Experimental study of the spray of a liquid-liquid coaxial swirl injector for different injection pressures

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An experimental study was conducted on a coaxial liquid-liquid swirl atomizer. Both visual and PDA measurements were used to investigate the behavior of this type of injectors in different injection pressures. It is observed that injection pressure and also merging process of inner and outer flow have a crucial effect on velocity profile and size distribution. Merging process increases the spray angle of inner flow to the angle of coaxial injection. The velocity of both components after merging for working pressures was almost the mean value of the velocity of inner and outer components. Merging process slightly increases the size of the droplets on the edge of the spray and out of it.

1. Introduction

Droplet size and velocity distribution are the main parameters influencing the combustion process. Hence, the knowledge about their behavior prior to entering the combustion chamber is of great importance. Coaxial Liquid-Liquid Swirl (CLLS) atomizers, are one of the most efficient injectors with the conical spray structure associated with a high degree of atomization. CLLS atomizers are specially employed in liquid bipropellant rocket engines aiming to high mixing efficiency within a given length of combustion chamber.

Enermous studies have been conducted on simple swirl atomizers and coaxial gas-liquid and airblast atomizers in comparison with CLLS atomizers and the literature of this kind of atomizers seems to be scarce. A sudy on the role of geometric parameters on the drop size characteristics of CLLS atomizers is presented by Sivakumar and Raghunandan. [1]. They used Malvern particle sizer to carry out their investigations with the conclusion that merging of liquid sheets increases the mean diameter of global spray. An investigation of the spray of a swirl coaxial gas-liquid injector operating at high gas/liquid momentum ratios is reported by Strakey et. Al. [2]. They used water as liquid part and nitrogen and helium as gasious part and compared the mixing and sixe characteristics of swirl and shear coaxial injectors. They concluded that spray angle and size of droplets will decreases if the momentum ratio increases. Hardalupas and Whitelaw [3] used Phase Doppler Anemometry (PDA) to investigate the spray properties formed by three identical coaxial airblast atomizers with their axes placed in a triangular arrangement. They studied the spray merging of three atomizers and they concluded that spray merging increased the air flow turbulence and the local mass fraction distribution of the air in the region between nozzle axes relative to the single spray which may influence the ignition process in pre-burner. Mao, Oechsle, and Chigier [4] measured size and velocity distribution in an air assist swirl atomizer altough their atomizer was not coaxial but there is a cocurrent flow of gas and liquid like coaxial atomizers and they found that Sauter mean diameter (SMD) increases with radial distance from the axis and with distance downstream along the center line. Another investigation is aslo conducted by Amagai and Arai on liquid coaxial nozzle [5] where liquid jet was injected and not swirling flow. In their studies, the effects of internal disturbance in a liquid jet on the disintegeration process was carried out by a visual study using stroboscope and camera.

Present authors have investigated a series of simple swirl injectors in different arragnments and flow conditions in previous studies [6-9]. For a configuration in this study, an injector is used in which the liquid fuel is injected through an inner orifice and the liquid oxidizer is injected through an outer concentric annular orifice. The spray behavior of a CLLS atomizer is experimentally investigated using both photography and PDA methods. A high-resolution digital camera is used for visual study of the liquid sheets of inner and outer orifices in low injection pressures. PDA is used to measure the droplet size and velocities in higher pressures. A test matrix has been developed to experiment the spray behavior under identical and different pressures for the fuel and oxidizer orifices and the results are compared. Different inner and outer injection pressures are near to actual working pressure drops of the engine.

2. Experimental Setup

The setup includes the PDA system, the working fluid supply mechanism, the data acquisition system "DAS", a high-resolution digital camera, a Stroboscope, and the injector block. The schematic of the setup used for visualization study is shown in figure 1.

The nozzle was mounted vertically on a test rig, and the working fluid, water, is supplied to the injector from a pressure vessel which is under pressure by pressurized air, allowing the variation of injection pressure. The fluid is injected vertically downstream through the atomizer into the room temperature and atmospheric pressure environment. Spray images are captured by a 640 by 480 pixel digital camera. Stroboscope was used as light source. The captured spray images were stored in a PC for off-line analysis.

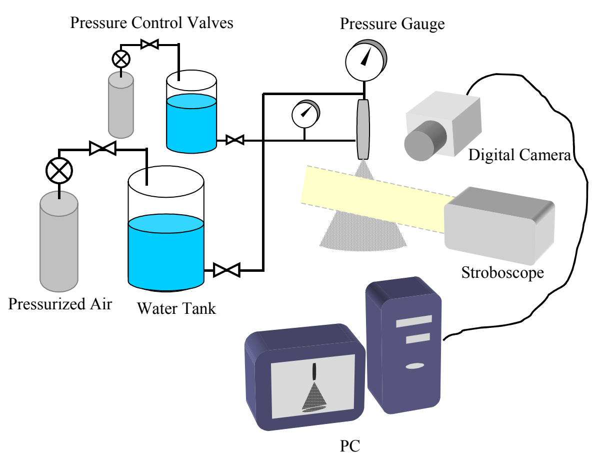

Fig. 1. Experimental Setup for Visulaization

A schematic illustration of the experimental setup for laser diagnostics is shown in figure 2. The PDA system uses a coherent Argon-ion laser as the light source. The laser beam is sent to the transmitter where the colors are separated. Three wavelengths are available: 1) green (514.5 nm) for the axial velocity, U_z, and diameter measurements; 2) blue (488 nm) for the transverse velocity, U_y, determination, and 3) violet (476.5 nm) employed for the laser light extinction measurements. There are four laser beams that make an elliptical volume used in fringe model to measure the particle velocities and sizes.

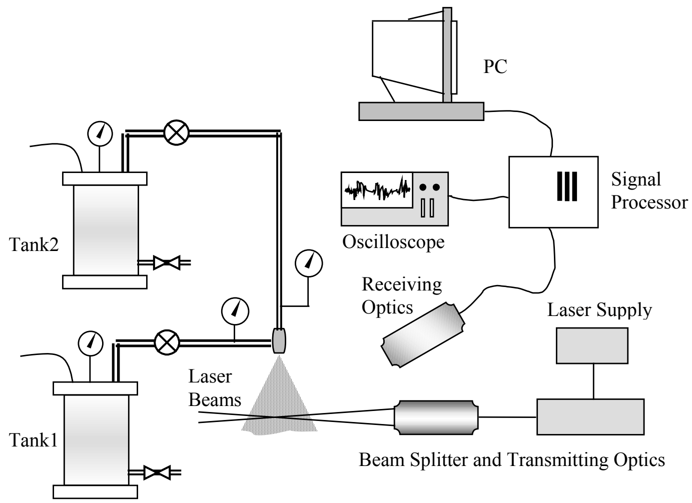

Fig. 2. PDA Experimental Setup

3. The Injector

The injector is schematically illustrated in figure 3. The major components of the injector are two coaxial annular chambers and their concentric orifices with diameters d_i and d_o for inner and outer orifices respectively. In this type of injector inner orifice is used to inject fuel and outer orifice is used to inject oxidizer. The liquid enters into each chamber through tangential inlets for making swirl motion in the flow. Number of tangential inlets is one of the important parameters of coaxial injectors. For present study, inner swirl chamber has two inlets while the outer one has four tangential inlets. The diameter of swirl chamber was 7 mm for outer injector and 6 mm for inner injector and the diameter of concentric orifices were about $d_i = 1\text{mm}$ and $d_o = 2\text{mm}$.

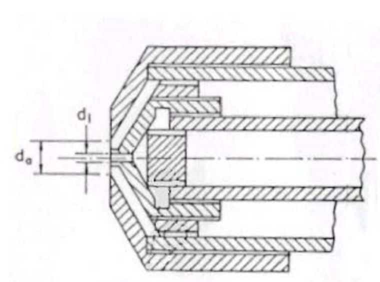

Fig. 3. Shematic of the injector

4. Results

In the case of visual study, the injection pressure of inner and outer sprays have been changed and the spray forming has been studied. The pressure drop across the inner orifice injecting the fuel is about 9bar as a working pressure in the engine. For outer orifice the working pressure drop to inject oxidizer was about 3bar. However, These two pressure drops was selected as actual or working pressure drops. First, the pressure drop of inner injector was changed from very low pressures near to zero up to the pressure of spray developing while the outer injector was not injecting. When one of the components either inner or outer orifice is not injecting, the other component is one simplex swirl injector. As for the present configuration, two simplex injectors form a coaxial swirl injector. Figure 4 shows the stages of inner spray forming by changing pressure drop.

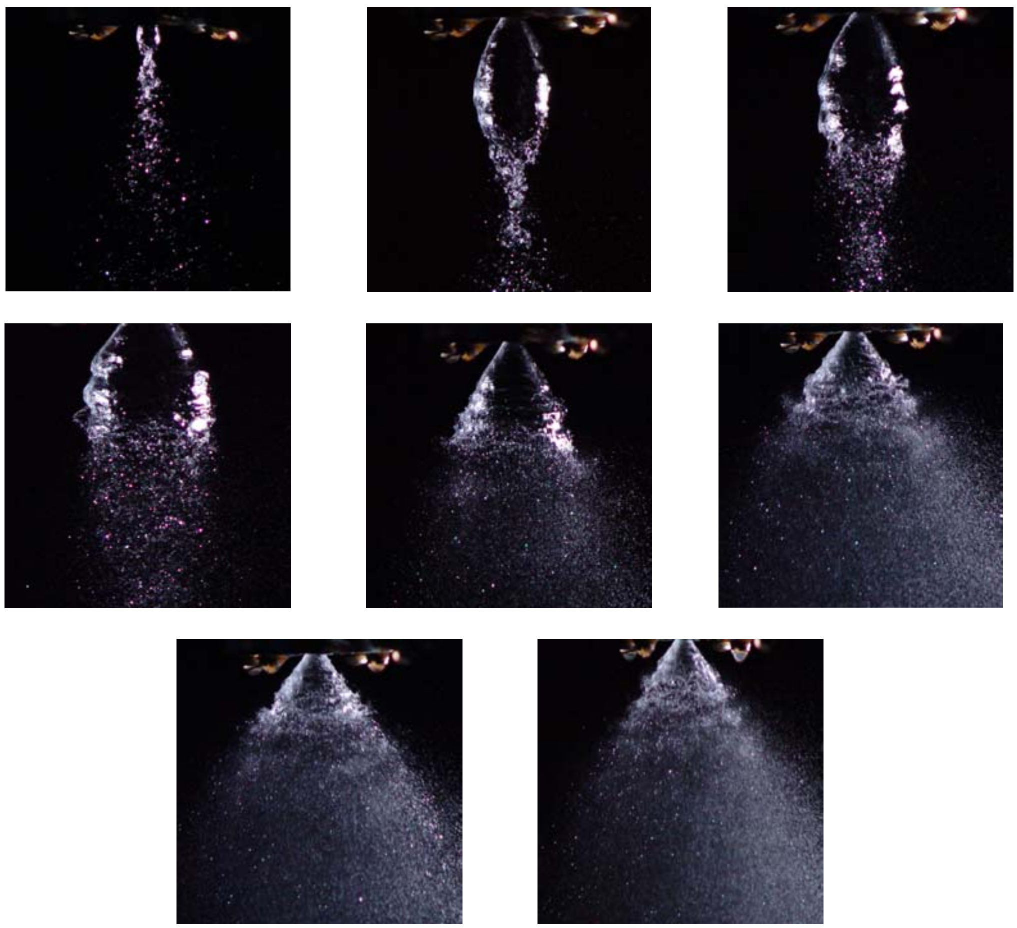

Fig. 4. Spray forming of inner component by changing pressure .

As seen from figure 4, for very low injection pressures $(\Delta P < 0.2\text{bar})$, at the discharging orifice, a hollow bubble shape of liquid sheet is formed called “Onion” stage and then the continuous liquid sheet disintegrates into drops. The length of the hollow bubble, which can be considered as breakup length for this mode, increases with increasing injection pressure. By increasing injection pressure, the bubble of liquid sheet explodes and changes to a conical smooth liquid film called “Tulip” stage in which the smooth conical liquid sheet disintegrates into drops by the loss of sheet stability. Further, as the distance from the injector increases, the thickness of the sheet decreases and perforations develop in thin areas. Furthermore, increase in injection pressure leads to disintegration of another mode shown in the figure 4. In this mode, annular waves appear and the sheet experiences wave disturbances. These annular waves are the primary cause of the sheet disintegration when the external forces dominate the surface tension forces in liquid. As shown in figure 4, by increasing the injection pressure, the wave frequency increases, short-length wave develop, and the breakup length decreases. This trend can be seen as the pressure drops increases. The spray formation of outer component follows the same trend of inner component as long as both are simplex atomizers.

Figure 5 shows the spray of both inner and outer components. In this figure, from the part 1 to 5, the pressure drop of inner component is kept in the range of Onion stage entering to Tulip stage. In addition, the pressure drop of outer spray increases from its own Tulip stage to wavy disintegration mode which can be seen in the part 5 of this figure.

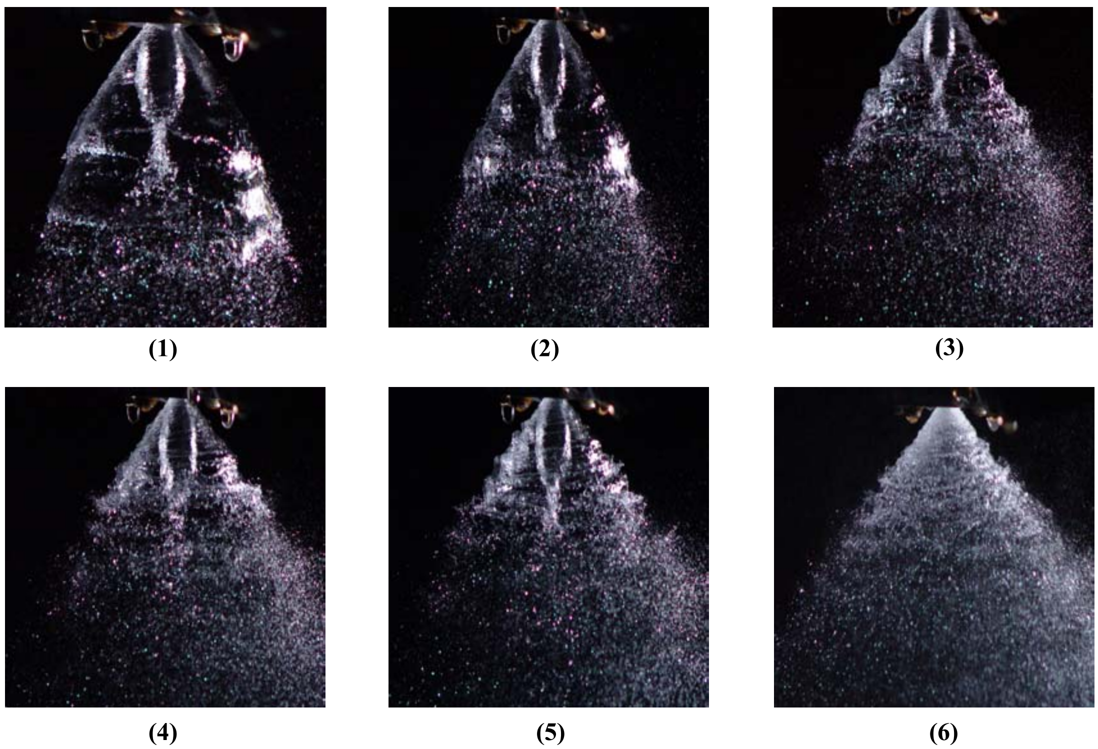

Fig. 5. Spray formation of coaxial injector when both two components are injecting

For the configuration in this study, as soon as the inner spray is translated from Onion to Tulip stage, the conical sheets of both components are merged quickly and form a unique

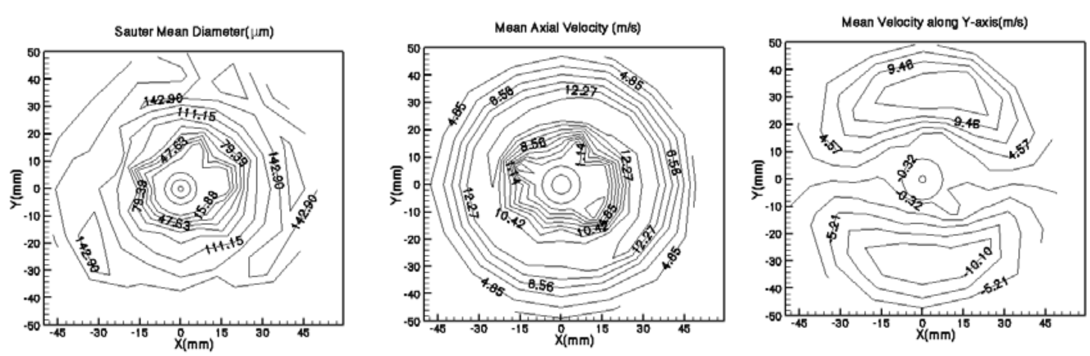

Fig. 6. SMD and velocity contours for coaxial injection

spray. The atomization of coaxial spray in working injection pressure for both components once the two sprays are merged is shown in part 6 of figure 5 in which the pressure drop of inner component is 9bar and the pressure drop of outer component is 3bar. The merging process of liquid sheets occurs due to the reduction in static pressure between the liquid sheets caused by air entrainment process. It can be concluded that since the Reynolds number of inner component is high, the liquid sheets are always in merged state forming a single conical sheet. This phenomenon is also experienced by other investigators [1].

PDA results are obtained on a plane of measurement of 30mm downward the nozzle perpendicular to its axis. Measured axial and radial velocity components and SMD contours are illustrated in figure 6. These measurements correspond to the case of coaxial injection with working pressure injections 9 and 3 bar for inner and outer components, respectively. It can be seen that maximum values of SMD were around 145 micrometer between radius 30

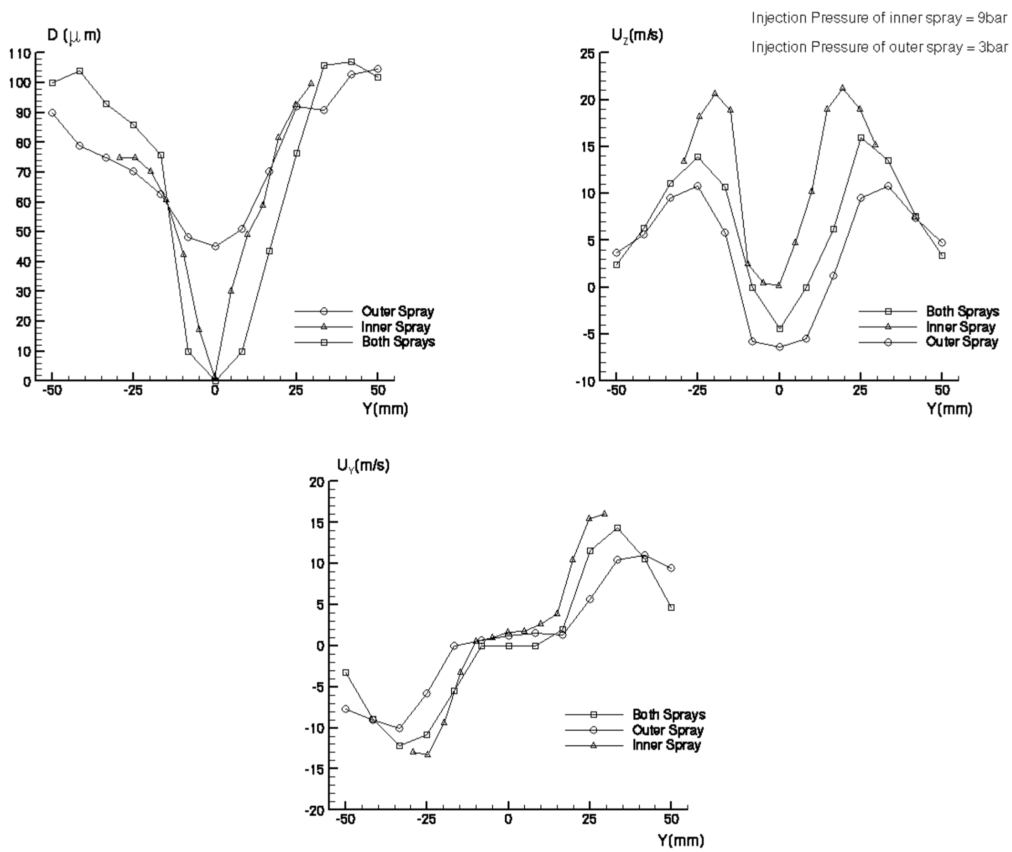

Fig. 7. Effect of spray merging on the properties

and 40mm from the center of spray. The process of air suction and entrainment through the spray caused by the high velocity of discharged liquid occurs in such a way that the moving air carries the smaller droplets near the axes of the spray. The peak of axial velocity is located between the radiuses of 20-30mm where the edge of the hollow cone spray can be seen. The droplets of this region of the spray cone have the maximum inertia of discharged liquid. Thus, one may conclude that the larger droplets are generated on the edge and immediately out of the edge of the spray cone. The velocity component in y direction reaches to its maximum of about 10m/s on the edge and near zero at the center.

The global behavior of the spray of one simplex swirl injector is the same as a coaxial injection as long as two liquid sheets are merged and form a single spray but the spray merging of two components is mainly responsible for some modification of the spray characteristics such as SMD and droplet velocities and also spray angle. On the other hand, good merging of two sprays leads to optimum mixing of fuel and oxidizer and better performance of the engine. In order to see the effect of merging on the spray characteristics, same properties are compared in figure 7 for three cases: 1) inner spray alone at 9 bar, 2) outer spray alone at 3 bar, and 3) coaxial spray when both inner and outer components are injecting.

The results shown in figure 7 are the distributions of mean diameter D, axial velocity Uz, and y component of velocity Uy along the x=0mm line and on the plane of measurement at z=30mm. Axial velocity of droplets generated by inner component is considerably higher reaching at most to 20m/s because the injection pressure of inner component is higher (9bar) and its orifice diameter is lower than outer one. Axial velocity profile for the case of coaxial injection is affected by both components as it is almost near to the mean of inner and outer profiles in value. This can be seen also in the profile of y velocity component. The negative value of Uy shows the change of direction of the droplet velocities by passing the center of the spray. In addition, the spray angle can be considered proportional to the distance between the two peaks in axial velocity profile. From figure 7, the spray angle of coaxial injection is almost equal to the spray angle of outer component. Thus, one may conclude that at the time of the merging process of the two sprays, the angle of inner spray increases to connect the outer spray. Further, one may deduce that at the time of merging, the static pressure between the two sprays decreases due to air entrainment. Furthermore, although the angle of outer spray decreases but its reduction is much smaller in comparison with the increase of the angle of inner spray.

The mean diameter profile in figure 7 shows that the larger droplets are generated on and slightly out of the edge of the spray cone. The inner spray generates smaller droplets especially in the center of spray. It is caused by high injection pressure and smaller orifice diameter of inner component. At the center of spray for coaxial injection the droplets are fine as much as inner spray but on and out of the edge the size of the droplets are higher than both inner and outer case. By this observation, it can be concluded that coaxial atomizers can generate larger droplets when their spray components are merged. It may come from the fact that after merging of liquid sheets, the thickness of liquid film increases before its disintegration into the droplets and the size of the droplets is proportional to the film thickness. As a result, larger droplets are generated.

Figure 8 illustrates the axial velocity profile for the same three cases but at different pressure drops for inner and outer sprays. The pressure drop was equal to 5bar for all cases to investigate the effect of change of pressure drop on coaxial atomization.The pressure drop of the inner spray decreased from 9 to 5 bar and for the outer spray it is increased from 3 to 5 bar. By this pressure change, it is expected that the trend of velocity profile of the spray of coaxial atomizer to be much more similar to outer spray. Here, since the total injection pressure of the inner component decreases while it increases for the outer component and since the inner component has lower out flux than outer one, the inertia of the droplets tends to the inertia of the outer liquid sheet even less than outer flow. This statement may be supported by observing figure 8 for axial velocity component. Therefore, if the injection pressure of inner flow decreases but remains merged to the outer flow, total velocity will be reduced and total flow rate of the atomizer decreases.

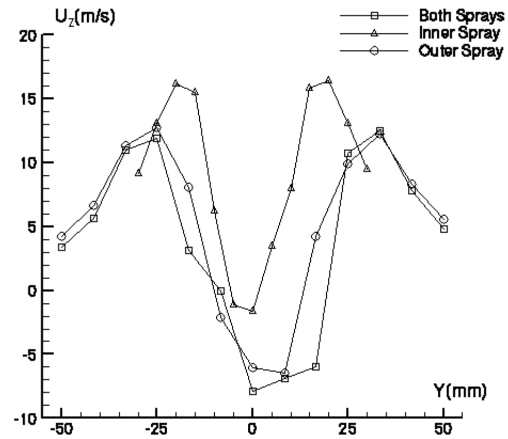

Fig. 8. Axial velocity while for both components pressure drop is 5bar

5. Conclusions

Pressure swirl atomizers are common in engine industry due to their good atomization characteristics. The associated flow field is rather complex; although, their geometry is relatively simple. Coaxial pressure swirl atomizers, with two concentric nozzles for fuel and oxidizer, are more complex than one simplex injector in geometry and spray field characteristics. The present study is performed in order to gain more detailed knowledge of the spray flow field for different injection pressures. Two experimental methods were employed. For low injection pressures a visual study was conducted and for higher pressures, the velocity components and size of the droplets are measured by using Phase Doppler Anemometer measurement technique.

Visual studies indicated that each of coaxial injector components similar to a simplex injector has a Onion, Tulip, and Wavy disintegration mode when injection pressure increases until the spray gets fully developed. For present coaxial configuration, as long as the inner flow of liquid sheet was in Onion mode the inner and outer spray were separated and as soon as the inner flow entered into Tulip stage the two sprays have been merged. Optimum merging of the sprays is important to get the proper Fuel/Oxidizer ratio for the engine.

From PDA results it was concluded that injection pressure and also merging process of inner and outer flow have a crucial effect on velocity profile and size distribution. Merging process increases the spray angle of inner flow to the angle of coaxial injection. The velocity of both components after merging for working pressures was almost the mean value of the velocity of inner and outer components. Merging process slightly increases the size of the droplets on the edge of the spray and out of it.

The role of injection pressure of both inner and outer components is very important to make the F/O ratio, the total flow rate, and the proper spray angle. It was concluded that by decreasing of inner injection pressure the two sprays may still remain merged with the same spray cone angle but it can considerably affect the axial velocity and reduce the total flow rate of the atomizer.

6. References

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