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Engineering Notes

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Analytical Formulation for Thermal Protection of Active Cooling Nosetips

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Nomenclature

H = total enthalpy, J/kg
h = static enthalpy, J/kg
L_v = vaporized latent heat, J/kg
$\underline{M}$ = total coolant mass, kg
$\bar{M}$ = molecular weight
$\dot{M}$ = coolant flow rate, kg/s
$\dot{m}$ = coolant mass flux, kg/m^{2}s
p = pressure, atm
q = heat flux, J/m^{2}s
$\underline{R}$ = universal gas constant, 8341.3 J/kg mole k
$\bar{R}$ = nose radius, m
S = surface area of porous matrix, m^2
T = temperature, K
t = time, s
Z = compressed coefficient
Γ = permeability, Darcy
μ = dynamic viscosity, kgs/m^2
ρ = density, kg/m^3

Subscripts

a = air
c = coolant
E = vaporous species of coolant
ex = external flow conditions
g = gas
in = interior flux conditions
l = liquid
l_a = laminar flow
r = radiation
s = stagnation-point condition
t = turbulent flow
w_1 = external wall
w_2 = interior wall

Introduction

THE active cooling nosetip design must determine the weight of the coolant and driver materials and select suitable coolant preliminary and applicable porous structures. Characterization of the porous structure for self-contained adaptive transpiration (SCAT) was achieved by determining liquid metal permeability at elevated temperature and pressure using liquid coolant. The subjects requiring considerably more analytical and/or experimental investigation are noted.

Theoretical studies can be adopted to solve some problems such as flow characteristics of porous media. Interaction and interchange of mass, momentum, and energy exist within the surface cooling flow, porous structures, and gas boundary layer due to transpiration-cooled nosetips at high heat transfer rates and stagnation pressure. Therefore, the permeable flow of transpiration-cooled nosetips is more complicated than general permeable flow. It is necessary to solve a partial differential equation group with four equations and to calculate the dual iteration of internal pressure, permeability, and wall thickness in numerical calculations. Therefore, it is necessary to explore a simplified calculation. One method will be provided in this Note.

Simplified Assumption

In the SCAT concept, coolant and driver materials are stored within the nosetip shell (reservoir). During re-entry, the majority of the coolant is molten and the driver vapor occupies a larger portion of the reservoir volume. A considerable amount of fluid convection takes place within the liquid coolant due to the deceleration load and temperature difference between forward and aft nosetip components. This results in enhanced heat transfer between the coolant and shell and within the coolant itself. For internal flow of the SCAT porous matrix, the following simplified assumptions are used.

1) The coolant flow in porous media is a one-dimensional, quasi-steady-state flow. Coolant chemical reaction with the porous media does not occur.

2) The liquid coolant is not vaporized in the reservoir but is vaporized wholly at the external surface of the porous nosetip, i.e., the liquid layer is thinnest or absent at the surface of the porous nosetip.

3) The thickness of the porous matrix is reduced, and the change of the thermal enthalpy in the porous wall of liquid coolant is much smaller with the vaporized heat in the reservoir. As it approaches steady-state flow, it yields

$$\frac{T_{w_1} - T_{w_2}}{T_{w_1}} \ll 1$$

Deduction of Calculative Formulas for Thermal Protection

The simplified calculation formulas of internal flow parameters are deduced based on previous simplified assumptions and energy equations of one-dimensional quasi-steady-state flow.

Calculate Formulas of Coolant Flow Rate

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

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

Assuming that the influence for output coolant flow of internal plenum pressure is smallest and internal plenum pressure and

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