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Research Paper

Thermodynamic analysis for recuperation in a scramjet nozzle with wall cooling

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HIGHLIGHTS

- The recuperation process in the nozzle can improve the performance of scramjets.
- The partially cooled nozzle has a greater potential than the fully cooled nozzle.
- 22.57% specific impulse will be increased in the partially cooled nozzle with the regenerator effectiveness of 30%.

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ABSTRACT

A thermodynamic analysis for recuperation in a scramjet nozzle with wall cooling was completed in this paper. The expansion process with recuperation was descripted using both diagrams and equations. A quasi-one-dimensional expansion model coupled with wall cooling was developed to support the description of the expansion process with recuperation, which consisted of two forms, namely, the fully cooled nozzle and the partially cooled nozzle. The results show that the recuperation process achieved by wall cooling in the nozzle has the potential to improve the performance of scramjets effectively. For both of two nozzle forms, the exhaust temperature and the area ratio of nozzle decrease with the regenerator effectiveness, and meanwhile the exhaust velocity increases when more heat is transferred back to combustor. The gains of specific impulse will be 16.24% and 22.57% for the fully cooled nozzle and the partially cooled nozzle respectively, if the regenerator effectiveness can reach to 30%. When taking no account of the thermal protection, the partially cooled nozzle has a greater potential than the fully cooled nozzle.

1. Introduction

Scramjet is treated as one of the most promising propulsion systems for hypersonic flight and has been researched and developed as a kind of key technology for years [1]. It can be used as either an independent engine [2,3] or a part of the combined cycle engines such as the turbine-based combined cycle (TBCC) [4] and the rocket-based combined cycle (RBCC) [5], which could provide the aircraft a wider range of flight Mach number and a better performance in the entire flight envelope. A typical scramjet is composed by an inlet, an isolator, a combustor and a nozzle which is the main component to produce thrust. To decrease the weight, produce the lift and keep the balance of force moment, a single expansion ramp nozzle (SERN) is always applied on scramjets [6].

Some researches on the scramjet nozzles have been carried out using experiments and computational fluid dynamics (CFD). Hirschen et al. [6,7] finished an experimental study on scramjet nozzle flows at a freestream Mach number of 7 using both the pressure-sensitive-paint and the pitot pressure measurement, and the experimental results showed that the nozzle pressure ratio and the freestream Reynolds number did not influence the static pressure ratio on the expansion ramp. Li et al. [8] investigated the influences of geometric parameters, including divergent angles, total lengths, height ratios, cowl lengths and cowl angles, upon the nozzle performances using the FLUENT. Watanabe [9] conducted an experimental research of scramjet asymmetric nozzle to investigate the effects on nozzle performance of the interactions between the exhaust and the hypersonic external flow, and the results showed that the external flow affected the model surface pressure only from the ramp side and suppressed the boundary-layer separation on the ramp surface. Huang et al. [10] simulated numerically the flow field in a single expansion ramp nozzle and

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Nomenclature

A	sectional area, m^2
C_f	skin-friction coefficient, dimensionless
D_h	hydraulic diameter, m
I_{sp}	specific impulse, s
KE	specific kinetic energy, J/kg
M_w	molecular weight, kg/mol
$\bar{M}_W$	mean molecular weight of a mixture, kg/mol
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
P_w	wetted perimeter, m
Q	specific absorption of heat, J/kg
Re	Reynolds number, dimensionless
R_g	gas constant, J/(kg K)
R_u	universal gas constant, J/(mol K)
T	temperature, K
Y	mole fraction, dimensionless
$a_{1\text{-}5}$	series of constant, dimensionless
c_p	constant pressure specific heat, J/(kg K)
k	coefficient, dimensionless
m	mass flowrate, kg/s
p	pressure, Pa
q	heat flux, W/m^2
r	recovery factor, dimensionless
s	specific entropy, J/(kg K)
u	velocity, m/s

Greek

α	forced convection coefficient, $W/(m^2\ K)$
γ	ratio of specific heat, dimensionless
η_b	overall fin surface efficiency, dimensionless
θ	wall thickness of the nozzle, m
λ	thermal conductivity, W/(m K)
μ	kinetic viscosity, Pa s
ξ	regenerator effectiveness, dimensionless
ρ	density, kg/m^3

Subscripts

4	the section of nozzle inlet
9	the section of nozzle outlet
Ref	reference
ave	average
aw	adiabatic wall
c	cooling
enh	enhancement
f	fuel
hf	heat flux
rec	recuperation
s	constant entropy
w	wall

Superscripts

$*$	evaluated at reference temperature

investigated the interactions between the parametric parameters and the objective functions by means of the data mining technique coupled with a design of the experiment. The results showed that the horizontal length of the inner nozzle, the external expansion ramp and the internal cowl expansion played an important role on the thrust force performance, and the discrepancies between the optimized performances and the numerical predictions were pretty small.

The technologies of nozzle cooling, including the regenerative cooling [11], the film cooling [12] and the transpiration cooling [13], have been widely investigated in the field of liquid rockets. Meanwhile, the regenerative cooling for scramjets, which can be treated as recuperation process, has drawn the attention of researchers. Qin et al. [14] built an experiment system and made a series of comparison at different fuel cooling conditions. The results indicated that the recuperation process consisted of chemical and physical recuperation processes, whose effectiveness could be improved by increasing fuel heating temperature. Qin et al. also researched the regenerative cooling of scramjets in the view of thermal management [15–17] to achieve a better energy utilization. Kanda et al. [18] integrated a film cooling model with a quasi-one-dimensional scramjet performance prediction model and proved that several advantages could be achieved by a combination of film cooling and regeneration cooling. Gascoin et al. [19,20] finished the investigation on the pyrolysis of supercritical endothermic hydrocarbon fuel for an actively cooled scramjet in both numerical and experimental ways. Gascoin et al. [21] also developed a one-dimensional transient numerical model with heat and mass transfer, fluid mechanics and pyrolysis chemistry, and the results obtained by model were in good agreement with the experimental results. However, the researches of scramjet recuperation are mainly concentrated upon the combustor at present, and the performance influence of recuperation only built by nozzle has not been reported yet. Hence, it is meaningful to investigate the performance of recuperation in a scramjet nozzle based on wall cooling.

For a hypersonic air-breathing engine, the compression component using the oblique shocks system can hardly provide a big enough cycle pressure ratio with the current technology, which makes the exhausting temperature extremely high. An exergy analysis developed by Zhang et al. [22] showed that the exhausting process produced the most exergy destruction, and a great amount of heat energy was not converted into kinetic energy, i.e. thrust. Hence, reducing the heat exergy loss of the exhausting process could improve the performance significantly. On the other hand, for a physical or a chemical recuperation process, the temperature of the heat source is lower, the gain can be obtained is bigger [23]. So it may be beneficial for improving the performance of a scramjet to transfer the heat from the inlet or the nozzle to the combustor.

In this paper, an expansion process with recuperation is descripted in the view of zero-dimension. To evaluate the performance of a scramjet nozzle with recuperation, an ideal quasi-one-dimensional model of expansion coupled with wall cooling is developed, and the calculation results of a fully cooled nozzle and a partially cooled nozzle will be presented and compared. Besides, the one-dimensional distributions of gas temperature and Mach number, and the area ratio of nozzle with different generator effectiveness will be presented and discussed in this article.

2. Description of an expansion process with recuperation

For an ideal scramjet, the recuperation in the expansion process can be described as a process of the fuel carrying the heat dissipation from the gas to the nozzle walls back to the combustor. To achieve a better description to the expansion process with recuperation, an isentropic expansion process is utilized for comparison. It is necessary to measure the influence of recuperation by keeping the pressure ratios of the two expansion as a constant, considering the great effect of pressure upon an expansion process.