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Full Length Article

The influences of variable sectional area design on improving the hydrocarbon fuel flow distribution in parallel channels under supercritical pressure

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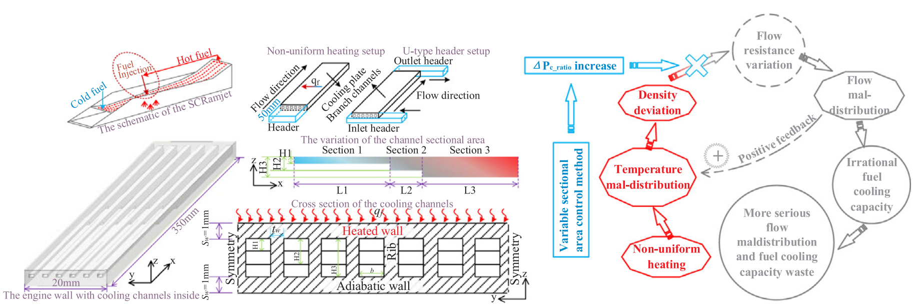
GRAPHICAL ABSTRACT

The SCRamjet is one of the most promising hypersonic flight vehicles. But the high flight Mach number also causes trouble to the engine cooling. In the cooling channels of SCRamjet, the pressure is normally supercritical to avoid the heat transfer deterioration. The fuel turns into supercritical state quickly because of the large engine thermal load. However, mal-distribution of coolant in regenerative cooling channels may happen. Over-temperature and fatal structure failure are likely to occur. This work focuses on this problem. An applicable control design is put forward and validated, in which the channel sectional area is decreased in the low temperature zone and enlarged in high temperature zone. It weakens the link between fuel density deviation in parallel channels and the flow resistance variation. The flow distribution and cooling effect are obviously improved. This design is very applicable and reliable since it is realized through channel geometry design. Besides, the design adapts to different heat flux distributions, which proves its applicability in varying duty cases. The design also presents good effect to the flow mal-distribution problem caused by geometry non-uniformity (U-type setup for example). It provides possible solution to the flow mal-distribution problem in cooling channels of scramjet.



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ABSTRACT

To help solve flow mal-distribution and cooling capacity utilization problems in parallel cooling channels of SCRamjet, the variable channel sectional area design is put forward. 3D modelling of the flow and heat transfer in multiple parallel channels is carried out under supercritical pressure. The flow distribution reasonability and cooling effect under different channel sectional area designs are numerically compared and analyzed. The analysis indicates the variable channel sectional area design improves the flow distribution reasonability obviously and lowers the wall temperature. Furthermore, the variable channel sectional area design adapts to different heat flux boundary conditions. Even in the flow mal-distribution problems caused by both inlet/outlet headers and non-uniform thermal boundary, the variable cross section area design works well because the ratio of channel pressure drop which is insensitive to the heating is increased. The fuel cooling capacity utilization is also refined.

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Nomenclature

b	channel width, m
e_t	total internal energy, J/kg
H	channel height, m
m	mass flow rate, kg/s
n_c	channel number
P, p	pressure, Pa
q_f	heat flux, W/m^2
q_r	expected cooling capacity, W
s_w	heated wall thickness, m
T	temperature, K
t_w	rib thickness, m
u	velocity of fuel, m/s
ε	porosity
λ	thermal conductivity,W/($m\cdot K$)
ρ	density, kg/m^3
τ	viscous stress
$\varnothing_{m_f}$	mass flow rate deviation
$\varnothing_{T_f}$	fuel temperature deviation
μ	dynamic viscosity,$Pa\cdot s$
ΔP	pressure drop, Pa
Δq_f	Heat flux deviation

Subscripts

branch	*branch channels*
c	*low temperature zone*
eff	*effective*
f	*fluid*
h	*high temperature zone*
header	*header*
w	*wall*

1. Introduction

The flow mal-distribution problem exists in various applications with parallel channels [1–4]. There are two main causes of the flow mal-distribution: the non-uniformity of geometry and the non-uniformity of thermal boundary [5]. Taking the regenerative cooling channels of SCRamjet for example, both causes exist [6,7]. As a result, serious mal-distribution of the coolant (for example, hydrocarbon fuel) may occur. The fuel cooling capacity is thus wasted, which is unacceptable especially when the fuel available is quite limited. Possibly it may also lead to over-temperature. To ensure the structure safety, the flow distribution should be improved carefully. However, the thermal boundaries of the cooling channels vary with the engine operation conditions [8]. It means the control of the flow mal-distribution should function well under different heat flux distributions. The method or design valid only for one certain heat flux distribution is not applicable in the SCRamjet. Therefore, an effective method of improving the hydrocarbon fuel flow distribution is in urgent need.

Many researches have been conducted regarding the control of flow mal-distribution problem. The manifold structure (header) is one of the key structures for this problem, the schematic of which is presented in Fig. 1. It is the junction between different parallel-channel-sections, which offers the design freedom to vary the channel quantity and dimensions. Ref [9] and [10] present the influences of the header layout on flow distribution. At the same time, the flow pattern in the header is also one of the research focuses, especially in some multi-phase cases [11,12] and the variation of the header flow area also receives much attention [13,14]. The design of flow path in the headers, for example tree structure, improves the flow distribution, too [15]. Besides the header structure, insertions are popular in improving the flow distribution, for example, the baffles [16,17]. Certain combination of baffles at the inlet of each branch channel makes it able to achieve expected flow distribution [18,19]. Moreover, flow passage configuration design is another common method to improve the flow distribution, especially in applications like fuel cells [20,21].

However, as shown in Table 1, most of the above mentioned studies are undertaken under or near the ambient temperature and pressure. Only Ref [16] carries out a high temperature study. But the pressure condition is ambient and the thermal properties are assumed to be linear temperature dependent in the simulation, which are both quite different with the situations in SCRamjet. Considering the high temperature, high pressure, complex fuel thermal property variation, non-uniform thermal boundary and compactness of space in SCRamjet, many above mentioned flow mal-distribution control methods are not applicable. In the previous work [22], a control method for high temperature hydrocarbon fuel flow mal-distribution in non-uniformly heated parallel pipes based on the tandem flow restrictions was put forward and validated. But to some extent, the local flow restriction may increase the risk of jam. To better solve the flow distribution problem, the study regarding improving flow distribution should be continued.

In this work, a variable channel sectional area design for improving the flow distribution is brought up. To the authors' knowledge, by far there are hardly no published studies regarding dedicated channel design for improving the flow distribution in cooling channels of SCRamjet or other similar applications using high-temperature hydrocarbon fuel under supercritical pressure. Considering it is risky to apply control methods like insertions in the compacted-high temperature channels. It will be much safer and more efficient if the flow distribution can be improved just through channel design. To study the effect of this design, 3D numerical modeling of the flow and heat transfer of n-Decane in multiple parallel channels is carried out. The pressure is set to be supercritical. The performance of this design is studied by comparing different cases. The design is also studied under different heat flux distributions and in flow mal-distribution problem induced by the geometry non-uniformity (U-type parallel configuration is used as an example). The wall temperature of the heated surface is selected as the

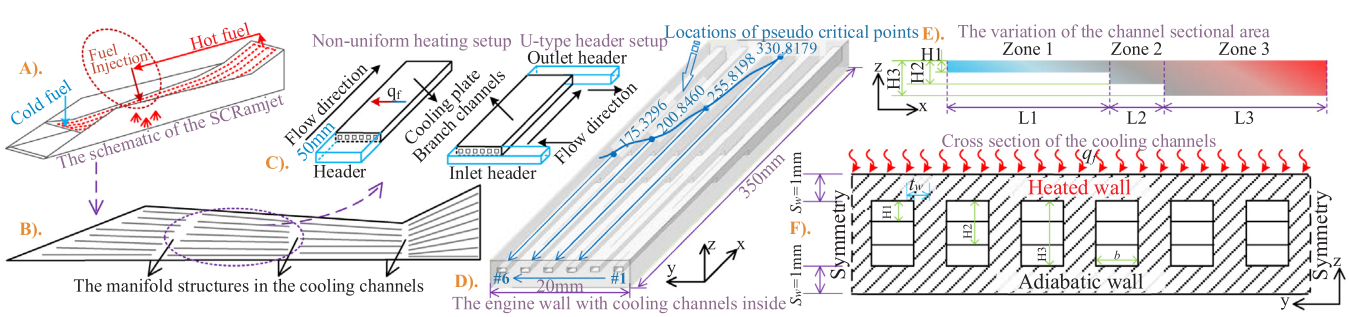

Fig. 1. The schematic of cooling channels.