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Scientific-Research Article

Effect of fuel injector on the performance of a gas turbine combustor

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The influence of fuel injector on the performance parameters of a can-type combustor were examined experimentally using LPG fuel and at atmospheric conditions. The first injector is a typical 45° conical injector with 6 holes on its curved surface, and the second injector is a swirl injector with 6 holes whose axes are not parallel with each other and are oriented at 19° in respect to the combustor's axis. Three operating points were selected, and temperature distribution in the intermediate zone of the combustor and at the outlet section of the combustor was obtained using k-type thermocouples. Results reveal that the swirl injector provides better air-fuel mixing (due to the tangential motion forced on the fuel flow), more uniform temperature distribution in the combustor, lower liner temperature, higher combustion efficiency, and lower pattern factor. In addition, stability curve was also obtained for two configurations, and the results showed that the conical injector provides better stability for the combustor and is operable in a wider range of operating conditions. The results also show that the flame is generally shaped near the walls and the vicinity of the combustor's liner and outlet walls are in contact with hot gases which reduces the combustor's lifetime.

Keywords: *Can-type combustor-Experimental investigation-LPG fuel-fuel injector*

Introduction

Combustors are the backbones of the gas turbines, and have been the center of studies for combustion engineers in the recent decades. Both numerical and experimental studies have been implemented to give the researchers a better understanding of the convoluted phenomena taking place in the combustors. The major goals of the researches regarding gas turbine combustors are centered around reducing liner temperature, reducing outlet pattern factor, reducing pollution, better stability, and increasing combustion efficiency which leads to less fuel consumption [1]. Meeting all these requirements is hard to get, and usually some compromise must be set. Micro gas turbines have also been increasingly used to generate power in recent years and is highly probable to continue to increase [2]. Less fuel limitation, higher combustion efficiency, and less final cost are the main privileges of micro gas turbine combustors. One of the most important factors controlling all the aforementioned parameters in a combustor is the swirl vane angle, which has been investigated by many researchers [3-7]. Shah and Banerjee investigated the effect of swirl angle on the performance of a can-type combustor and concluded that by increasing swirl angle, the NOx emission increases and the CO emission decreases [7]. They attributed these observations to the fact that by increasing swirl vane angle, better mixing occurs (which leads to more efficient combustion and lower CO emission) in the combustor which gives rise to higher temperature and higher NOx levels. In 2018, they investigated the influence of a new fuel injection method called

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reverse fuel injection in which the fuel leaves the fueling device in reverse axial direction of the inlet air and moves towards the dome [8]. In this method, the air-fuel mixing enhances and their studies show that combustion efficiency increases and outlet CO decreases without increasing NOx emission. Heitor and Whitelaw investigated the effect of the air-fuel ratio on the combustion characteristics of the same combustor and showed that by increasing air-fuel ratio, the pattern factor increases and combustion efficiency decreases [9]. Mishra et.al investigated the effect of spray cone angle on the temperature distribution and stability curve of an annular combustor using Kerosene fuel. Their results show that with increase in the spray cone angle, the stability limit increases and the flame moves towards the combustor's dome at constant operating temperature and pressure [10]. Kankashver et.al investigated the temperature distribution and stability curve of the same combustor using Kerosene fuel [11,12]. They showed that the flame is generally formed near the liner and the center axis of the combustor is exposed to lower temperature. In this study, the influence of two fuel injectors have been experimentally investigated in a micro gas turbine combustor, and their performance parameters such as temperature distribution, outlet pattern factor, combustion efficiency and stability curve have been discussed and compared.

Combustor Geometry

A can-type combustor was investigated in this study, with 21 cm. length and maximum diameter of 67 mm. Two rows of holes were pierced on the liner, 1 cm. in diameter each, 6 holes on the first row and 12 on the second row. Outlet section of the combustor is also rectangular 10 cm. in width and 2.5 cm. in height (see Fig. 1). The combustor is installed inside a casing with 162 mm. diameter. The air swirler has 18 flat vanes oriented at 45° and with 0.56 mm. thickness which gives a swirl number of 0.85.

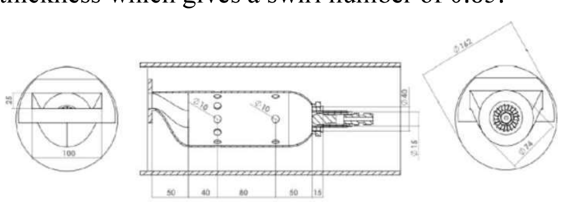


Fig. 1:Geometry of the combustor (All dimensions are in mm.)

Swirl number is calculated using Eq. (1) [5]:

$$\frac{2}{3}\times\frac{1-\left(\frac{D_{hub}}{D_{sw}}\right)^{3}}{1-\left(\frac{D_{hub}}{D_{sw}}\right)^{2}}\times tan\theta = 0.85$$

As mentioned before, two different fuel injectors were investigated in this study. The first injector is conical with 45-degree half-cone angle with 6 holes pierced on its sides 4 mm. in diameter each. (see Fig. 2). This injector gives the fuel flow only radial and axial motion.
The second injector, which is called swirl injector throughout this paper, has 6 holes, 2 mm. in diameter each. The holes' axes are neither parallel with the injector's axis nor with each other and they are oriented at 19° respected to the injector's axis (see Fig. 3). This type of hole arrangement not only gives a radial and axial motion to the fuel flow, but also generates a tangential motion which improves the air-fuel mixing in the combustor.
The hole diameters are designed based on a specific design point using Eq. (2):

$$\dot{m} = CdAh\sqrt{2p1(p1-p2)}$$

Where $\dot{m}_h$ is air mass flowrate through the holes, C_d is discharge coefficient of the holes, A_h is hole area, ρ_1 is flow density upstream of the hole, P_1 is total pressure upstream of the hole and p_2 is static pressure downstream of the hole.

Test Stand Apparatus

Air supplier is a centrifugal blower with maximum air flow rate of 400 cubic meter per hour. The inlet air temperature and pressure were recorded using thermometer and barometer respectively. Fuel properties such as flowrate, temperature and pressure were also recorded. Fig. 4 and Fig. 5 show the P&ID and the view of the combustor test section respectively. The outlet of the combustor test section is followed by a stack in which the exhaust gas is cooled by cooling water and is subsequently directed out of the laboratory.

Fig. 2:Conical fuel injector

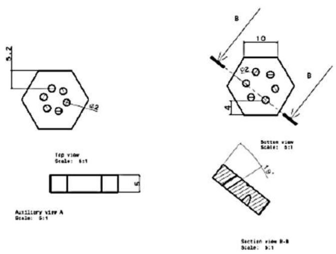


Fig. 3:Swirl fuel injector (All dimensions are in mm.)

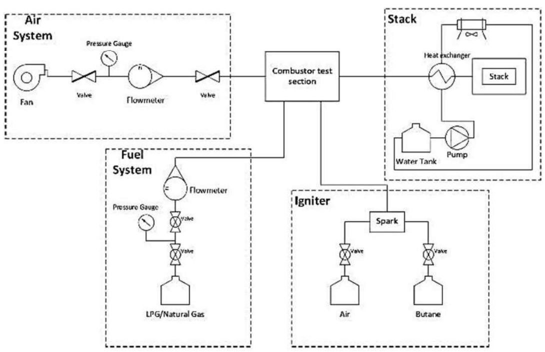
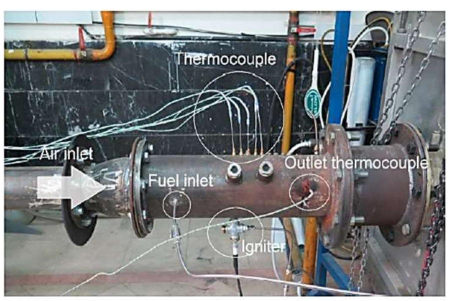


Fig. 4:P&ID of the gas turbine combustor test stand



To record the temperature, 6 K-type thermocouples were used. Fig. 6 shows the measuring points to obtain temperature distribution. Five thermocouples at different axial locations were traversed through the mid-plane of the combustor with 5 mm. spacing (see Fig. 6-a). One other thermocouple was also traversed along the mid-lane of the outlet section. (see Fig. 6-b). It is noteworthy to state that temperatures were recorded for 3 minutes at each point, and the average of the temperatures was reported.

Results

First, the stability curves of the two injectors were obtained. The lean blowout limit of the combustor is defined as when the flame in the chamber is not stable

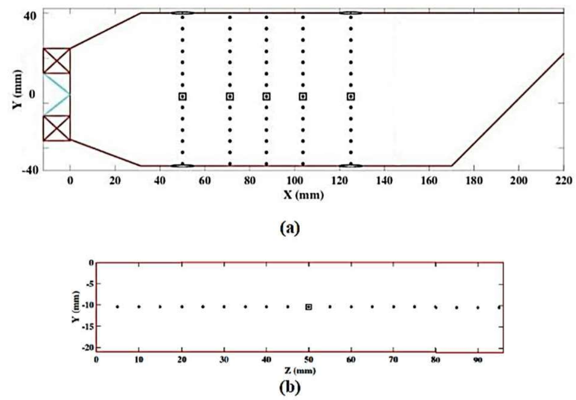


Fig. 6: Temperature measure points (Circles) – (a) inside the combustor (midplane), (b) outlet section of the combustor (mid-line)

and extinguishes in a short time or does not ignite at all. The rich blowout limit, on the other hand, is defined as when the flame exceeds the outlet section of the combustor, which is not favorable in that the turbine blades will be at direct contact with the flame which reduces their lifetime. Fig. 7 shows the combustor's outlet view when the flame exceeds the rich blowout limit (Left) and when the flame is in the stable region and is totally formed in the chamber (Right).

Fig. 8 shows the stability curves of the combustor. The upper and lower part of each curve depicts rich blowout limit and lean blowout limit respectively. The region between the rich blowout and lean blowout is known as the stable region. The wider the stable region, the more stable the combustor is and can operate in more operating conditions. The figure reveals that the conical injector gives better rich blowout limit compared to the swirl injector. This observation can be attributed to the fact that the conical injector imposes more radial motion to the fuel flow (due to its wider injection angle compared to the swirl injector), and consequently the flame is formed closer to the injector.

The second set of experiments were to examine the temperature distribution. Three operating points in which the combustor was stable in both configurations were chosen (Table 1), and temperature was recorded in the intermediate zone and outlet section of the combustor as explained in Fig. 6.

Fig. 9 shows the temperature contour for the operating points mentioned in Table 1. It can be concluded that swirl injector provides better mixing in the chamber, due to lower temperature gradient and also less frequent hotspots, and also the flow temperature in

Table 1: Selected operating points to measure temperature

Operating Point	Air flow rate (m^3/h)	Fuel flow rate (lit/min)	Equivalence ratio
A	150	19	0.24
B	180	19	0.2
C	140	17	0.21

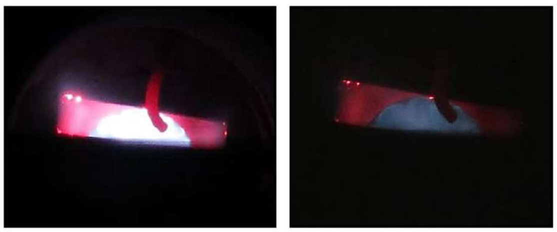


Fig. 7- Left: combustor's outlet view when the flame exceeds the rich blowout limit **-** Right: combustor's outlet view when the flame is in the stable region

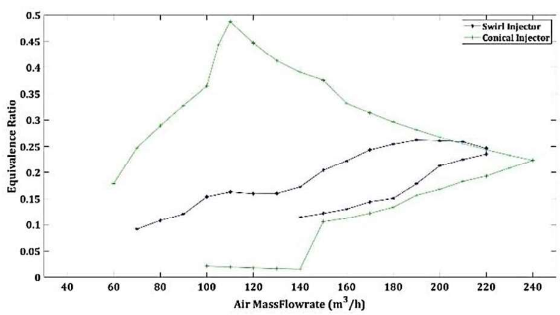


Fig. 8: Comparison of the stability curve of the two injectors

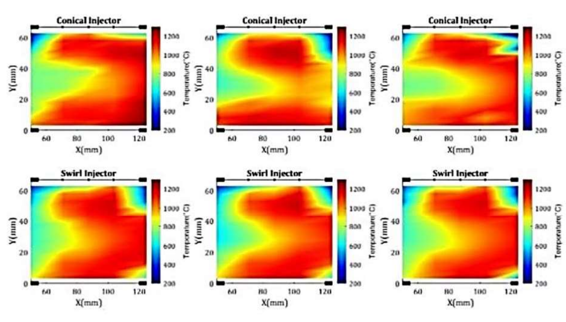


Fig. 9: Temperature distribution in the intermediate zone of the combustor for conical and swirl injectors in 3 operating points-Left: Operating Point A, middle: Operating Point B, Right: Operating Point C

the vicinity of the liner is lower compared to the conical injector, which is a great benefit. In conical injector configuration, flame is generally formed near the liner, and the center axis of the combustor is exposed to colder flow, but in the swirl injector configuration, the flame extends to the combustor's center axis and provides more uniform flame. As mentioned, conical injector configuration has more frequent and more intense hotspots, which can lead to higher amounts of NO_x and CO emission and less combustion efficiency.

Outlet temperature profile was also obtained in the selected operating points, and crucial parameters such as pattern factor and combustion efficiency were calculated. Pattern factor is calculated using Eq. (3) [1]:

$$Pattern\ factor = \frac{T_{maximum-\ average}}{T_{average-T_{inlet}}}$$

Where $T_{maximum}$ and $T_{average}$ are maximum and average temperature at outlet section respectively and T_{inlet} is combustor's air inlet temperature.

and combustion efficiency is calculated using Eq. (4) [1]:

$$\eta_{combustion} = \frac{C_p(T_{average,exit-T_{inlet}})\dot{m}_{air}}{\dot{m}_{fuel}\ LHV_{fuel}}$$

Where C_p is air heat value at constant pressure and inlet conditions, $\dot{m}_{air}$ is combustor's inlet air mass flowrate, $\dot{m}_{fuel}$ is fuel mass flowrate and LHV_{fuel} is the lower heat value of the fuel.

Table 2 and Table 3 show the mentioned performance parameters for conical injector configuration and swirl injector configuration respectively.

Table 2: Performance parameters for conical injector configuration

Operating Point	Mean outlet temperature(°C)	Pattern Factor	Combustion Efficiency
A	884	0.2	0.85
B	806	0.25	0.91
C	807	0.25	0.87

Table 3: Performance parameters for swirl injector configuration

Operating Point	Mean outlet temperature(°C)	Pattern Factor	Combustion Efficiency
A	907	0.13	0.87
B	817	0.13	0.94
C	858	0.16	0.93

Comparing the results presented in Table 2 and Table 3, it can be deduced that the swirl injector performs much better due to its lower pattern factor and higher combustion efficiency in all 3 operating points.

Fig. 10-11 show the outlet temperature profile for the operating points A, B, and C respectively (measuring points explained in Fig. 6-b). They show that combustor with swirl injector has more uniform and more compact outlet temperature compared to the conical injector. The swirl injector has both lower peak temperature and higher least temperature compared to the conical injector. Also, it is noticeable that temperature is higher in the vicinity of the outlet wall which is unfavorable [13].

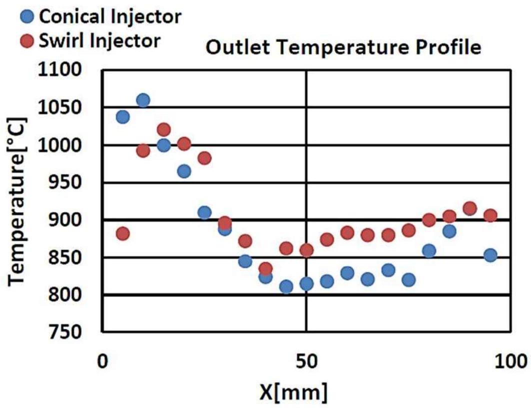


Fig. 10:Outlet temperature profile for operating point A

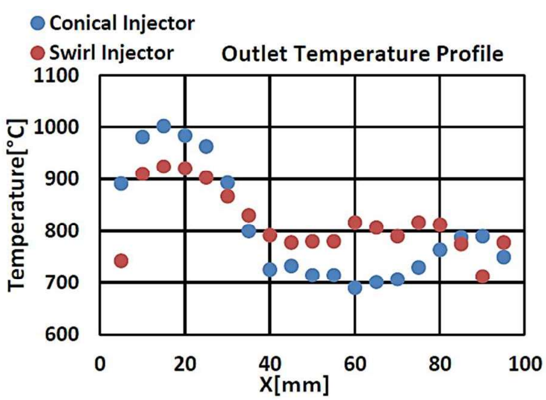


Fig. 11:Outlet temperature profile for operating point B

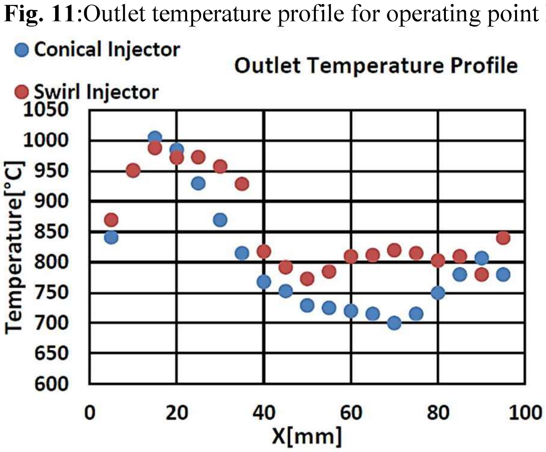


Fig. 12:Outlet temperature profile for operating point C

Conclusion

In this study, the performance of a can-type combustor is examined using LPG fuel at atmospheric conditions. A typical conical fuel injector and a swirl fuel injector were used as fueling device. The results reveal that the swirl injector provides better mixing and more uniform temperature distribution in the combustor. Moreover, better pattern factor and combustion efficiency is also observed for the swirl injector, and also the liner is exposed to a colder flow comparing to the conical injector. However, conical injector provides wider stability curve (especially for rich blowout limit).

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