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Influence of porous filling on internal flow and heat transport for the gap-cavity structure subjected to high speed airflow

Chun Shen [a,b,c,*], Xin-lin Xia [c,*], Yong-zhen Wang [b], Feng Yu [b]

[a] State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, China
[b] Department of Thermal Energy Engineering, Jilin University, Changchun, China
[c] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China

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ABSTRACT

In this paper, using all-speed preconditioned conjugate heat transfer numerical method and wind tunnel experiment, it is investigated the mechanism of the transient process that high speed hot airflow invades into gap-cavity sealing link structure. On the condition of porous material sealing in top gap of the linking structure, via the experimental method, it is found that there is existing increment–decrement–increment phenomenon of variation of temperature magnitude inside the cavity. Meanwhile this variation phenomenon could be reproduced by the all-speed preconditioned conjugate heat transfer numerical method and it is demonstrated that, the effectiveness of the numerical method established for this invading problem in this paper. Then by the numerical method, the more details with respect to the invasion process are shown to analyze the mechanism corresponding to this increment–decrement–increment phenomenon of variation of temperature magnitude. Finally, the symmetry and stability characteristics of the flow status with and without porous sealing are compared and the differences of the invasion process with and without sealing are further summarized.

1. Introduction

Sealing is a significant key thermal protection for turbomachine [1,2], hypersonic flight vehicle, hypersonic ramjet engine [3–5]. In general, the porous material is located in the gap between the adjacent structures, in order to prevent the hot airflow from invading in. However, due to the penetration feature of porous material, it can't prevent the heat and mass transfer entirely, especially for the condition that there is large pressure difference on both sides of porous material filling in the gap. The objective of this paper is to further investigate this penetration and heat transfer phenomenon for the gap-cavity structure which is equivalent to the real sealing link structure in hypersonic flight vehicle.

In general, the external space outside the linking structure on hypersonic vehicle should be the hypersonic compressible flow field, and the internal space inside the linking structure is generally the analogous cavity structure where the internal flow field would be subsonic compressible [6]. If the sealing porous material is filled in the gap which connects the outside hypersonic field and the inner cavity, the velocity of invading hot air into the cavity would be tens or even several meters per second and so the inner flow field should be subsonic incompressible flow. Hence for the link structure with porous sealing in the hypersonic flow, the fields outside and inside the structure are hypersonic/supersonic and subsonic incompressible, respectively, so the entire flow field involved is all-speed flow field which partially consists of supersonic/hypersonic transonic and subsonic flows. Meanwhile, multiple physical processes including conjugate heat transfer among porous, fluid and solid domains, penetration inside the porous media are involved.

For sealing structure with porous sealing, a lot of researches were implemented by the experimental approaches [7–10]. However, these researches primarily focused on the penetration through porous material and summarize the range of penetrating rate of mass flow under the conditions of different pressure drop across the porous sealing zone. After the hot air passes through the porous sealing zone, it will continue to invade into the inner cavity, and the thermal shock that is harmful to the inside parts is formed. Therefore, in order to grasp the mechanism of the thermal shock, this subsequent invasion of hot air into the deep gap and inner cavity of the sealing structure needs to be investigated further. So in this paper, the flow and heat transfer process of hot air invading into the inner cavity of the sealing structure is concentrated on.

* Corresponding authors at: State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun, China. Tel.: +86 0431 85095196 (C. Shen).
E-mail addresses: shench@jlu.edu.cn (C. Shen), xiaxl@hit.edu.cn (X.-l. Xia).

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Nomenclature

a	speed of sound
c	specific heat capacity (J/(kg K))
d_p	the particle diameter of porous phase (m)
E	total energy (J/kg)
E_c, F_c, G_c	convective flux vectors
E_v, F_v, G_v	viscous flux vectors
F	inertia coefficient; view factor
G_o	external contribution to the irradiation
H	external incident irradiation (W/m^2)
H_f	height of the upper flow field
H_L	whole width of the solid structure
H_s	whole height of the solid structure
J	effective radiative power (W/m^2)
K	permeability
$\boldsymbol{n}$	vertical direction of the boundary
N	the total number of the grid cells
p	pressure (Pa)
q	net radiative heat flux (W/m^2)
Q	vector of primitive variables
t	time (s)
$\boldsymbol{S}$	source term
T	temperature (K)
U	velocity vector (m/s)
U_{ref}	reference velocity
$\boldsymbol{U}_\infty$	fixed reference velocity

Greek symbols

τ	pseudo time
λ	conductivity (W/(m K))
ε	porosity of porous; emissivity
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
ρ	density (kg/m^3)
ϕ	relative error
Γ	preconditioning matrix

Subscripts

dimless	dimensionless
i	index number
ini	initial
k	surface element index
f	fluid phase
r	radiation
s	solid phase
x,y,z	coordinate axes x, y and z

In this paper, the experimental test and numerical simulation method are both adopted to study the invasion of external airflow into the gap-cavity sealing structure. For the fluid/porous coupling problem, density-based algorithm [11–13] or pressure–velocity correction algorithm [14–21] could be used to reproduce the conjugate heat transfer process. The density based method is more accurate for the supersonic/hypersonic flow, and the pressure–velocity method is much better for the transonic and subsonic flow. In this paper, the flow field outside the sealing structure is supersonic/hypersonic, so the density based algorithm is more proper for the flow field outside the sealing structure. Meanwhile, the inside of the sealing structure with porous sealing material in the gap is more inclined to the subsonic incompressible flow. Hence, the entire flow field, including external and internal regions outside and inside the sealing structure, especially for the structure with porous material sealing, possesses the all-speed flowing feature, and the density-based preconditioned all-speed algorithm is more appropriate for this all-speed flow [22–24].

In general, the actual linking structure could be simplified to assembly of gasp and cavities [6], which is called gap-cavity structure in this paper. For requirement of sealing, the porous material is filled in the gap. In this paper, this simplified gap-cavity structure with porous sealing in the gap is used as the substitution for actual sealing link structure, to investigate the process of hot airflow invasion.

In this paper, the experimental test that high-speed hot airflow flows over the gap-cavity structure is implemented in the wind tunnel. The temperature data on the bottom surface and in the cavity is obtained by the experimental test. Meanwhile, based on the preconditioned all-speed algorithm, the conjugate porous/fluid/solid domains method is established and is validated via the experimental data. All the numerical programs are developed in OpenFOAM [25], where the density based preconditioned all-speed algorithm for fluid domain has already been established [24] and it mainly includes preconditioning method with time-derivative term and all-speed advection discrete scheme, AUSM+(P), AUSM+up, etc., Finally, associating the results produced by the numerical algorithm with the experimental data, it is investigated that the the flow and heat transfer features in the transient process that external hot air invades into the inner cavity inside the sealing link structure.

2. Physical and mathematical model

2.1. Experimental and computational geometric models

Fig. 1 shows the experimental gap-cavity structure in the wind tunnel. Fig. 2 illustrates the two-dimensional cross section diagram corresponding to actual experimental structure shown in Fig. 1, and it is the numerical computational geometric model in x–y plane.

As shown in Figs. 1 and 2, the porous material fills in the top gap (gap 1 in Fig. 2) at the middle of the graphite plane. The high speed airflow aerodynamically heats the graphite plane and the high temperature gas invades into the cavity along gap 1 (full of porous material) and gap 2 of which the length is 2 mm. The permeability and the porosity of the sealing porous material used in the experimental test are $1 \times 10^{-7}\,m^2$ and 0.9, respectively. The graphite plane is supported by the metal shell which is made of steel. There are two pieces of thermal insulation blocks. The cavity and gap 2 shown in Fig. 2 are cut at the top and middle part of these two blocks, respectively, and these two blocks are put into the metal shell. These two thermal insulation blocks could prevent the heat of the invading hot air from transferring to the internal solid structure through the gap's and cavity's walls and hence, it's much easier to increase the temperature of the air in the cavity.

The temperature data at dot 2 and dot 6 (shown in Fig. 2) is measured by the thermocouple wires of which the legs are welded together at one end. The whole structure is surrounded by the thermal insulating material and then put it in the high speed wind tunnel. The whole height and width of the structure H_s and H_L is 200 mm and 250 mm, respectively. According to the wind tunnel conditions, the velocity, temperature and pressure of the inlet in the upper flow field (shown in Fig. 2) are approximately equal to 2350 m/s, 1770 K and 1600 Pa, respectively, and the initial pressure and back pressure are both 400 Pa.