the exit orifice. Assembly of the atomizer is shown in Fig. 2. A swirler is a simple arrangement of helical grooves through which water flows and gains tangential momentum. Two different swirlers with 2-start and 4-start helical grooves which result in different swirl numbers are employed in these experiments. A larger orifice diameter is investigated to aid better flow visualization so as to obtain a clearer understanding of the mechanisms involved in the spray break up. The orifice diameter, *d* is 2 mm and *L*/*d* ratio of the orifice is unity as shown in Fig. 2. Pressure drop across the atomizer is varied from 0.1 to 3 bars.

Swirl number, *SN* is used to characterize different swirlers. Swirl number is a non-dimensional parameter based on geometric dimensions of a swirler. Physically it may be treated as the ratio of angular momentum flux to the axial momentum flux. Applying this definition to the swirler geometry used in the current study, the swirl number is derived to be represented by the expression, $SN = \pi d D_s / 4nwh$. Swirl number of the pressure swirl jet is varied by using swirl pieces of different starts (two-start and four-start) having similar groove dimensions. The design of the injector is shown in Fig. 2 and the details of different swirl pieces are tabulated in Table 1.

The swirl jet atomizer differs from the plain orifice atomizer by the fact that it converts part of the pressure drop into angular

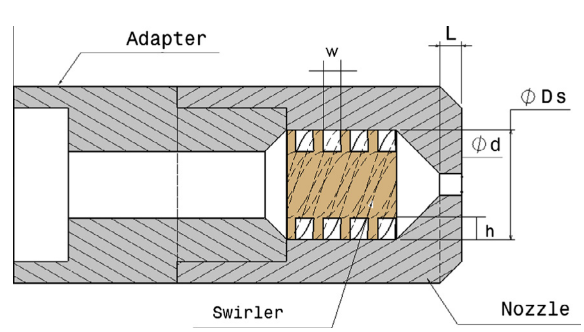

Fig. 2. Design and dimensions of the pressure swirl atomizer.