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Thermal management method of fuel in advanced aeroengines

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A B S T R A C T

The method to improve the heat sink utilization of fuel is the primary issue for thermal management of advanced aeroengines. In order to study the methods to control the fuel heat sink utilization, a one dimensional model of flow and heat transfer process in a single cooling channel of endothermic hydrocarbon fuel cooled scramjet in terms of endothermic reaction is developed, which is validated by corresponding experimental data. Different methods are put forwarded to control the utilization level of fuel heat sink and effective residence time of fuel during fuel cooling process is defined to distinguish global method and local method. The control of fuel mass flow rate or the height of cooling channel can be regarded as a global method, while the control of operating pressure in the cooling process can be considered as a local method. Analytical results indicate that the control methods can effectively improve the fuel heat sink utilization. However, the efficiency of the global method is limited by the allowable wall temperature. In contrast, the local method can be used not only to control the utilization of fuel heat sink, but also to improve the heat transfer and pressure drop performance of fuel.

1. Introduction

Thermal management of fuel in advanced aeroengines is always a significant challenge especially for advanced aeroengines used to power aircraft, rockets, and missiles. As flight speed increases to a supersonic or hypersonic regime, the temperature of ram air taken on board a vehicle becomes so high that the fuel has to be used as the primary coolant to cool the structure of vehicle [1]. The engines for future aircraft are projected to operate at high pressures and fuel/air ratios, which exacerbate their thermal management task.

Thermal management has become one of the key concerns, and scramjet is the one with the largest heat load of all the advanced aeroengines. In order to meet the thermal management requirement for an aeroengine with high flight Mach number, endothermic hydrocarbon fuels has to be used to replace the conventional hydrocarbon fuel and to provide extra heat sink for cooling through endothermic thermal cracking [2].

It is a very efficient method to increase the fuel heat sink by developing an endothermic hydrocarbon fuel [3]. However, the utilization of fuel heat sink has the following limitations as detailed below. 1. The highest heating temperature of fuel is limited by the allowable wall temperature of thermal structure, which reduces the practical utilization of fuel heat sink because the total amount of fuel heat sink is mainly determined by the temperature of fuel [4]. 2. The temperature of fuel must be kept safely below the coking temperature and the upper limit Mach number of a hydrocarbon fueled airbreathing hypersonic aeroengine is restricted to Ma8 because coking must be avoided within the cooling channel at all cost [5]. 3. The heating of Airframe (external surface) at a high Mach number will cause a significant heating of fuel tank which decreases the heat sink capacity of fuel (coolant) [6]. 4. The lack of heat sink confines a hypersonic vehicle to a relatively low flight speed. Because more fuel than required has to be carried for the mission when fuel heat sink is insufficient and the excess fuel has to be abandoned [7]. Therefore, it is very important to make full use of heat sink of fuel under limitations in addition to the development of fuel with high heat sink.

Some researchers have further pointed out recently that fuel heat sink is affected not only by temperature, but also by velocity and pressure [8]. However, the previous studies are carried out theoretically. The fuel heat sink in a real engine is confined by the structure of engine and the size of its cooling passage, and the engine can work in a wide range of conditions with different Mach numbers and fuel/air ratios, and its heat load and cooling requirement may also vary greatly. All of these will further increase the difficulty in making full use of heat sink. So, with a scramjet used as the object of study and endothermic hydrocarbon fuel used for cooling of the scramjet, different schemes are worked out in accordance with the design and operating characteristics of a fuel

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Nomenclature

A	pre-exponential factor, s^{-1}
C_p	constant-pressure specific heat of hydrocarbon fuel, J/(kg K)
D	hydraulic diameter of cooling channel, m
Ea	activation energy, J/mol
ff	friction factor
h	heat sink, J/kg
I	electric current, A
k	reaction rate, s^{-1}
L	length of cooling channel segment, m
Lp	length of pipe, m
mf	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
q_w	heat flux, W/m^2
Q	heat absorption, W/m
R	universal constant, J/(mol K)
Re	Reynolds number
s	thickness of wall, m
t	time, s
T	temperature, K
U	voltage, V
u	velocity, m/s
W	width of the cooling channel, m
x	axial coordinate, m
Z	conversion of fuel
λ	thermal conductivity of metal wall material, W/(m.K)
μ	dynamic viscosity, Pa s
ρ	fuel density, kg/m^3
Subscripts	
c	coolant
ci	coolant inlet
co	coolant outlet
crack	cracking reaction
f	fuel
g	gas
j	segment number
w	wall
wc	coolant side wall
wg	gas side wall

cooling system so that the fuel heat sink available can be fully utilized.

2. Description of scramjet and cooling-channel

As shown in Fig. 1, the scramjet is located on the lower surface of a hypersonic vehicle and consists of a series of ramps that merge with the lower surface of the vehicle, and a cowl which helps capture the air compressed by the vehicle fuselage and the engine ramps. The major components of the engine are inlet, isolator, combustor, and nozzle.

The combustor section experiences the highest heat flux. The nozzle, isolator and inlet experience lower heat fluxes, and among them, the inlet experiences the lowest heat fluxes. The typical ramp heat fluxes of a scramjet vary from 2 to 20 MW/m^2.

As shown in the upper portion of Fig. 1 [9], the cooling channels are the rectangular ducts encircling the thermal structure of engine and they can be described using channel width (W), channel height (H), fin thickness (t), and heated wall thickness (s).

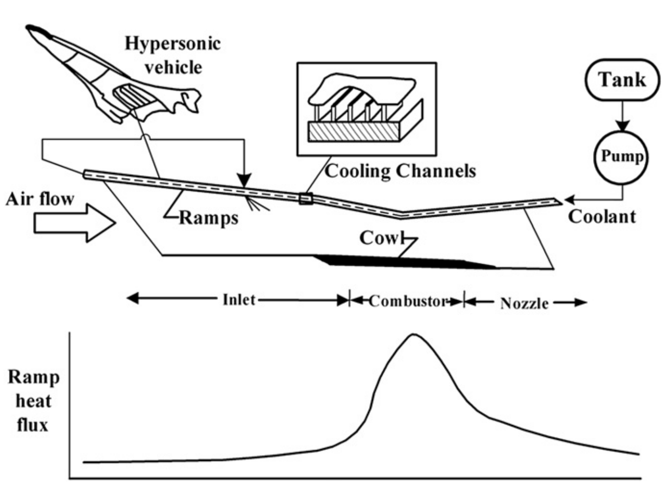

Fig. 1. Schematic of scramjet engine with typical heat fluxes.

As shown in Fig. 1, the working process of the cooling system can be described as follows: the fuel of the engine is firstly pumped into the cooling channels to fully cool the thermal structure of the engine, and then the heated fuel is injected into the combustor as propellant to generate the thrust. In order to avoid the deterioration of heat transfer caused by boiling phenomenon, the pressure in the cooling channels is kept above the critical pressure of the fuel.

3. Computational model

A one-dimensional model is usually used to study the flow and heat transfer characteristics of a reactive flow and to design the structure of a cooling channel [10]. A one-dimensional flow and heat transfer model with the cracking reaction taken into consideration is used in this article to study ways and means to control the utilization of fuel heat sink.

During either the calculations or the experiments reported in this paper, the coolant is working under supercritical condition to avoid the deterioration of heat transfer. Under the supercritical pressure, the phase of fuel changes continually without boiling. Ward et al. built a numerical model to simulate the flow and heat transfer characteristics of aviation fuel under supercritical conditions, and boiling phenomenon is not considered to exist under such conditions [11].

In addition, the thermodynamic properties of fuel change greatly along with the increase in temperature, especially when the temperature is near the critical point. So the real thermodynamic properties of fuel must be considered. The properties of fuel and its cracked products are obtained from National Institute of Standards and Technology (NIST) Thermodynamic and Transport Properties of Pure Fluids database and NIST Chemistry Web Book [12].

3.1. Geometry model and basic assumptions

As shown in the upper portion of Fig. 1, the cooling jacket of a scramjet is composed of many single rectangular cooling channels. With a usual and reasonable assumption, coolant flow and heat flux are assumed to be uniform across the cross section of a scramjet [13]. Under such an assumption, the fuel mass flow rate and heat flux of each single channel are the same, and so, a single