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EXPERIMENTAL CHARACTERIZATION OF FUEL-AIR MIXING IN A MULTI-HOLE TUBE

Chi Zhang, Quanhong Xu, Yuzhen Lin
National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics
School of Jet Propulsion
Beijing University of Aeronautics and Astronautics
Beijing, P. R. China

Jing Zhu
Business Unit of Space Launch & Specialty Vehicles
China Academy of Launch Vehicle Technology
Beijing, P. R. China

Yixiang Yuan
Institute of Engineering Thermophysics
Chinese Academy of Sciences
Beijing, P. R. China

Chih-Jen Sung
Department of Mechanical Engineering
University of Connecticut
Storrs, CT 06269, USA

ABSTRACT

This paper reports our recent research work on the mixing of fuel and air in a multi-hole tube. The multi-hole tube is an important component used for Lean Premixed Prevaporized (LPP), low emission combustion in a micro gas turbine. A baseline configuration of the multi-hole tube is investigated herein. Mixing characterization experiments are conducted by mapping the distribution of fuel-air ratios at the tube exit with a gas analyzer. Experimental results indicate that the matching of fuel atomization and flow field is the primary factor affecting fuel-air mixture uniformity. Based on the experimental results of the baseline configuration, a systematic and parametric configuration optimization can be then attempted. Experimental results with a modified configuration demonstrate improved mixing uniformity at the tube exit as compared to the baseline configuration, thereby signifying the importance of developing multi-hole tube design rules.

NOMENCLATURE

LPP	Lean premixed prevaporized
f/a	Fuel/air ratio
n	Number
SMD	Sauter mean diameter
Sn	Swirl number
X	Molar concentration
ϕ	Equivalence ratio
π	Equivalence ratio deviation
Subscript	
a	Air
f	Fuel
r	Radial direction

INTRODUCTION

As the core of the distributed energy systems, the micro gas turbine has advantages of low noise, easy maintenance, and long life expectancy. Recognizing that these engines would be usually installed near the residential buildings, the low emission combustion holds the key to the successful application and development for such energy systems.

Emissions of CO and UHCs (Unburned hydrocarbons) are related to the incomplete combustion, while most of NOx emissions are produced in the high temperature zone within the combustor. Lefebvre [1] summarized various low-pollution combustion technologies, and indicated LPP is the most promising one. For the use of liquid fuels, the LPP concept has a good potential to meet the low emission standards due to its higher combustion efficiency and lower combustion temperature. In the LPP technology, evaporation of liquid fuel via the heated air and the subsequent mixing between fuel vapor and air lead to lean combustion, in which the flame temperature is controlled to reduce NOx emissions while maintaining efficient combustion. Considering the mixing uniformity between fuel and air in the LPP operation can significantly affect the combustion emissions, it is therefore imperative to characterize the extent of fuel and air mixing at the exit of the multi-hole tube and analyze the effect of geometry parameters on mixing phenomena.

Liedtke et al. [2] developed a LPP micro gas turbine using high temperature gas to evaporate the liquid fuel and a compact tube structure to complete the fuel-air mixing, with both NOx and CO emissions being less than 10 ppm. Fujiwara et al. [3] studied the combustor performance with different premixed-prevaporized tube structures, and achieved NOx emission of less than 24 ppm. Yoon and Lee [4] studied the effects of equivalence ratio, pressure, and temperature on the emissions and designed a LPP combustor without cooling due to the associated low temperature lean premixed flame, resulting in less than 25 ppm NOx emissions.

Since the key of successful LPP low emission combustion technology requires perfect liquid fuel evaporation as well as the subsequent mixing with air uniformly in a limited space, the effective configuration of the LPP tube structure is essential. Typically, the axial high temperature air flow is used to evaporate the fuel and mix, while the swirler located at the premixed tube exit is employed to form a recirculation zone for stable combustion, as that used in Ref. [5]. However, weak turbulence in the axial flow premixed tube leads to a longer distance required for complete vaporization and mixing [6]. As a result, such a configuration cannot meet the compact structure requirement for micro turbine combustor.

Recently, it has been shown that using swirling flow in the premixed prevaporized tube can enhance the fuel evaporation and fuel-air mixing, and hence the length of the mixing section can be shortened. Moreover, the swirling flow jets that enter the combustor also result in recirculation zones for stable combustion [7,8]. Tacina [9] compared the fuel-air mixture uniformity under various swirl numbers in the premixed tube, and found that the stronger the swirling flow, the better the fuel-air mixed.

In Ref. [10] large swirl vanes were adopted to mix the fuel, which was directly injected into the channels, and air within the swirl vanes, while in Ref. [11] some tubes were tangentially placed to make the air into the premixed prevaporized tube instead of the swirl vanes. ABB's second-generation low emission combustion technology introduced the swirling flow by using tangential gaps, but the effect of mixing for liquid fuel and air was not perfect [12]. A premixed prevaporized tube designed by Capstone was investigated, using several tangential slots to achieve high evaporation efficiency and fuel-air mixture uniformity, but high pressure air was need to atomize the liquid fuel [13,14]. Recently, the atomization, vaporization, combustion, and emissions of the Capstone tube had been researched for gas turbine operation on biodiesel [15,16]. It was indicated that the fuel injector would need some modifications to overcome the deleterious effects of biodiesel [15,16].

In a review of the low emission combustion technology for the large and medium gas turbines [17], it was pointed out that the current premixed prevaporized approach of LPP combustion has issues such as complex structure, excessively long premixed prevaporized section, and unexpected evaporating and mixing effects. Therefore, it is necessary to identify a suitable lean premixed prevaporized approach for the micro gas turbine combustors, in regard to turbulence intensity enhancement and improvement of heat and mass transfer.

In the present investigation, a multi-hole tube is adopted to achieve the LPP low emission combustion in a micro gas turbine with liquid fuel. Pressure atomizer and tangential multi-hole jets are used in the multi-hole tube, and complete evaporation of the liquid fuel and uniform premixture are achieved in a limited tube space. The potential of such a low emission combustor with similar structure has been demonstrated in our previous studies [18,19].

In the multi-hole tube, if complete fuel evaporation cannot be achieved, it would be difficult to make the combustion temperature uniform. Reference [20] has indicated that the liquid fuel can evaporate completely with 480 K inlet air for the multi-hole tubes. Moreover, imperfect fuel-air mixing can also result in nonuniform combustion. The local fuel rich conditions further lead to high temperature to increase NOx emissions, and the excessively fuel lean region may cause unstable and inefficient combustion. It has been demonstrated [21-23] that the combustor emissions increase with increasing mixture nonuniformity. Additionally, the mixture uniformity can affect the combustion efficiency, the life expectancy, and the outlet temperature distribution of the combustor.

In view of the above, we aim to research the fuel-air mixing performance of the multi-hole tube, which is an important evaluation criterion of the premixing module. Due to the complex two-phase flow and the coupling effects among fuel distribution, evaporation, and mixing in the multi-hole tube, it is challenging to quantitatively simulate fuel-air mixing phenomena with high fidelity. Therefore, it is necessary to conduct systematic mixing characterization experiments in the multi-hole tube configurations, which is the primary goal of this paper. Furthermore, while the present system is a two-phase setup, prevaporized conditions in experiments are chosen and ensured such that the complicating factors associated with fuel evaporation can be isolated.

MULTI-HOLE TUBE CONFIGURATION

Figure 1 shows the structure of the multi-hole tube and the air flow path. A pressure fuel atomizer is located at the nozzle section in the front of the multi-hole tube According to the locations and structures of the different holes, the air can be divided into three parts: nozzle section air, radial jet air, and tangential jet air.

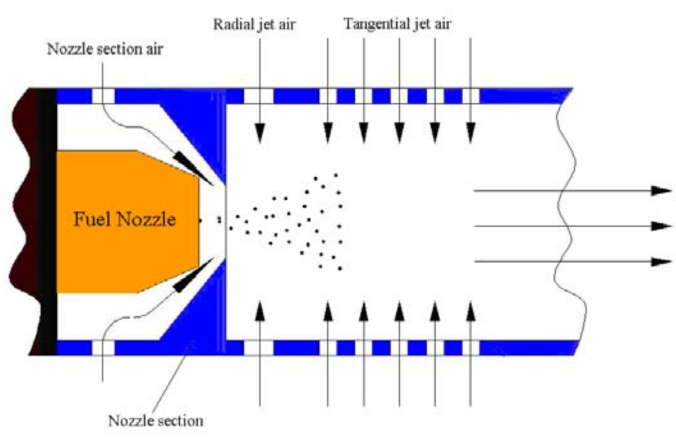


Figure 1 Schematic of multi-hole tube and illustration of air flow path.

Through the nozzle section holes, a part of the air jets flows into the gap between the fuel nozzle and the nozzle section wall, and then flows through a convergent section and enter the main tube section. The fuel atomizer is close to the nozzle section exit, and the fuel is injected into the multi-hole tube through the same exit as the nozzle section air. Note that the nozzle section air plays an important role in initial atomization and mixing. Downstream of the nozzle section, the straight holes are employed to direct the radial jet air into the multi-hole tube along the radial direction, and the radial jet air rapidly mixes with the fuel-air mixture from the nozzle section. This radial jet air also prevents the fuel droplets from wetting the main tube wall. Following the straight holes, additional air jets enter the tube through the multi tangential holes and form a swirl flow. This swirl can enhance the turbulence intensity in the multi-hole tube, facilitate the evaporation process, and improve the heat and mass transfer between the fuel and air, thereby promoting the fuel-air mixture uniformity at the multi-hole tube exit.

EXPERIMENTAL METHODS AND SYSTEM

Test conditions

The completely evaporated conditions are chosen for the mixture uniformity tests. All tests are performed at atmospheric pressure and 480 K inlet air temperature. The overall fuel-air equivalence ratio is 0.6, with Chinese aviation kerosene (RP-3) being the liquid fuel. The operating parameters of the experiments are listed in Table 1.

Table 1 Operating Conditions

Air Temperature (K)	480
Air Flow Rate (kg/s)	0.0136
Fuel Flow Rate (kg/h)	2
Equivalence Ratio	0.6

The fuel pressure in the pressure atomizer is fixed at 0.57 MPa, and the corresponding SMD is ~40 μm as measured in our previous study [20]. The resulting spray has a conical distribution, as shown in Fig. 2.

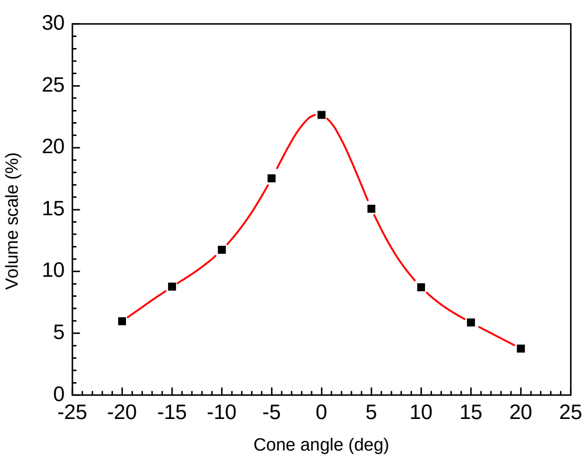


Figure 2 Conical distribution of atomizer spray.

Test configurations

Two multi-hole tube schemes are investigated herein, as shown in Fig. 3. All of the tested tubes have a diameter of 30 mm and 73 mm in length.

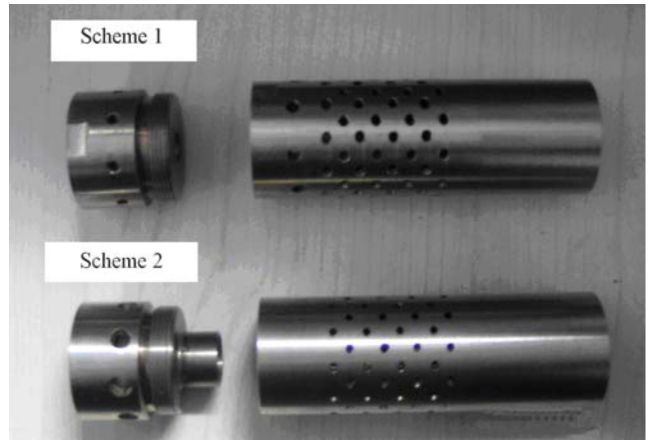


Figure 3 Comparison of two test configurations.

Scheme 1 is the baseline configuration with 8 rows of staggered multi tangential holes to generate a swirl with swirl number of Sn=0.97, which can yield stable lean combustion. A part of air passes through 8 straight holes into the nozzle section to atomize the fuel. There are 8 straight holes of 3.2 mm diameter and 88 tangential holes of 2 mm diameter in Scheme 1. Totally, the ratio between the swirl air flowrate and the axial air flowrate is 2.5:1 in the tube section.

Scheme 2 is a modified configuration, having the same tangential jet angle and staggered pattern, but smaller tangential holes (1.5 mm in diameter) and without straight holes on the tube. Thus, Scheme 2 has no radial jet air, and has a reduced amount of tangential jet air as compared to Scheme 1. Although Scheme 2 also has 8 straight holes in the nozzle section, the hole diameter of 5 mm is larger, thereby larger air flowrate and enhanced axial momentum. Moreover, Scheme 2 has a flowrate ratio of 1.5:1 between the swirl air and axial air (nozzle section air). The lower swirl of Sn=0.63 associated with Scheme 2 is expected to have reduced centrifugal effect on the fuel droplets.

Test Methods

The fuel-air equivalence ratio at the multi-hole tube exit is measured by the gas analysis technique [20,24]. The liquid fuel used in this study is Chinese aviation kerosene (RP-3) with a formula of $(CH_2)_{10.8}$ and molecular weight of 151.2 g/mol. The stoichiometric air/fuel mass ratio is a/f=14.7, so the relationship between the equivalence ratio ϕ and air/fuel mass ratio can be expressed as: $\phi=14.7/(a/f)$.

The lean combustion reaction of RP-3 and air can be written as:

$$CH_2 + A(O_2 + \beta N_2) \rightarrow CO_2 + H_2O + (A - 1 - 0.5)O_2 + \beta A N_2 ,$$

where β represents the molar ratio of nitrogen and oxygen in the oxidizer, with β=3.76 for air.

After water is removed from the reaction product, the molar concentration of CO_2 is calculated as:

$$X_{co_2} = \frac{1}{4.76A - 0.5} \qquad (1)$$

The fuel/air mass ratio is:

$$f/a = \frac{14}{28.9 \times 4.76A} \qquad (2)$$

which can be calculated from the molar concentration of CO_2 as:

$$f/a = \frac{X_{co_2}}{2.06 + 1.03X_{co_2}} \qquad (3)$$

Hence, the equivalence ratio can be calculated as:

$$\phi = \frac{14.7X_{co_2}}{2.06 + 1.03X_{co_2}} \qquad (4)$$

Experimentally, the fuel-air mixture is sampled by a probe and sent to a catalytic reactor for complete oxidation. After drying the reaction product, the CO_2 concentration is measured using a gas analyzer. Then the fuel-air equivalence ratio of the mixture can be obtained by Eq. (4).

Experimental system

Figure 4 shows the current experimental system for fuel-air mixture uniformity testing. The CO_2 infrared gas analyzer QGS-08 is used in the experiments, with an accuracy of ±1%. Prior to each experiment this device is calibrated using pure N_2 for zero and standard CO_2 for maximum.

Before entering the CO_2 analyzer, the fuel-air mixture from the multi-hole tube exit needs a series of processing, such as thermal heating/insulation, catalytic reaction, dehydration, drying, dilution, etc. The test setup, sampling probe, and sampling points are shown in Fig. 5. The sampling probe is a tube with 1.5 mm inside diameter. To avoid the fuel vapor condensation within the sampling tube, the tube is heated to a temperature higher than 420 K using electric heating wire. The fuel-air mixture then reacts in the catalytic reactor, with platinum particles as the catalyst. In order to ensure the complete reaction of fuel-air mixture in the reactor, the catalyst temperature is required to be above 1000 ℃, achieved by electric heating.

The sampled mixture reacts in the catalytic reactor to produce CO_2 and water vapor. After Cooling and drying, the product gas is sent into the gas analyzer by a vacuum pump, and the flow rate is monitored and regulated by a rotameter. Since the CO_2 concentration of the product gas typically exceeds the full-scale detection range of the analyzer, a known amount of dilution air is added to the product gas to keep the CO_2 concentration within the measurement range of the instrument. For measuring the equivalence ratio distribution at the multi-hole tube exit, the sampling points are arranged as shown in Fig. 5(c). The sampling probe is mounted on a two-dimensional translation device for moving in the X-Y plane, with the coordinate origin being the center of the cross section.

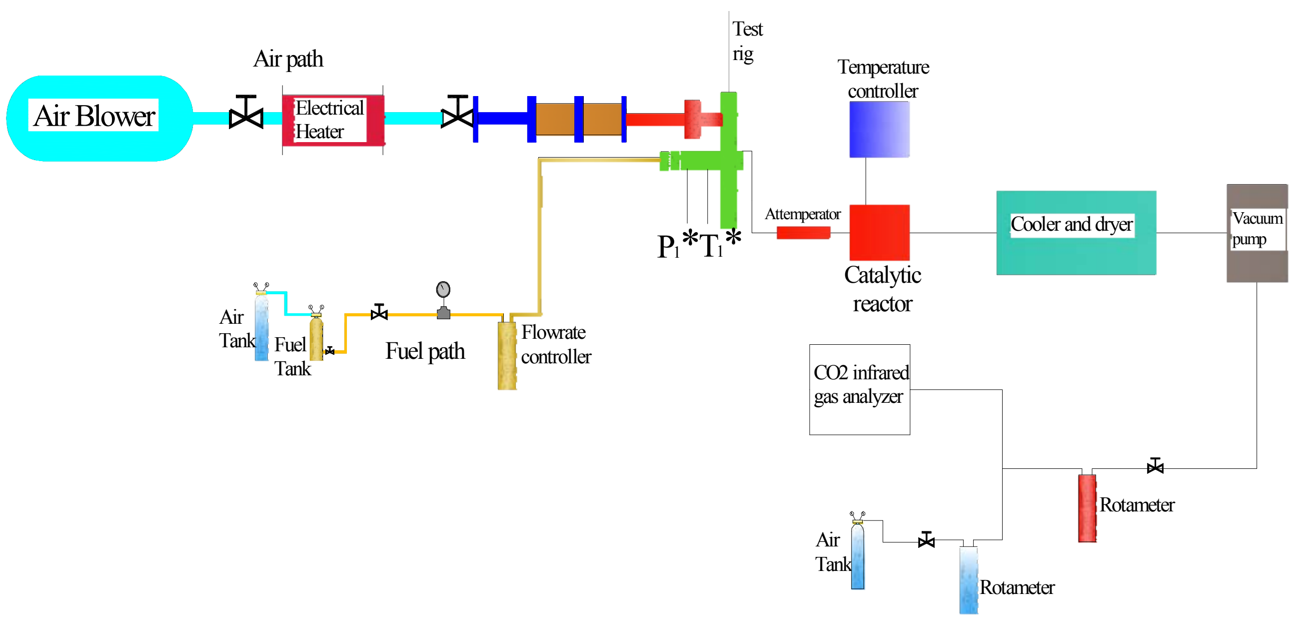
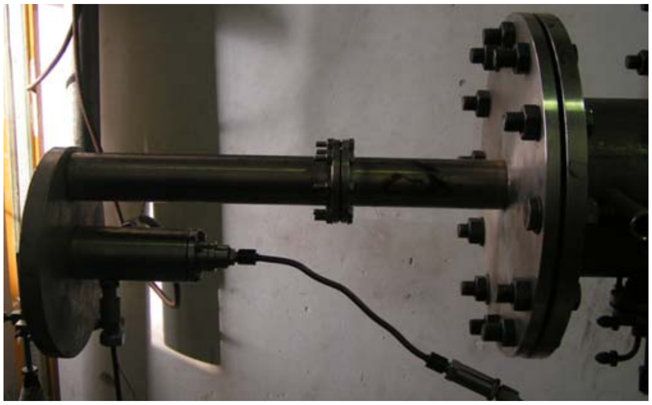
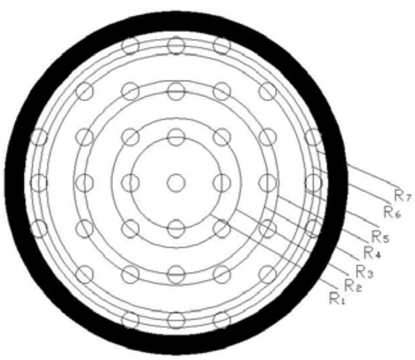


Figure 4 Facility of fuel-air mixture uniformity testing.



(a) Test setup

(b) Sampling probe



(c) Sampling points

Figure 5 Setup for fuel-air mixture uniformity experiments.

Measured data processing method

The average equivalence ratio at the measurement cross section is:

$$\bar{\phi} = \frac{\sum_{i=1}^{n} \phi_i}{n} \tag{5}$$

where n denotes the number of the test points. In order to compare the distribution of the equivalence ratio at the multi-hole tubes exit for different configurations, the equivalence ratio deviation at every sampling point is used as a parameter, which is calculated as:

$$\pi = \frac{\phi_i - \bar{\phi}}{\bar{\phi}} \times 100\% \tag{6}$$

A positive (negative) value of π then indicates the local equivalence ratio is higher (lower) than the average equivalence ratio.

Besides the equivalence ratio deviation contour, the equivalence ratios at different radii of the cross section at the multi-hole tubes exit are also compared. If the values of ϕ_{ri} represent the equivalence ratios of the test points at the same radius, the average equivalence ratio at this radius can be calculated as:

$$\bar{\phi}_r = \frac{\sum_{i=1}^{n_r} \phi_{ri}}{n_r} \tag{7}$$

Similarly, the deviation of the average equivalence ratio at this radius is:

$$\pi_r = \frac{\bar{\phi}_r - \bar{\phi}}{\bar{\phi}} \times 100\% \tag{8}$$

This value of π_r indicates the nonuniformity of the equivalence ratio along the radial direction.

Based on the operating conditions and the accuracy of the instruments, the uncertainty of the deviation of the average equivalence ratio is estimated to be ±12% in the present research.

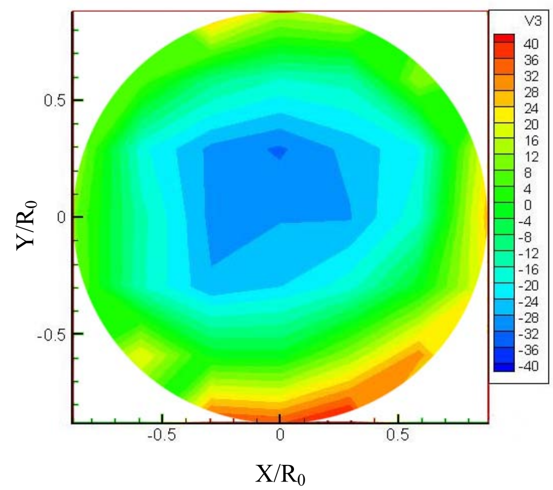
EXPERIMENTAL RESULTS AND ANALYSIS

Scheme 1

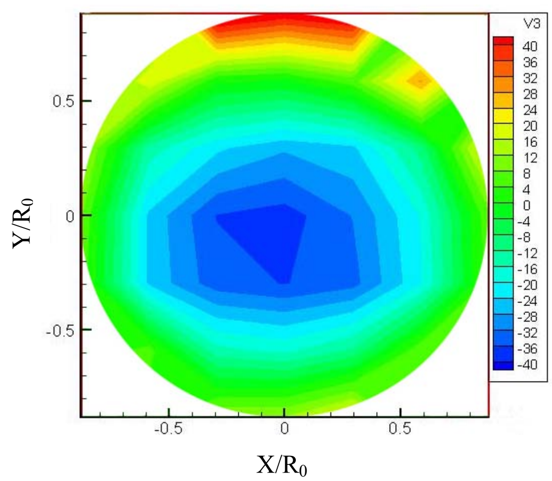
To further understand the fuel-air mixing process inside the multi-hole tube, the fuel-air mixture uniformity at three cross sections of different axial locations is measured. Section 3 is the exit of the tube, and Section 1 and Section 2 are located at 20 mm and 10 mm upstream of the exit, respectively. The test results are shown in Fig. 6, while the changes in equivalence ratio deviation along the radial direction are plotted in Fig. 7.

It can be seen from Figs. 6 and 7 that the trends of the fuel-air mixture uniformity at the three different cross sections are similar. Especially, the equivalence ratio in the central region is almost the lowest, and the distribution near the wall is of higher value, but more uniform. It also has to be pointed out that the locations of the "fuel rich" pocket (positive π_r) are different for the three cross sections, owing to the effect of the swirl flow.

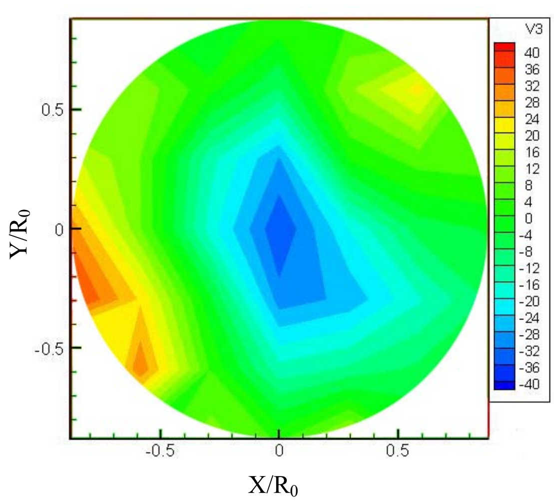
Fig. 6(c) further shows the contours of equivalence ratio deviation at the exit of Scheme 1 tube. It can be seen that the equivalence ratio is lower in the central region, and is higher near the wall. It is shown in Fig. 7 that at the exit (Section 3) the equivalence ratio deviation of the central region is close to –35%, and it is less than +20% near the wall region.



(a) Section 1



(b) Section 2



(c) Section 3

Figure 6 Contours of equivalence ratio deviation at three different cross sections of Scheme 1.

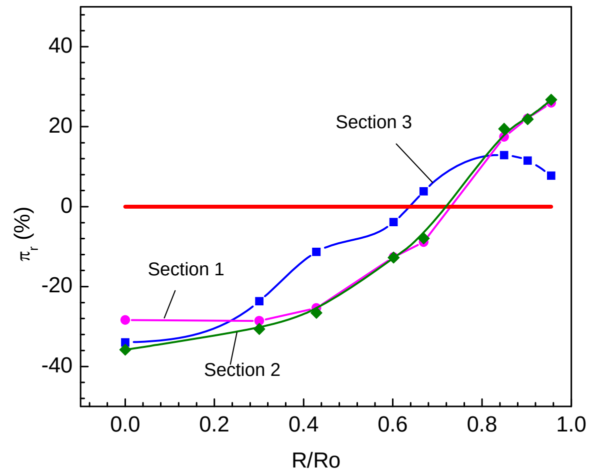


Figure 7 Comparison of the radial equivalence ratio deviations at three different cross sections of Scheme 1.

As shown in Fig. 2, the resulting spray of the fuel nozzle is denser in the central region. Since the velocity of the nozzle section mixture is mainly along the axial direction, it has axial impact effect on the fuel spray, but has not much influence on the radial distribution of the spray. Thus, Scheme 1 is to utilize the impact effect of the radial air jets downstream of the nozzle section to disperse the fuel in the central region. Subsequently, with the aid of the swirl flow, the improved spray distribution as well as the uniform fuel-air mixture can be achieved.

A numerical experiment is subsequently conducted using a commercial CFD code, FLUENT, to provide insights into the flow characteristics within the multi-hole tube and suggest guidelines for configuration modifications. The simulated configuration generally follows Scheme 1, except only 4 rows of tangential holes. In the FLUENT simulation, the realizable k-ε turbulence model and standard wall functions are used, and there are 1.2 million tetrahedral unstructured cells in the computational domain. The three-dimensional computational domain is shown in Fig. 8. The flow inlet is set as a mass flow inlet, and the flow outlet is set as a pressure outlet. Other wall boundaries are set to be adiabatic.

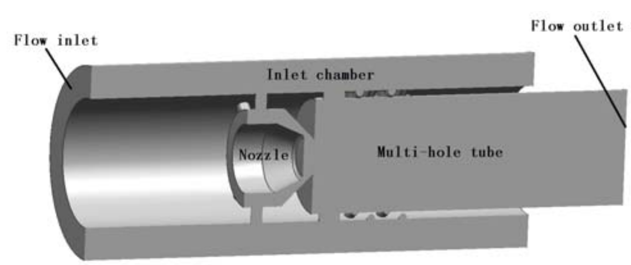
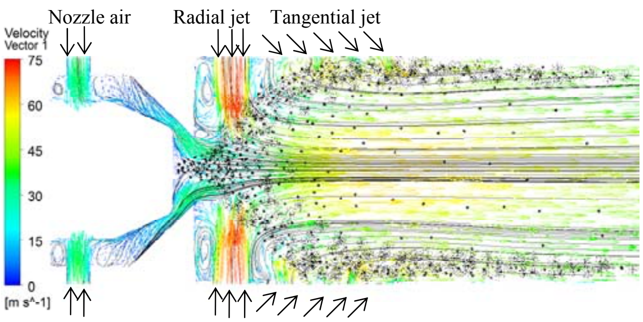
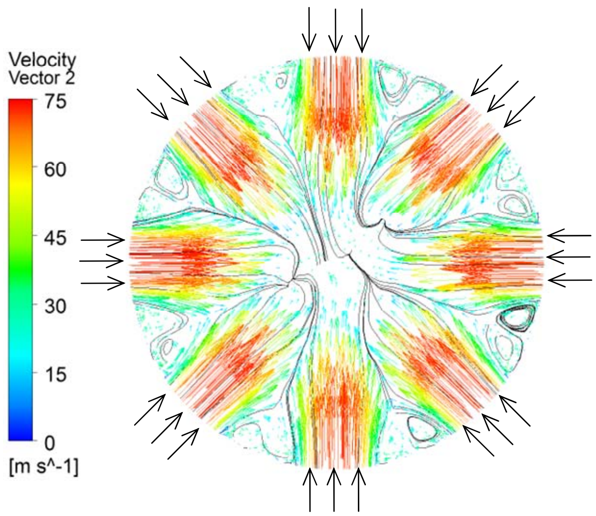


Figure 8 Three-dimensional computation domain.

Figure 9 shows the CFD-simulated vector maps, highlighting the entire tube system and the radial jets. It is seen from the simulated results that although the radial jets can impinge the fuel spray, their overwhelming impact effect perhaps carry too much fuel to the wall. This leads to nonuniform fuel-air mixture, as demonstrated in Figs. 6 and 7. Therefore, a modified configuration to improve the uniformity is needed. In particular, the effect of radial jets perhaps should be weakened so that less fuel is carried to the wall. Further, the swirl number in the tube should be reduced as well.



(a) Sectional view of the entire tube system



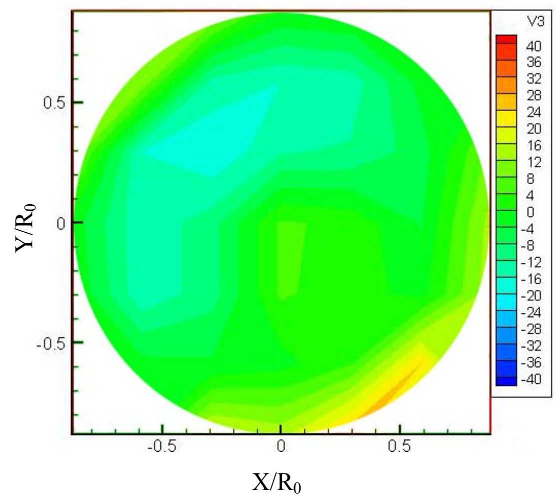
(b) Sectional view of radial jets

Figure 9 CFD-simulated vector maps.

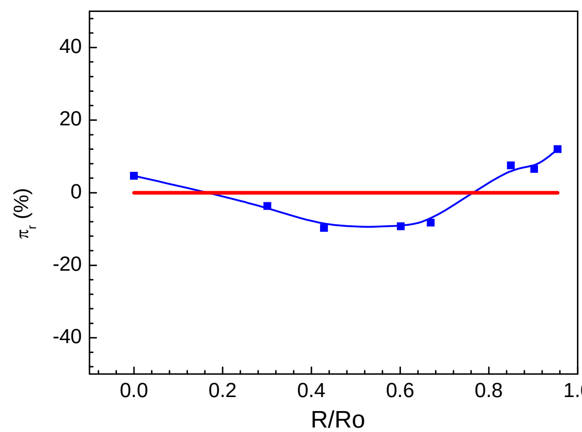
Scheme 2

Compared with Scheme 1, Scheme 2 has no radial jet air to impact on the fuel spray, while it increases the air flowrate in the nozzle section. This configuration can improve the axial momentum of the initial fuel-air mixture, and the additional straight section (without radial air holes) can guide the movement of the mixture towards the axial direction. As discussed earlier, Scheme 2 is expected to increase the fuel concentration in the center region at the tube exit and improve the fuel-air mixture uniformity. The experimental results of fuel-air mixture uniformity testing for Scheme 2 are shown in Fig. 10.

Fig. 10(a) clearly shows much improved uniformity at the multi-hole tube exit as compared to Fig. 6(c). The radial equivalence ratio deviation results shown in Fig. 10(b) also indicate that the equivalence ratio at the center is now increased to +5%, and the equivalence ratio near the wall is still slightly higher due to the swirling flow. Even for the lowest fuel concentration region at the 1/2 radius location, the equivalence ratio deviation is merely –10%.



(a) Contours of equivalence ratio deviation



(b) Radial equivalence ratio deviation

Figure 10 Experimental results of Scheme 2.

Due to the strong axial momentum produced by the nozzle section air in Scheme 2, most of the fuel would be retained around the centerline of the tube. There may be some large fuel droplets that impinge on tube wall, forming a fuel film. Even when the fuel film vaporizes due to the hot wall, the fuel vapor near the wall cannot diffuse into the inner layer because of the swirling flow. This could explain why the equivalence ratio near the wall is higher. Recognizing the potential problem of coking on the heated tube wall and its impact on the life expectancy of the micro gas turbine, the wall wetting by the fuel should be avoided in the future configuration modification and optimization.

The uniformity test results of two different schemes demonstrate that the matching of the mixture axial and swirl velocity is important to improve the premixed prevaporized performance. The fuel is mixed rapidly with the axial air flow in nozzle section, and the straight section is utilized to enhance the axial momentum. The purpose is to avoid the fuel spray interacting with the swirl air prematurely. The swirling flow enhances the turbulence intensity, improves the mixing, and also plays a role of stabilizing the flame. However, improper centrifugal force could cause the fuel to wet the wall, leading to high fuel concentration near the wall, carbon deposits on it, and reduction of the durability expectations. By optimizing the flowrate ratio of the nozzle section axial jet to the swirling jet as well as the axial jet momentum, the present experimental investigation shows that enhanced fuel-air mixture uniformity can be achieved.

CONCLUSIONS

As a key technology of low emission micro gas turbines, the fuel-air mixing performance of the premixed prevaporized multi-hole tube is studied experimentally. According to the experimental results of two multi-hole tube configurations, baseline and modified schemes, the key factors affecting the fuel-air mixing are summarized below.

(1) For a give fuel atomizer, an overwhelming radial jet in the multi-hole tube can cause unwanted high fuel concentration near the wall, which in turns influences the mixture uniformity at the tube exit.

(2) The effect of nozzle section axial jet is significant for the mixing, while the swirl effect in the tube should not be too strong. Better fuel-air mixture uniformity in the multi-hole tube can be achieved by optimizing the flowrates of the axial jet and the swirling jet as well as the axial jet momentum.

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