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Research Paper

Numerical investigation on thermal behaviors of active-cooled strut in RBCC engine

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HIGHLIGHTS

- Numerical model coupling heat transfer in RBCC engine and strut is proposed.
- Strut temperature is within the allowable range with current cooling structure.
- Impingement flow enhances thermal efficiency at cost of huge pressure drop.
- Strut manifold homogenizes flow velocity and lowers the strut temperature.

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ABSTRACT

Integrating strut ejector with air-breath engine is an effective method of enhancing fuel/air blend and combustion efficiency. In the present study, a stainless steel strut with active cooling structure is designed for thermal protection in severe combustor environment in Rocket Based Combined Cycle (RBCC) engine. The numerical model is proposed that conjugates turbulent combustion in thrust chamber and convective heat transfer in strut. The flow and thermal behaviors in the strut are evaluated under four mass flow rates of kerosene coolant at the flight condition of Mach 6. The numerical pressures are in good agreement with the experimental data. Results indicate that the strut temperature is maintained within the allowable limit with the designed cooling structure. The highest temperature (1100 K) is discovered at the rear of the strut due to the high thermal resistance at the strut corner. The perturbation at leading edge and the flow separation at strut back lead to vorticity augmentation and velocity decrease at the vicinity of strut bound. Both coolant velocity and thermal efficiency increase in the manifold due to the sudden pressure drop at the manifold entrances.

1. Introduction

Rocket Based Combined Cycle (RBCC) engine has been widely considered as one of the most promising propulsion systems for future space transportation and hypersonic aircraft, since it owns a variety of advantages involving ground-takeoff capability, high performance at wide range of flight height and speed, low cost and reusability [1,2]. RBCC takes the merits of high-specific-impulse of air-breathing engine and high thrust-to-weight ratio of rocket. Throughout the flight, the engine operates in four different modes roughly based on the flight Mach number, i.e. ejector mode (Ma $0 \sim 3$), ramjet mode (Ma $3 \sim 6$), scramjet mode (Ma $6 \sim 8$) and rocket mode (Ma $8 \sim 10$). In ramjet and scramjet modes, the ejection rocket functions to ignite the wall-injection fuel and the coming air, thus working in relatively low flow rate [3–8]. Even so, in supersonic combustion, the penetration distance of fuel to the jets reduces to only few diameters even at high injection pressure. Moreover, the conventional injection schemes such as wall injection are not applicable to fulfill the mixing efficiency requested for actual RBCC engine due to the enlarged volume. Therefore, the organizations of sufficient blend and efficient combustion are becoming crucial, yet difficult to deal with in RBCC combustor [9].

In order to guarantee high performance of the combustor, researchers have carried out a variety of investigations, among which strut injector is considered one of the most efficient structures, whose main advantages are [10–12]: (1) to fulfill the whole combustor with fuel; (2) to help the mixing of fuel and coming flow; (3) to complete the compression of the air intake; (4) to enhance the ignition and stabilize the combustion. However, the existence of the strut in the combustion has inevitably increased

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Nomenclature

c_p	specific heat at constant pressure (J/(kg·K))
Ch	cooling channel
d	hydraulic diameter (m)
D_ω	cross diffusion term
D	diffusion coefficient of chemical component
E	energy (J/kg)
ER	equivalence ratio
E_r	activation energy (J/(kg·mol))
f	Darcy drag coefficient
f_{dr}	friction factor
F	body force (N)
$\widetilde{G}_k$	generation of turbulence kinetic energy
G_ω	generation of ω
h	convective heat transfer coefficient (W/(m^2·K))
k	turbulence energy
l	length of the pipe (m)
l_0, l_1, l_2	relative length of different part of the RBCC engine (m)
L	coordinate along the leading edge middle line (m)
m	mass fraction
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
q'	heat flux (W/m^2)
T	temperature (K)
u, v, w	velocities of x, y, z axis (m/s)
$\underline{U}$	internal energy (J/kg)
$\vec{V}$	velocity vector (m/s)
Y_k	dissipation of k
Y_ω	dissipation of ω
Z	production rate in unit volume
IJ	center line of the leading edge
MN	center line of the strut back wall

Greek symbols

δ	thickness of the wall (m)
ϕ	dissipative function
λ	thermal conductivity (W/(m·K))
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/(m·s))
τ	stress (Pa)
ω	specific dissipation rate
Γ_k	effective diffusivity of k
Γ_ω	effective diffusivity of ω

Subscripts

aw	adiabatic wall
c	coolant
f	fluid
i	chemical component
in	from gas to the outer strut wall
out	from inner strut wall to coolant
s	strut wall
wg	wall adjacent to the hot gas
wc	wall adjacent to the coolant

the drag and reduced the total pressure of coming flow [13–15]. Therefore, the strut structure should be shaped in stream-line structure and the leading edge radius should be small. However, the strut, particularly the leading edge is prone to withstand extreme aerodynamic heat (100 MW/m^2, Ma 12) and is more vulnerable to suffer from ablation [9]. Due to this fact, thermal protection of the strut injector becomes one of the most important and difficult tasks of air-breathing engine. To tackle this problem, numerical and experimental investigations have been carried out to study the thermal behavior of strut in thrust chamber.

Bouchez et al. [9] designed the strut of C/C composite material with cooling channels and conducted experiment at the condition of Ma 6 to test the cooling effect. The strut was cooled by hydrogen, which was proved capable of withstanding the high temperature. However, this type of C/C strut was still limited in applications mainly due to the low structural strength and extensive cost. Rene-Corail et al. [11] applied a cooling technology called "regenerative circuit" to the scramjet injection strut. Results showed that the maximum strut temperature was still below 900 K and gaseous hydrogen temperature as the coolant increased by about 200 K. The French Joint Composite Scramjet (JCS) program [16] carried out a series of investigations on C/SiC composite strut in thermal protection application. Their experiments verified that the composite material could withstand high heat flux (10 MW/m^2, Ma 8) for 150 s. Droeske et al. [17] experimentally and numerically investigated heat transfer performances of an internal-cooled strut with hydrogen and helium as coolant, respectively. The results revealed that the dimensionless surface temperature along the injector did not fluctuate considerably as the main flow temperature varied. However, the experiment was conducted only at the cold flow condition and the maximum temperature only increased to 550 K.

As for numerical investigations, Chen and Zhong [18,19] numerically studied the thermal protection of active-cooled strut made of stainless steel with kerosene as the coolant. Different cooling channel structures, coolant mass flow rates and the optimized design of strut were revealed and discussed. Huang et al. [20] numerically investigated transpiration cooling efficiency and its main impact factors for the designed metal porous strut in scramjets. Their results showed that increasing both coolant blowing ratio and thermal conductivity of material can improve the cooling efficiency. In addition, the wedge had an optimum angle of 30°. Later, they simulated the transpiration cooling for sintered foamed metal strut of different structures and coolant conditions in scramjet [21,22]. Conclusions were extracted that effective thermal protection was achieved with a thin coolant film established at the leading edge to prevent heat from transferring into strut. However, the porous structure has inevitably suppressed the convective flow to great extent although it can provide high thermal performance [23–25].

As stated above, previous literatures mainly focused on the thermal characteristics of strut cooled by gaseous coolant or on the performances of struts in porous composite material. The investigations on the design of cooling channel configuration have been inadequate. Furthermore, to the best knowledge of the authors, few literatures were proposed on the conjugated model of combustion in the engine and combined convective-diffusive heat transfer in the strut. In the present study, a metal strut integrated with high efficient cooling channels in RBCC combustion chamber is designed. The numerical model is proposed that couples combustion in thrust chamber and heat transfer in strut. Predicted results reveal the flow and thermal behaviors in the strut as well as in the combustion chamber under scramjet mode (Ma 6). Additionally, the effect of mass flow rate of coolant is also investigated.