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Film Cooling Effect of Hydrogen on Cylinder in Supersonic Airflow

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The film cooling effect of hydrogen on a cylindrical body in supersonic airflow is investigated, attention being paid to the effect of the reaction of hydrogen with the hot airflow. Comparisons of the cooling efficiencies of a reactive gas (hydrogen) and inert gases (nitrogen and helium) are presented. The cooling efficiency of hydrogen becomes almost the same as that of helium at the same mass flow rates for the case in which the static air temperature is 800 K because of the combustion of hydrogen. In the region where the stagnation temperature is higher than the flame temperature or too low to maintain reaction, the cooling efficiency of hydrogen is highest. In addition, the effects of the means of injection of coolant gas and the slot number are simulated. The results obtained show obvious differences between a combustible gas and inert gases.

Nomenclature

C = cooling efficiency
E = energy, m^2/s^2
$\boldsymbol{E}$ = vector of convective fluxes in ξ direction
$\boldsymbol{E}_v$ = vector of viscous fluxes in ξ direction
$\boldsymbol{F}$ = vector of convective fluxes in η direction
$\boldsymbol{F}_v$ = vector of viscous fluxes in η direction
J = Jacobian
M = Mach number
m = mass flow rate, kg/(m^2 s)
p = pressure, MPa
$\boldsymbol{Q}$ = vector of conservation variables
q = heat flux term, kg/s^3
$\boldsymbol{S}$ = vector of source terms
T = temperature, K
t = time, s
U = contravariant velocity
u = velocity in the x direction, m/s
v = velocity in the y direction, m/s
x, y = space coordinates, m
η, ξ = generalized curvilinear coordinates
ρ_i = density of i species, kg/m^3
τ_{ij} = viscous shear tensor, kg/(m s^2)
ω_i = production rate of species i, kg/(m^3 s)

Subscripts

ad = adiabatic value
c = coolant
w = wall
0 = main flow

Superscript

d = diffusion term

Introduction

THERE are various technical problems that must be overcome in the development of an aerospaceplane or a supersonic transportation system. In particular, the development of the scramjet engine and the protection of its body and engine from strong heating are most important and difficult issues. For the cooling of high-speed vehicles, many types of systems have been investigated. Among them, film cooling appears to be promising because of its high efficiency, though the structure entailed is complicated. More than 10 kinds of coolant gases have been investigated theoretically and experimentally. A major finding of past studies is that the cooling efficiency becomes higher with smaller molecular weight and larger heat capacity of the coolant gas[1–3] (helium is considered to be the most suitable coolant, and many experiments on helium have been conducted). The reason for this is that small molecular weight results in a thick cooling layer for constant mass flow rate, and large heat capacity means that a large amount of heat can be absorbed.

However, the necessity of carrying tanks for storage of coolant gas places difficult demands on an aerospaceplane with regard to efficiency. Therefore, hydrogen loaded as a fuel is a candidate for use as the coolant gas for the body of an aerospaceplane. Of course, it can also be used for cooling of the engine. When hydrogen is ejected into a hot air stream, the possibility of establishing a diffusion flame must be considered. In that case, it is unclear whether a cooling effect can be obtained or not. Sutton's analysis[4] showed that the effect of the reaction of combustible coolant gas on cooling efficiency becomes smaller as the allowable wall temperature of a high-speed vehicle increases. Also, Aihara[5] reported that an injection of hydrogen along the body of an aerospaceplane decreases friction on the body. Therefore, the properties of hydrogen as a coolant are of great practical interest.

In this study, the cooling efficiency of hydrogen for a cylindrical body in supersonic airflow is investigated in comparison with the efficiency of nonreactive gases (nitrogen and helium) by solving the two-dimensional multispecies Navier–Stokes equations including full chemistry. Differences in the cooling effect between combustible gas and nonreactive gas are apparent in the results obtained.

Formulation

The configuration of the flowfield is shown in Fig. 1. A cylinder with one slot is placed behind a detached shock wave in a supersonic airflow. A coolant gas issued uniformly from a slot located over 5 deg from the centerline of the cylindrical body. Other experimental studies on cooling effects with helium or other coolant gases[1,2] were conducted using the same configuration as that of Fig. 1.

The two-dimensional compressible Navier–Stokes equations in the generalized curvilinear coordinate for several species are considered as governing equations:

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial (\boldsymbol{E} - \boldsymbol{E}_v)}{\partial \xi} + \frac{\partial (\boldsymbol{F} - \boldsymbol{F}_v)}{\partial \eta} = \boldsymbol{S} \tag{1}$$

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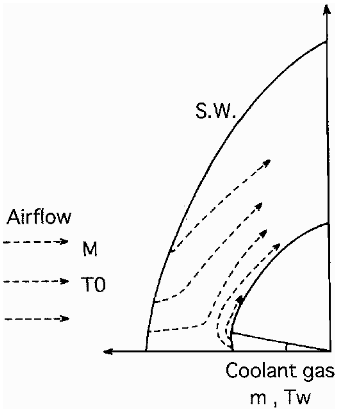

Fig. 1 Schematic of flow configuration.

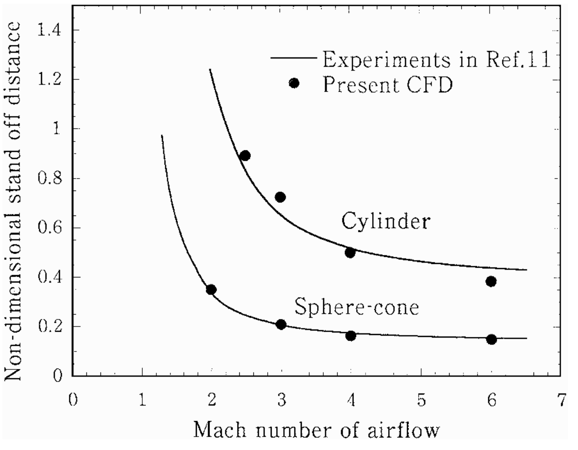

Fig. 2 Comparison of shock standoff distances between calculation and experiments.[11]

Representative terms are expressed as follows:

$$Q = \begin{pmatrix} \rho_1 \\ \vdots \\ \rho_n \\ \rho u \\ \rho v \\ E \end{pmatrix}, \qquad E = J \begin{pmatrix} \rho_1 U \\ \vdots \\ \rho_n U \\ \rho u U + \xi_x p \\ \rho v U + \xi_y p \\ U(E + p) \end{pmatrix}$$

$$E_v = \begin{pmatrix} -\rho_1 U_1^d \\ \vdots \\ -\rho_n U_n^d \\ \xi_x \tau_{xx} + \xi_y \tau_{xy} \\ \xi_x \tau_{xy} + \xi_y \tau_{yy} \\ \xi_x \beta_x + \xi_y \beta_y \end{pmatrix}, \qquad S = J \begin{pmatrix} \omega_1 \\ \vdots \\ \omega_n \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\beta_x = u\tau_{xx} + v\tau_{xy} - q_x, \qquad \beta_y = u\tau_{xy} + v\tau_{yy} - q_y$$

Specific heats and formation enthalpies for each species, including nitrogen and helium, are determined from the JANAF tables,[6] and transport coefficients are obtained from the kinetic theory.[7,8] The hydrogen–oxygen combustion model by Stahl and Warnatz[9] constituted from 8 species (H_2, O_2, H_2O, H, HO_2, OH, O, and H_2O_2) and 37 elementary reactions is used in the present calculation.

Governing equations are solved by the finite difference method using the computer code developed by the author[10] only for the upper side of the cylinder because of the symmetry conditions. The validity of this computer code is confirmed by comparison with experimental data on the shock standoff distances conducted by Billig.[11] Figure 2 shows good agreement between data of the present computational fluid dynamics (CFD) and those of experiments. Also, the author confirmed that an increase of pressure behind a bow shock developed in front of a blunt body in supersonic flow coincided with a value calculated from shock relations.[12] As for the combustion model, there are no experimental results available concerning the configuration of Fig. 1 itself. However, calculations for a hydrogen flame using Stahl and Warnatz's model show good agreement with experimental data on the flammability limit, ignition delay time, and so on.[13] Moreover, Ju[14] recently applied this model to combustion of hydrogen in supersonic flow, and he obtained good agreement with other combustion models. Therefore, the choice of the combustion model is suitable at this stage for this study, whose main purpose is not to discuss the flame structure but to clarify the cooling effect.

The Mach number, temperature, and pressure of the main airflow and the mass flow rate and temperature of the coolant gas are given as boundary conditions. The injection velocity is assumed to be subsonic to avoid the oscillation of the shock-wave surface or interface that appeared in an experiment on a supersonic reverse jet.[15] Only steady-state solutions are considered in the results. An adiabatic wall, except for the injection slot, is assumed, and outflow boundary conditions are determined by extrapolation from the upstream values. The diameter of the cylinder is set at 0.01 m and is constant.

Results and Discussion

Cooling Effect of Nonreactive Gas (Nitrogen)

Nitrogen was initially chosen as the coolant gas to understand the film cooling effect. The conditions of airflow are set at $M = 3.0$, $P_0 = 0.01$ MPa, and $T_0 = 500$ K (the stagnation temperature is about 1300 K), and temperature of the coolant gas is 700 K. Figure 3 shows wall temperature distributions along the surface for four cases of mass flow rates, including the case of no injection. As the mass flow rate of nitrogen increases, the wall temperature decreases. This is due to the increase in thickness of the cooling layer. The cooling effect of nonreactive gas depends mainly on the heat capacity and the molecular weight of the coolant gas.[1,2] The reasons are that the absorption of heat by a coolant gas increases with the heat capacity of the gas, and the thickness of the cooling layer at the same mass flow rate is greater for gases with smaller molecular weight. Various studies have shown helium to be the most feasible coolant.[1,2] Figure 4 shows a comparison of wall temperature distributions between nitrogen and air. The difference is slight because these two gases have almost the same molecular weight and heat capacity.

In this study, the following cooling efficiency is used for consideration of cooling effects of three kinds of coolant gases (nitrogen, helium, hydrogen):

$$C = \frac{T_{ad} - T_w}{T_{ad} - T_i} \tag{2}$$

In the geometry of Fig. 1, the adiabatic wall temperature decreases with an increase in angle from the centerline because of acceleration of the airstream. Of course, the case of $m = 3.6$ has maximum cooling efficiency, about 0.3, in Fig. 3.

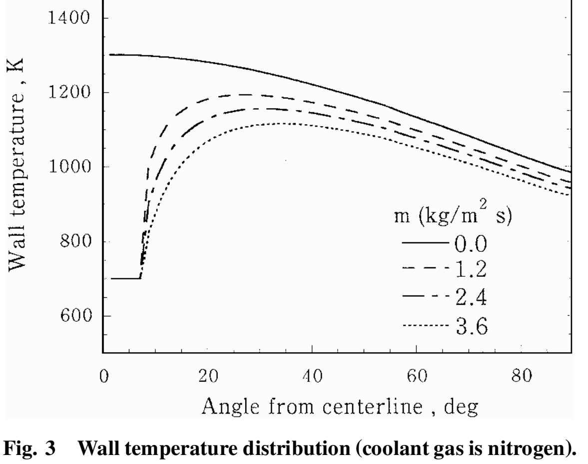

Fig. 3 Wall temperature distribution (coolant gas is nitrogen).

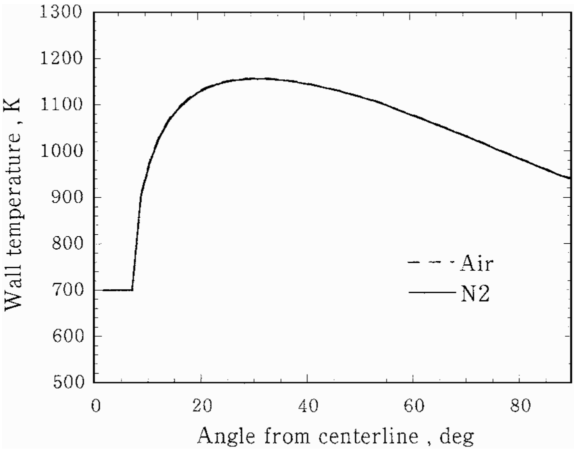

Fig. 4 Comparison of wall temperature between air and nitrogen.

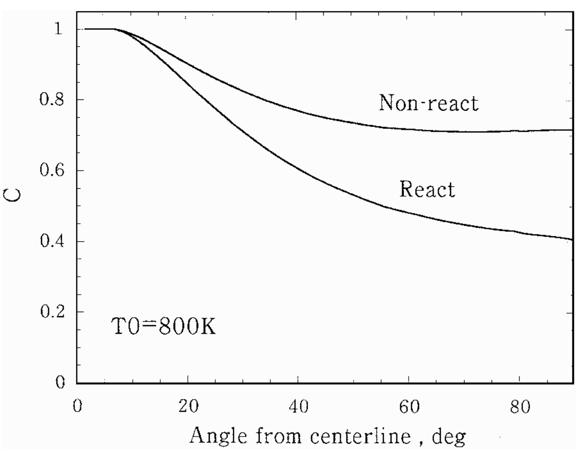

Fig. 5 Effect of reaction on cooling efficiency.

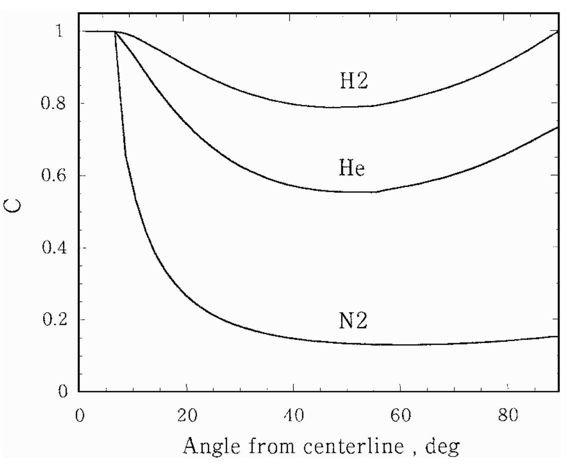

Fig. 6 Comparison of cooling efficiency (T_0 = 500 K).

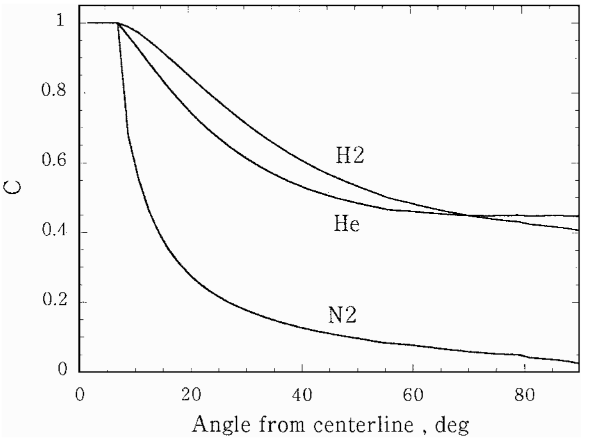

Fig. 7 Comparison of cooling efficiency (T_0 = 800 K).

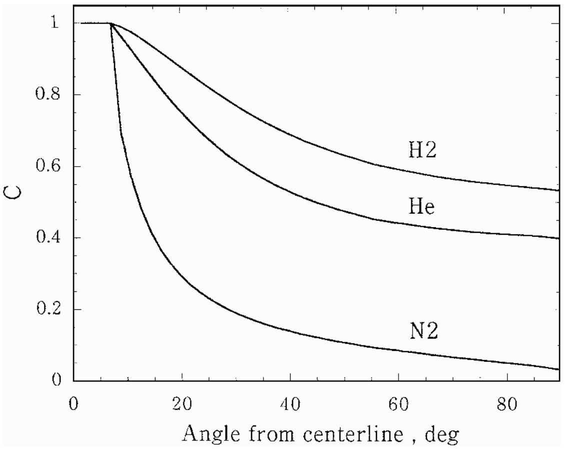

Fig. 8 Comparison of cooling efficiency (T_0 = 1100 K).

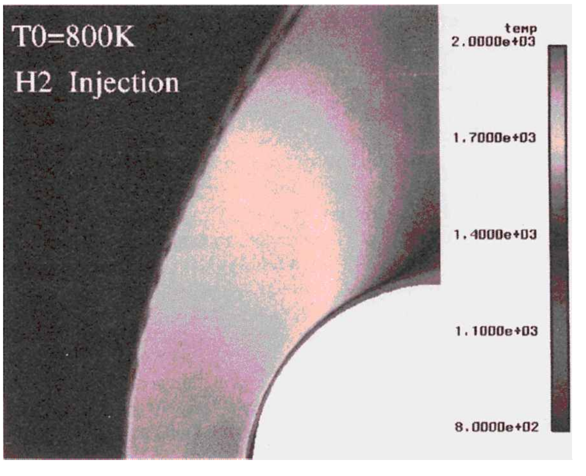

Fig. 9 Temperature contours around the cylinder (T_0 = 800 K, hydrogen).

Cooling Effect of Hydrogen

The cooling effect of hydrogen is investigated by comparisons with nonreactive gases (helium and nitrogen) in Mach 3 airflow. First, the comparison between the case that reactions are numerically omitted and the case with full chemical reactions for hydrogen is shown in Fig. 5, displaying the decrease in cooling efficiency due to the reaction of hydrogen. If the effect of the reaction is omitted, hydrogen has the greatest efficiency of all the gases because it has the highest heat capacity and lowest molecular weight. The cooling efficiency decreases by about 0.2–0.3 (equivalent to a wall temperature of 200–300 K) because of the combustion of hydrogen.

Comparisons of the cooling efficiency of hydrogen with those of nitrogen and helium are shown in Figs. 6–8 for three static air temperatures. In Fig. 6, it can be seen that the cooling efficiencies of hydrogen and helium increase gradually at a large angle from the centerline because cooling gases are greatly accelerated by the main stream of air. Hydrogen has the greatest efficiency because little reaction occurs and unburned hydrogen covers the cylinder at the low air stagnation temperature (about 1300 K). However, as shown in Fig. 7, the cooling efficiency decreases considerably with combustion of hydrogen in the case of a static air temperature of 800 K (the stagnation temperature is about 2000 K). Figure 9 shows temperature contours around the cylinder, clearly showing the cooling layer. Figures 10 and 11 show H_2O and OH radicals contours around the cylinder. It is recognized from Fig. 10 that burned gas (H_2O) covers the cylinder body and that the flame region where the strongest reaction occurs is a little apart from the cylinder surface. The cooling efficiency of hydrogen recovers again in Fig. 8, where the static air

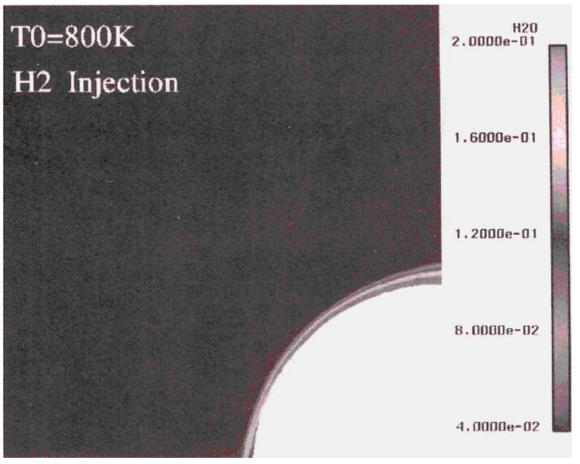

Fig. 10 Mass fraction of H_2O contours around the cylinder (T_0 = 800 K, hydrogen).

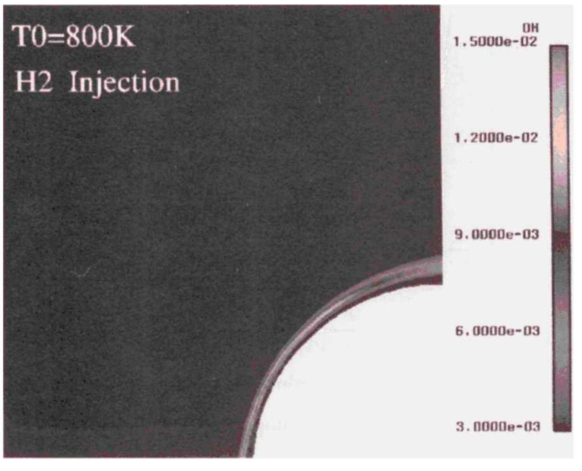

Fig. 11 Mass fraction of OH contours around the cylinder (T_0 = 800 K, hydrogen).

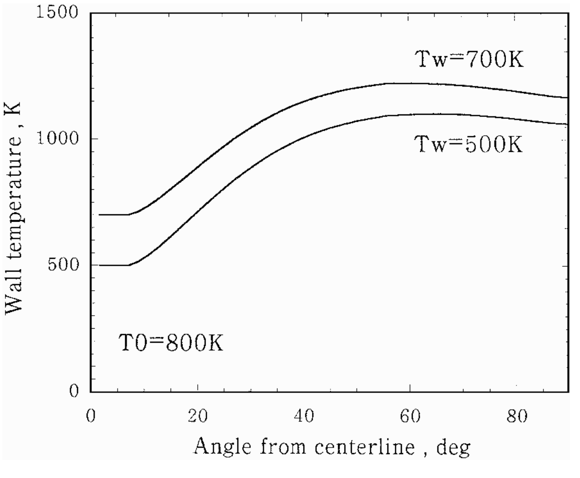

Fig. 12 Effect of temperature of hydrogen on wall temperature.

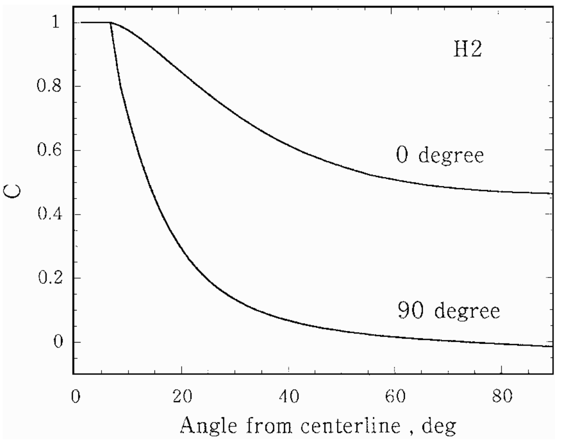

Fig. 13 Cooling efficiency in the case of the injection to tangential direction.

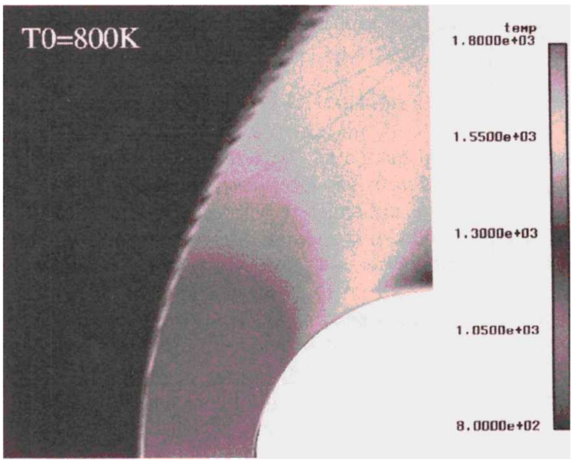

Fig. 14 Temperature contours around the cylinder (tangential, T_0 = 800 K, hydrogen).

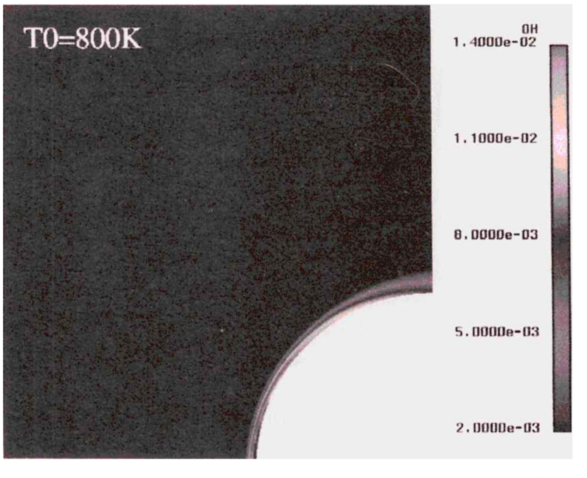

Fig. 15 Mass fraction of H_2O contours around the cylinder (tangential, T_0 = 800 K, hydrogen).

temperature is 1100 K (the stagnation temperature is about 2800 K). This is due to the very small difference between flame temperature and air stagnation temperature. The increases of airflow velocity and stretch rate, corresponding to high static temperature and high sonic velocity, cause a decrease of heat release from chemical reaction.[10]

Figure 12 shows the effect of hydrogen temperature on the wall temperature. A decrease of hydrogen temperature results in a decrease of flame temperature, and thus it is equivalent to an increase of cooling efficiency. This is interesting information from a practical point of view because the allowable wall temperature is the most important parameter in the realistic design of an aerospaceplane. Thus, injection at lower temperature must be effective.

Effects of Slot Configurations

Not only the kind of coolant gas, but also the configuration of injection, is an important factor for film cooling efficiency. The effects of angle and number of injection slots are described in the following discussions.

First, the angle of injection is investigated in Fig. 13. When a coolant gas is ejected perpendicularly to an airstream as an ideal model, the cooling efficiency decreases drastically in comparison with an upstream ejection. Figures 14 and 15 show the contours of temperature and of the mole fraction of OH radical around the cylindrical body in the case of injection normal to the airstream. It is obvious from Fig. 15 that coolant temperature is higher than

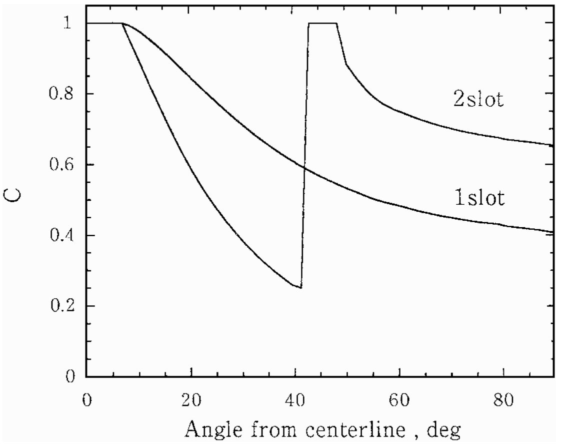

Fig. 16 Cooling efficiency of the case of two slots.

the static air temperature downstream. Moreover, the reaction zone where OH radical concentrations are high sticks to the wall, in contrast to the situation in Fig. 11. This is due to the decrease of the cooling efficiency of hydrogen in comparison with Fig. 6. The cooling efficiency of injection tangential to the surface can be assumed to be better for nonreactive gases.[16] However, numerical results for hydrogen show that an estimation for nonreactive gases cannot be applied to combustible gases. The cooling efficiency of reactive gases depends on the amount of gas that reacts and the distance from the surface to the flame.

It has been demonstrated by many experiments that the film cooling efficiency of one slot decreases toward the downstream area. Local film cooling employing many slots has been proposed for improvement of this decrease of cooling efficiency. Naturally, there are an optimum number of slots and an optimum distance between slots. However, it is not difficult to see that there is a great difference between a combustible gas and a noncombustible gas with regard to the feasible configuration of injection of the coolant. Figure 16 shows a comparison of the cooling efficiencies between one slot and two slots. In the case of two slots, coolant gases are injected into the airflow with the same mass flow rate at 0 and 45 deg from the center of the cylinder. The cooling efficiency downstream of the center slot is much lower than for one slot, although it becomes higher downstream of the second slot. The second slot dams up the coolant flow, which results in a strong reaction around the second slot and yields lower cooling efficiency.

This study is limited to low flow rate and a small cylindrical body, but the effects of combustion of a coolant on cooling efficiency depend strongly on the flow rate and the size of the body. Moreover, a more serious heat condition, for example, type 4 interaction of shock waves,[17] can also be considered. In such a study, direct interaction between the shock wave and the flame must be as important as the turbulence model in compressible flow.

The calculation of this paper can be applied to cooling of an engine. Recently, an experiment on shock-wave impingement on the film cooling layer was conducted,[18] and it was shown that mixing of nitrogen as a coolant gas with the main supersonic flow was greatly promoted by impingement of the shock wave. This must result in promotion of combustion (equivalent to a decrease of cooling efficiency) for the case of hydrogen. Thus, considerations on the reactiveness of cooling gas must be important.

Concluding Remarks

The cooling efficiency of hydrogen was investigated numerically in this study. A summary of the results is as follows.

1) Hydrogen has the greatest efficiency in two regions of static air temperature. One is low static air temperature ($T_0 = 500$ K), where combustion cannot occur, and the other is very high static air temperature ($T_0 = 1100$ K), where the stagnation temperature becomes nearly equal to the flame temperature. However, the cooling efficiency of hydrogen decreases considerably and becomes almost the same as that of helium in the middle region of static air temperature ($T_0 = 800$ K).

2) When hydrogen is injected perpendicularly to the main airflow, the cooling efficiency decreases rapidly because the flame sticks to the wall.

3) Effects of the injection configurations of coolant gas on cooling efficiency change considerably according to whether a coolant gas is combustible or not. The total amount of hydrogen in a reaction and the distance from the wall to the flame must be important in the latter case.

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