Zhang *et al. Advances in Aerodynamics* (2022) 4:31
https://doi.org/10.1186/s42774-022-00123-z

Advances in Aerodynamics

RESEARCH **Open Access**

Design method of supercritical hydrocarbon fuel injection for a scramjet

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Abstract

Both the fuel transfer control scheme and the knowledge of fuel temperature and pressure values before injection are important to a scramjet engine. A measurement method of the fluid temperature suitable for small channel is presented, and a fluid transfer control scheme of the area of injecting holes is designed using the balance equations of fluid mass, energy and entropy. A convective heat transfer experiment is conducted to evaluate the temperature measurement and the fluid transfer control design method of the heat absorbing supercritical hydrocarbon fuel. The results show that during the heating process the injecting pressure meets the requirement, and the fluid transfer control system works well. Such results suggest that the design method in the present work would be useful in the design of regenerative cooling for scramjet engines.

Keywords: Supercritical hydrocarbon fluid, Temperature measurement, Transfer control, Scramjet engine

1 Introduction

The scramjet engine has attracted wide interest of scientists and engineers for over decades. It can achieve high specific impulse over a wide range of flight Mach numbers and altitudes. Liquid hydrocarbon fuels are used as a coolant to cool the scramjet engine structures before being injected into the combustor as fuel, which is called regenerative cooling. The liquid hydrocarbons that named as endothermic fuels, can absorb extra amount of heat within the cooling channels of the engine structure while decomposing at high temperatures. Such a property is regarded as an advanced and ideal heat sink approach by many researchers [1–4].

To develop the scramjet engine, the flow and heat transfer of hydrocarbons in small heated tubes have been tested to validate the primary cooling ideas of scramjets for many years [5, 6]. In a hydrocarbon fueled scramjet engine, a mixture of liquid hydrocarbon cools the metallic structure as it flows through very small longitudinal cooling channels as shown in Fig. 1. The typical size of a cooling channel cross section for a scramjet engine panel is about 2 mm × 2 mm. To meet the requirement of fuel injecting pressure at the scramjet engine fuel injecting holes and the fluid transfer for its circulation, the fuel pressure is usually supercritical inside the cooling channels.

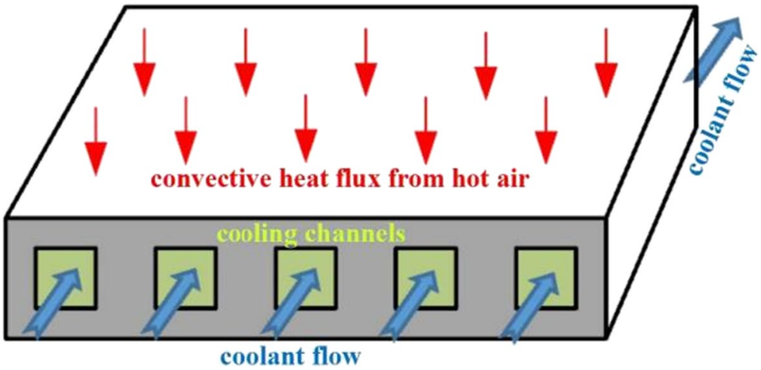

Fig. 1 The small longitudinal cooling channels inside a panel

While absorbing heat from the structure, the fuel temperature rises and the density decreases to a value much smaller than its original value [7]. For example, the fuel density at room temperature (300 K) is 0.79×10^3 kg/m^3, and the fuel pressure is fixed to 5 MPa. When the fuel is heated and its temperature rises to 850 K, the fuel density decreases to about 0.14×10^3 kg/m^3, which is less than one fifth of its original value. The fluid speed increases to several times its original value. Meanwhile, the pressure loss accompanied by the flow inside the small channel can increase too much if the total area of the passages is equal. This brings difficulties to the fluid transfer control since overmuch pressure loss is unacceptable to the fluid transfer system.

The fuel may crack into smaller hydrocarbons when its temperature is higher than 850 K, thus the physical and chemical properties change dramatically in the cooling channel [7]. The fluid transfer system, such as one injecting the hydrocarbon mixture into the scramjet engine at both low and high temperatures, must meet the requirement of transferring fuels over very different fluid densities. It is of crucial importance to evaluate the physicochemical properties of hydrocarbons inside the cooling structure of a scramjet engine, especially for the design of the fluid transfer system. The fluid transfer system must reduce the pressure loss if the fluid temperature is high.

Since the fuel transfer control scheme is key to a practical scramjet engine, one can easily understand that the predicting method of supercritical flow passing a different area is of critical importance. Previous works seldom discuss the balance equations of fluid mass, energy and entropy, which are necessary for the predicting method. In fact, the details for both the calculation method and the fuel transfer control scheme are not reported in public references to the knowledge of the authors. The same is true for the details of the fluid temperature measurement at high pressure and high temperature.

In this paper, a measurement method of the fluid temperature suitable for small channel is given, and a fluid transfer control scheme of the area of injecting holes is designed using the balance equations of fluid mass, energy and entropy. A convective heat transfer experiment is conducted to evaluate the temperature measurement and fluid transfer control methods of the heat absorbing supercritical hydrocarbon fluid. The results would be useful for the design of regenerative cooling for scramjet engines.

2 Thermophysical properties of the hydrocarbon mixture

Accurate evaluation of the thermophysical properties of hydrocarbon mixture is a key step for predicting its flow and heat transfer. The thermodynamic and transport properties of mixed hydrocarbons are estimated by the extended corresponding-states method with propane as a reference material [5, 7] including density, heat capacity, viscosity, and thermal conductivity. The hydrocarbon fuel of interest is a mixture of over 100 hydrocarbon components. The properties of the hydrocarbon mixture corresponding to specific temperature and pressure are calculated by a surrogate model and a program of thermophysical properties evaluation. This method has been proven effective in many applications [8, 9].

Mixtures such as China aviation kerosene RP-3 consist mainly of n- and iso-paraffins, naphthenes, and aromatics, and detailed components and thermophysical properties of China RP-3 aviation kerosene can be found in Refs. [10] and [11]. To reduce the computational cost, a four-species surrogate (molar percentage: 25% n-decane, 50% n-dodecane, 12% n-tridecane and 13% butyl-cyclohexane) is adopted to approximately evaluate the thermophysical properties of China RP-3 aviation kerosene.

Figure 2 shows the comparison of the calculated density, heat capacity, thermal conductivity and viscosity of China RP-3 aviation kerosene under the pressure of 5 MPa. The thermophysical parameters are calculated with the present surrogate (four-species) and a ten-species one. The latter surrogate model was applied for China RP-3 aviation kerosene in Ref. [12]. The relative errors of density, heat capacity, viscosity and thermal conductivity between two surrogate models in the temperature range of 300–1200 K are less than 3.03, 3.64, 3.91 and 3.15%, respectively. The calculated critical temperature T_c and pressure p_c of China RP-3 aviation kerosene are 649.6 K and 2.31 MPa respectively, which is close to the measured data 645.5 K and 2.39 MPa [10].

According to the low relative errors mentioned above, the four-species surrogate is considered to be reliable for the following investigation. The calculation of the thermophysical properties of the hydrocarbon mixture China aviation kerosene RP-3 using the present four-species surrogate is more time-efficient than the ten-species surrogate. The enthalpy, density, entropy and sound speed of China aviation kerosene RP-3 are shown in Fig. 3. It is assumed that no pyrolysis occurs at the whole temperature range in calculation. These thermophysical properties of the hydrocarbon mixture will be used in

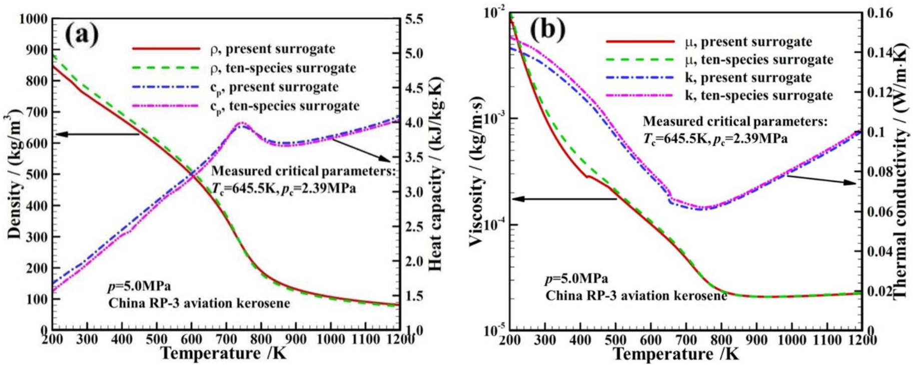

Fig. 2 Thermophysical properties predicted using a four-species surrogate and a ten-species surrogate in Ref. [10], (a) density and heat capacity; (b) viscosity and thermal conductivity

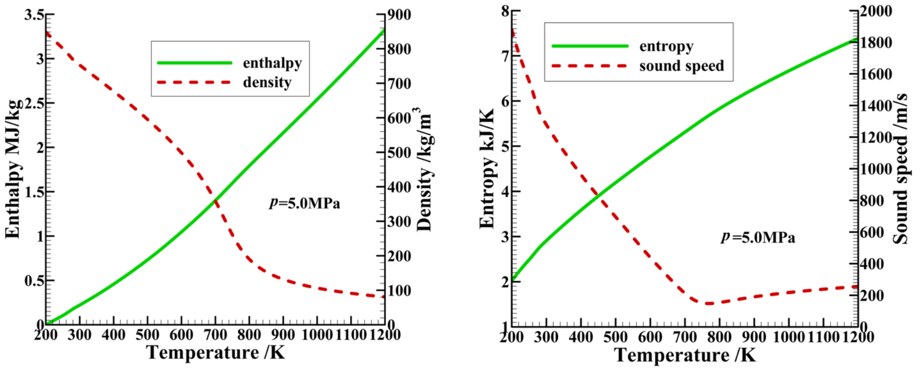

Fig. 3 Thermophysical properties of China RP-3 aviation kerosene estimated using the present surrogate, (a) enthalpy and density; (b) entropy and sound speed

the following studies. It is known that the fuel may crack into smaller hydrocarbons when the temperature is higher than 850 K. Thus it should be noted that the calculation is not accurate enough in the temperature range of 850-1200 K. In the present study, the maximum fuel temperature is less than 900 K, and the calculation of the thermophysical properties is supposed to be acceptable.

3 Temperature measurement for supercritical fluid

For the development of long time working scramjet engines, many tests have been conducted to study the flow and heat transfer of hydrocarbon mixture in small heated tubes since the 1990s, which has greatly contributed to the cooling design and fuel technology [5, 6]. In a ground test, the measurable parameters of the scramjet engine include wall temperature, wall pressure, thrust, fuel temperature, fuel pressure, etc. The measurement of fluid temperature, as well as the measurement of fluid pressure, is necessary for the inspection of the working status of the scramjet engine. Nevertheless, the details for the measurement of fluid temperature at high pressure and high temperature are seldom reported in the present references.

In order to reduce the pressure loss of high temperature fluid, one can let the fluid flow through passages (or holes) with a larger area when its temperature is higher. This indicates that the area of flow passages in the fluid transfer system can be adjusted according to the fluid temperature. From Fig. 2, one can see that the fluid temperature can be used to predict the physicochemical properties of hydrocarbons including density inside the cooling structure of a scramjet under a certain approximately equal pressure, which is useful for the design of the fluid transfer control.

The measurement method of the fluid temperature suitable for small channels is shown in Fig. 4. The size of the cooling channel cross section for the cooled panel is 1.8 mm × 1.8 mm. The probe diameter of the thermal couple is 1.6 mm. To accommodate the probe which is the cephalic cone of the thermal couple (type K with a measurement range of 273 K ~ 1573 K and a relative measurement error 0.75%), a hole of diameter 2 mm is drilled through the outer wall of the cooled panel. The mounting stud used to fix the thermal couple is welded onto the outer wall surface. A specially made cover with a suitable hole is screwed onto the mounting stud, in order to root the cephalic cone of the thermal couple to a proper position. Seals are also very important

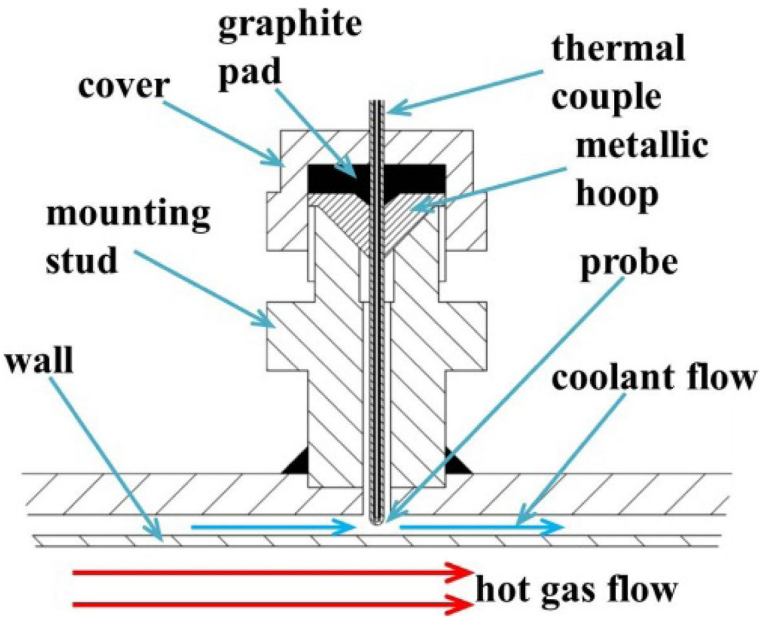

Fig. 4 Measurement method of the fluid temperature suitable for small channel

to a successful temperature measurement. The metallic hoop and the graphite pad given in Fig. 4 insure the seal purpose to avoid the leakage of the high pressure hydrocarbon mixture at both low and high temperatures.

Such a measurement method can reliably sense the fluid temperature. According to Fig. 3, the density and other thermal properties at a pressure of 5 MPa can be predicted using the temperature of the hydrocarbon mixture. So the fluid transfer system is able to adjust the area of flow passages accordingly when the system acquires fluid temperature. The fluid transfer system can adjust the fluid flow in passages (or holes) to a larger area when its temperature is higher. In this way the fluid transfer system can reduce the pressure loss of high temperature fluid.

In a ground test, the pressure of the hydrocarbon mixture just before the injecting holes can be easily measured even at a high temperature. This value can also be used as an indication to adjust the area of flow passages for the fluid transfer system. Nevertheless, fluid temperature measurement should not be ignored. Pressure is a complementary measured value for the fluid transfer system, and the importance of using different types of indication should not be underestimated. The fluid temperature measurement, as well as the fluid pressure measurement, is necessary for both the validation and improvement of the fuel transfer control of a scramjet.

4 Design method of supercritical hydrocarbon transfer with fuel injecting holes

The requirements for the fluid pressure just before the injecting holes, hereafter denoted as $p_{\mathrm{inj},}$ include three aspects. Firstly, the pressure of the hydrocarbon mixture during the circulation should not be significantly less than its critical value, 2.3 MPa [8]. Secondly, steady combustion requires p_{inj} to be higher than 1.5 MPa. Lastly, the driving pressure of the fluid transfer system requires p_{inj} should not be too high. Otherwise, the circulation of the hydrocarbon mixture will be severely affected and the cooling structure will be destroyed. Thus, these requirements must be met by the fluid transfer system.

To design a fluid transfer system that works with acceptable values of p_{inj}, the following two relationships must be considered. One is how the fluid pressure p_{inj} relates to the fluid temperature, and the other one is how p_{inj} reacts to the area of injecting holes [9, 13].

The fuel injecting holes, as shown in Fig. 5, are composed of many small ventages which can restrict the fluid flow mass rate. The supercritical fluid flow through them can be approximated with the fluid flow through a contracting passage and the maximum fluid speed is the local sound speed. Such a process can be treated as a one dimensional isentropic flow passing a different area if the three dimensional and dissipative effects are ignored. So the balance equations of mass, energy, and entropy can be adopted to solve the flow, which are [14–16]

$$\rho u A = \dot{m}_0 \tag{1}$$

$$h(T,p) + a^2(T,p)/2 = h_{\mathrm{f,t}}\left(T_{\mathrm{f,t}}, p_{\mathrm{f,t}}\right) \tag{2}$$

$$s(T,p) = s\left(T_{\mathrm{f,t}}, p_{\mathrm{f,t}}\right) \tag{3}$$

where, h is the enthalpy of the hydrocarbon mixture, ρ the density, u the fluid speed, $\dot{m}_0$ the mass flow rate, a the sound speed, T the temperature, p the pressure, s the entropy, A the total area of the injecting holes, and the subscript f means fluid and subscript t means the value at the stagnation point. The area of the flow before the injecting holes is much bigger than A, so $p_{\mathrm{f,t}}$ and $T_{\mathrm{f,t}}$ can be treated as the values just before the injecting holes (p_{inj} and T_{inj}). Using these balance equations and the relationship between ρ, T and p (Fig. 2), the one dimensional isentropic flow passing a different area can be solved after certain iterations of algebraic calculation and the relationship between the mass flow rate and $p_{\mathrm{f,t}}$ (p_{inj}) can be determined.

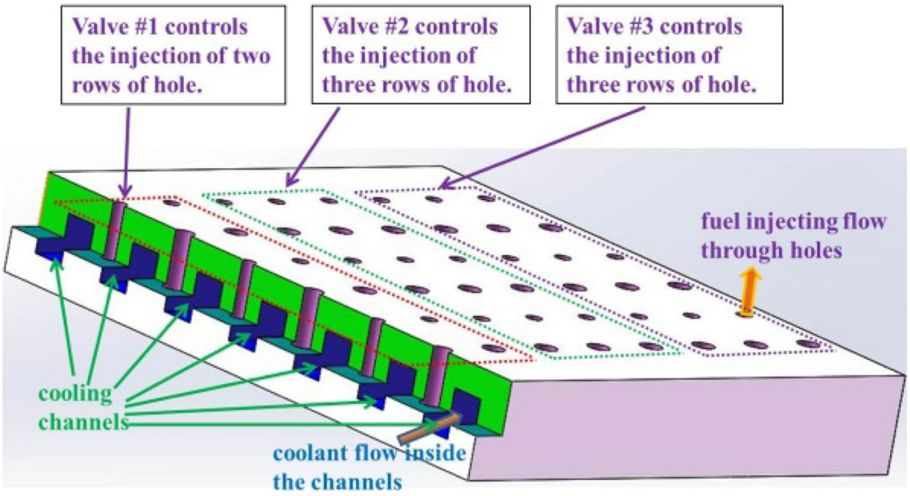

Fig. 5 Fuel injecting holes and cooling channels

According to the three balance equations above, one can increase the total area of the injecting holes (A) to decrease $p_{f,t}$ (p_{inj}). And this is the regulating scheme of the total area of the injecting holes (A) for the fluid transfer system [17, 18]. To consider the operational performance and to limit the number of fuel pipes, three groups of injecting holes are chosen to design the fluid transfer system as shown in Fig. 5. The regulating scheme of the area of fuel injecting holes is shown in Fig. 6. As one can see, the area adjustment of the injecting holes in the system is achieved by opening and shutting three valves, and the p_{inj} in isentropic flow analysis refers to the fluid pressure at the downstream of the valves.

The regulating criterion is the key to the above control scheme. Inappropriate criteria may lead to an underestimated p_{inj} and result in the failure of the scramjet engine. Applying the three balance equations of mass, energy, and entropy, one can construct a modeling tool to obtain the relationships among p_{inj}, A and T_{inj}. For the chosen three groups of injecting holes, the predicted relationships among p_{inj}, A and T_{inj} obtained from three balance equations are shown in Fig. 7.

5 Validation of the temperature measurement method and design of fluid transfer system

To validate the abovementioned measurement method of the fluid temperature suitable for small channels (Fig. 4) and to validate the regulating scheme of the area of fuel injecting holes (Fig. 6), a convective heat transfer test is conducted on a direct-connected combustion test platform. The parameters of the test flow are $M = 2.5$, total temperature $T_t = 1350$ K, total pressure $p_t = 1.9$ MPa, and the air flow mass rate is 2.6 kg/s. The fluid temperature and pressure before the injecting holes are measured during the test.

As shown in Fig. 8, the test procedure is given in the following: (1) The circulation of the hydrocarbon mixture begins before hot air blows (cold air blows at this time); (2) The valve #1 opens and the injection begins as the hot air blows; (3)The valve #2 opens as the fluid temperature rises to 600 K; (4)The valve #3 opens as the fluid temperature reaches

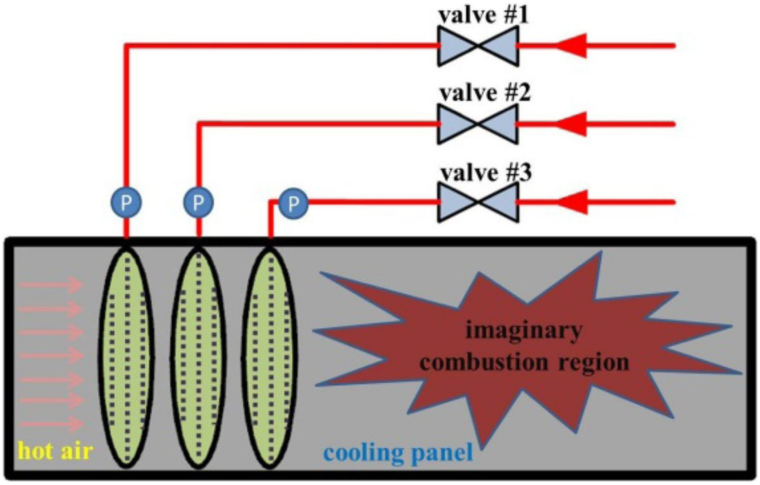

Fig. 6 The regulating scheme of the area of fuel injecting holes

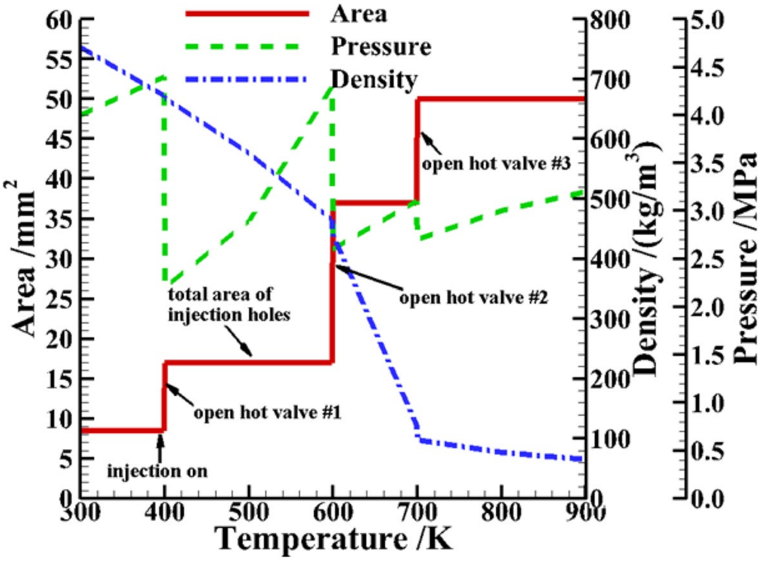

Fig. 7 The fuel injecting area and pressure vs. temperature

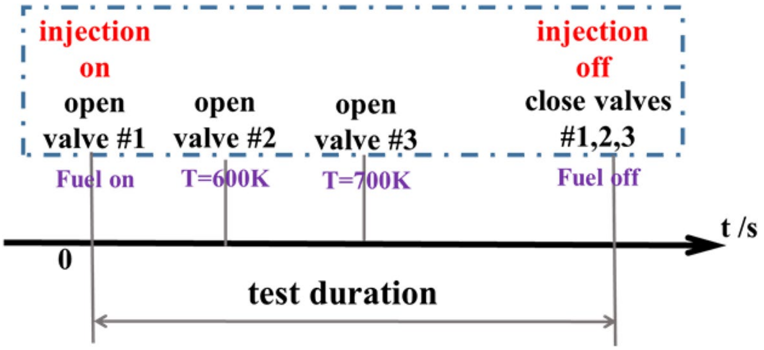

Fig. 8 Procedure of the convective heat transfer test

700 K; (5) At the end of test duration, valves #1, 2 and 3 are closed and the injection stops; (6) cold air blows until the close procedure of the platform finishes.

A typical relationship of the fluid temperature and pressure before the injecting holes with the opening of three valves is shown in Fig. 9. One can see that the injecting pressure p_{inj} reaches 2 MPa in about 1 s after hot air blows, and this value of p_{inj} is suitable for the combustion of a scramjet engine. As the fluid temperature T_{inj} reaches 600 K, p_{inj} rises to over 4.5 MPa. While the valve #2 opens, p_{inj} decreases to 1.8 MPa. As the fluid temperature T_{inj} reaches 700 K, p_{inj} rises to over 3.0 MPa. While the valve #3 opens, p_{inj} decreases to 2.3 MPa. At the end of test duration, p_{inj} is about 4.8 MPa, and this is allowable for the fluid transfer system.

In order to quantitatively evaluate the assumption of one dimensional isentropic flow passing a different area [Eqs. (1-3)] which is used to solve the supercritical fluid passing the injecting holes, one run data shown in Fig. 10 is adopted. One can see that the maximum deviation of pressure p_{inj} between the calculation and measurement is about 7.0%. In the calculation, the pressure p_{inj} is determined using the measured fluid temperature T_{inj}.

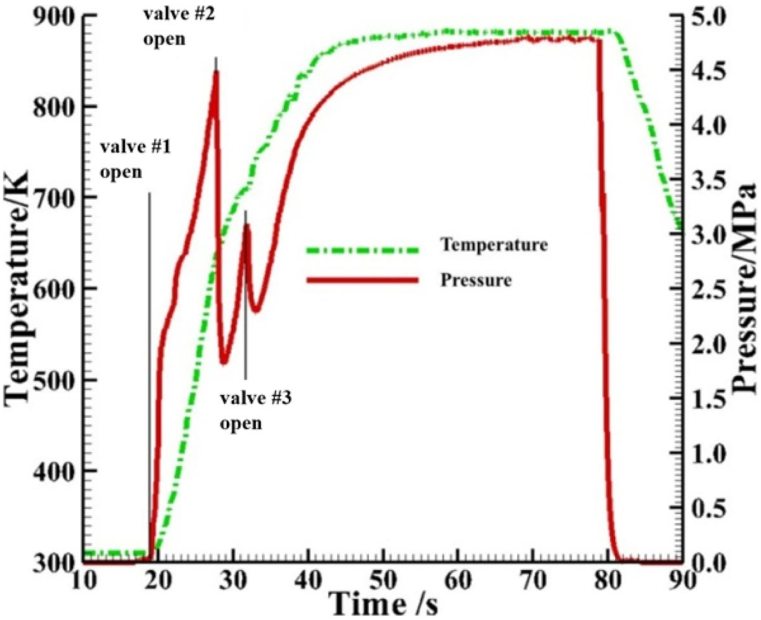

Fig. 9 Fluid temperature and pressure before the injecting holes and the opening of three valves

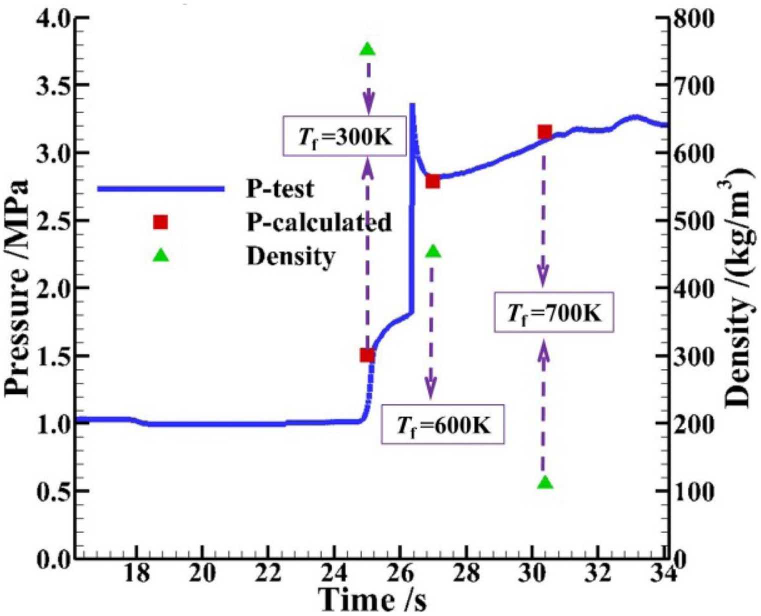

Fig. 10 The comparison of the injecting pressure between test and calculation

6 Conclusions

A measurement method of the fluid temperature, fluid transfer control method of supercritical fluid supply and one predicting method of supercritical flow passing a different area are given and validated with a convective heat transfer test. The following points can be drawn from the results:

(1) The temperature measurement for high pressure supercritical hydrocarbon mixture in small heated tubes is effective.
(2) The design method of supercritical hydrocarbon transfer with fuel injecting holes works well during tests.
(3) The agreement between prediction and measurement indicates that the assumption of the one dimensional isentropic flow used to solve the supercritical flow passing the injecting holes is accurate.

The results would be useful to the design of scramjet engines.

Acknowledgements
The authors would like to thank Zhihui Yan for his contribution in the convective heat transfer test.

Authors' contributions
The research output comes from joint efforts. All authors read and approved the final manuscript.

Funding
This work was supported by the National Natural Science Foundation of China (No. 51976233), and the National Science and Technology Major Project (No. 2017-III-0005-0030).

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 16 April 2022 Accepted: 17 August 2022

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