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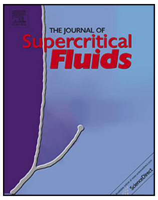

Numerical analysis of convective heat transfer characteristics of supercritical hydrocarbon fuel in cooling panel with local flow blockage structure

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ABSTRACT

The convection heat transfer of hydrocarbon fuel at supercritical pressure has a great influence on the regenerative cooling technology of a scramjet engine. A three-dimensional numerical simulation was conducted for the convection transfer of hydrocarbon fuel in the cooling panel of a combustion chamber wall. And the flow field around the local flow blockage structure and the outlet flow rate distribution characteristics of fuel in the cooling channels were analyzed in detail. The results of analyses indicate that with the optimized local flow blockage structure, the outlet flow rate distribution of fuel among the cooling channels become more uniform, as the area of local flow dead zone decreases. However, as the fuel temperature increases, the dramatic variation of thermodynamic physical properties of fuel has a strong influence on the flow field around the local flow blockage structure. Especially, a local flow dead zone can be easily formed in the supercritical temperature region. Meanwhile, transverse pressure gradient around the throat region of blockage structure and additional loss, which is caused by turbulence fluctuation and energy exchange of fluid in the downstream area, affect the outlet flow rate distribution of fuel among the coolant passages seriously. It can therefore be concluded that the local flow blockage structure is more suitably designed in the subcritical temperature region by taking above-mentioned factors into consideration.

1. Introduction

Regenerative cooling technology with hydrocarbon fuel used as the coolant is an effective method of thermal protection. Before entering the combustor, the fuel cools the combustor wall using the heat sink of itself [1,2]. In order to avoid phase change and to improve heat transfer in the cooling process, the operational pressure of the hydrocarbon fuel in the cooling panel is maintained under the supercritical condition [3,4]. Because of the high thermal load, it is very important to optimize the cooling structure during engine design to provide sufficient cooling effect and to avoid local overheat. Experimental and numerical studies have therefore been conducted by many researchers [3–8]. However, these studies are mainly related to the optimization of cooling channels with respect to the cooling panel. Because the fuel carried by an aircraft is limited [9], it is very important to reduce local overheat and non-uniformity of fuel flow rate distribution among the cooling channels to reduce the waste of fuel.

Local flow blockage structure (blockage structure) is a special structure in the cooling panel of a scramjet. A fuel injector is usually installed on the combustion chamber wall and some space of the cooling panel is occupied by a fuel injector. So, some fins are cut off to form a blockage structure. A local flow dead zone can be easily formed in the downstream flow region of blockage structure to cause the deterioration of local heat transfer and local overheat of wall. Moreover, the flowing area distribution among the cooling channels of cooling panel is disturbed by the blockage structure, which changes the flow rate distribution of fuel. Therefore, different factors must be taken into consideration during the design of a cooling panel with blockage structure to reduce local overheat and non-uniformity of flow rate distribution among cooling channels as much as possible.

Therefore, the design and optimization of a blockage structure is described in detail in this paper. In the design and optimization process, Engine, GDE-1 [10], is used as the research model, and the cooling panel with fuel injector is used as the computation model. In accordance with the variation of thermodynamic physical properties variation with temperature, the working temperature region

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Nomenclature

H	specific total enthalpy, J kg^{-1}
t	time, s
P	pressure, Pa
U	vector of velocity
u	internal energy, J kg^{-1}
v	specific volume, $v = 1/\rho$, m^3 kg^{-1}
T	temperature, K
C_p	specific heat capacity at constant pressure, J kg^{-1} K^{-1}
C_v	specific heat capacity at constant volume, J kg^{-1} K^{-1}
l	coordinate values along the flow direction of the computational domain
M	flow rate of channel, kg s^{-1}
D	diameter of the tube, m
Greek	
ρ	density, kg m^{-3}
δ	identity matrix, $\delta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
τ	viscous stress, N m^{-2}
μ	dynamic viscosity, Pa s
λ	thermal conductivity, W m^{-1} K^{-1}
Subscripts	
in	inlet
out	outlet
i	a location along the wall of blockage structure
x,y,z	the three coordinate directions of Cartesian coordinate system

of fuel is divided into subcritical temperature, trans-critical temperature and supercritical temperature regions. With an optimized blockage structure, a numerical study is conducted on the convective heat transfer characteristics of fuel in the three temperature regions. The influence of blockage structure on the flow characteristics of fuel in the cooling panel is analyzed in detail with the blockage structure placed in different temperature regions. The reasonable location of blockage structure is discussed with different current factors taken into consideration.

2. Physical model

As shown in Fig. 1, the engine consists of a series of ramps that merge with the combustor section experience the highest heat flux. The nozzle and the inlet experience a lower heat fluxes with the inlet at the lowest. The typical ramp heat fluxes of a scramjet vary from 2 to 20 MW/m^2 [11], and the temperature of fuel increases from 300 K to 1000 K in the cooling process. So the temperature rise is very great. The fuel under the supercritical pressure conditions generally undergoes three regions with temperature rising. The difference in the thermodynamic physical properties of fuel is very great in this process, [12], which causes different flow and heat transfer characteristics [13,14].

In addition, before being injected into combustor, the fuel flows into cooling channel to cool the combustor wall. Because a fuel injector has to be installed, some channels are cut off to form the blockage structure in the cooling panel. As shown in Fig. 1, in the area around the blockage structure, the fuel coming out from the upstream is then distributed to the downstream channels. Because the downstream flow area increases in the flow direction, the flow velocity of fuel decreases and the pressure increases, which causes the flow separation easily around the downstream wall of the blockage structure. Therefore, the local flow field and the downstream flow rate distribution of fuel are influenced. In this paper, the convective heat transfer characteristics of fuel have been discussed in detail with the blockage structure placed in different temperature regions of the cooling panel.

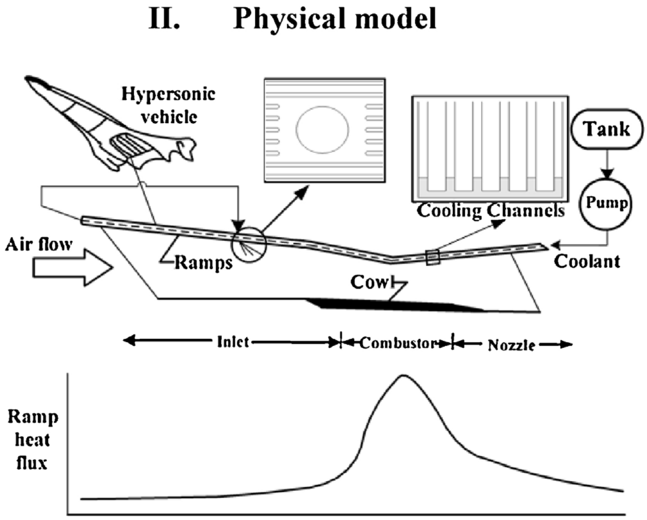

Fig. 1. Typical heat fluxes in scramjet engine.

3. Theoretical formulation

3.1. Governing equations

(1) The mass equation, momentum equation and energy equation are used for the distribution of convective heat transfer in the cooling channel.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \otimes U) = -\nabla P + \nabla \cdot \tau$$

$$\frac{\partial (\rho H)}{\partial t} - \frac{\partial P}{\partial t} + \nabla \cdot (\rho U H) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau)$$

where

$$U = [U_x, U_y, U_z]^T$$

$$\tau = \mu \left(\nabla U + (\nabla U)^T - \frac{2}{3} \delta \nabla \cdot U \right)$$

$$U \otimes U = \begin{bmatrix} U_x U_x & U_x U_y & U_x U_z \\ U_x U_y & U_y U_y & U_y U_z \\ U_x U_z & U_y U_z & U_z U_z \end{bmatrix}$$

Since hydrocarbon fuel is a mixture of various alkanes, it is very difficult to calculate the thermodynamic physical properties of fuel. However, according to [15] the main composition of hydrocarbon fuel is n-decane, the thermodynamic physical properties of hydrocarbon fuel can be replaced by n-decane. Therefore, the n-decane can be used as the working fluid in the present numerical study.

(2) Since the hydraulic diameter of channel is small, while the flow velocity in the channel is high, i.e., the flow velocity can reach 30 m/s in the supercritical temperature region. The buoyancy