Temperature measurement and transfer control of a supercritical hydrocarbon fluid

Lei Zhang (zl20051038@163.com)
CARDC: China Aerodynamics Research and Development Center https://orcid.org/0000-0002-8877-6692
Ruoling Zhang
CARDC: China Aerodynamics Research and Development Center https://orcid.org/0000-0003-2056-2919
Xiangyi Wang
CARDC: China Aerodynamics Research and Development Center
Jin Jiang
CARDC: China Aerodynamics Research and Development Center

Research Article

Keywords: Supercritical hydrocarbon fluid, temperature measurement, transfer control, propulsion system

Posted Date: April 25th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1539154/v1

Abstract

The 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 result shows during the heating process the injecting pressure meets the requirement, and the fluid transfer control system works well. The result can be useful for the design of regenerative cooling for hypersonic propulsion system.

Introduction

Hypersonic propulsion system can achieve high specific impulse over a wide range of flight Mach numbers and altitudes. The liquid hydrocarbon fuels are designed to be used as coolant to cool the propulsion system structure before injected into combustor as fuel, due to the limitations of material. Known as endothermic fuels, they can decompose and also absorb extra amount of heat within the fuel system under extreme heating. This is viewed as an advanced heat sink approach [1–4].

For the development of hypersonic propulsion system, the flow and heat transfer of hydrocarbons in small heated tubes have attracted interests for the cooling designs of scramjets over years [5,6]. For a hydrocarbon fueled propulsion system, liquid hydrocarbon mixture cools the metallic structure as it passes through very small longitudinal cooling channels as shown in Fig. 1. The typical size of a cooling channel cross section for a propulsion system panel is about 2mm×2mm. The fuel pressure is usually supercritical inside the cooling channels. While absorbing heat from the structure, the fuel temperature rises and the density decreases to one tenth of its original value. The fluid speed increase to ten times of its original value, and the pressure loss accompanied by the flow inside the small channel can increase to a very high level if the total area of the passages is equal. This brings difficulties to the fluid transfer control because a too high level of pressure loss will be unacceptable to the fluid transfer system.

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

In this paper, one 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 result can be useful for the design of regenerative cooling for hypersonic propulsion system.

Thermophysical Properties Of The Hydrocarbon Mixture

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

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 kerosenen can be found in Refs. 8 and 9. To reduce the computation 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 density, heat capacity, thermal conductivity and viscosity of China RP-3 aviation kerosene at the pressure of 5MPa. The thermophysical properties are predicted with present surrogate and a ten-species surrogate once applied for China RP-3 aviation kerosene [10]. The maximum relative errors of density, heat capacity, viscosity and thermal conductivity are 3.03%, 3.64%, 3.91% and 3.15% within the temperature range of 300–1200 K, 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, while the measured data are 645.5 K and 2.39 MPa [8]. Thus, the four-species surrogate is thought to be reliable for the investigation.

Since the thermophysical properties of the hydrocarbon mixture China aviation kerosene RP-3 can be simulated using the present four-species surrogate, and it is more time efficient than the ten-species surrogate, the present four-species surrogate is used in the following studies. 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 following studies.

Temperature Measurement For Supercritical Fluid

For the development of long time working propulsion system, the flow and heat transfer of hydrocarbon mixture in small heated tubes have attracted interests for the cooling designs since 1990s [5,6]. Before it is injected into the propulsion system through the fuel injecting holes, liquid hydrocarbon mixture cools the metallic structure as it passes through very small longitudinal cooling channels. The typical size of a cooling channel cross section for a scramjet is about 2mm×2mm. To meet the requirement of fuel injecting pressure at the propulsion system fuel injecting holes and the fluid transfer for its circulation, the fuel pressure is usually supercritical inside the cooling channels.

While absorbing the heat from the structure, the fuel temperature may rise to over 800K and the density may decrease to one tenth of its original value. As the density decreases to one tenth of its original value, the fluid speed increases to ten times of its original value, and the pressure loss accompanied by the flow inside the small channel can increase to a very high level if the total area of the passages is equal. The fuel may crack into smaller hydrocarbons when its temperature is higher than 850K, so the physical and chemical properties change dramatically in the cooling channel [11–15]. A too high level of pressure loss is unacceptable to the fluid transfer system. These bring great difficulties to the fluid transfer control.

To inject the hydrocarbon mixture into the combustor at both low and high temperature, the fluid transfer system must meet the transfer requirement over very different fluid densities. The fluid transfer system must reduce the pressure loss if the fluid temperature is high. To reduce the pressure loss of high temperature fluid, one can let the fluid flows in passages (or holes) with larger area when its temperature is higher. This means the fluid transfer system can adjust the area of flow passages 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 at a certain approximately equal pressure inside the cooling structure of a scramjet, and this should be useful for the design of the fluid transfer control.

The measurement method of the fluid temperature suitable for small channel is shown in Fig. 4. The size of the cooling channel cross section for the cooled panel is 1.8mm×1.8mm. The probe diameter of the thermal couple is 1.6mm. To accomodate the probe which is the cephalic cone of the thermal couple, a hole of suitable diameter 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, so that the cephalic cone of the thermal couple is rooted to the proper postion and the leakage of the high pressure hydrocarbon mixture is avoided at both low and high temperatures.

This measurement method can reliably sense the fluid temperature. According to Fig. 1, the density and other thermal properties at a pressure of 5MPa can be predicted using the temperature of the hydrocarbon mixture. So the fluid transfer system can adjust the area of flow passages accordingly after the fluid temperature value is transfered to the system. The fluid transfer system can let the fluid flows in passages (or holes) with larger area when its temperature is higher. In this way the fluid transfer system can reduce the pressure loss of high temperature fluid.

In ground test, the pressure of the hydrocarbon mixture just before the injecting holes can be easily measured even at high temperature. This value can also be used as the indication to adjust the area of flow passages for the fluid transfer system. Nevertheless, the fluid temperature measurement should not be ignored. It is a complementary measured value for the fluid transfer system, and the importance of having values of different type should not be underestimated. The fluid temperature measurement, as well as the fluid pressure measurement, is necessary for the inspection of the working status of the propulsion system. Sufficient parameter collection is very meaningful for both the validation and improvement of the propulsion system design.

Design Of Transfer System With Fuel Injecting Holes

In ground test, the measured values include propulsion system wall temperature, wall pressure, thrust, fuel temperature, fuel pressure, etc. During a test, these can be used to inspect the working status of the propulsion system and to control fluid transfer system. Concretely, the measured values of fuel temperature and fuel pressure can be used to control fluid transfer system.

The fluid transfer system, such as one of injecting the hydrocarbon mixture into the propulsion system at both low and high temperature, must meet the transfer requirement over very different fluid densities. To reduce the pressure loss of high temperature fluid, one can let the fluid flows in passages (or holes) with larger area when its temperature is higher. This means the fluid transfer system can adjust the area of flow passages according to the fluid temperature.

The requirements for the fluid pressure just before the injecting holes, hereafter denoted as $p_{\text{inj},}$ include three aspects. Firstly, the pressure of the hydrocarbon mixture during the circulation should not be markedly less than its critical value which is about 2.3MPa[11]. Secondly, steady combustion requires p_{inj} should be higher than 1.5MPa. 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. These requirements must be met by the fluid transfer system.

To meet the requirements for p_{inj} and design the fluid transfer system, one should understand the following two things first. One is the relationship between the fluid pressure p_{inj} and its temperature. The other is the matching between p_{inj} and the area of injecting holes.

The fuel injecting holes, as shown in Fig. 5, are composed by many small holes which can restrict the fluid flow mass rate. The supercritical fluid flow across them can be approximated by the flow past a contracting passage and the maximum fluid speed is the local sound speed. The fluid flow before the injecting holes and passing them can be treated as a one dimensional isentropic flow passing 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

$$puA = \dot{m}_0 \quad (1)$$

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

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

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 stagnation point. The area of the flow before the injecting holes is much bigger than A, so $p_{f,t}$ and $T_{f,t}$ 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 relationship between the mass flow rate and $p_{f,t}$ (p_{inj}) can be determined after some iterations of algebraic calculation.

According to the above three balance equations, one can also 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. To consider the operational performance and to limit the number of the fuel pipes, three groups of injecting holes are chosen to design the fluid transfer system, the regulating scheme of the area of fuel injecting holes is shown in Fig. 6.

The regulating criterion is the key to the regulating scheme. Inappropriate criterion may lead to a too low p_{inj} and the extinction of propulsion system. Applying the three balance equations of mass, energy, and entropy, one can construct a modeling tool to calculate the relationships among p_{inj}, A and T_{inj}. For the chosen three groups of injecting holes, the relationships among p_{inj}, A and T_{inj} are shown in Fig. 7.

Validation Of The Temperature Measurement Method And Design Of Fluid Transfer System

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

As shown in Fig. 8, the test procedure is: (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 reaches 600K; (4)The valve #3 opens as the fluid temperature reaches 700K; (5) At the end of test duration, valves #1, 2 and 3 are closed and the injection stops; (6) cold air blows untill the close procedure of the platform finishes.

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

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

Conclusions

The measurement method of the fluid temperature and fluid transfer control method of supercritical fluid supply are given and validated through a convective heat transfer test. The agreement between calculation and measurement indicates the assumption of one dimensional isentropic flow which are used to solve the supercritical flow passing the injecting holes is accurate. The result can be useful for the design of regenerative cooling for an airbreathing propulsion system.

Declarations

Acknowledgements

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

Authors’ contributions

The research output comes from joint efort. All authors read and approved the fnal manuscript.

Funding

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

Competing interests

The authors declare that they have no competing interests.

References

1. Heiser WH, Pratt DT (1994) Hypersonic Airbreathing Propulsion[M]. American Institute of Aeronautics and Astronautics, Inc., pp 479–553
2. DRUMMOND JP, COCKRELL C E Jr et al Hypersonic airbreathing propulsion – an aerodynamics, aerothermodynamics, and acoustics competency white paper[R]. NASA/TM-2002-211951.
3. JACKSON T. A., EKLUND D. R., FINK A. J. High speed propulsion: Performance advantage of advanced materials [J]. JOURNAL OF MATERIALS SCIENCE, 39 5905–5913, 2004
4. Boudreau AH Hypersonic Air-Breathing Propulsion Efforts in the Air Force Research Laboratory[R]. AIAA 2005–3255.
5. Linne DL, Meyer ML, Edwards T, Eitman DA (1997) Evaluation of Heat Transfer and Thermal Stability of Supercritical JP–7 fuel, AIAA Paper 1997–3041,
6. Huang H, Sobel DR, L.Spadaccini J (2002) Endothermic Heat-sink of Hydrocarbon Fuels for Scramjet Cooling, AIAA Paper 2002–3871,
7. Zhao GZ, Song WY, Zhang RL (2015) Effect of pressure on thermal cracking of china RP-3 aviation kerosene under supercritical conditions. Int J Heat Mass Transf 84:625–
8. Sun QM, Mi ZT, Zhang XW (2006) Determination of Critical Properties (tc, pc) of Endothermic Hydrocarbon Fuels: RP-3 and Simulated JP-7. J Fuel Chem Technol 34:466–470
9. Deng HW, Zhang CB, Xu GQ, Tao Z, Zhang B, Liu GZ (2011) Density Measurements of Endothermic Hydrocarbon Fuel at Sub- and Supercritical Conditions. J Chem Eng Data 56:2980–2986
10. Zhong FQ, Fan XJ, Yu G, Li JG, Lu XN, Sung CJ “Heat Transfer of Aviation Kerosene at Supercritical Conditions,” AIAA 2008–4615, 2008.
11. Zhang L, Zhang RL, Xiao SD, Jiang J, Le JL (2013) Experimental investigation on heat transfer correlations of n-decane under supercritical pressure. Int J Heat Mass Transf 64:393–400
12. JIANG J, Zhang RL, Le JL et al (2014) Regeneratively cooled scramjet heat transfer calculation and comparison with experimental data[J]. J Aerospace Eng 228:1227–1234
13. ZHANG H (2011) Investigation of hydrocarbon-fueled scramjet feed system scheme[D]. National University of Defense Technology. (in Chinese)
14. Kays W, Crawford M, Weigand B (2005) Convective Heat and Mass Transfer [M]. 4th edition. New York: McGraw – Hill Book Company, Inc.,
15. Wennerberg JC, Anderson WE, Haberlen PA et al Supercritical Flows in High Aspect Ratio Cooling Channels[R]. AIAA 2005–4302.

Figures

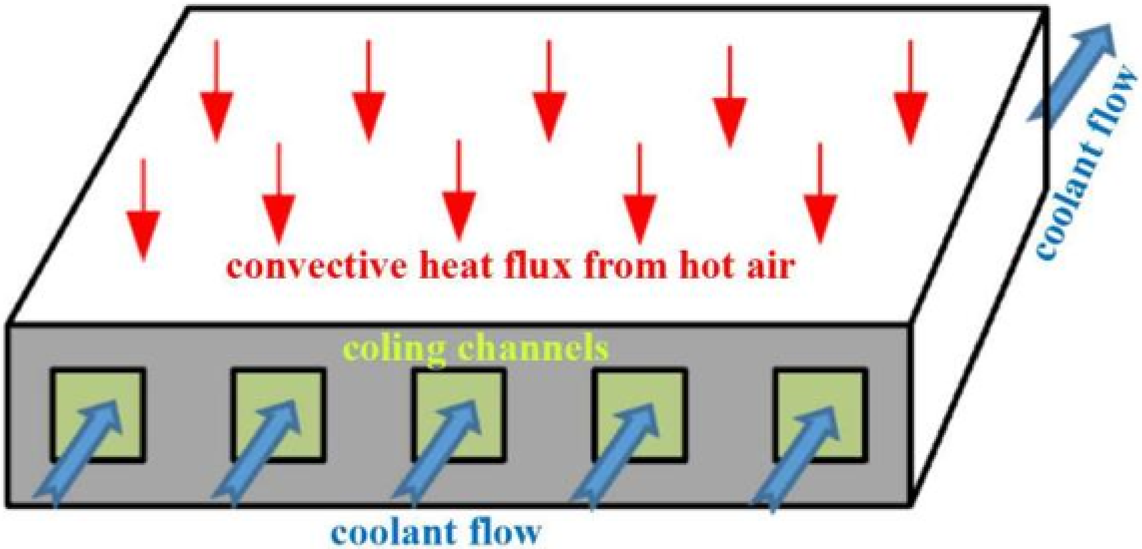

Figure 1

The small longitudinal cooling channels inside a panel

Figure 2

Thermophysical properties of China RP-3 aviation kerosene estimated using present surrogate and a ten-species surrogate in Ref. 8, (a) density and heat capacity; (b) viscosity and thermal conductivity

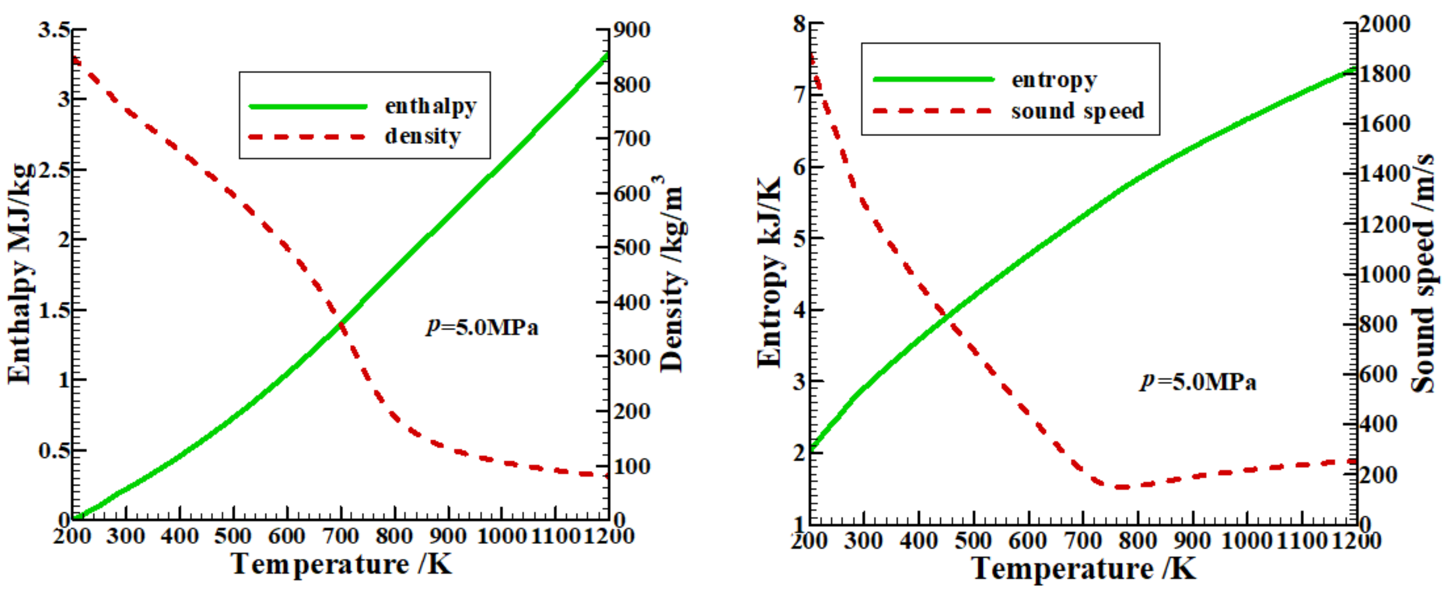

Figure 3

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

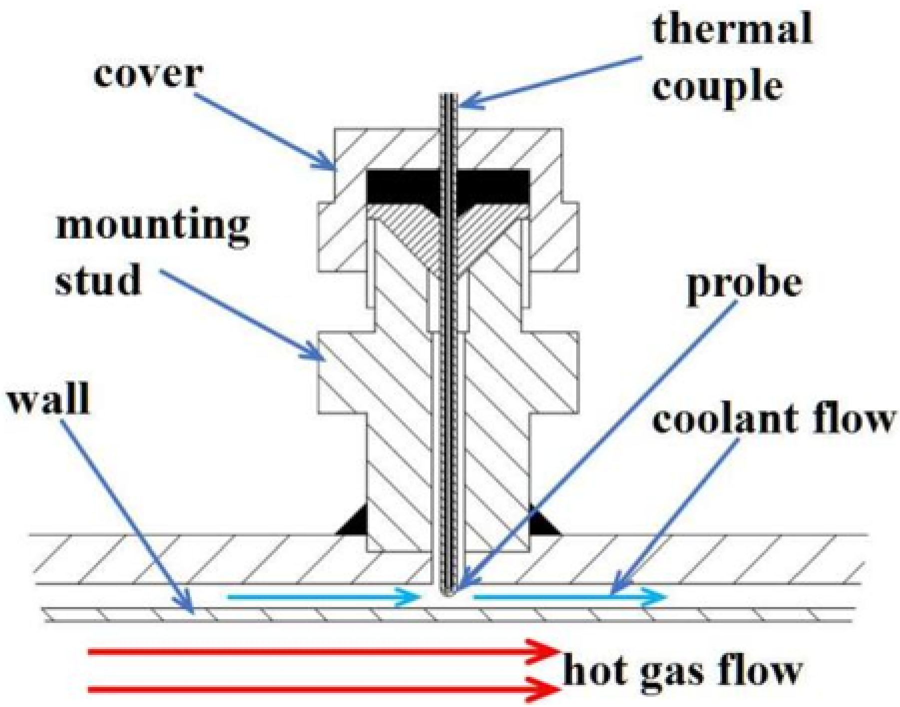

Figure 4

Measurement method of the fluid temperature suitable for small channel

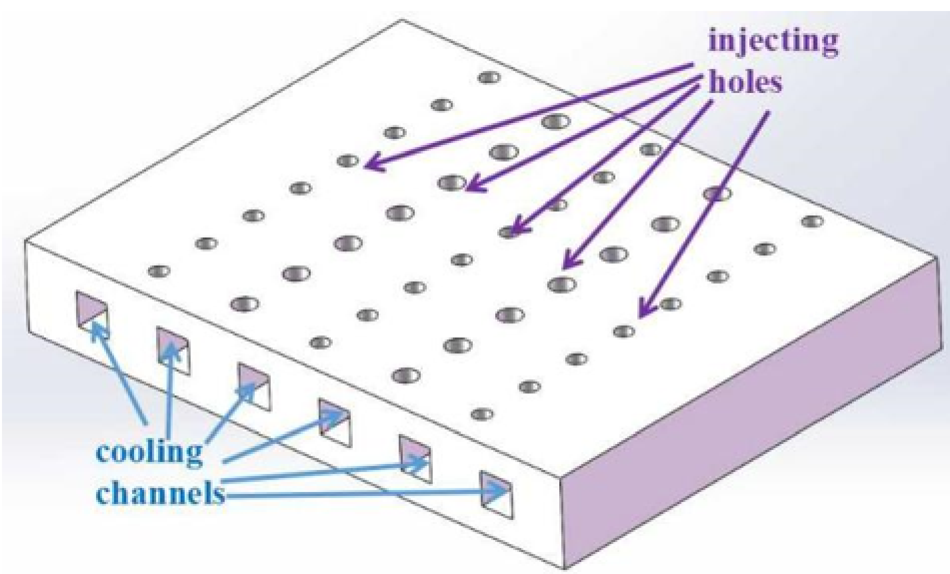

Figure 5

Fuel injecting holes and cooling channels

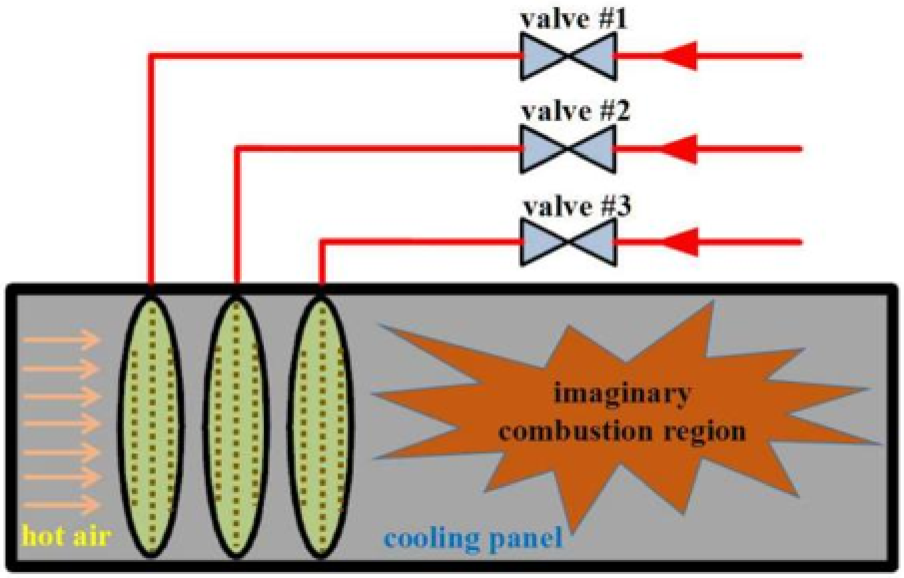

Figure 6

The regulating scheme of the area of fuel injecting holes

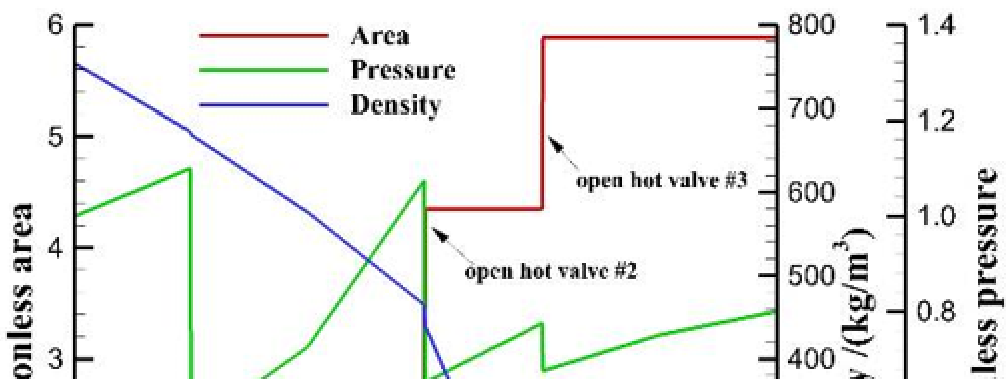

Figure 7

The fuel injecting area and pressure vs. temperature

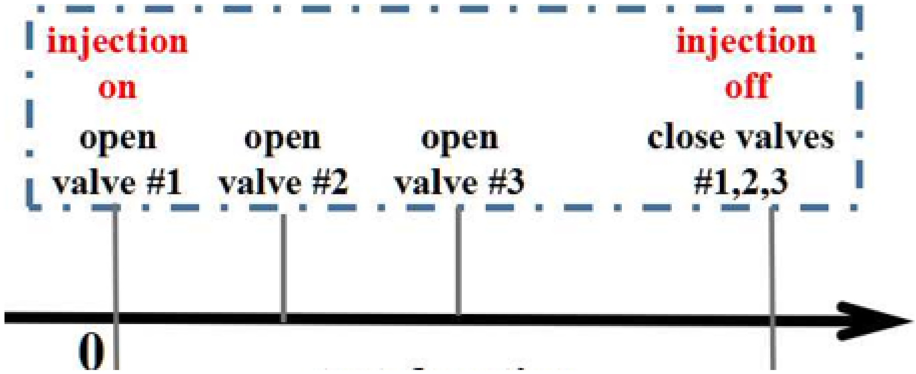

Figure 8

Fluid temperature and pressure before the injecting holes and the opening of three vavles

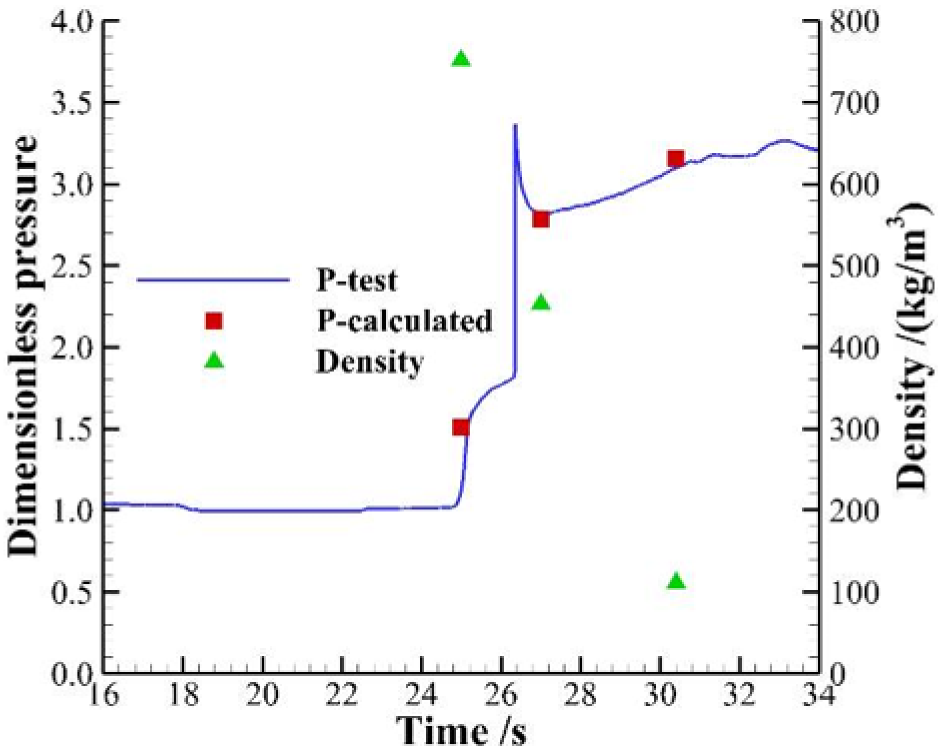

Figure 9

The comparison of the injecting pressure between test and calculation