International Journal of Heat and Mass Transfer 126 (2018) 267–276

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Parametric study on the hydrocarbon fuel flow rate distribution and cooling effect in non-uniformly heated parallel cooling channels

Yuguang Jiang [a,b], Jiang Qin [a,*], Khaled Chetehouna [b], Nicolas Gascoin [b], Wen Bao [a,c]

[a] Harbin Institute of Technology, Key Laboratory of Aerospace Thermophysics, MIIT, Harbin 150001, PR China
[b] INSA Centre Val de Loire, University Orléans, PRISME, EA 4229, F-18020 Bourges, France
[c] Harbin Institute of Technology, Shenzhen, Guangdong 518055, PR China

ARTICLE INFO

Article history:
Received 26 December 2017
Received in revised form 26 March 2018
Accepted 24 May 2018

Keywords:
Flow distribution
Parametric study
Parallel channels
Engine cooling
Design optimization

ABSTRACT

Advanced aero-engines with higher flying Mach number, like SCRamjets, offer good solution to the hypersonic propulsion. However, the thermal boundary condition of the engine cooling channels is normally non-uniform, which may cause fuel mal-distribution. Serious fuel cooling capacity waste and even over-temperature may occur. To ensure the reasonable flow distribution and wall temperature, a parametric study of the cooling channel geometries is conducted under non-uniform thermal boundary condition. A 3D numerical model considering the flow and heat transfer under supercritical pressure in parallel cooling channels is developed and validated. The results indicate that the flow distribution and cooling effect both improve with the reasonable design of the channel geometry. Higher aspect ratio (AR) improves the flow distribution and cooling effect. The variations of rib thickness and total channel flow area show greater impact on the heat transfer performance than on the flow distribution. At last, the results of channel geometry optimization are validated under different heat flux distributions. It can be concluded that the channel geometry optimization in this work improves the flow distribution and lowers the wall temperature, which provides reference for the design of cooling channels in aero-engines like SCRamjets.

1. Introduction

The modern aero-engines are capable of higher and higher flying Mach number [1–6]. The aero-dynamic heat and combustion heat are thus much larger. Engine cooling becomes essential and effective to ensure the structure safety. Taking the SCRamjet for example, the Mach number normally exceeds 5. The thermal environment is severe. Different cooling methods are applicable, such as regenerative cooling [7], endothermic pyrolysis of fuel [8], effusion cooling [9] and film cooling [10], etc. Among them, the regenerative cooling using hydrocarbon fuel is one of the most promising cooling methods [11–13]. The fuel flows through cooling channels to cool the hot structure before injected into combustion chamber. However, the non-uniformity of thermal boundary may lead to the fuel mal-distribution in cooling channels. As a result, the fuel cooling capacity could be seriously wasted and over-temperature may occur in the engine structure. The flow and fuel temperature distribution has become one of the key problems in the design of cooling channels in SCRamjet.

The problem of flow distribution actually exists in many commonly seen applications, which threatens the operating efficiency and the application safety. Pan et al. [14,15] developed a model using fluid network to study the flow distribution in the cooling wall of the boiler. Baikin M et al. [16] developed a transient model of parallel pipes to study the flow distribution of water and steam in a direct steam generator. Hossain et al. [17] studied the header geometries to improve the distribution of reactants in a proton exchange membrane fuel cell. Naphon et al. [18] numerically investigated the flow distribution in the mini-heat sink for CPU. Xia et al. [19] studied the flow and temperature distribution in a plate-type fuel reactor core. Jiang et al. [20,21] investigated the flow distribution of hydrocarbon fuel in cooling channels of SCRamjet and put forward a control method. The research focuses include the header design and modification [22–24], the effects of boundary conditions [16,25], the fluid properties [26–28], the transient features [29,30], etc.

Another frequently used method to improve the flow distribution is parametric study of the channel geometries. It is commonly seen in cooling channels of heat exchangers and heat sinks. The

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

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.124
0017-9310/

Nomenclature

A	area, m^2
AR	aspect ratio
b	channel width, m
c_p	specific heat, $J/(kg \cdot K)$
e_t	total internal energy, J/kg
H	channel height, m
L	channel length, m
m, m_f	mass flow rate, kg/s
n_c	channel number
P, p	pressure, Pa
Q	flow rate, m^3/s
Q_{ratio}	the heat exchange ratio
q	heat absorption rate, W
q_f	the heat flux, W/m^2
q_r	the ideal cooling request, W
s_w	heated wall thickness, m
T	temperature, K
t_w	rib thickness, m
u	velocity of fuel, m/s
β	mass flow rate deviation coefficient
μ	dynamic viscosity, $Pa \cdot s$
λ	thermal conductivity, $W/(m \cdot K)$
ρ	density, kg/m^3
τ	viscous stress
$\varnothing_m$	mass flow rate deviation
$\varnothing_q$	heat absorption deviation
$\varnothing_{Tf}$	fuel temperature deviation
μ	dynamic viscosity, $Pa \cdot s$
ΔP	pressure drop, Pa

Subscripts

average	average values
eff	effective
HE	heat exchange
i	channel number index
side	side surfaces
t	total
t&b	top and bottom surfaces
w	wall

studies about geometries like aspect ratios, the fin thickness, are commonly seen in single channel cases [31–34], which also show obvious effects in parallel cases [35].

As we know, the non-uniformity of structure geometries and thermal boundary are two main reasons of flow mal-distribution. In our previous work [35], the parametric study about the flow mal-distribution caused by non-uniform geometries has been done. The flow distribution could be improved through optimal design of the channels. However, the parametric study on flow mal-distribution caused by non-uniform thermal boundary of the engine is still in need. It is worth noting that the thermal boundary of cooling channels varies with the engine operation conditions. Even under the same heat flux deviation, the heat flux distribution could be different. Therefore, the channel design should be valid under different heat flux distributions.

In order to optimize the channel geometries for the flow distribution under non-uniform heat flux distribution, a 3D numerical model of multiple parallel channels with n-Decane under supercritical pressure is established. The effects of geometry parameters, such as the aspect ratio, rib thickness and total branch channel flow area, on the flow and fuel temperature distribution are investigated. The wall temperature of the heated surface is selected as the indicator of the cooling effect.

2. Model description

2.1. Geometry description

The configuration of the cooling channels is determined based on the experimental data in Ref. [4]. The schematic of the cooling channels in the SCRamjet is shown in Fig. 1. Usually, a parallel channel system with at least 3 channels is considered typical and representative. It is able to present the complex coupling paths between different channels. The 20 mm domain in this work contains at least 6 (up to 32) channels, which is enough for the parallel system study. To balance the computing time, it is selected to represent the cooling wall. A 50 mm long header is set as shown in Fig. 1, which ensures a uniform flow distribution if the heat flux distribution is uniform. As we can see, this configuration gets rid of the influences of geometry non-uniformity and focuses on the effects of non-uniform heat flux distribution. The material of the solid used is high temperature alloy GH 3128, the properties of which come from Ref. [36].

As shown in Fig. 1, the cross section of the parallel cooling channels is described by the channel width (b), channel height (H), rib thickness (t_w), and wall thickness ($s_w = 1$ mm). The branch channel closest to y = 0 is defined as No. 1 and the number of the rest channels increases along the y direction.

2.2. Principles of the channel geometry parameters configuration

To carry out the parametric study on flow distribution in cooling channels, a reasonable principle of parameter configuration is needed, similar to the works in Refs. [31], [37] and [38]. In this work, the SCRamjet combustor working conditions from Ref. [4] are used and similar constraints with our previous work [35] are adopted.

The mass flow rate of the coolant for the engine is set to be 232 g/s, which is the rounded value of the fuel mass flow rate for combustion at Mach 5 in Ref. [4]. The total mass flow rate for the computing domain is calculated to be 16.5 g/s.

The channel aspect ratio is defined as

$$AR = H/b \quad (1)$$

The surface area of the heated wall is constant

$$n_c(b + t_w) = const \quad (2)$$

When studying the effects of aspect ratio and rib thickness, the total flow section area is kept constant as the following equation. (However, this constraint does not apply to the work focusing on the effects of total flow section area.)

$$n_c \cdot AR \cdot b^2 = const \quad (3)$$

The rib thickness t_w and fuel velocity u are set to be 2 mm and 2.25 m/s respectively as initial values for the parameters determination. According to the constraints above, for given mass flow rate $m_f = 16.5$ g/s, and aspect ratio AR, the geometric parameters (H, b, n_c) can be calculated. Considering the calculated value of the channel number may not be an integer, it needs to be rounded.