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Spray characteristics of the rotating fuel injection system of a micro-jet engine[†]

Seong Man Choi[1,*], Seong Ho Jang[2], Dong Hun Lee[3] and Gyong Won You[4]
[1]*Department of Aerospace Engineering, Chonbuk National University, Jeonju, 561-756, Korea*
[2]*Graduate School, Chonbuk National University, Jeonju, 561-756, Korea*
[3]*Senior Researcher, Samsung Techwin Co., LTD, Changwon, 641-717, Korea*
[4]*Senior Researcher, Agency for Defense Development, Daejeon, Korea*

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Abstract

In micro-turbojet engines with less than 350 kW power, it is not easy to find a suitable fuel injector with good spray quality. However, the rotating fuel injection system can potentially provide high atomization quality without the high-pressure fuel pump through the centrifugal forces of the engine shaft. With this motivation, a very small rotating fuel injector with 40 mm diameter is designed for the micro-turbo jet engine. It is directly linked to a high-speed rotational spindle capable of a speed up to 100,000 rpm. The droplet size, velocity, and spray distribution from the PDPA (Phase Doppler Particle Analyzer) system are measured. The spray is also visualized by a high-speed camera. The test results show that the length of liquid column from injection orifice is controlled by the rotational speeds and that SMD (Sauter Mean Diameter) is decreased with increasing rotational speeds. At a rotational speed of 73.3 m/s (35,000 rpm), SMD is lower than 60 μm at the entirety of the measuring space in the case of Type 2 (injection orifice diameter of 1.5 mm) and Type 3 (injection orifice diameter of 2.2 mm). Therefore, conceptually, it is possible to apply this small rotating fuel injection system to the micro-turbojet engine combustor.

Keywords: Rotating fuel injection system; Micro jet engine; Spray; Disintegration; SMD

1. Introduction

Annular combustors with rotating fuel injection systems have been frequently employed in gas turbines. Such system is successfully adopted in a number of Turbomeca engines and others. The system is advantageous mainly because it is inexpensive and simple. In terms of atomization, the rotating fuel injection system produces a fine fuel spray even at partial-loading or idle conditions [1].

The role of a gas turbine fuel atomizer is to distribute the drops into the combustion zone. The spatial distribution depends on the penetration of the fuel spray into the primary zone and is closely coupled to the aerodynamic flow pattern. A pressure swirl atomizer or an air-blast atomizer can meet these requirements. These injectors require many high-quality components such as axial or radial swirlers, swirl chamber, filter, and discharge orifice; however, the rotating fuel injection system can be applied more economically than conventional injectors.

The rotating fuel injection system has been studied by Morishita [2] and Dahm et al. [3, 4]. In those studies, the atomization process is explained by limited measurement data of droplet size and velocity. Morishita measured droplet size by collecting droplets on a silicon oil film made on a glass plate. Microscopic photography was used to measure the droplet size. The droplet size was measured at a distance of 100 mm from the outer periphery of the rotating disc single point. From his measurement, empirical Eq. (1) for water was derived. This equation is good for understanding the general concept of a rotating fuel injection system. The droplet size is a function of the peripheral velocity and flow rate.

$$SMD = 3{,}300\frac{Q^{0.2}D^{0.3}}{{U_P}^{0.7}} \tag{1}$$

Dahm et al. studied the atomization process by visualization in a variety of fuel slinger geometries over a range of operating conditions. That study attempted to make some correlations from the experimental data of Morishita [2]. From the study by Dahm et al., empirical Eq. (2) between the SMD and the liquid film thickness was derived.

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[*] Corresponding author. Tel.: +82 63 270 3996, Fax.: +82 63 270 2472
E-mail address: csman@jbnu.ac.kr

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$$SMD \propto \left(\frac{\sigma}{\rho_L} \delta \right)^{0.5} \tag{2}$$

Dahm et al.'s study categorized the disintegration process as subcritical , transition, and supercritical breakup by changing the rotational speeds of the injector [3, 4]. The subcritical breakup forms ligaments that undergo a Rayleigh breakup to produce relatively large drop sizes. Supercritical breakup provides finer drop sizes due to direct atomization of the thin liquid film being produced from channel exit. In this study, the atomization performance is properly expressed by a fundamental correlation in terms of the Weber number, which is based on a length scale appropriate for the liquid breakup regime.

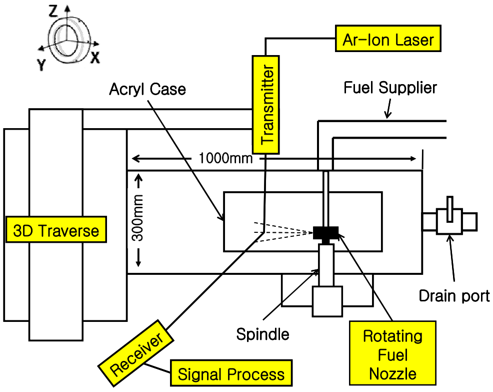
Meanwhile, the capability to control the fuel injection process is essential for the gas turbine combustor. When designing and developing the gas turbine combustor, it is crucial to determine the spray distribution, droplet size, and velocity fields in the primary combustion zone. Unfortunately, previous researchers could not use the laser diagnostics technique. Consequently, spray information in the overall flow fields could not be presented due to the limited measurement data. In this study, a spray test rig was constructed for measuring spray characteristics of the rotational fuel injection system by applying Phase Doppler Particle Analyzer (PDPA) laser diagnostic technique. By using this system, the droplet size (SMD), velocity distribution, and spray pattern were measured.

2. Experimental conditions

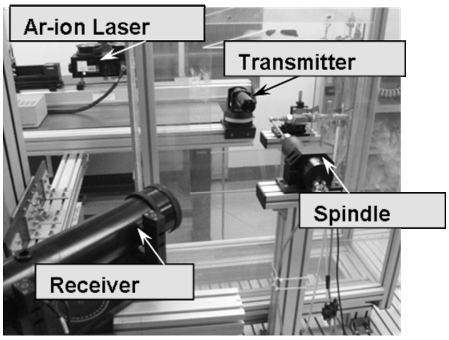
The diagram of the spray test rig is shown in Fig. 1(a), and its photograph is shown in Fig. 1(b). The experimental apparatus consists of a high-speed rotational device (air-spindle), water feeder, pressurized water tank, rotational water injection nozzle, acrylic case, and PDPA system. The air-spindle and shaft are directly connected to the rotational fuel injection nozzle. The axial direction of the metering orifice coincides with the injection orifice. Water is used as the test fluid instead of an aviation fuel (e.g., JP-8) in order to avoid harm to human bodies.

The water supply process is as follows. Water is pressurized by high-pressure air and goes to the metering orifices of the fuel-supplying nozzle. Water is spread out on the inner wall of the rotational injection nozzle through centrifugal forces. Water then enters several injection orifices. After passing through the injection orifices, water is spouted to the surroundings. The thin film or ligament is then gradually broken and atomized to droplets. Sprayed water is continuously drained through the drain port at the bottom of the acrylic case.

A PDPA system is composed of a laser source (6W Ar-Ion), a transmitter, a receiver, a signal processor, and 3-D traverse system. Spray visualization is performed by a Photron Fastcam SA1.1 camera with a 150 W HVC-SL light source. The three types of injection orifices shown in Fig. 2 and Fig. 3 are used. The detailed specifications of the Type 1, Type 2, and

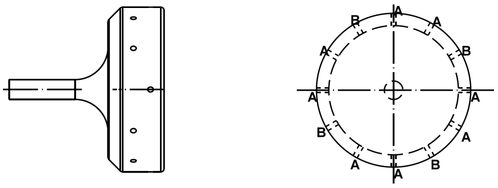


(a) Diagram of the test rig

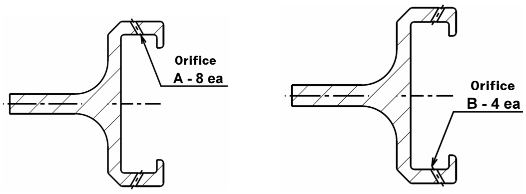


(b) Photograph of the test rig

Fig. 1. Spray test rig with PDPA system.

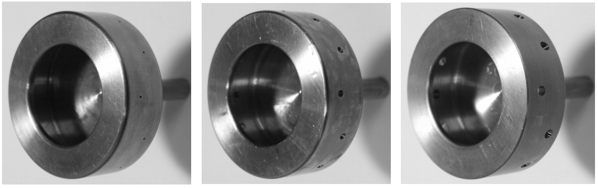


(a) 3-D View (b) Front View



(c) Section A-A (d) Section B-B

Fig. 2. Diagrams of the rotating fuel injector.



Type 1 Type 2 Type 3

Fig. 3. Photographs of the rotating fuel injector.

Table 1. Types of rotating fuel injector.

	Number of orifice (ea)			Orifice diameter (mm)	Orifice total area (mm^2)
	Section A	Section B	Total		
Type 1	8	4	12	0.5	2.36
Type 2	8	4	12	1.5	21.20
Type 3	8	4	12	2.2	45.59

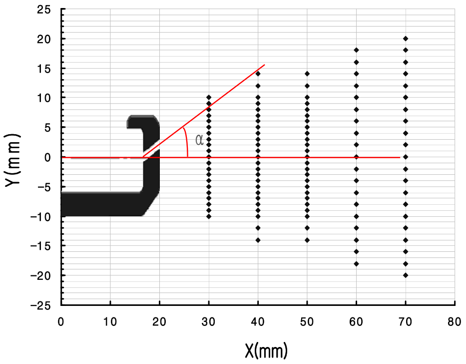


Fig. 4. PDPA measurement points.

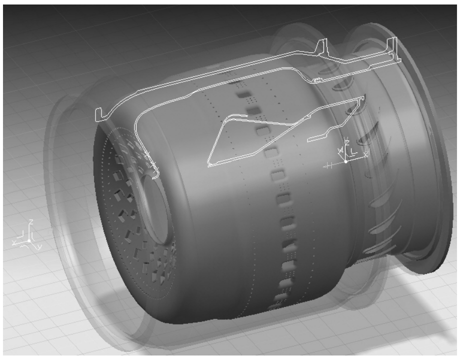
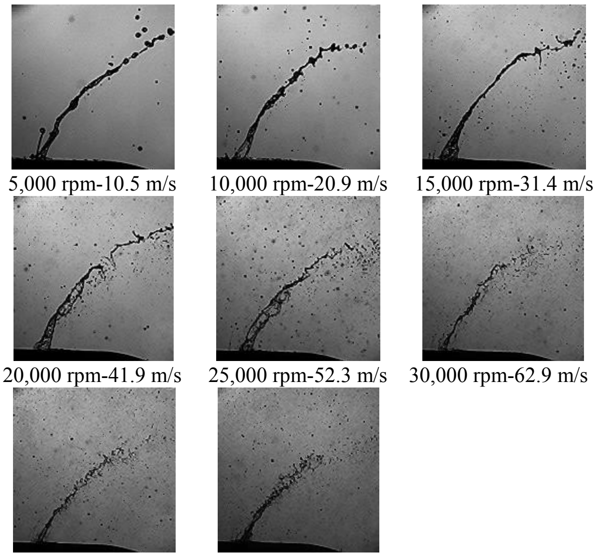


Fig. 5. Combustor layout.

Type 3 injectors are shown in Table 1. The diameters of the injection orifices are 0.5, 1.5, and 2.2 mm, respectively. The injection orifices are placed on both sides along the center line of the injector surface. There are eight orifices at Section A and 4 orifices at Section B. The spray test is performed with water at a flow rate of 15 kg/h and rotational speeds of 15,000, 20,000, 25,000, 30,000, and 35,000 rpm under ambient conditions. PDPA measuring grids are shown in Fig. 4. The measuring positions are 111 points on the X-Y plane. These are automatically moved by a 3-D traversing system. The maximum sampling data is 10,000 and the maximum measuring time is 20 s for each point.

The slinger combustor, which incorporates the rotating fuel injection system, is shown in Fig. 5. The length of combustor is approximately 200 mm, and the diameter of outer liner is approximately 160 mm. Considering that the diameter of the rotating injector is 40 mm, the effective reaction region for primary combustion should take place at less than 50 mm in height from the outer surface of the rotating injector to the outer liner. Due to this geometrical limitation, spray characteristics and droplet behavior were studied from a location less than 50 mm from the rotating nozzle surface.



5,000 rpm-10.5 m/s 10,000 rpm-20.9 m/s 15,000 rpm-31.4 m/s

20,000 rpm-41.9 m/s 25,000 rpm-52.3 m/s 30,000 rpm-62.9 m/s

35,000 rpm-73.3 m/s 40,000 rpm-83.7 m/s

Fig. 6. Spray visualization with rotational speed values of a Type 2 injector (rpm-disc peripheral velocity).

3. Results and discussion

3.1 Visualization

The breakup processes of the spray with rotational speeds of 5,000, 10,000, 15,000, 20,000, 25,000, 30,000, 35,000, and 40,000 rpm on a mass flow rate of 15 kg/h are shown in Fig. 6. The liquid disintegration processes of the rotating fuel injection system based on Fig. 6 are shown in Fig. 7. Dahm et al. [4] divided the breakup process into subcritical, transitional, and supercritical breakup. In a subcritical breakup with a small Reynolds number, the liquid sheets spouted from the injection orifice disintegrate a single liquid column into large drops of fairly uniform size. This is the Rayleigh mechanism of breakup. In a transitional breakup, the jet is broken up by jet oscillations with respect to the jet axis. The magnitude of these oscillations increases with air resistance until a complete disintegration of the jet occurs. A wide range of drop sizes is produced. In a supercritical breakup, the atomization is complete within a short distance from the discharge orifice.

As shown in Figs. 6 and 7, the breakup process of the spray with rotational speed values up to 15,000 rpm corresponds to a subcritical breakup. The liquid sheets that come out of the injection orifice are drawn into a single liquid column that then undergoes a breakup process. In a subcritical breakup, surface tension is sufficiently strong relative to the film inertia to draw the liquid into a single large ligament. At 20,000–30,000 rpm, large numbers of ligament take place. The diameters of the ligament decrease, and this leads to fine drop sizes. At the same time, the distance of liquid column is rapidly decreased. At over 30,000 rpm, the jet nearly disintegrates from

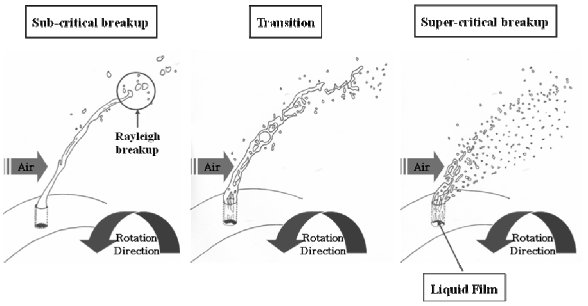


Fig. 7. Schematics of liquid disintegration of the rotating fuel injection system.

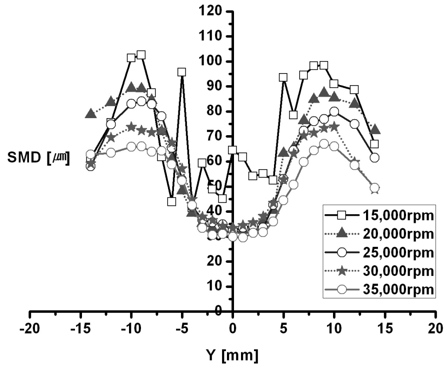


Fig. 8. SMD with rotational speed at X=50 mm (Type 1).

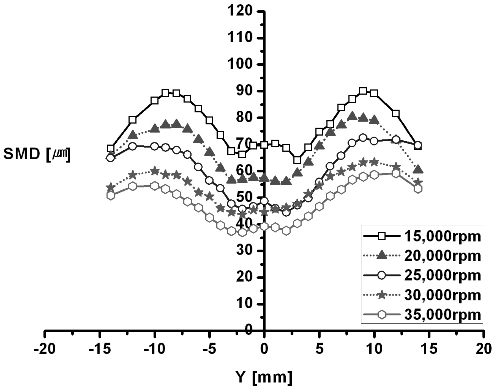


Fig. 9. SMD with rotational speed at X=50 mm (Type 2).

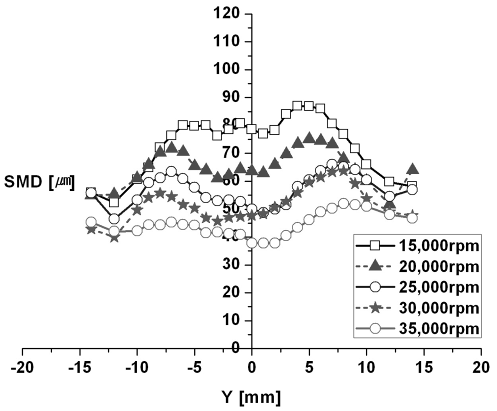


Fig. 10. SMD with rotational speed at X=50 mm (Type 3).

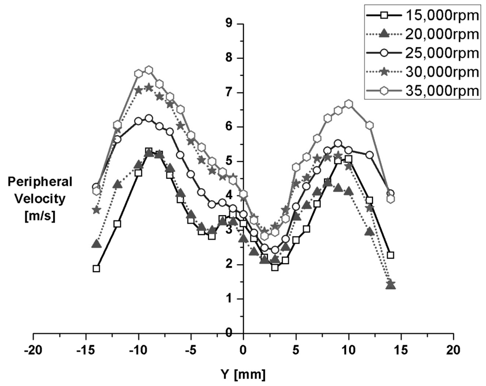


Fig. 11. Droplet peripheral velocity with rotational speed at X=50 mm (Type 2).

the injection orifice. This corresponds to a super-critical breakup condition. In a supercritical breakup, inertial effects cause the film to break into many smaller ligaments.

3.2 PDPA measurement

The SMD (droplet size) distributions with several rotational speeds at X=50 mm are shown in Figs. 8-10. In this experiment, the main flame location is expected to be at a distance of 50 mm from the shaft axis. The flame location is verified from the micro-turbojet engine combustor test by Lee et al. [6]. As the rotational speed increases, the droplet diameter decreases. This result can be explained by the visualization from Fig. 6 and the velocity data from Fig. 11. When the rotational speed is increased, the drop peripheral velocity is likewise increased, therefore, the relative velocity between the surround gas and the ejected water is increased. As shown in Fig. 6, these velocity differences shorten the length of the liquid column until it finally becomes well atomized. At 35,000 rpm, the droplet diameter of Type 1 varies from 29.59 μm to 67.03 μm. That of Type 2 and Type 3 varies from 36.99 *μm* to 59.22 μm and from 37.82 μm to 50.94 μm, respectively, under the same conditions. Choi et al. [5] performed ignition and combustion tests with a rotating fuel injection nozzle. From their experimental test results, ignition of the rotating fuel injection system is possible with a droplet diameter of approximately 60 μm, and stable combustion is observed at the droplet diameter of 50 μm. Therefore, the ignition point of combustion on a rotating disc system with a 40 mm diameter occurs at approximately a rotating speed value of 35,000 rpm or a disc peripheral velocity of 73.3 m/s of Type 2 or Type 3. In Fig. 8, there are large fluctuations in the 15,000 rpm case. This might be due to the unstable disintegration process at a low rotational speed.

The droplet peripheral velocity (V_p) profile with several rotational speeds at X=50 mm is shown in Fig. 11. From Fig. 11, the droplet peripheral velocity increases with increasing rotational speeds. Furthermore, the droplet peripheral velocity on the Y (-) zone is larger than on the Y (+) zone. This dissymmetry is caused by the arrangement of the injection orifices.

The Y (-) zone has injection orifices two times larger than the Y (+) zone. This result also can be seen in the volume flux contours in Fig. 12. The volume flux shows spatial distribution with several rotational speeds of Type 2. The ejecting spray is concentrated along the injection orifice angle of 30º at 15,000 rpm. As rotational speeds increase, volume flux is spread out to a wide area. Thus, droplets are sprayed more widely in higher rotational speeds. The volume flux with various injector types of 35,000 rpm rotational speed are shown in Fig. 13. The spatial distribution of the volume flux is separated at both sides in a Type 1 injector, but as the injector orifice diameter is increased, a more uniform volume flux is found in Type 2 and Type 3. A uniform spray is promising for better combustion performance.

The liquid film diagram within a rotating channel of diameter d_0 when Coriolis force on the flow in the channel is small is shown in Fig. 14. From this, the liquid film thickness calculated by Eq. (3) from Dahm's study can be derived.

$$t = \left(\frac{3}{\pi}\right)^{1/3} \left(\frac{\mu_L q}{\rho_L R \Omega^2 d}\right)^{1/3} \tag{3}$$

The liquid film thickness from the Eq. (3) relative to the peripheral velocity is shown in Fig. 15. Liquid film thickness decreases with peripheral velocity and orifice diameters. In this figure, the liquid film thickness of Type 1 is quite different from those of Types 2 and 3. The SMD relative to the peripheral velocity at an X=50 mm distance on the maximum velocity position is shown in Fig. 16. In conclusion, the SMD has direct relation to the rotational speed and the number of injection orifice. In addition, a large orifice diameter offers some advantage for producing a finer drop distribution. The SMD relative to the liquid film thickness is shown in Fig. 17. Here, SMD increases with increasing liquid film thickness in all three types. Thus, there is a close correlation between the SMD and the film thickness.

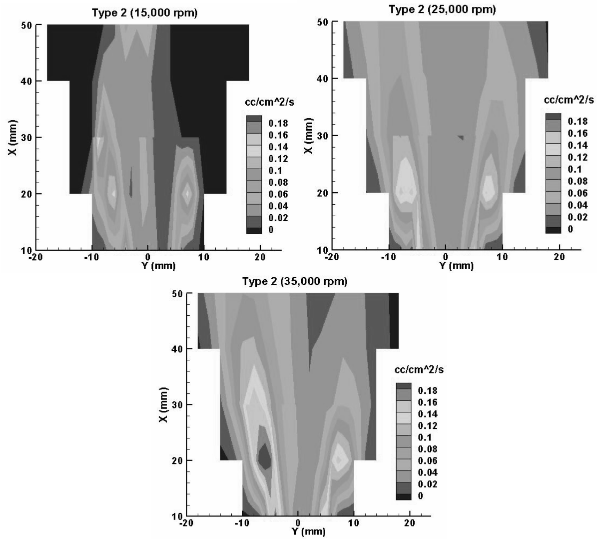


Fig. 12. Volume flux with rotational speed (Type 2).

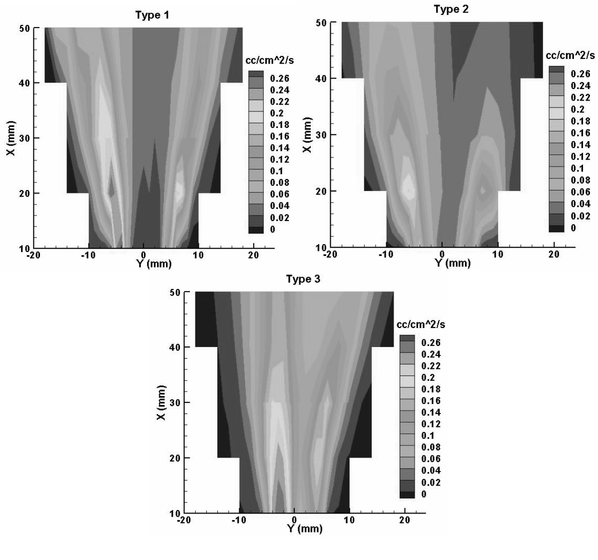


Fig. 13. Volume flux with injector types (35,000 rpm).

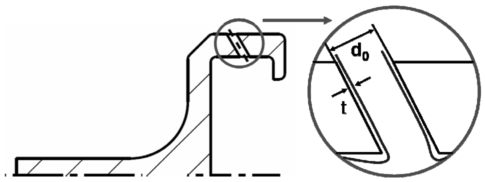


Fig. 14. Diagram of the liquid film of the rotating fuel injector.

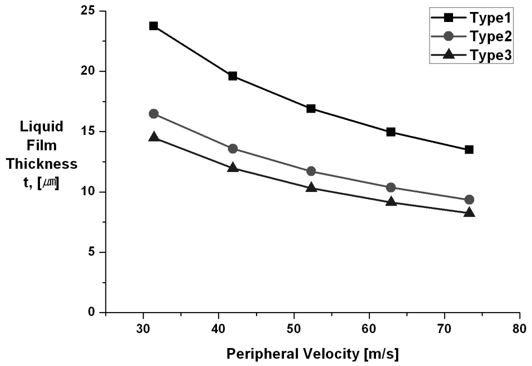


Fig. 15. Liquid film thickness relative to the peripheral velocity.

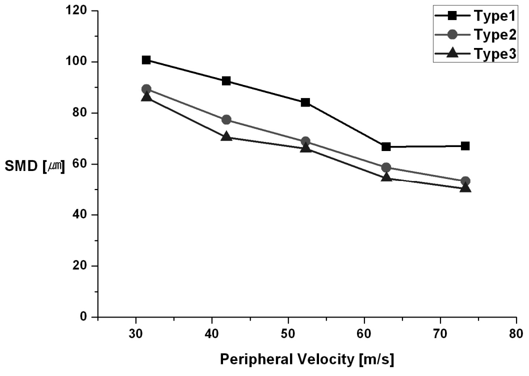


Fig. 16. SMD relative to peripheral velocity at X=50 mm.

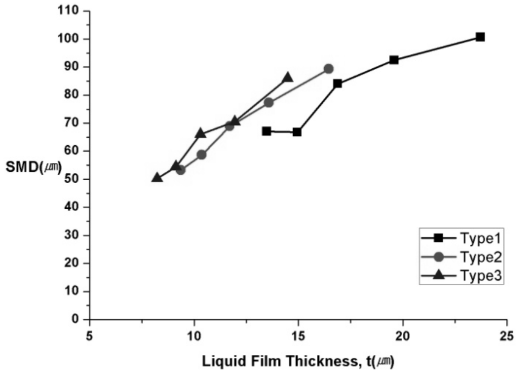


Fig. 17. SMD relative to the liquid film thickness.

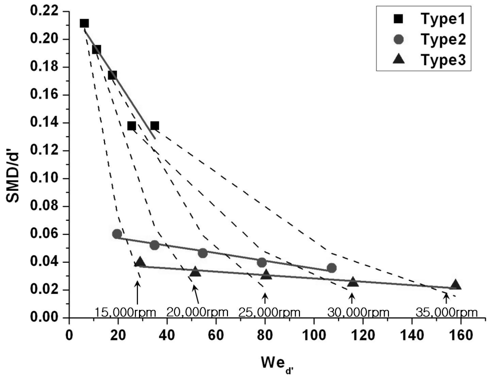


Fig. 18. SMD/d' relative to the Weber number.

The non-dimensional droplet size (SMD/d') relative to the Weber number, which is based on the equivalent orifice diameter d', is shown in Fig. 18. The Weber number based on the equivalent orifice diameter is expressed as Eq. (4):

$$We_{d'} \equiv \frac{\rho_g U_P{}^2 d'}{\sigma} \quad \text{(where, } d' \equiv d_0 - t\text{)} \tag{4}$$

The gas density is $\rho_g = 1.225\ kg/m^3$, and liquid surface tension is $\sigma = 0.072\ N/m$. This equation gives valuable correlation between SMD, orifice diameter (d_0), liquid film thickness (t), and Weber number. In Fig. 18, the non-dimensional droplet size (SMD/d') decreases with increasing Weber number ($We_{d'}$) in all three cases. Mazallon et al. [7] divided the atomization processes by the Weber number as "liquid column break up", "bag-shear break up," and "shear breakup". Arai et al. [8] showed that increasing the relative velocity between the air and liquid shortens the breakup length for the disintegration of liquid sheets injected into a co-flowing airstream. These studies show that the disintegration of a droplet is determined by the aerodynamic force. This result also follows general trends of the disintegration mechanism. Thus, in the rotating fuel injection system, aerodynamic force induced by the rotational speed controls the disintegration process of the droplet.

Meanwhile, the non-dimensional droplet size of Type 1 decreases more rapidly than those of the other two cases, but it is limited by the low boundary of droplet size. In SMD measurement, the spray quality of Type 1 is essentially very poor, with low rotating speed conditions. On the other hand, the overall SMD distributions of Types 2 and 3 are considerably better than the Type 1 case, even though the SMD reduction rate is not larger than in the Type 1 case. The main difference between Type 1 and the other two cases (Types 2 and 3) is the liquid film thickness (Fig. 15). The liquid film thickness decreases with increasing injection orifice diameter at the same rotational speed and disintegrates into the small diameter of the droplet. Consequently, injection orifice diameter also controls liquid film thickness, and this liquid film thickness has a strong influence on the disintegration process of the droplet under the same rotational speed. Thus, increasing the orifice diameter is more effective for reducing SMD than increasing the rotational speed.

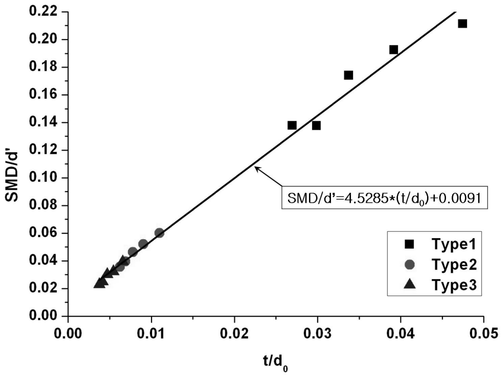


Fig. 19. SMD/d' relative to the non-dimensional liquid film thickness t/d_0.

The data analysis indicates that the critical variables of droplet disintegration of the rotating fuel injection system are the rotational speed, liquid film thickness, and diameter of injection orifice. From the coupled variables, correlations can be made between non-dimensional droplet diameter (SMD/d') and non-dimensional liquid film thickness (t/d_0). The correlation between non-dimensional droplet diameter and non-dimensional liquid film thickness is shown in Fig. 19. There is a strong correlation, expressed as Eq. (5), between the non-dimensional parameters. In this case, the correlation coefficient is 0.993. Therefore, the general spray information of the rotating fuel injection system can be determined using this equation because it utilizes the variables of the rotational speed and injector orifice diameter.

$$\frac{SMD}{d'} = 4.5285\frac{t}{d_0} + 0.0091 \tag{5}$$

4. Conclusion

The main objective of this study is to determine the possibility of applying the small diameter of rotating fuel injector to the micro-turbojet engine. This requires the determination of the disintegration process of the high-speed rotational fuel injection system relative to the rotational speed and the diameter of the injection orifices. To acquire quantitative information, the droplet size, distribution, and velocity of the spray were measured by PDPA, and the spray was visualized by a high-speed camera. A summary of the test results is as follows:

At over 35,000 rpm (peripheral velocity=73.3 m/s), measured droplet diameter is lower than 60 μm in most parts of the measuring points of Type 2 and Type 3. Therefore, conceptually, it is possible to apply this small rotating fuel injection system to the micro-turbojet engine combustor at a rotating disc peripheral speed over 73.3 m/s.

When the rotational speed increases, the length of the liquid column diminishes, the peripheral velocity of droplet increases, and the SMD decreases.

When the orifice diameter increases, the disintegration location becomes closer to the orifice exit plane and produces a finer drop size than small orifice diameters.

The liquid film thickness in the channel serves a crucial role in the disintegration process of the rotating injectors. There is a linear correlation between the non-dimensional droplet size and the non-dimensional liquid film thickness.

Acknowledgment

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Nomenclature

δ : Liquid film thickness at order diameter of the rotating disc [m]
σ : Surface tension of liquid [N/m]
μ_L : Absolute viscosity of liquid [N · sec/m^2]
Q : Total liquid flow rate [m^3/sec]
D : Outer diameter of rotating disc [mm]
Ω : Angular velocity [rad/sec]
t : Liquid film thickness [mm]
d : Orifice diameter [mm]
d' : Equivalent orifice diameter ($d' \equiv d_0 - t$) [mm]
q : Volume flow rate on a per-channel [m^3/sec]
R : Outer radius of rotating nozzle [mm]
U_P : Peripheral velocity [m/s]
ρ_L : Liquid density [kg/m^3]
SMD/d : Non-dimensional droplet diameter
t/d_0 : Non-dimensional liquid film thickness

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Seong Man Choi received his B.S., M.S., and Ph.D. degrees in Aerospace Engineering from Seoul National University in 1987, 1989, and 1994, respectively. He worked for Samsung Techwin Co. Ltd. from 1994 to 2005 as a Principal Research Engineer. He has been an Associate Professor in the Aerospace Engineering Department of Chonbuk National University, Korea, since 2005. His research interests focus on gas turbines and rocket combustion systems. In particular, he is interested in spray dynamics of the fuel injection systems, visualization of the flame in a gas turbine sector combustors, and supersonic exhaust systems.

Seongho Jang received a B.S. degree in Aerospace Engineering at Chonbuk National University in 2007. He is currently an M. S. candidate in the Department of Aerospace Engineering of Chonbuk National University, Korea. His research interests are in the field of micro-turbojet engine and rotating fuel injector.

Dong Hun Lee received his B.S. and M.S. degrees in Aerospace Engineering from Chungnam National University in 1997 and 1999, respectively. He has been a Senior Researcher in Power Systems R&D Center, Samsung Techwin Co., Ltd. in Korea since 2001 and is currently a Ph.D. candidate in the Aerospace Engineering Department of Chungnam National University. His research interests focus on fuel injections and combustion of gas turbines. In particular, he is interested in spray and atomization characteristics in gas turbine combustor and laser diagnostics for investigation of spray dynamics.

Gyong Won You received his B.S. and M.S. degrees in Precision Mechanical Engineering from Chonbuk National University in 1994 and 1996, respectively. He has been a Senior Researcher in the Agency for Defense Development in Korea since 1996. His research interests focus on the fuel injection, combustion of gas turbine and fuel transfer systems of vehicles.