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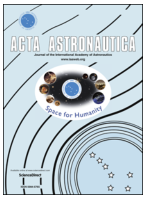

Experimental investigation on the characteristics of thermo-acoustic instability in hydrocarbon fuel at supercritical pressures

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ABSTRACT

In the investigation of forced-convection heat transfer in a small-scale channel, the phenomenon of thermo-acoustic instability was observed in hydrocarbon fuel (RP-3) at supercritical pressures. The heat transfer was obviously enhanced when thermo-acoustic instability occurred. To understand the relationship between the enhancement on heat transfer and thermo-acoustic instability, the characteristics of thermo-acoustic instability were firstly investigated. The pressure drop fluctuations were used to represent the characteristics of thermo-acoustic instability. And two pivotal characteristics of thermo-acoustic instability are amplitude and duration. The characteristics could be affected by three operating parameters: fuel mass flow rate, channel inlet temperature and channel operating pressure. A series of experiments were designed to study the effect of these three parameters on the characteristics. It is found that the amplitude increases with increasing mass flow rate, while the duration reaches the maximum value when mass flow rate is a certain value; the effects of operating pressure on the characteristics of thermo-acoustic instability are strongly interactive with the threshold power. And an increase in operating pressure causes the amplitude and duration to decrease since the variation trends of thermal physical properties become smooth; an increase in inlet temperature causes the amplitude and duration to decrease and increase, respectively, when operating pressure is below 3.0 MPa. And the duration change indistinctively with increasing inlet temperature when operating pressure exceeds 3.5 MPa.

1. Introduction

As one of the most prospective candidates for hypersonic air-breathing propulsion system, the scramjet has attracted an increasing attention worldwide [1]. However, the aerodynamic heat attributed to high speed flight is still a challenge for current engine technology. Among the available cooling methods, the regenerative cooling technology using supercritical endothermic hydrocarbon fuel as coolant is recognized as the most effective way [2].

The operating pressure and temperature in the cooling channel are usually higher than the critical pressure and critical temperature of the fuel. Large fluctuations in fluid mass flow rate, pressure, and temperature have been observed in hydrocarbon fuel at supercritical pressures [3–13]. The instability has significant influences on the safe operation of a scramjet engine. The large cyclic

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pressure and thermal transient can catastrophically reduce the lifespan of heat exchanger components [10]. Moreover, the instability often leads to critical failure in thin-walled test sections, because the flow oscillations can cause the tube to resonate when the natural frequency is matched [7]. However, it was noted that the heat transfer can be enhanced by high frequency lateral oscillation [14]. The presence of the oscillations can substantially increase the fuel-side heat transfer coefficient, and allow better utilization of the fuel heat sink [3,10,15].

Many works have been done on the instability of hydrocarbon fuel at supercritical pressures. The results indicate that there are two unstable regions in supercritical hydrocarbon fuel cooling system, namely, critical temperature region and cracking temperature region [4]. The instability in critical temperature region occurs when the reduced pressure is below 1.5, the fuel bulk temperature is lower than the pseudo-critical temperature, and the tube wall temperature is higher than the pseudo-critical temperature [5,6,9,13]. The flow regains stable state when the fuel bulk temperature is higher than the pseudo-critical temperature [15]. The instability in cracking temperature region occurs when the density decreases sharply due to the cracking of large molecules in the hydrocarbon fuel [4].

The parametric investigations indicate that the relative change rate of density is the decisive factor causing the system to be unstable [4]. And the heat flux has a significant effect on the instabilities by interacting with both mass flow rate and inlet temperature [7]. A statistical model was generated by Linne et al. [7] to explain the effects of the control variables on the strength of the instability. The results revealed that the model coefficient of inlet temperature was negative while the model coefficient of mass flow rate was positive. Moreover Brad et al. [8] found that turbulating insert could be used to restrain the pressure oscillation of supercritical hydrocarbon fuels.

Recently, Yang et al. [3] have investigated the heat transfer characteristics of supercritical hydrocarbon fuel in a short horizontal tube. Their results revealed that the heat transfer is obviously enhanced by thermo-acoustic instability. However the relationship between the thermo-acoustic instability and the heat transfer process is not mentioned.

Up to now, few works [3,5,10,16] have been done on the thermo-acoustic instability of hydrocarbon fuel at supercritical pressures. The characteristics of thermo-acoustic instability and the effects of operating parameters on the characteristics are still unclear. The present study is to get a further understanding of the characteristics of thermo-acoustic instability. And the effects of three operating parameters, namely mass flow rate, inlet temperature, and operating pressure, on the characteristics of thermo-acoustic instability are experimentally investigated.

2. Experimental facilities

2.1. Experimental facilities

Fig. 1 gives the experimental set-up for studying the thermo-acoustic instability of hydrocarbon fuel at supercritical pressures. Kerosene kind fuel RP-3 stored in the tank is driven into the preheater by the pump. The fuel is preheated in the pre-heater and then flows through the test section. The hot fuel is cooled down in the heat exchanger and flows into the fuel sump. The test section heated electrically is used to simulate the cooling channel. The mass flow rate, inlet fuel bulk temperature and operating pressure of the cooling channel are adjusted by the pump, the pre-heater and the back-pressure valve, respectively.

The pre-heater is a straight 304 stainless steel circular tube, with 2000 mm in length, 2 mm in thickness, and 6 mm in outer diameter and it is heated by an AC power with maximum heating capability of 50 kW. The test section is a vertical straight 304 stainless steel circular tube of 300 mm in length, 1 mm in thickness, and 3 mm in outer diameter. It is heated by an AC power with maximum heating capability of 20 kW. The utilization of 304 stainless steel circular tube ensures that the heat flux along the axis is uniform, due to the small resistance variation with temperature. The whole test section is thermally insulated to minimize the heat loss.

As shown in Fig. 1, the mass flow rate is measured using a Coriolis force flow meter. The operating pressure is measured using a pressure sensor before the test section. The pressure drop along the test section is measured using a pressure drop sensor. The inlet and outlet fuel bulk temperature are measured using armored thermocouples of 0.5 mm in diameter. The wall temperature is measured using wall thermocouple of 0.1 mm in diameter. All the

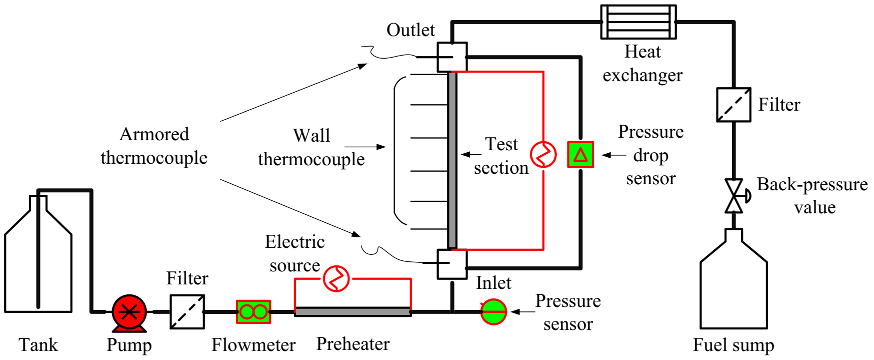

Fig. 1. The schematic drawing of test facility.