Table of the partial calculation results

coolant parameter	T1	In	Sn	H_2O
$\overset{\circ}{m}$ [kg/m^{2}s]	181. 58	76. 27	61. 99	107. 31
m [kg]	4. 50	2. 01	1. 92	2. 92
Δp [atm]	92. 90	62. 44	70. 55	494. 62
Pin [atm]	192. 90	162. 44	170. 55	594. 66

pressure $P_{In} < P_{Sn} < P_{T1} < P_{H_2O}$. The computational example results show that the thernal protection effect of coolant In is best, and the thermal protection effect of coolant H_2O is worst, because the internal pressure (P_{H_2O}) is too high, by which the porous nosetip is detroyed, the H_2O is an unadaptable coolant.

From above result analyses of calculation examples we can derive the following conclusions.

1. The theoretical analysis method based on three simplified assumption is dependable and more accurate.

2. The simplified calculative results agree fairly with the numerical computation of Ref. [1]. The difference between our simplified calculation and numerical compulation of Ref. [1] is about 0. 01- 12 percent.

3. The present calculative method can be used in prediction before the ground simulation experiment, and it can be satisfied for the request of engineering application department.

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SCAT 弹头热防护的简化计算方法

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摘要 本文对自适应发汗冷却(SCAT)弹头的热防护问题作了简化分析, 并导得了热防护计算的简化计算公式。对铊, 铟, 锡和水四种冷却剂的情况, 给出了算例。本文导行的公式, 计算较简便, 可作为弹头热防护设计的一种工程计算方法。这种工程计算方法亦可以用于地模拟实验前的予算。

主题词 发汗冷却 烧蚀 热防护

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A Simplified Calculative Method for Thermal Protection of SCAT Nosetip

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ABSTRACT *Simplified analysis for thermal protection of the Self-Contained Adaptive Transpiration (SCAT) nosetip is provided and the simplified calculation formulas of thermal protection are deduced. The calculation examples of thallium, indium, tin and water coolants are given. The deduced fomulas in this paper are simple and convenient. An engineering calculation method of nosetip thermal protection design is obtained in this paper. It can be used in prediction before the ground simulation experiment.*

KEY WORDS Transpiration cooling Ablation Thermal protectionon

Nomenclature

H = total enthaply
h = static enthaply
L_v = vaporized
m = total coolant mass flux
$\overset{\circ}{m}$ = coolant mas flux rate
M = moleculax weight
p = pressure
q = heat flux
R = universal gas constant
$\overline{R}$ = nose radius
S = surface area of porous matrix
T = temperature
t = time
Z = compressed coefficient
ρ = density
Γ = permeability
μ = viscosity

Subscripts

a = air
c = coolant
E = vaporous species of coolant
ex = external flow conditions
g = gas
in = interior flux condidions
l = liquid
la = laminar flow

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r = radiation	ω_1 = external wall
S = stagnation point condition	ω_2 = interior wall
t = turbulent flow	

Introduction

The Self- Contained Adaptive Transpiration (SCAT) is adopted in the thermal protection for advanced reentry vehicles. The SCAT nosetip design must determine the weight of the coolant and driver materials, and to select suitale coolant preliminary and applicability porous structures. Characterization of the prous structure for SCAT was achieved by determining their liquid metal permeability at elevated temerature and pressure using liquid coolant. These subjects requiring considerably more analytical and/or experimental investigation are noted. Theoreticalstudies can be adopted to solve some problems such as flow characteritics of porousmedia (i. e. internal flow of SCAT). Because of transpiration- cooled nosetip at high heat transfer rates and stagnation pressure interaction and interchange of mass, momentum and energy exist within the surface cooling flow, porous structures and gas boundary layer. Therefore the permeable flow of transpiration-cooled nosetip is more complicated than that of general permeable flow. It is necessary to solve a partial differental equation group with four equations and to calculate the dual iteration of internal plenum pressure, permeability and wall thickness in numerical calculation. Therfore it is very neccessary to explore a simplified calculation. A simplified calculation method being satisfied with engineering presision is provided in this paper.

Analysis and deduction of calculative formulae

In the SCAT concept, coolant and driver materials are stored within the nosetip shell (reservoir). During reentry, the coolant is melted and the driver materials is vaporized as a result of aerodynamic heating to the nosetip and conduction through the shell. During early reently when only a small region of the coolant at the forward portion has melted and most of the driver is still in its solid form. At a later state of reentry, additional coolant gas melted and the driver materials has melted and is vaporizing at the rear of the reservoir. Deceleration forces tend to locate the higher density liquid and solid coolant toward the front of the nose tip and the lower density liquid and vapor driver at rear. The liquid coolant, pressurized by the driver in this manner, flows onto the nose tip surface through the porous or channeled matrix. Thermal protection of the matrix and solid shell are provided through energy absorbed by the coolant as it vaporizes, boils, and absorbs heat in the gas boundary layer.

Later in reentry, the majority of the coolant is molten and the driver vapor occupies a larger portion of the reservoir volume. There is considerable fluid convection taking place within the liquid coolant due to the deceleration load and temperature difference between forward and aft nose tip components, which results in enhanced heat transfer between the coolant and shell and within the coolant itseld. For internal flow of SCAT porous matris the following simplified assumption are used:

1. The coolant flow in porous media is an one-dimensional quasi-steady-state flow, its chemical reaction with porous media is not occurred (see Fig. 1).

2. The liquid coolant is not vaporized in the reservoir, and is vaoprized wholly at external surface of porous nosetip (i.e. the liquid layer is thinnest or no exits in the surface of porous nosetip).

3. The thickness of porous matrix is thinner, the change of thermal enthalpy in porous wall of liquid coolant is far small with its vaporized heat in reservoir. During reaching or apporaching steady-state flow, then yield:

$$(T_{w1} - T_{w\omega2})/T_{w\omega1} \ll 1。$$

Deduction of calculative formulas for thermal Portection

According to above simplified assumption and enegy equation of one-dimensional quasisteady-state flow the simplified calculation formulae of internal flow parameter are deduced.

1. Calculative formulae of coolant mass flow rate

According to the mechanism of transpiration cooling thermal protection and simplified assumptions 1, 2, the one-dimensional quasi-steady-state energy equation is deduced:

$$q_{w\,ig} - q_{rw_1} - \mathring{m} h_{w_1}(g) + \mathring{m} h_{w_2}(l) = q_{sw_2} \tag{1}$$

Assuming that influence for output coolant flow of internal plenum pressure is smallest, internal plenum pressure and temperature are approaching constant, then $q_{sw_2} \approx 0$.

Because the wall temperature of transpiration cooling nosetip is lower, q_{rw_1} in equation (1) may be negligible. Substitute l_v, $h_{w_1}(l)$ into equation (1), then yields

$$q_{w_1 g} - \mathring{m}[hw_1(g) - h_{w_1 E} + c_{pl}(T_{w_1} - T_{w_2}) + L_v] = 0$$

where

$$\mathring{m} L_v = \mathring{m}[h_{w_1 E} - h_{w_1}(l)] \tag{3}$$

$$h_{w1}(l) = h_{w2}(l) + c_{pl}(T_{w_1} - T_{w_2}) \tag{4}$$

$$\Delta H \equiv h_{w_1}(g) - h_{w_1 E} + c_{pl}(T_{w_1} - T_{w_2}) + L_v \tag{5}$$

then

$$q_{w_1g} - \overset{\circ}{m}\Delta H = 0 \tag{6}$$

According to simplified assumption (3), the $c_{pl}(T_{w_1} - T_{w_2}) \ll L_v$, *then* $c_{pl}(T_{w_1} - T_{w_2})$ may be negligible generally. In order to proving the $[h_{w_1}(g) - h_{wis}] \ll L_v$, $h_{w_1}(g) - h_{wis}$ may be negligible, a detailed analysis of following is necessary.

$$q_{w_1g} = \left(k\frac{\partial T}{\partial y}\right)_{w_1} - \left(\sum j_i h_i\right)_{w_1} \tag{7}$$

$$\left.\begin{aligned} w_i &= \overset{\circ}{m}K_{iw_i} + j_{iw_i} \quad i \neq E \\ \overset{\circ}{m} + \overset{\circ}{w}_E &= \overset{\circ}{m}K_E + j_E \end{aligned}\right\} \tag{8}$$

Substitute equations (7) and (8) into (2), then yields:

$$\left(k\frac{\partial T}{\partial y}\right)_{w_1} - \sum_{i \neq E}(j_i + \overset{\circ}{m}K_i)_{w_i}h_{iw_1} - (j_E + \overset{\circ}{m}K_E - \overset{\circ}{m})_{w_1}h_{w_1E} - \overset{\circ}{m}L_v - \overset{\circ}{m}c_{pl}(T_{w_1} - T_{w_2}) = 0$$

When the chemical reaction has not occurred at porous wall w_1, the second and third term are equal zero in the above equation, then the enthalpy of injected species h_{w_iE} is separated by two terms

$$h_{w_iE} = (L_v + h_E^{\circ}) + h^*_{w_1E} \tag{9}$$

Substitute equation (7), (8) and (9) into equation (2), then yields:

$$\left[k\frac{\partial T}{\partial y} - \sum_{i \neq E} j_iK_i - j_Eh_E^*\right]_{w_1} - \overset{\circ}{m}\left[\sum_{i \neq E}K_ih_i - K_Eh_E^*\right]_{w_1} + \overset{\circ}{m}h^*_{Ew_1} - \overset{\circ}{m}[L_v + c_{pl}(T_{w_1} - T_{w_2})] = 0 \tag{10}$$

Where

$$q^*_{w_ig} = \left[k\frac{\partial T}{\partial y} - \sum_{i \neq E} j_ih_i - j_Eh_E^*\right]_{w_1} \tag{11}$$

Then, the equation (10) becomes

$$q^*_{w_1g} - \overset{\circ}{m}\left[\left(\sum_{i \neq E}K_ih_i + K_Eh_E^*\right)_{w_1} - (1 - K_{Ew_1})h^*_{w_1E} + L_v + c_{pl}(T_{w_1} - T_{w_2})\right] = 0 \tag{12}$$

where

$$\Delta H_* \equiv \left[\left(\sum_{i \neq E}K_ih_i + K_Eh_E\right)_{w_1} - (1 - K_{Ew_1})h^*_{w_1E} + L_v + c_{pl}(T_{w_1} - T_{w_2})\right] \tag{13}$$

The $h^*_{sw_1}$ of equation (13) in frist and second right terms all have not included the contribution of L_v and h_e^*. Generally, $h_i \ll L_v$ therefore in above approximate calculative formula of heat flux for injected influence, the ΔH_* may be approximately as following

$$\Delta H^{*} \approx L_{v} + c_{pl}(T_{w_1} - T_{w_2}) \approx L_{v} \tag{14}$$

Now combining Eqs (12) and (14) yield:

$$\overset{\circ}{m} \frac{q^{*}_{w_1 g}}{\Delta H^{*}} = \frac{q^{*}_{w_1 g}}{L_{v}} \tag{15}$$

The formulae of approaching heat flux in Ref. [2] has been employed in the present analysis. Substituting formulae of approached heat flux in Ref. [2] into Eq. (15) yields:

$$\overset{\circ}{m}_{la} = \frac{q_{w_0}}{L_{v}\left[1 + 0.6\left(\frac{M_a}{M_c}\right)^{\frac{1}{3}}\right]} \tag{16-a}$$

$$\overset{\circ}{m}_{t} = \frac{q_{w_0}}{L_{v}\left[1 + 0.2\left(\frac{M_a}{M_c}\right)^{\frac{1}{10}}\right]} \tag{16-b}$$

2 Caculative formulae of taotal coolant mass flux

According to the simplified assumptions 1 and 3, the Eqs (16-a) and (16-b) can be integrated

$$\mathrm{m}_{\mathrm{la}} = \iint_{t_0 s_0}^{t\ s} \frac{\psi q_{w_0}}{\mathrm{L}_{\mathrm{v}}\left[1 + 0.6\left(\frac{\mathrm{M}_{\mathrm{a}}}{\mathrm{M}_{\mathrm{c}}}\right)^{\frac{1}{3}}\right]} d s d \mathrm{t} \tag{17-a}$$

$$\mathrm{m}_{\mathrm{t}} = \iint_{t_0 s_0}^{t\ s} \frac{\psi q_{w_0}}{\mathrm{L}_{\mathrm{v}}\left[1 + 0.2\left(\frac{\mathrm{M}_{\mathrm{a}}}{\mathrm{M}_{\mathrm{c}}}\right)^{\frac{1}{10}}\right]} d s d \mathrm{t} \tag{17-b}$$

3 Calculative formulate of internal flux pressure for nosetip shell

According to the simplified assumption (2) the equation of coolant mass flow rate, $\overset{\circ}{m}$, is deduced by one-dimensional monmentum equation directly

$$\overset{\circ}{m} = -\Gamma \frac{\rho}{\mu} \frac{\mathrm{d}P}{\mathrm{d}x} \tag{18}$$

For the liquid coolant, the density is constant, integration of Eq. (18) leads to desired internal flux pressure; for the gas coolant, the density is not constant, in integration of Eq. (18) the gas state equation has been employed. The calculative formulae of internal flux pressure for nosetip shell is for the liquid coolant.

where

$$\frac{P}{\rho} = ZRT \tag{19}$$

$$\overset{\circ}{m} \int_{\bar{R}_{in}}^{\bar{R}_{er}} \mathrm{d}\bar{R} = -\int_{P_{in}}^{P_{ex}} \frac{\Gamma P}{ZRT\mu} \mathrm{d}P \tag{20}$$

$$\therefore \quad \overset{\circ}{m} = \frac{\Gamma(p_{in}^{2} - p_{ex}^{2})}{2\mu ZRT(\bar{R}_{ex} - \bar{R}_{in})} \tag{21}$$

for the gas coolant

$$P_{(in)la} = \left\{ \frac{2\mu ZRT(\overline{R}_{ex} - \overline{R}_{in})q_{w0}}{\Gamma L_v\left[1 + 0.6\left(\frac{M_a}{M_c}\right)^{\frac{1}{3}}\right]} + P_{ex}^2 \right\}^{\frac{1}{2}} \tag{22}$$

$$P_{(in)t} = \left\{ \frac{2\mu ZRT(\overline{R}_{ex} - \overline{R}_{in})q_{w0}}{\Gamma L_v\left[1 + 0.2\left(\frac{M_a}{M_c}\right)^{\frac{1}{10}}\right]} + P_{ex}^2 \right\}^{\frac{1}{2}} \tag{23}$$

for liquid coolant

$$P_{(in)la} = \frac{q_{w0}\mu(\overline{R}_{ex} - \overline{R}_{in})}{\rho\Gamma L_v\left[1 + 0.6\left(\frac{M_a}{M_c}\right)^{\frac{1}{3}}\right]} + P_{ex} \tag{24}$$

$$P_{(in)t} = \frac{q_{w0}\mu(\overline{R}_{ex} - \overline{R}_{in})}{\rho\Gamma L_v\left[1 + 0.2\left(\frac{M_a}{M_c}\right)^{\frac{1}{10}}\right]} + P_{ex} \tag{25}$$

Calculate exmaples and conclusion

For a check of validity of simplified method a computation example is given. According to the parameters of ballistic missle reetry thermal protection of SCAT with four different physical character coolant are calculated. The partial calculated results are given in table and shown in Figures 1- 2. It is known from Figure 1 and 2 that in reentry process the pressure and coolant flow rate have changed with reentry time for collant of thallium.

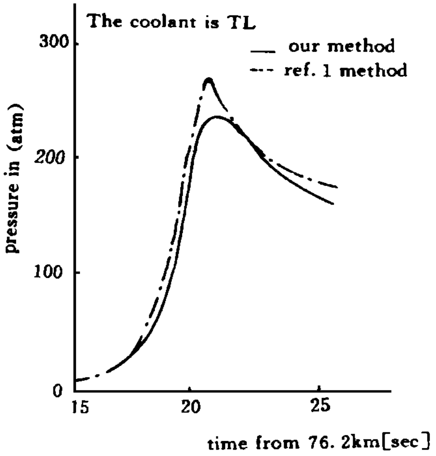

Fig. 1 Change of pressure in reenty process

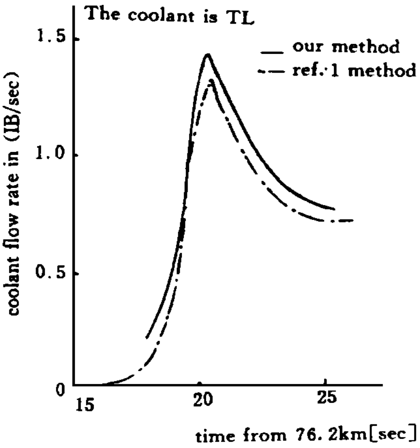

Fig. 2 Coolant flow rate history in reenty process

The table shows that total coolant mass flow $m_{Sn} < m_{In} < m_{H_2O} < m_{TL}$; the interal