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Density Wave Instability of Supercritical Kerosene in Active Cooling Channels of Scramjets

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Abstract**—**Experimental investigations were made on the instability of supercritical kerosene flowing in active cooling channels. Two approaches were used to control the pressure in the channel. One is the back-pressure valve while the other is the venturi. In both conditions, a kind of low-frequency oscillation of pressure and temperature is observed. And the oscillation periods are calculated. By comparison with the flow time, it is concluded that the instability occurred in active cooling channels is probably one kind of density wave instability. And its period has no relationship with the cooling channel geometry, nor the pressure, but only depends on the flow time of kerosene in active cooling channels. When the mass flow rate, density and pressure drop couple with each other, the density wave instability will appear.

Keywords**—**scramjets; active cooling; instability; density wave

I. INTRODUCTION

FLOW instability of gas and liquid two-phase mixtures has been observed for a long time, and its possible damage to equipments is also realized. For boiler, water-cooled reactor, steam generator, heat exchanger and other facilities with gas and liquid two-phase mixtures, flow instability not only lowers working performance but also causes safety problems [1]. However, few studies are reported about the instabilities inside the active cooling channels of scramjets, nor are the possible effects on the engines.

Two phase instability can be divided into two types, the static instability and the dynamic instability. Further more, the static instability includes mass flow drift (namely Ledinegg instability), boiling crisis, flow pattern transition and so on [2].

The dynamic instability is referred as periodic self-sustaining pulsations of mass flow rate and other dynamic parameters. Density wave instability is the most common dynamic instability, and it is usually caused by periodic pulsations of mass flow rate when two-phase mixtures with different densities alternatively flow through the channels [3]. Hitch et al. [4] have found two instabilities in JP-7 flow experiments, one is the low frequency Helmholtz oscillation and the other is the high frequency acoustic oscillation. The Helmholtz oscillation is considered analogous to spring damp oscillation mode, and it is caused by elastic oscillation of flow between the two ends of the tube. The high frequency acoustic oscillation is like the organ principle, namely acoustic resonance vibration. Linne et al. [5] have done a lot of experiments, and found that there seems to be no rule that when instabilities will happen, and the results can not be repeated even at the exactly similar conditions. However, when increasing the inlet temperature, the intensity of the instability could be reduced.

The current research on two-phase flow instability is not so thorough, and there have been few studies about the instability of aviation kerosene in active cooling channels of scramjets so far. However, it truly exists and has great effects on the heat transfer characteristics and scramjets cooling design. So it is significant to perform relative researches on this.

II. EXPERIMENTAL APPARATUS

A. The radiation heater

A radiation heater with maximum power of 18KW for simulation of the thermal resource of scramjets is designed, see Fig. 1.

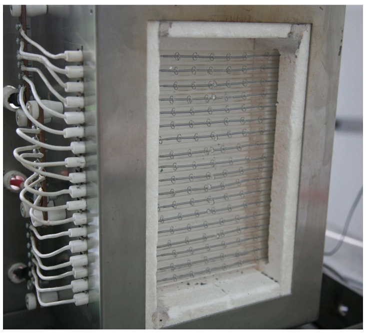

Fig. 1 the radiation heater

The radiation heater is mainly made up of 18 infrared quartz tubes which are paralleled placed. The power of the heater could be continuously exported from zero to maximum by a control system. And there are two heating modes, manual and automatic. Either the power or the temperature could be controlled when in automatic mode. The effective heating area of the radiation heater is 140mm×240mm, and the maximum heat flux is approximately 0.54MW/m2.

B. The cooling panel

Panel with single channel in it is designed for simulating the scramjet combustion chamber. It mainly consists of a motherboard and a cover board. The motherboard is grooved with single cooling channel and receives radiation from the heater. The cover board is welded to the motherboard every four cooling channels in order to insure the structural strength and make sure that kerosene flows exactly along the channel. Temperature and pressure measuring points are arranged along the channel, see Fig. 2 and Fig. 3.

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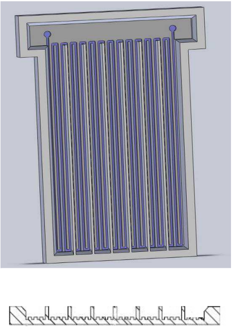

Fig. 2 The motherboard of the cooling panel

TABLE I
TEST CONDITIONS WITH BACK-PRESSURE VALVE

Test number	Cooling channel geometry mm×mm	Back pressure MPa	Mass flow rate g/s
1	1.5×1.5	3.1	1.0
2	3×3	2.3	

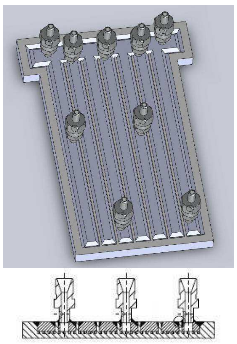

Fig. 3 The assembly of the cooling panel

The cooling panel is tested by 6MPa water before experiments. And according to the effective heating area of the radiation heater, the area of the cooling panel is a little smaller than that. In order to be expedient for mounting, a fixed mounting board with size of 300mm×200mm is designed. In every experiment, it only needs to mount the cooling channel into the mounting board and fill asbestos between them in order to prevent heat loss, see Fig. 4 And the cooling panel being heated in experiments is just as Fig. 5 shows.

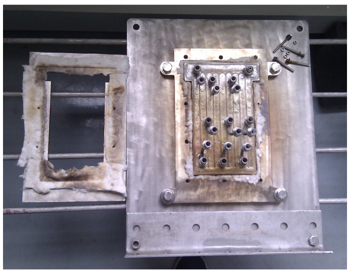

Fig. 4 The cooling panel and mounting board

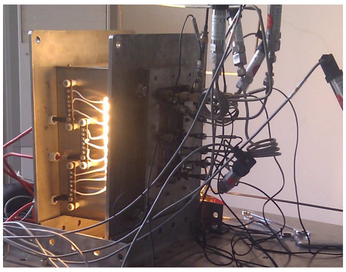

Fig. 5 Photograph of the cooling panel in experiments

III. RESULTS AND DISCUSSION

Two equipments have been used to control the pressure in the cooling channel. One is the back-pressure valve while the other is the venturi. Pressure oscillations are observed in both conditions.

A. Flow instability when using back-pressure valve

Pressure oscillation appeared in some conditions when using back-pressure valve. Flow instability has been found at different working conditions for different panels. The working conditions are as Table 1 shows.

The local zoomed pressure curves for test 1 and test 2 are shown in figure 6 and figure 7. To be pointed out, the sharp decrease at 60s for test 1 is caused by the manual adjust of the back-pressure valve.

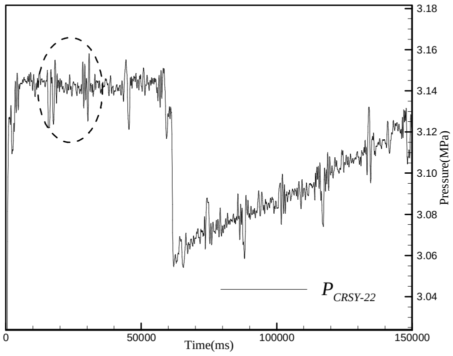

Fig. 6 pressure curve for test 1

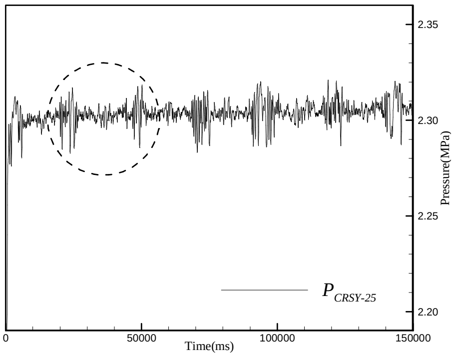

Fig. 7 pressure curve for test 2

As can be seen in Fig. 6 and Fig. 7, the pressure curves present regular low-frequency oscillations, see the dashed circles in the figures.

And the oscillating period is calculated by average of several periods. The oscillating period for test 1 is T1≈ 12.6 and for test 2 is T2≈ 25.5s.

According to the characteristics of different two-phase flow instabilities, the low-frequency oscillation found in experiments is more coincident with the density wave theory. According to the theory, when the inlet mass flow rate decreases, the fluid will be heated to a higher temperature, resulting in decrease of density. As the flow resistance is proportional to the density and flow velocity, when the low density wave transfers along the channel and arrives at the choke element (such as bake-pressure valve or venturi), the flow resistance will decrease. If the pressure drop between the inlet and the outlet is fixed, the mass flow rate will increase as the flow resistance decreases, resulting in increase in density and resistance, and the inlet mass flow rate will decrease again. Thus an oscillation period is completed. Since the feedback effects could only be generated when the change of the inlet mass flow rate arrives at the outlet, the period of the density wave instability is usually equal to or two times the flow time along the channel [2].

The kerosene density change versus temperature is calculated by NIST Supertrapp software [6], as shown in Fig 8.

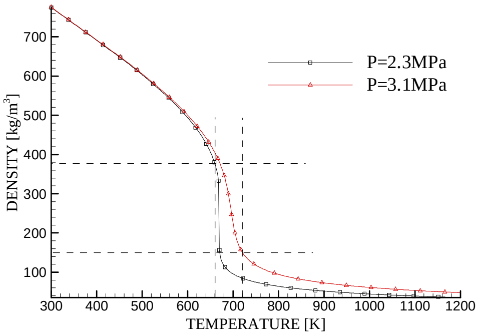

Fig. 8 Density calculation of kerosene in test 1 and test 2 from supertrapp [6]

The highest temperature of kerosene in test 1 is approximately 723K while it is approximately 663K in test 2. According to Fig 8, the minimum density of kerosene in the two tests is 150kg/m3 and 380kg/m3, respectively.

Thus, the inlet velocity for test 1 and test 2 is as follows:

$$v_1 = \frac{\dot{m}}{\rho_{\text{入口}} A_1} = \frac{1.0\times10^{-3}}{740\times\left(1.5\times10^{-3}\right)^2} = 0.6\, m/s \tag{1}$$

$$v_2 = \frac{\dot{m}}{\rho_{\text{入口}} A_2} = \frac{1.0\times10^{-3}}{740\times\left(3\times10^{-3}\right)^2} = 0.15\, m/s \tag{2}$$

The maximum inlet velocity for test 1 and test 2 is:

$$v_{1\max} = \frac{\rho_{\text{入口}}}{\rho_{\min}} v_{\text{入口}1} \approx \frac{740}{150}\times0.6 = 2.96\, m/s \tag{3}$$

$$v_{2\max} = \frac{\rho_{\text{入口}}}{\rho_{\min}} v_{\text{入口}2} \approx \frac{740}{380}\times0.15 = 0.29\, m/s \tag{4}$$

The total length of cooling channels for test 1 and test 2 is 6.4m and 4.4m, respectively. Thus, the flow time of kerosene for test 1 and test 2 is:

$$2.2s \approx \frac{6.4}{2.96} = \frac{l_1}{v_{1\max}} < t_1 \le \frac{l_1}{v_{1\min}} = \frac{6.4}{0.6} \approx 10.7s \tag{5}$$

$$12.6s \approx \frac{4.4}{0.35} = \frac{l_2}{v_{2\max}} < t_2 \le \frac{l_2}{v_{2\min}} = \frac{4.4}{0.18} \approx 24.4s \tag{6}$$

Since the radiation from the heater is not so homogeneous, and the high temperature area only appears at the centre of the panel, kerosene flows in the channel at a relative low density and velocity in most time. So the averaged flow time of kerosene in test 1 and test 2 is mostly closer to 10.7s and 24.4s, respectively.

The oscillation period for test 1 and test 2 is T1≈ 12.6s，T2 ≈ 25.5s, very close to the flow time, coincident with the density wave theory. Further more, the flow time for test 2 is about twice that for test 1, and the oscillation period for test 2 is also about twice that for test 1. Based on the above discussion, It can be concluded that the instability that occurred in two-phase kerosene flow is probably density wave instability.

Fig. 9 shows the low-frequency oscillation of wall temperature for test 2, and the oscillation period is approximate 20s, close to the flow time and pressure oscillation period for test 2. This confirms the conclusion that the instability is a kind of density wave instability.

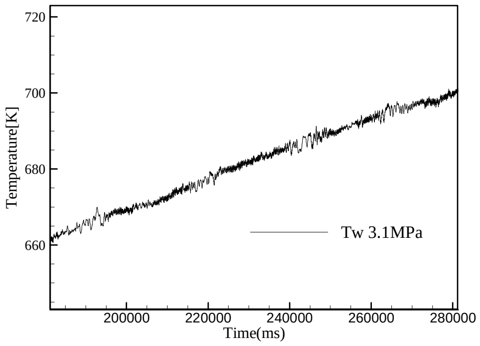

Fig. 9 Low-frequency oscillation of wall temperature in test 2

B. *Flow instability when using venturi*

Low-frequency oscillation of pressure is also observed when using venturi. The test conditions are as table 2 shows. The cooling panels in both tests are the same while the throat size of the venturi and the mass flow rate are different.

The pressure curves of the two tests are as Fig. 10 and Fig. 11 shows,

TABLE II
TEST CONDITIONS WITH VENTURI

Test number	Cooling channel geometry mm×mm	Back pressure MPa	Mass flow rate g/s
1	2×2	0.5	2.0
2		0.4	1.8

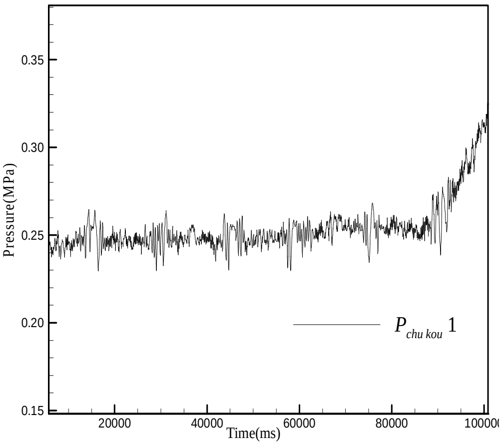

Fig. 10 pressure curve for test 3

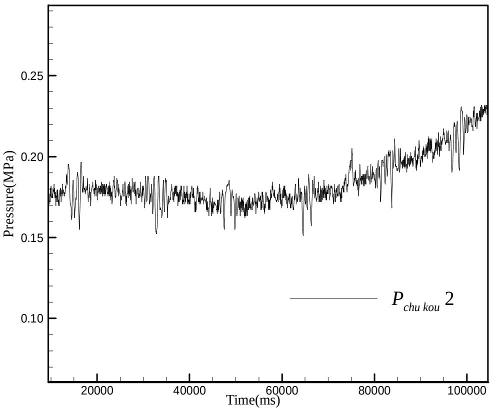

Fig. 11 pressure curve for test 4

The calculated oscillation periods of test 3 and test 4 are 15s and 20s, respectively. The difference is mainly caused by the difference of mass flow rate. When at the same flowing area conditions, different mass flow rate results in different flow velocity, and then different flow time. As the mass flow rate of test 1 is large, the flow time is short, corresponding to a lower oscillation frequency. This agrees with the calculated results of oscillation periods.

IV. CONCLUSIONS

Low-frequency oscillations of pressure and temperature are observed in kerosene flow either with back-pressure valve or venturi. It doesn’t depend on the way by which the pressure is controlled, but rather some kind of nature characteristics of the kerosene flow. After comparison of the calculated oscillation period with the flow time as well as analysis of the flow process, it is concluded that the instability that happens in the cooling channels is probably some kind of density wave instability. The period of this instability has no relationship with the cooling channel configurations, nor the pressure in the cooling channel, but only depends on the flow time. When the mass flow rate, the density and the pressure drop couple with each other, the density wave instability will occur.

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