Experimental study on spray characteristics of air-blast atomizer unit and optimized injector in low emission combustor of gas turbine

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Abstract. In this paper we focus on the request of low emission combustion in gas turbine and propose an improved solution of fuel injector with air-blast atomizer unit. Researches on the characteristics of the air-blast fuel spray injected into the cross flow are based on experimental study by Malvern instruments. Results reveal that specific parameters such as main air cross flow velocity and assisted atomization air pressure drop determine the performances of air-blast atomizer unit. We use these units to improve the structure of fuel injectors in gas turbine combustor. Contrast tests show Sauter mean diameter of optimized solution decreases obviously while uniformity of fuel spray becomes better. It will provide references for improving the performance of low emission combustor in gas turbine.

1. Introduction
Gas turbines play a key role in electricity generation, which are also widely used as power plants in industry and aviation. Prominent performance requirements of gas turbines are high efficiency and low emission. The attainment of low emission from gas turbines is not only of considerable environmental concern but also has become competitive among different manufacturers [1]. The emission of primary concern is oxides of nitrogen, the others are carbon monoxide, unburned hydrocarbons and smoke. Mechanisms of pollution producing are complicated. The concept of emissions reduction is founded by control of flame temperature. Low emission combustion can only be organized in particular range of equivalence ratio.

Gas turbines can use both gas fuel and liquid fuel such as kerosene and diesel. Some of industrial gas turbines and all of aero-gas turbines employ liquid fuels, which must first be atomized and vaporized before they can burn, so that liquid fuel with low emission combustion technology has much more challenges. It is the key to research and design of combustion chambers at present. As the increasing requests of reducing emission, many new design ideas for fuel injectors come out to achieve the goal [2-7]. For instance, LM-6000 gas turbine and Twin Annular Premixing Swirler (TAPS) combustion chamber of GE Company represents a direction and trend of development on low emission combustion technology, in which multi-point injection and lean premixing are proven effective by researchers.

However, there are still room for improvement to further low emission. Lean premixing of fuel and air requests fast evaporation and mixing before combustion, which depends on fuel drop size and contribution sprayed by injectors. Various definitions of mean drop size are available, of which the most widely used is the Sauter Mean Diameter (SMD), which represents the volume surface ratio of the liquid in the spray [1]. SMD can be expressed in the form
where \( n_i \) is the number of drops which diameters are \( d_i \). A widely used expression for drop size distribution is that of Rosin-Rammler, which can be expressed in the form

\[
1 - Q = \exp\left[ -\left( \frac{d}{D} \right)^n \right]
\]

(2)

where \( Q \) is the fraction of the total volume contained in drops of diameter less than \( D \), while \( d \) and \( n \) are constants. Thus, the Rosin-Rammler relationship describes the drop size distribution in terms of the two parameters \( d \) and \( n \). The exponent \( n \) provides a measure of the spread of drop sizes. The higher the value of \( n \), the more uniform is the spray.

Reference to this background, a clear goal for low emission combustors of gas turbines is to design injectors which can make fuel spray with less SMD value and more uniform distribution. Less SMD value means less vaporising time and more uniform distribution means more uniform temperature field, so that flame temperature can be controlled. In this paper, we provide a solution after experimental researches of the characteristics of air-blast atomizer unit. In most multi-point injectors, these units can be used. Thus the original way of fuel injection into the cross flow directly can be improved to fuel spray injecting into the cross flow. This method is an application of Wave Theory of spray characteristics of fuel injection into the cross flow [8-10].

2. Methods

Figure 1 shows the structure of air-blast atomizer unit. Structure parameters of air-blast atomizer unit are given in Table 1. In this study, the air-blast atomizer unit is designed as a conventional circular nozzle. In the study on the structure and flow characteristics of the air-blast atomizer unit, spray injection into the cross flow is observed and measured. The air-blast atomizer unit is put on the bottom of a rectangular channel which height is 60mm and width is 40mm, shown in Figure 2.

Study on the spray characteristics of the air-blast atomizer unit, the central point of the air-blast atomizer unit nozzle is chosen as the coordinate origin, the top and cross flow downstream direction for the positive direction of the coordinate axis, and 2 points are selected to test, respectively \( X=30\)mm, \( Y=15\)mm and \( X=35\)mm, \( Y=15\)mm. According to the range of each parameter, we select working conditions to test in the experiment, as shown in Table 2.

| Outlet configuration | Outlet diameter | Inner nozzle diameter | Number of side holes | Diameter of side holes |
|----------------------|-----------------|----------------------|----------------------|-----------------------|
| Circle               | 2.4mm           | 0.4mm                | 8                    | 1.2mm                 |

| Cross flow velocity (m/s) | Liquid velocity (m/s) | Pressure drop (%) |
|---------------------------|-----------------------|-------------------|
| 50–70                     | 20–40                 | 2–5               |

Figure 1. Structure of air-blast atomizer unit.
The experimental platform includes gas supply system, liquid supply system, testing system, data acquisition system and recovery system, as shown in Figure 3. The room temperature gas supply system provided by the compressor station. There is a main gas path with an auxiliary gas path for testing each structure of air-blast atomizer unit spray characteristics. Spray experiment of assembled fuel injector structure which is optimized by using air-blast atomizer units does not need the auxiliary gas path. Fluid supply system adopts the high-pressure nitrogen gas cylinders in the pressure to the
liquid tank way for liquid. Different technical test in the test system are different, the data acquisition is realized by computer software. The operation parameters in the experiment are mainly composed of the various positions on the pressure gauge reads, control operation was performed by each pipeline valve. The laser particle size analyzer Malvern is used in the testing system, and using kerosene as the liquid medium.

3. results and discussion
In the experimental Study on the spray characteristics of the air-blast atomizer unit, Figure 4 shows the influence of air pressure drop on Sauter mean diameter (SMD). In the same cross flow velocity (CFV) and liquid jet velocity (LV) conditions, the increase of pressure drop of assisted atomization air causes SMD into smaller trend, because the interaction of air-liquid two phases is more violent, while the air-liquid ratio (ALR) is increasing. Reducing ALR is adverse for the particle size distribution and uniformity of spray.

![Figure 4](image)

Figure 4. Influence of assisted atomization air pressure drop on SMD at X=30mm and X=35mm position.

Figure 5 shows the influence of the cross flow velocity on SMD. In the same liquid jet velocity and assisted atomization air pressure drop conditions, the increase of the cross flow velocity causes SMD into smaller trend. An increase in cross flow velocity changes the Weber number and its effect on droplet is great. Therefore, in the fuel injection rate in 20m/s and assisted atomization pressure drop in 2~5% conditions, when the cross flow velocity increases from 50m/s to 70m/s, SMD decreases obviously.

A typical fuel injector structure is optimized by using air-blast atomizer units, as shown in Figure 6. Figure 7 shows the comparing performances of the two injectors in different conditions of air pressure drop. SMD decreases sharply as air-blast atomizer units are working, especially in low working condition. The exponent n of Rosin-Rammler drop distribution increases from 2.55 to 2.87 in average.
Figure 5. Influence of cross flow velocity on SMD.

Figure 6. Original and optimized structure of fuel injector, which are assembled in a rectangular channel with a spray picture.

Figure 7. Performances of original and optimized fuel injector.
4. Conclusions
Advanced laser test equipment has been used to reveal the atomization characteristics of fuel spray inject into cross flow. As the results of testing spray characteristics of air-blast atomizer unit injection into the cross flow, it reveals that variation tendency of spray characteristics accords to the atomization theories. The changing of main parameters for describing atomization including We, ALR, momentum ratio $q_2$ will cause the changing of spray droplets parameters SMD and distribution accordingly. Comparing with spray performances of original and optimized fuel injection structures with air-blast atomizer units, it demonstrates that the latter has smaller SMD and better spray droplets distribution in every working condition obviously.

The conclusions are as follows:
1) Each structure of the air-blast atomizer units injects into cross flow is in good condition. Spray phenomena trends are obviously reasonable. Increasing the cross flow velocity causes that SMD of spray droplet becomes smaller and evenness index exponent $n$ of R-R distribution becomes bigger.
2) The pressure drop and assisted atomization air mass are associated. Increasing the air-liquid ratio has a positive effect on decreasing SMD.
3) The main assembled structure of fuel injector improved by the air blast atomizer units is obviously better than that of the original in spray characteristics. The improved structure in various working conditions reduces SMD by 10%–30%, while the droplets distribution is more uniform.

References
[1] Lefebvre A H 1995 Theroleoffuelpreparationin low emissioncombustion ASME J. Eng. Gas Turbines Power 117 617- 654
[2] Mongia H C 2003 TAPS-A 4th generation propulsion combustor technology for low emissions AIAA 2003-2657
[3] Stouffer S, Ballal D, Zelina J, Shouse D, Hancock R and Mongia H 2005 Development and Combustion Performance of a High Pressure WSR and TAPS Combustor AIAA Paper 1416
[4] Mongia H C 2001 Combustion Research Needs for Helping Development of Next-Generation Advanced Combustors AIAA 3853
[5] Hukam Mongia and Willard Dodds 2004 Low Emissions Propulsion Engine Combustor Technology Evolution Past, Present and Future GE Aircraft Engines, Cincinnati, Ohio, U.S.A. ICAS2004 Papers-609
[6] Sulabh K Dhanuka, James F Driscoll, Hukam C Mongia 2008 Instantaneous Flow Structures in a Reacting Gas Turbine Combustor AIAA 4683
[7] Hukam C Mongia 2004 Perspective of Combustion Modeling for Gas Turbine Combustors GE Aircraft Engines Cincinnati, U.S.A. AIAA 156
[8] Wu Pei-Kuan, Kevin A Kirkendall, Raymond P Fuller, Abdollah S Nejad 1996 Breakup processes of liquid jets in subsonic crossflows AIAA Paper 3024
[9] Wu Pei-Kuan, Kevin A Kirkendall, Raymond P Fuller 1998 Spray Structures of Liquid Fuel Jets Atomized in Subsonic Crossflows AIAA 714-536
[10] Samir B Tambe and San-MouJeng, HukamMongia and George Hsiao 2005 Liquid Jets in Subsonic Crossflow AIAA 731