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Experimental investigation on the onset of thermo-acoustic instability of supercritical hydrocarbon fuel flowing in a small-scale channel

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ABSTRACT

Thermo-acoustic instability accompanied with abnormal sounds was observed for supercritical hydrocarbon fuel (RP-3) flowing in a heated small-scale channel. The instability appears when the applied heating power exceeds a threshold value. The threshold power can 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 threshold power. It is found that the threshold power changes monotonously with fuel mass flow rate; while there is no simple linear effect of inlet temperature and operating pressure on the threshold power. Two dimensionless parameters, namely, sub-pseudo-critical number and true trans-pseudo-critical number were used to study the boundary of the thermo-acoustic instability. The result reveals that the system stability is significantly enhanced by increasing operating pressure; while the effect of mass flow rate on the system stability is strongly coupled with inlet temperature.

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 the current engine technology. Among the available cooling methods, the regenerative cooling technology using 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, thus the fuel becomes supercritical.

Large fluctuations in mass flow rate, pressure, and temperature have been observed in supercritical hydrocarbon fuel [3–13]. The instability has significant influences on the safe operation of scramjet engine. The large cyclic pressure and thermal transient can catastrophically reduce the lifespan of heat exchanger components [10]. Moreover the instability can lead 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]. On the other hand, it was noted that the heat transfer can be enhanced by high frequency lateral oscillations [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].

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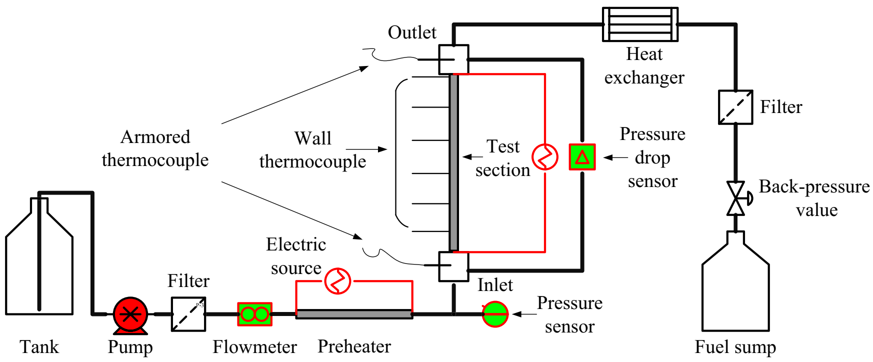

Fig. 1. The schematic drawing of test facility.

Many works have been done on the instability of hydrocarbon fuel at supercritical pressure. 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 of the fuel decreases sharply due to the cracking of large molecules [4].

The parametric investigations indicate that the relative change rate of density is the decisive factor causing the system to be unstable [4]. The heat flux has a significant effect on the instabilities interactive with both mass flow rate and inlet temperature [7]. A statistical model was generated by Linne et al. [7] to explain the effects of 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 fuel.

Recently, Yang et al. [3] have investigated the heat transfer characteristics of supercritical hydrocarbon fuel in a short horizontal tube. Their results showed that the heat transfer is obviously enhanced by thermo-acoustic instability. Thermo-acoustic instability was also widely observed in combustion systems [16–19] and Rijke tubes [20–24]. However few works [3,5,10,25] have been done on the thermo-acoustic instability of supercritical hydrocarbon fuel. Yang et al. [3] claimed that the thermo-acoustic instability was caused by the rapid collapsing and condensing of micro-bubbles formed on the gasification cores of the heated tube. These pseudo-bubbles were found to propagate in the fluid with the speed of sound [10,25]. Others claimed that the thermo-acoustic instability was related to the large variations in thermophysical properties [4,5,7].

The previous work [3] revealed that the thermo-acoustic instability had significant influences on the design of cooling channel. However there is not a generally accepted explanation for the thermo-acoustic instability. And how to promote and restrain the thermo-acoustic instability is still unclear. The present study is to get a further understanding of the onset of thermo-acoustic instability of supercritical hydrocarbon fuel. The influences of three parameters, mass flow rate ($\dot{m}$), inlet temperature (T_{in}), and operating pressure (P), on the onset of thermo-acoustic instability are experimentally investigated.

2. Experimental facilities

2.1. Experimental facilities

Fig. 1 gives the schematic drawing of the experimental set-up for studying the thermo-acoustic instability of supercritical hydrocarbon fuel. Kerosene kind fuel RP-3 stored in the tank is driven into the preheater by the pump. The fuel is pre-heated in the pre-heater and then flows through the test section. The hot fuel is cooled down in the heat exchanger and then flows into the fuel sump. The test section heated electrically is used to simulate the cooling channel. The mass flow rate, fuel bulk temperature at the test section inlet and the operating pressure 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. The tube 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 sampled data are recorded using a PCI data acquisition card. The uncertainty of the measurements is shown in Table 1.