SIMULTANEOUS MEASUREMENTS OF TEMPERATURE AND HEAT FLUX IN SUPERSONIC COMBUSTOR BY ITO THIN FILM THERMOCOUPLE

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Abstract

For detecting the combustion processes more accuracy, ITO thin film thermocouples are designed and fabricated to measure transient wall temperature and heat-flux in combustor. Effects of fuel type and injection pressure on the dynamic characteristics of combustion were quantitative analyzed. The maximum measured wall temperature and heat flux were 550 ℃ and 9.3 MW/m^2. Additionally, the fluctuations of combustion were analyzed by the frequency spectrum of heat flux, where the combustion of Kerosene has similar frequency but higher amplitude than Hydrogen.

1 Introduction

Wall temperature and heat-flux are crucial parameters for characterizing and optimizing the combustion processes. By analyzing and predicting time-solved wall temperature and heat flux, researchers can improve the safety, performance and longevity of combustor [1-3].
Therefore, many novel strategies are developed to measure and analyze the inner wall temperature and heat flux during combustion in recent years. Such as Zhang and his co-workers embedded thermocouples in the wall and used a mathematical model to improve the precision of measurement [4]. Yu and Dong utilized the thermocouples to measure the temperature distribution on the wall of scramjet and compared with the wall pressure to describe the flow field in combustion [5].
However, traditional sensors can hardly capture the dynamic information due to their slow response speed [6,7]. For capturing and detecting the combustion characteristic in vary dramatically environment, the sensors should have extremely fast response speed, in-situ measurement and high spatial resolution.
Thin film thermocouples (TFTCs) with negligible thermal mass are considered as a suitable sensor to measure the transient wall temperature as they exhibit rapid response, excellent spatial resolution and high precision [8, 9]. Since the sensitivity elements of TFTCs contact directly with the combustion flame without any thermal barrier structure, the sensors can provide real-time measurement of wall temperature. Additionally, combining with the semi-infinite heat transfer model, the inner wall heat flux can be calculated by the transient wall temperature [10, 11].
In current research, ITO (Indium tin oxide) thin film thermocouples are designed and fabricated to measure the transient wall temperature and heat flux in combustor. Comparing with metal, the high thermal stability and oxidation resistance of ITO ensure it can tolerant the extremely hostile environment during testing. The experiment results show that the sensor can be used to capture the time-solved wall temperature, heat flux and fluctuation. Additionally, by analyzing the frequency spectrum of heat flux, the fluctuation of combustion was researched.

2 ITO thin film thermocouple

Two films with different materials - In_2O_3 and In_2O_3:SnO_2 (90:10 wt%) were deposited on two sides of Al_2O_3 substrate to form the thin film thermocouple (Fig. 1). The substrates are made by purity Al_2O_3 ceramic to ensure the thermal stability and electrical insulation under high temperature.

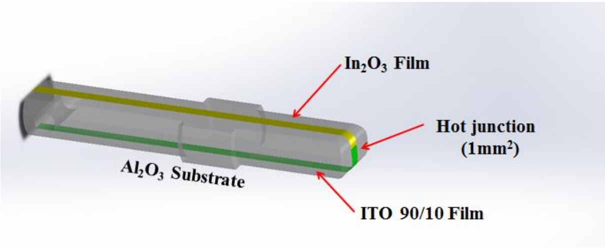

Fig.1 The schematic of ITO thin film thermocouple.

Additionally, for protection against the strong heat-shock and vibration during combustion, a stainless steel cushion sheet is designed to fix the sensor on the wall of combustor. By this structure, the hot junction of thermocouples can directly contact with flow field, and the cold junction is maintained in the room temperature to enlarge the temperature difference load on thermocouple. Then, the sensor was flush installed on the inner wall surface of combustor, as shown in Fig. 2.

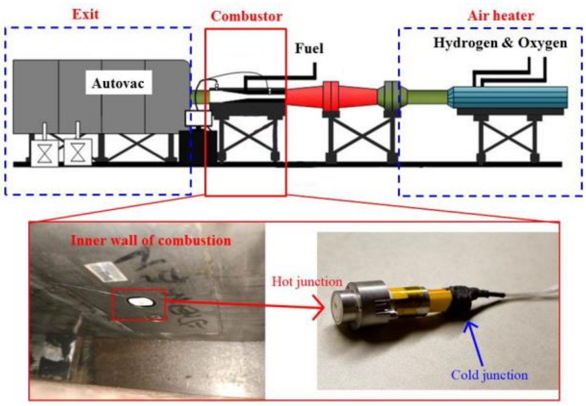

Fig.2 The installation method of sensor on combustor.

3 Combustion Experiments

3.1 Calibration of thermocouple

The thermoelectricity of ITO thermocouples should be calibrated before using it to measure the wall temperature. To load the temperature difference on thermocouple, the hot junction is placed in the hot zone of a tube furnace and the cold junction is maintained outside the furnace. The hot and cold junction temperature is monitored by type S and K thermocouples, respectively. The thermoelectricity propriety of ITO thermocouples is shown in Fig. 3, where the output voltage (U) of sensor has a linear relationship with temperature difference (ΔT) as the Eq. 1.

$$\Delta T = 0.734U \tag{1}$$

Since the cold junction of thermocouples maintained room temperature during experiments, the hot junction temperature can be calculated by Eq. 2.

$$T_h = 0.734U + T_c \tag{2}$$

where T_h is the inner wall temperature of combustor, T_c is room temperature.

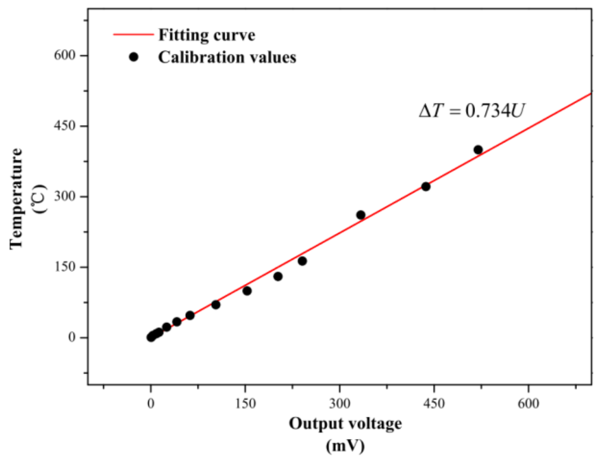

Fig.3 The relationship between output voltage and temperature difference of ITO thin film thermocouples.

3.2 Wall temperature

To verify the time-resolved wall temperature measured by ITO thin film thermocouples can be used to detect and reflect the transient supersonic combustion processes accurately, the pressure of combustor during experiments is measured by instrument through a pressure taps at 1 kHz and compared with wall temperature.

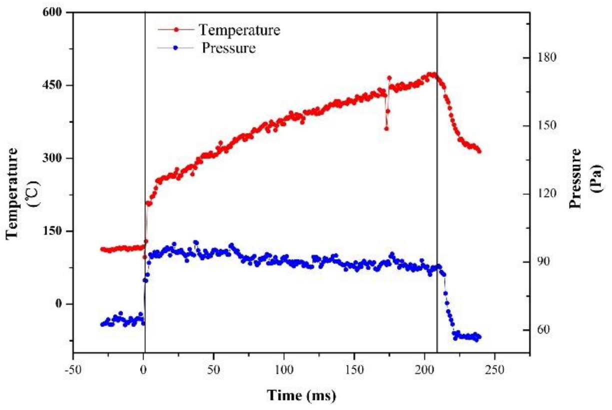

Fig.4 The contrast of dynamic wall temperature and combustor pressure during combustion.

Fig. 4 shows the wall temperature and pressure during combustion with the fuel of 1.5 Mpa Hydrogen respectively, where the temperature and pressure have similar changing processes. This results show that wall temperature measured by ITO thin film thermocouple can be used as an available detecting method for combustion. The transient wall temperature under different supply pressure (1.2, 2.0 and 4.0 Mpa) of Hydrogen were also measured as shown in Fig. 5.

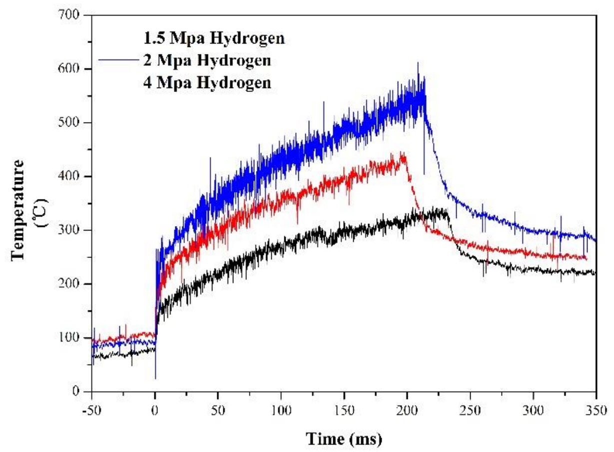

Fig. 5 The simultaneous wall temperature during combustion for Hydrogen injection pressure of 1.5, 2.0 and 4.0 Mpa

Testing results show that the heating rates of wall temperature is increased with the supply pressure of Hydrogen. The maximum temperature is about 550 ℃ during combustion. Additionally, the effect of fuel's type on combustion is researched by comparing the combustion of Hydrogen and Kerosene. As shown in Fig. 6, the wall temperature has different change processes during the combustion of Hydrogen and Kerosene. The combustion stability of Hydrogen is obviously better than Kerosene.

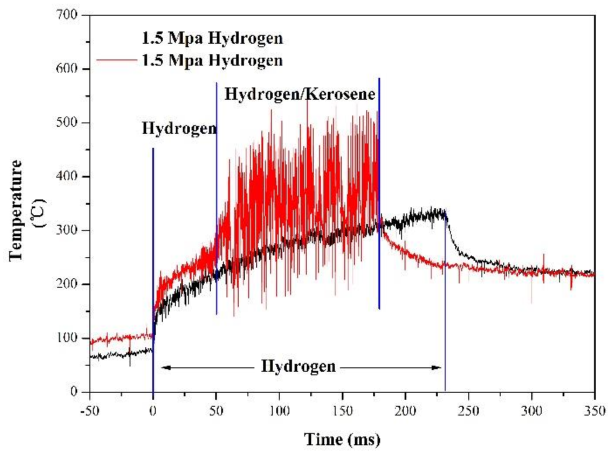

Fig.6 The wall temperature of single hydrogen and combined Hydrogen/Kerosene combustion

3.3 Wall heat flux

To get the simultaneous wall heat flux of combustor, the Cook-Felderman method based on semi-infinite heat transfer model is used to describe the heating processes on wall and calculate the stationary combustion status. The relationship between wall temperature and heat flux can be resolved as following equation:

$$q(t_n)=\frac{2\sqrt{k\rho C}}{\sqrt{\pi}}\sum_{j=1}^{n}\frac{T_j-T_{j-1}}{\sqrt{t_n-t_j}+\sqrt{t_n-t_{j-1}}} \qquad (3)$$

where q is the wall heat flux, T_j is the wall temperature at j moment. The k (24.6 W/(m.K)*,* ρ (3930 Kg/m^3), c (885 J/Kg.K) represent the thermal conductivity, density and specific heat of Al_2O_3 substrate, respectively. By this equation, the simultaneous wall heat flux can be calculated through wall temperature.

The heat flux under different supply pressure of Hydrogen is shown in Fig. 7, where the heat flux is increased with the pressure. Table 1 provides more detail data of the wall temperature and heat flux during combustion.

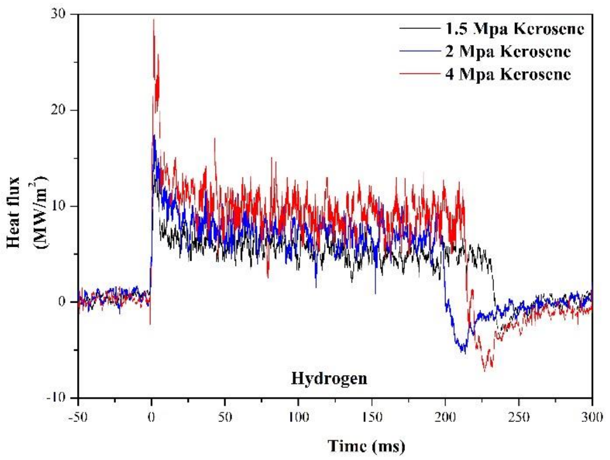

Fig.7 The calculated heat flux during supersonic combustion for hydrogen injection pressure of 1.5, 2.0 and 4.0 Mpa.

It is clearly that the transient wall heat flux can be described clearly in this method. The initial temperature increases with the injection pressure of fuel cause higher pressure would inject more fuel into the combustor and induce stronger combustion. The injection pressure equal to 1.5, 2, and 4 Mpa, the wall heat flux are about 5.4, 6.3 and 9.3 MW/m^2, respectively.

TABLE 1 Combustion Data at Different Inject Pressrure

Inject hydrogen pressure (Mpa)	*Initial temperature (℃)*	*Heating rates (℃/ms)*	*Heat flux (MW/m^2)*
1.5	150	0.87	5.4
2	214	1.17	6.3
4	291	1.511	9.3

The different heat flux during the combustion of Hydrogen and Kerosene are show in Fig. 8. The mean heat flux during two combustion are similar but the fluctuation of Kerosene's combustion are higher than Hydrogen's combustion. Therefore, Fast Fourier Transform (FFT) was used to analysis the frequency spectrum of wall heat flux to research the fluctuation of combustion. The analyzing results in Fig. 9 show that the combustion of Hydrogen and Kerosene has the similar fluctuation frequency, which means there exist a regular fluctuation during combustion. However, the combustion of Kerosene has higher amplitude, which means the stability of Kerosene's combustion is lower.

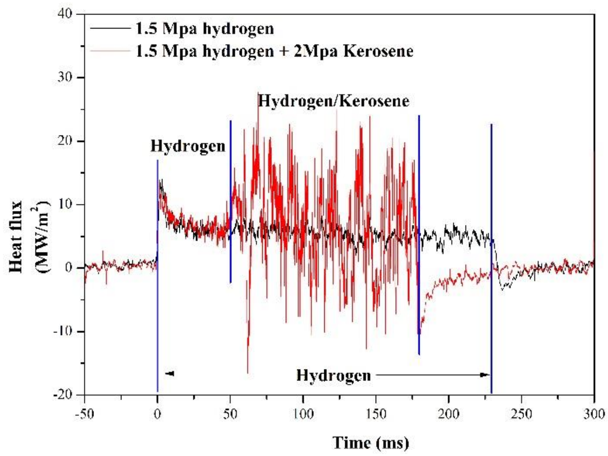

Fig.8 The heat flux of single hydrogen and combined hydrogen/ kerosene combustion.

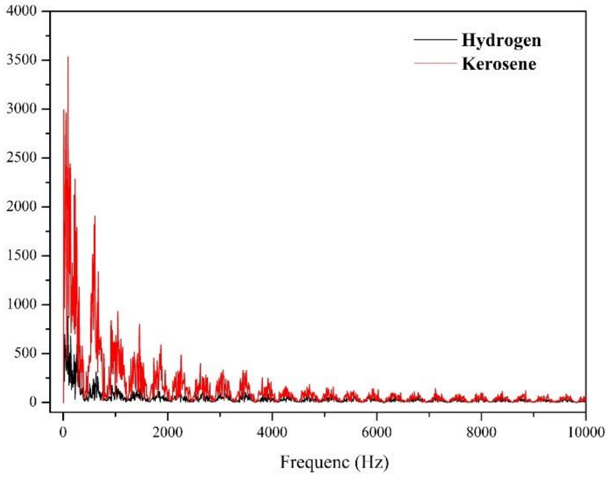

Fig. 9 The frequency spectrum of heat flux during single hydrogen and combined Hydrogen/Kerosene combustion

4 Conclusion

To capture the simultaneous wall temperature and heat flux during supersonic combustion, ITO thin film thermocouples is designed and fabricated. The sensor has simply structure, the ability of on-line measurement, high reliability and low cost, which can provide an efficient analysis method for researchers.

The results show that the transient wall temperature measured by this sensor has high accuracy. Additionally, the Cook-Felderman method is used to calculate and analysis the time-resolved wall heat flux under different combustion conditions.

In the end, the influence of fuel with different pressure and type on combustion status are analyzed by time-resolved wall temperature and heat flux. Results show that the wall temperature and heat flux are increased with the supply injection of Hydrogen. Additionally, the combustion stability of Hydrogen and Kerosene was characterized by the FFT analysis of transient wall heat flux. The combustion of Hydrogen and Kerosene has the similar fluctuation frequency, but the fluctuation amplitude of Kerosene has higher, which means a lower combustion stability.

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