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Mixing Characteristics of Pulsed Air-assist Liquid Jet into an Internal Subsonic Cross-flow

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Penetration depth, spray dispersion angle, droplet sizes in breakup processes and atomization processes are very important parameters in combustor of air-breathing engine. These processes will enhance air/fuel mixing inside the combustor. Experimental results from the pulsed air-assist liquid jet injected into a cross-flow are investigated. And experiments were conducted to a range of cross-flow velocities from 42~136 m/s. Air is injected with 0~300kPa, with air-assist pulsation frequency of 0~20Hz. Pulsation frequency was modulated by solenoid valve. Phase Doppler Particle Analyzer(PDPA) was utilized to quantitatively measuring droplet characteristics. High-speed CCD camera was used to obtain injected spray structure. Pulsed air-assist liquid jet will offer rapid mixing and good liquid jet penetration. Air-assist makes a very fine droplet which generated mist-like spray. Pulsed air-assist liquid jet will introduce additional supplementary turbulent mixing and control of penetration depth into a cross-flow field. The results show that pulsation frequency has an effect on penetration, transverse velocities and droplet sizes. The experimental data generated in these studies are used for a development of active control strategies to optimize the liquid jet penetration in subsonic cross-flow conditions and predict combustion low frequency instability.

Keywords: cross-flow; penetration; pulsed air-assist liquid jet; pulsation frequency

Introduction

Combustion efficiency in propulsion engines depends on injection characteristics which are distribution of specific quantities of atomized fuel to specific locations and air/fuel mixing injected into a combustion chamber. So air/fuel must be mixed in extremely short time to the molecular level in the near field of the fuel injection. In order to increase combustion efficiency, droplet transporting dynamic and spray structures must be studied and investigated [1]. When the heat release and pressure wave oscillation are coupled, combustion instability occurred in specific frequency domain. Many studies conducted to investigate cause and occurrence of combustion instability. But now a days, combustion instability is not fully solved, and development of combustor is retarded [2][3]. The combustion of using pulsed jet instead of more conventional steady flow combustors has many advantages including higher thermal efficiency, higher heat release and low emission levels of NOx and CO [4]. In aircraft and industrial gas-turbine engine, turn-down problem and combustion instabilities are solved with modulating injection frequency and changing injection location. Also spray injection which are pulsated by mechanical pulsator and solenoid valve is the good method for spray mixing, dispersion and penetration.

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Table 1 Test conditions

Parameter	Water	Air
Temperature (K)	293	217
Density (kg/m^3)	998	1.21
Surface tension(N/m)	0.0727	
Orifice diameter (mm)	0.5	–
Orifice length (mm)	1.5	

Table 2 Experiment conditions

Parameter	Range
Fuel flow (g/s) (water)	0~8.3
Air-assist flow (g/s) (air)	0~49.3
Air to Liquid mass flow ratio	0~59.4
Cross flow velocity, U_{cross}(m/s)	42~136
$\mathrm{Re}_{cross} = \dfrac{\rho_g U_{cross} d_{cross}}{\mu_g}$	3.03x10^5
Hydraulic diameter, d_{cross}(mm)	120
$We_{blast} = \dfrac{\rho_g (U_{blast} - U_L)^2 d}{\sigma_L}$	260~1252
Air-assist jet momentum flux, q^2	35.9~106.4

Atomization process is the definition for the breakup process of liquid column, ligaments and droplets and this process is broken down to three levels. First level is extension of liquid column. Second level is break-up level of liquid ligaments which was governed with Weber number. And final level is atomization process for the droplet which was generated by vibration, collision and cross flow drag. Droplet break-up is affected by atmospheric gas density, liquid jet viscosity, and other variables. The purpose of the current study is to experimentally investigate spray penetration depth, spray dispersion angle and droplet velocities using external mixing pulsed air-assist injector. The experimental results in the course of this study will elevate the current understanding of fundamental aspects of atomization process, theoretical spray model, and spray mixing characteristics. These will help us to determine the parameter (GLR, pulsation frequency) that can be used to control the spray penetration and mixing inside the combustion chamber.

Experimental Procedure & Apparatus

Spray characteristics of pulsed air-assist injector in subsonic cross-flow field were investigated using shadow graph method and PDPA measurements. Test environment conditions were shown in Table 1 and experiment conditions were shown in Table 2. The pulsed air-assist liquid injector was flush mounted on the bottom plates of the subsonic wind tunnel that is operated by blow type motor.

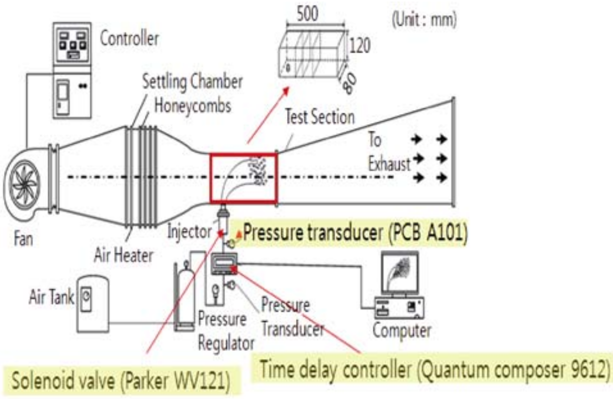


Fig. 1 Schematic of experiment system

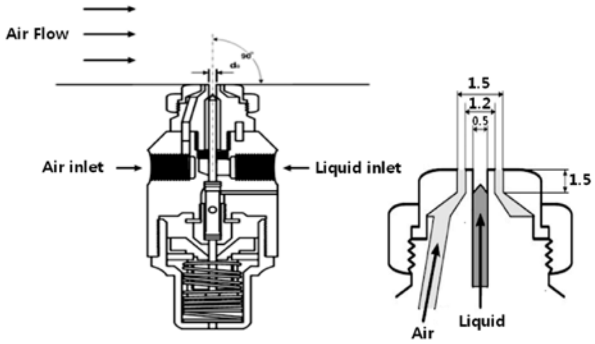


Fig. 2 Injector and nozzle cross-section view

Fig. 1 illustrates schematic of experiment system & blow type wind tunnel. The test section has a rectangular shape 120 mm (width), 80 mm (height) and 500 mm (length). For providing visual observation and optical instrumentation, the test section installed quartz window. Air stream velocities ranged from 42~136 m/s. Pressure drop across the orifice about 13% of reservoir pressure, diameter of the orifice is 0.5 mm and length of orifice is 1.5 mm. Nozzle inlet is tapered by 45° to the exit diameter. Temperature of the air stream is 293.16 K and humidity of test section condition is fitted with 50%. When experiments are conducted, gravity force was disregarded. Test liquids were filled into liquid tank and pressurized by air compressor. Liquid jet is injected into a cross-flow field about 90° injection angle. Liquid volumetric flow rate was controlled by pressure regulators and measured by a flow meter. The flow meter was calibrated to an uncertainty of less than 2 %. Injection pressure of liquid and air were measured by pressure transducer (PCB A101), and pulsation pressure were controlled with electric solenoid valve(Parker WV121) and time delay controller(Quantum composer 9612). A phase Doppler particle analyzer was also used to determine properties of droplets. To measure droplet properties, measurement was conducted to an increment 2.54mm at Z/d=20. Regions with unbroken liquid core, regular ligaments, and non spherical drops, where PDPA measurements cannot be carried out reliably, were avoided for the determination of detailed structures of the entire cross-section shown in Fig. 3. Microscopic characteristics of liquid jet were measured in the jet injection Y/d direction, depending on pulsed spray jet.

Results and Discussion

The liquid was supplied to 8.3 g/s with constant mass flow rate and air was supplied 0 to 49.3 g/s. The cross-flow Reynolds number was 3.03×10^5 and Weber number was fixed to 38.66. The characteristics of good phenomenon for the spray atomization were observed in the field of a typical air-assist jet as increasing GLR. As increasing GLR, liquid jet was more disintegrated and atomized. Some of the large droplets eventually go through the upper field of the test section, due to the surface impinging for air. The increasing of spray penetration depth is caused by effective jet-to-air momentum flux ratio. The real reason of this phenomenon is resulted from impinging of assisted air. As can be seen in Fig. 4 liquid jet was injected into cross-flow condition. The air-assist force helps to break the liquid column into ligaments and droplets. As the liquid column experiences the aerodynamic force from the free stream and the growth of the turbulence from the liquid column itself, the liquid column begins to bend toward the downstream direction. As inertia momentum of liquid was interrupted by the increased inertia momentum of air stream, spray penetration of liquid jet, Y/d, was decreased and trajectory of liquid jet was more downward. In case of same experimental condition, mist like droplets which are generated from the collision of liquid jet and air assist jet do not penetrate to the cross-flow upper region. Large droplet which was not affected by air –assist jet penetrates to the upper region. Looking at the comparison with air-assist and cross-flow effect, air-assist effect was the more powerful parameter to breakup liquid jet. But at normal condition which was pure liquid jet injection, liquid jet was more affected by cross-flow drag. At GLR = 59.4%, mist like spray go through to the cross-flow bottom region. Using the air-assist injector, atomization process was more efficient than pure liquid jet injector. The equation of momentum ratio of pure liquid jet injected into a cross-flow is expressed as Eq.1 and air-assist jet of momentum ratio is expressed as Eq.2 [5].

$$q_1 = \frac{q_l U_l^2}{q_a U_a^2} \qquad \text{(Eq.1)}$$

$$q_2 = \frac{(\rho_L U_L^2 A_{fuel} + \rho_g U_L^2 A_{fuel}) / A_{spray}}{\rho_g U_{cross}^2} \qquad \text{(Eq.2)}$$

Experiments of pulsed injection were conducted to using solenoid valve which was intermittently injected to maximum frequency with 20 Hz. Fig. 5 shows pulsed air-assist jet injected into a cross-flow region. Pulsating air was run into the liquid column, liquid column was atomized by pulsating air. And liquid puffs are emerged into liquid column to the cross-flow direction. These liquid puffs are atomized at very short time and improving mixing ratio due to the increasing turbulence intensity. Fig. 6 demonstrates the spray image between maximum gage pressure of the air 102 kPa and minimum pressure 98 kPa at 2 Hz. Spray angle was defined in Fig.3.

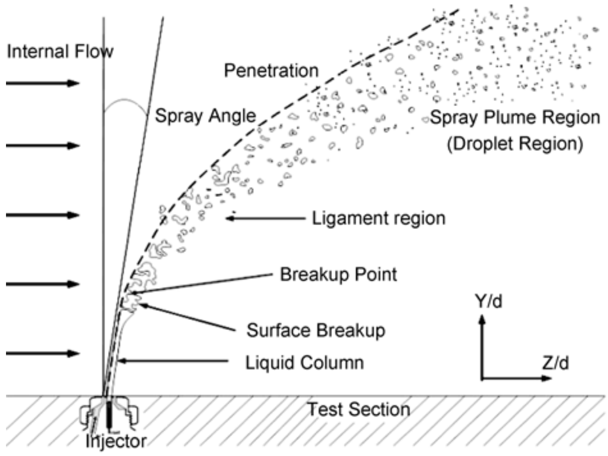
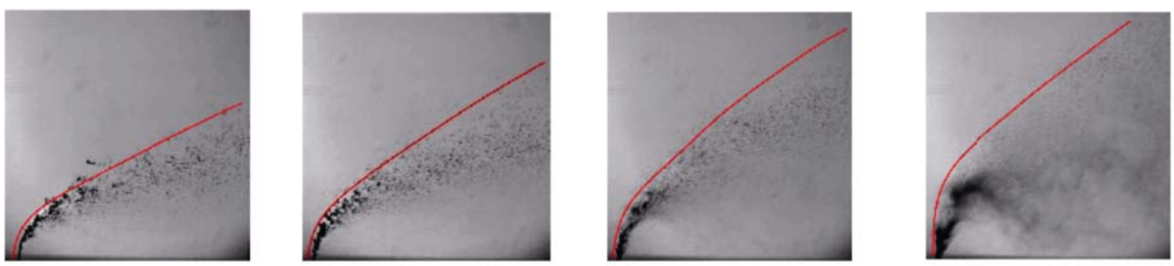


Fig. 3 Parameters of liquid jet in cross-flow



(a) GLR 0%, q_1=35.2 (b) GLR 16.8%, q_2=39.77 (c) GLR 27.9%, q_2=57.98 (d) GLR 59.4%,q_2=106.46

Fig. 4 Images of external air-assist liquid jet with various GLR

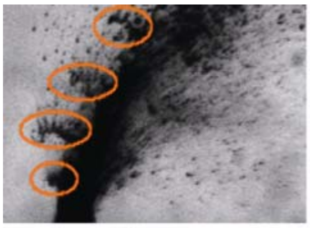
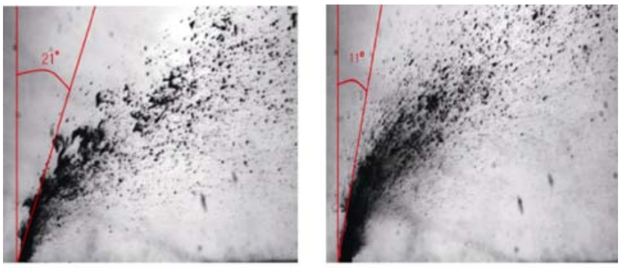


Fig. 5 Spray characteristics of pulsed air jet



2Hz, 98kPa
Minimum pressure

2Hz, 102kPa
Maximum pressure

Fig. 6 Images of pulsed air-assist jet

When pulsed air-assist jet was moved away from cross-flow field periodically, spray jet angle was 25°at 98 kPa and 13° at 102 kPa respectively. This phenomenon is due to that liquid jet was affected by air flow around the injector. This air flow is increasing or decreasing the vertical momentum of liquid jet. To the study of this phenomenon, we just design optimal combustion chamber and at the actual combustion condition we will predict periodical pressure perturbation. As shown in Fig. 7, trajectory of air-assist jet in cross-flow is illustrated. When GLR was increased, spray penetration depth of air-assist jet is also observed to be increased. The maximum penetration was limited to GLR 59.4% and the overall breakup process was fastest in comparison with pure liquid jet. Penetration depth of air-assist jet with various GLR can be seen in Fig. 8, when increasing GLR, Y_p/d is also increased. The penetration depths in various GLR and momentum ratio are measured at Z/d=20. As increasing of GLR and momentum ratio, the penetration depth is increased.

Large droplets with higher momentum in the jet injection direction can travel to the outer boundary of the spray plume. To control GLR which modulate air mass flow or liquid mass flow, penetration depth of air-assist spray jet can be controlled. Fig. 9 shows the spray angle with various pulsation frequency and GLR. The definition of spray angle was illustrated in Fig. 3. As increasing pulsation frequency, spray angle was decreased. This is due to that periodical oscillation motion of low frequency is bigger than high frequency. At low frequency, liquid jet impacts the air some time delays but at high frequency, liquid jet continuously impacts the air at very short time So the liquid jet always has the same structure.

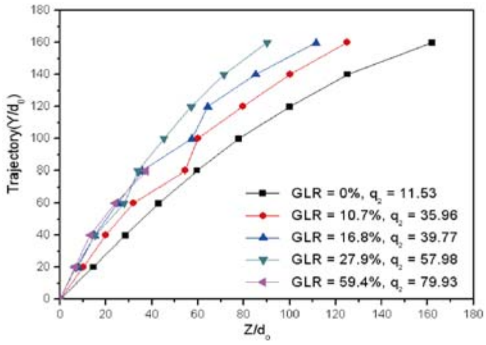


Fig. 7 Trajectories of air-assist jet in cross-flow

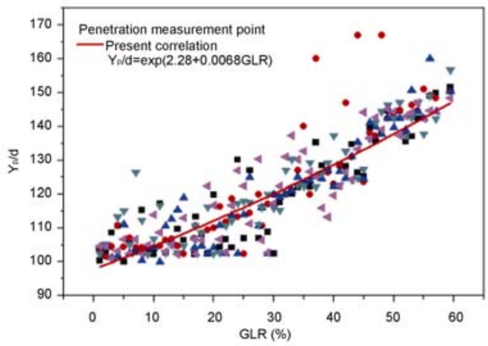


Fig. 8 Penetration depth of air-assist jet with various GLR

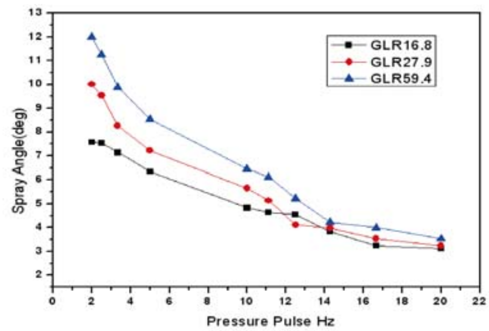


Fig. 9 Spray angle with various pulsation frequencies and GLR

In this result, as decreasing pulsation frequency, spray angle was increased and as increasing GLR, penetration depth and spray area increased. Finally, spray using optimal pulsation frequency and air-assist will give a good mixing efficiency. Fig. 10 demonstrates the droplet horizontal velocity with various pulsation frequencies. PDPA measurements were performed at fixed position with Z/d=40 and with GLR=27.9%. As increasing pulsation frequency, droplet velocities increased. But droplet velocities of 20Hz are decreased more in comparison with 2~10 Hz over the penetration region at Y/d=45. Oscillation motions of spray jet were not observed at the range of higher frequency more than 10 Hz, for example, 20 Hz.

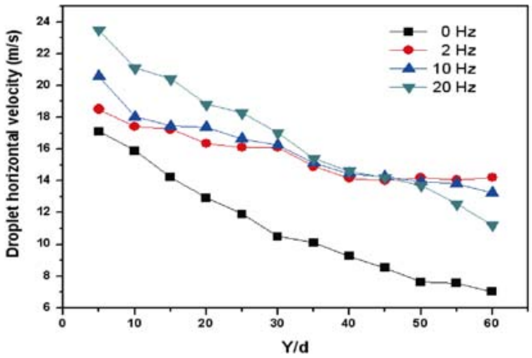


Fig. 10 Droplet horizontal velocity with various pulsation frequency

Conclusion

The spray structures of pulsed air-assist jet vertically injected into a subsonic cross-flow were studied experimentally.

(1) For a pulsed air-assist spray jet, as increasing pulsation frequency, liquid puffs are emerged into surfaces of liquid column to the cross-flow direction. These liquid puffs affecting the turbulence intensity increase spray mixing.

(2) Atomization process is mainly governed by air-assist jet in external air-assist injector. However, atomization process is not much improved beyond certain GLR, for example GLR=59.4%. Pulsation frequency also have an effect on increasing mixing process due to the oscillation motion.

(3) Oscillation motions of spray jet were observed at the range of 2 Hz to 10 Hz. Spray patterns in higher frequency more than 10 Hz, for example 20 Hz, look like that of continuous spray.

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