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Research Paper

A control method for flow rate distribution of cracked hydrocarbon fuel in parallel channels

Yuguang Jiang, Silong Zhang, Yu Feng, Jie Cao, Jiang Qin *, Wen Bao *

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

HIGHLIGHTS

- Mal-distribution of coolant causes a waste of heat sink and even over-temperature.
- A flow control method based on tandem flow restriction was brought up and validated.
- The connect between fluid property and the control effect was studied.
- The pressure drop of the method was presented and analyzed.

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ABSTRACT

With the development of hypersonic vehicles, regenerative cooling becomes an effective method of thermal protection, in which fuel is thus used as coolant. However, it presents the problem of fuel mal-distribution and the waste of heat absorption capacity. In this work, a flow control method based on tandem flow restriction is brought up and experimentally studied with a two-parallel-pipe system. The variation of control effect with different position and corresponding fuel temperature of the restrictors is analyzed. Compared with the single flow restriction, tandem flow restriction method achieves better control effect and allows larger flow restrictors with lower and self-adaptive pressure drop. The fuel heat sink utilization will be improved by proposed effective method for flow rate distribution and corresponding recuperation effectiveness of the engine cycle is improved.

1. Introduction

Scramjet is a promising propulsion system for hypersonic missile and reusable air-space integrated flight vehicle because of its good performance at hypersonic region [1,2]. However, the high combustion temperature and heat transfer rate that come along with the hypersonic flight make cooling a major concern. And regenerative cooling has become an efficient cooling method. Fuel flows through the parallel cooling channels inside the wall as coolant [3]. The dissipated heat of the engine is recovered and brought back to the combustor by fuel, which forms a chemically recuperated cycle. However, with a rectangular main flow passage, the heat flux is usually not uniform or constant across the wall of a scramjet, which leads to a mal-distribution of coolant and a waste of heat sink. The chemical recuperation effectiveness falls and the performance of the engine is affected [4]. Further, considering strictly limited fuel onboard, the risk of local overheat along with the coolant mal-distribution and waste of heat sink is definitely unacceptable.

Mal-distribution of mass flow rate has also been a common cause of performance loss and even failure in boilers, heat exchangers and fuel cells [5–7]. The two-phase flow makes it more complicated to control the mass flow rate distribution [8,9] and researchers showed a continuous interest in studying the thermal and fluid-dynamic behavior of the two-phase flow distribution in systems with parallel channels [10–12]. The orientation of header and channels have been found to be a main factor as well as the inlet and outlet location influencing the flow distribution [13–16]. Flow inside the header also has a pronounced effect on the flow distribution in parallel channels [17]. Various kinds of perforated grids and headers of with a special structure were designed to homogenize the flow distribution [18–20]. Besides, physical properties of the fluid also affect its distribution in parallel channels [21].

However, there're few researches about the mass flow rate distribution of cracked hydrocarbon fuel in parallel channels. Qin

* Corresponding authors at: No. 92, West Da-Zhi Street, Harbin, Heilongjiang 150001, PR China (W. Bao).
E-mail addresses: qinjiang@hit.edu.cn (J. Qin), baowen@hit.edu.cn (W. Bao).

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found two deviation amplification zones in the hydrocarbon fuel instead of a single one in the common fluid like two-phase water [22]. Limited by the compact structure and severe environment, many existing control methods don't apply to the applications like scramjet and fuel cell.

In this work, a new flow control method based on tandem flow restriction was brought up and a two-parallel-pipe test bench was established. The variation of control effect with different position and corresponding fuel temperature of the restrictors is analyzed followed by the comparison of tandem flow restriction with single restriction. The effect of this new flow control method on homogenizing the flow rate distribution of cracked hydrocarbon fuel was validated on this dedicated test bench.

2. Fuel mal-distribution in parallel channels and the corresponding control methods

2.1. Fuel mal-distribution in parallel cooling channels

In a regenerative cooling scramjet, fuel flows through the cooling channels to cool the wall. While the thermal load is usually time variant and non-uniform making it difficult to obtain a matched fuel distribution. As a result, unreasonable fuel distribution tends to occur. Part of the fuel heat sink is wasted and the local overheat may even happen. Thus, the mal-distribution needs to be analyzed in detail.

When encountered with an uneven thermal load across the width of the cooling channels, some channels experience higher temperature than others. The deviation in fuel temperature occurs and leads to the difference in fuel density in different channels. As shown in Fig. 1 (N-decane is taken as an example and its density is calculated by SRK equation and using a PPD pyrolysis mechanism), the fuel density decreases with the temperature. Consequently, the fuel density in channels with higher temperature becomes smaller. The velocity increases accordingly making the flow resistance increase and larger pressure drop tends to occur. However, limited by the parallel geometry, the pressure drop of all channels in a parallel system is the same (the influence of headers is ignored for now since it's not the focus of this work). The mass flow rate in channels with higher temperature thus decreases to balance the pressure drop while in other channels things go toward an opposite direction. Thus far, the mal-distribution occurs, which further widens the deviation in fuel temperature unfortunately. In turn, the mass flow rate deviation broadens again. A positive feedback emerges and makes the deviations in mass flow rate and fuel temperature wider. In addition, the viscosity of hydrocarbon fuel decreases with the temperature, which reduces the flow resistance in channels with higher temperature. This means there will be more fuel coming in if it gets hotter in this channel and maldistribution won't happen. Then the viscosity leads to an opposite effect with density variation. However, according to the momentum equation and results in [22], the influence of viscosity is much smaller than density and the maldistribution may occur severely. So the following discussion will be focused on density variation.

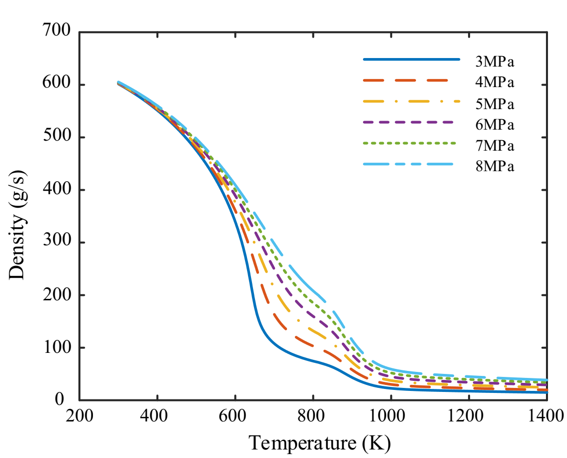

Fig. 1. The density of N-decane versus temperature.

More importantly, it can be seen in Fig. 1 that density of hydrocarbon fuel falls sharply with temperature around the pseudo-critical point and pyrolysis area, which means the same deviation in temperature will cause much larger density deviation and the positive feedback of mass flow rate mal-distribution will be enhanced greatly in these two nonlinear zones. Much more fuel is distributed into channels with lower thermal load. Deviations in fuel temperature will thus be much larger too. Especially when pyrolysis begins in some of the channels, they may experience temperature which is close to the limit of the structure and the fuel heat sink is well utilized. While the fuel temperature of others is several hundred degrees lower and severe waste of heat sink happens. What's worse, with the ongoing positive feedback in fuel mal-distribution, local overheat may occur and cause a structure failure. As a result, corresponding flow control methods have to be adopted to adjust the flow distribution.

2.2. The flow distribution control scheme

As analyzed above the flow mal-distribution in parallel channels is closely linked up with the uneven thermal load by the nonlinear varying pattern of the hydrocarbon fuel density. So the mal-distribution can be controlled by weakening this coupling.

For convenience, the pressure drop that independent of heat flux is defined as ΔP_c and the pressure drop closely related to the thermal load is called ΔP_h. When encountered with an uneven thermal load, if ΔP_c is large enough to weaken the coupling between thermal distribution and pressure drop variation, the influence of ΔP_h will be much smaller and violent flow redistribution will not occur. In fact, flow restriction in cold section is an easy way to provide ΔP_c and it's considered as a feasible flow distribution control method. However, for the hydrocarbon fuel, there are two deviation amplification areas and the flow control method is requested be effective in the whole common used temperature zone (up to about 1000 K). As a result, the problem is much more challenging compared with other fluid, like water. Actually, single flow restriction may not be capable to control the mal-distribution and the flow area of restriction tends be undersized which increases the risk of jam. Fortunately, tandem flow restriction may solve these problems better. Enough ΔP_c can be obtained through different stages of flow restrictions and the flow area of each restrictor is thus allowed to be larger. Further, more degrees of freedom are brought into enhance the flow control effect. Compared with the flow control methods focused on headers, tandem flow restriction targets closely to the physical/chemical property of hydrocarbon fuel to solve the mal-distribution caused by uneven thermal load and avoid the waste of fuel heat sink.

3. Experimental set-up

A two-parallel-pipe test bench was established to study the control method of flow mal-distribution. As shown in Fig. 2, two high temperature alloy pipes with an inner diameter of 2 mm were used to simulate the parallel cooling channels. The length of heating zone is 1.1 m. China No. 3 kerosene (RP-3) was used as the target hydrocarbon fuel, which was supplied through a constant flow pump. The heating power was regulated through a zigzag form