Technical Notes

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Surface Cooling by Transpiration of a Freezing Liquid

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Introduction

At hypersonic speeds, it may be impossible to find a material that can survive the aerodynamic heating environment. Under these circumstances, some cooling mechanism must be provided. Ablation offers the convenience of being a passive type of external cooling, but for some applications the resulting changes in shape are undesirable. In those cases, a controlled transpiration appears to be a more promising cooling method. A wind-tunnel experiment was undertaken, therefore, to help in the development of some simple means of estimating how much liquid coolant would be required for a given mission.

The objective of the wind-tunnel test was to measure the surface cooling produced on a test model using liquid injection through a porous nose tip. The tests were performed in the Naval Surface Warfare Center (NSWC) Supersonic Wind Tunnel 2. However, the water used as the liquid injectant quickly froze and covered all or part of the model with a layer of ice even though the stagnation temperature was about 685° R (380.6 K) and the adiabatic wall temperature on the model was approximately 645 °R (358.3 K). In fact, when the tunnel was shut down, the front part of the model was found to be covered with ice while the rear half was too hot to touch. A possible explanation of this observation was that the evaporation process removed a significant portion of heat from the injected cooling water, enough to cause it to freeze. In the remainder of this report, the test will be described and the results will be discussed.

Facility and Model Description and Test Conditions

All tests were carried out in the NSWC Supersonic Wind Tunnel 2. Tunnel 2 is a 16 × 16 in. (40.6 × 40.6 cm) cross section horizontal tunnel. For these tests, the tunnel was operated in a continuous mode at Mach 4. The supply temperature was 685 °R (380.6 K) and the supply pressure was 1.3 atm resulting in a unit Reynolds number of 1,300,000/ft (4,260,000/m).

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Conical Test Model

The test model (hemisphere-cylinder-cone configuration) is shown in Fig. 1. A metered quantity of cooling water was supplied to the porous part of the model's nose tip, through the hollow support sting. This porous section was cut from commercially available, porous tubing. The conical section of the test model was Plexiglas instrumented with thermocouples.

The only coolant used in this test series was water. It was pumped from an external reservoir by the pressure difference between the exterior ambient pressure and the much lower wind-tunnel pressure. A needle valve controlled the coolant flow rate.

Experimental Test Results

Water at 510 °R (283.3 K) froze solid when it was injected through the porous material onto the model surface where the adiabatic wall temperature was 645 °R (358.3 K). Apparently the evaporating vapor at the surface extracted a significant part of its heat of vaporization from the remaining liquid, thus causing it to freeze. The formation of ice sealed the porous cylinder, shutting off the flow of cooling water. When the ice melted, water flow was restored at the porous section, thus initiating a cyclic process that automatically regulated the coolant supply, maintaining part of the surface approximately at the freezing point of the coolant.

Model surface temperatures are shown in Fig. 2, plotted as a function of distance along the model surface at various instants of time after the beginning of the run. At $t = 2.5$ s, coolant flow had not started and the model temperature was approximately constant at the value of 645 °R (358.3 K), the adiabatic wall temperature for a pointed cone. After 47.5 s, the front part of the cone began to cool; and at $t = 107.5$ s,

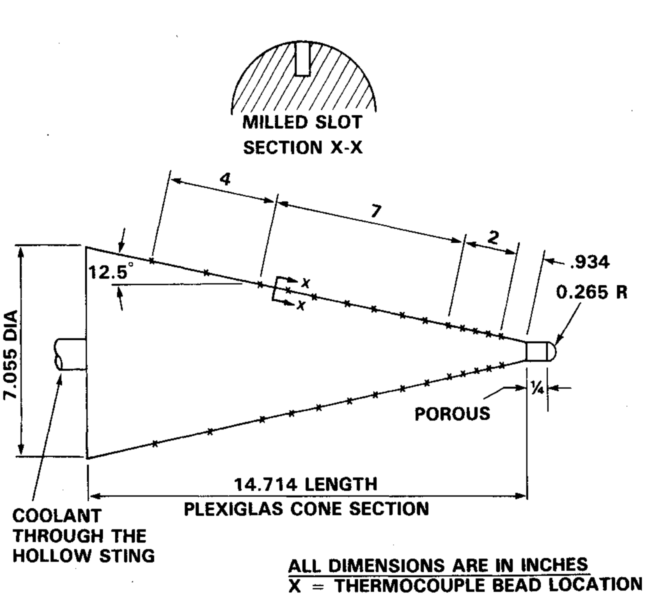

Fig. 1 Radome cooling test model.

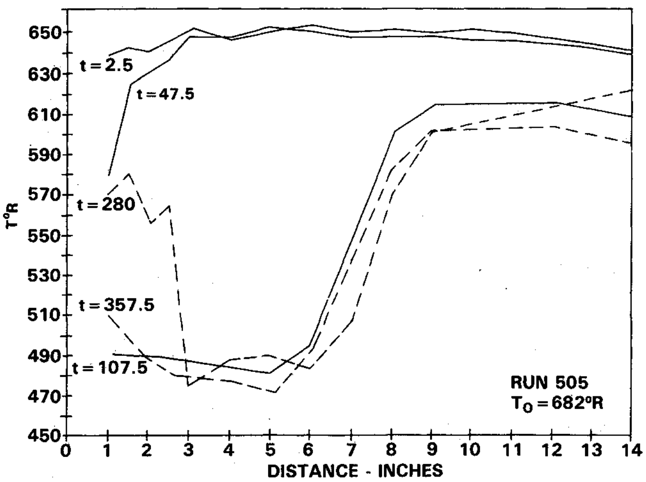

Fig. 2 Temperature distributions.

the front 6 in. (15.2 cm) of the cone were covered with ice at about 485 °R (269.4 K). Beyond that point, the temperature rose rapidly toward the adiabatic wall value. At t = 280 s the ice melted from the first 2.5 in. (6.4 cm), and then froze again at the end of the test (t = 357.5 s). A more detailed description of the test may be found in Ref. 1.

Modeling of Results

The temperature distribution along the conical portion of the model can be computed by various analytical methods. For example, the method of Rubesin and Inouye[2] may be applied to the present case. If the temperature on the part of the model covered with ice is fixed at the freezing point and the rest of the model is assumed to be nonconducting, the analysis predicts a much more rapid rise in temperature as a function of distance along the surface than that observed in the experimental result shown in Fig. 2. Apparently, water vapor from the subliming ice diffuses into the boundary layer producing a region of about 2.5 in. (6.35 cm) over which this diffusion process results in a linear temperature rise.

Applications of Freezing Liquid

The freezing-liquid cooling method can be likened to an ablation-cooled surface which employs one or more bands of ablating material to keep the maximum temperature within safe limits. The geometry is shown schematically in Fig. 3. As the material ablates, it is automatically replaced by new frozen liquid.

This phenomenon might be useful in applications where the geometry change due to ablation produces undesirable side effects. For example, ablative radomes are likely to undergo undesirable changes in transmissive properties.[3] Transpiration cooling by a freezing liquid applied at the tip of the radome might achieve the desired cooling effect without interfering with its downstream geometry.

Water is unlikely to freeze upon transpiration into a hypersonic boundary layer because its heat of vaporization would not be sufficient to lower the temperature of the emerging liquid to its freezing point. A coolant that melts at a temperature slightly lower than the adiabatic wall temperature would be required. Furthermore, the properties of the coolant vapor should be selected to maximize the downstream effect of its diffusion into the boundary layer. Thus, the radome temperature could be maintained within the limits of material integrity without the need for further cooling at downstream sections. Liquid copper might be chosen as a possible coolant for flight at a Mach number of 8 at 50,000 ft (15,240 m). The heat of vaporization of the copper should be large enough to cause solidification of the emerging liquid copper analogous to the water-freezing process observed in the wind-tunnel test. Because of its high density and high conductivity, the copper

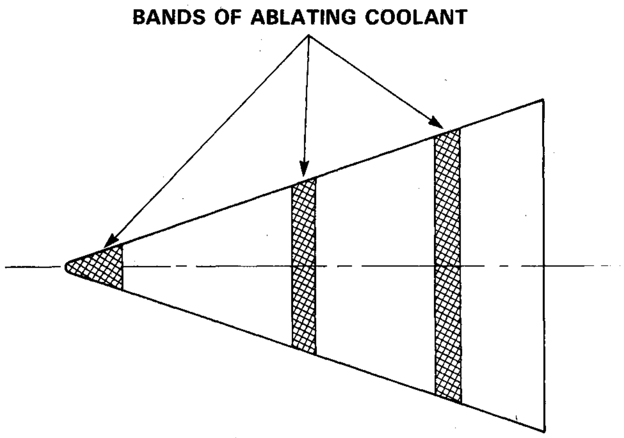

Fig. 3 Schematic of hypothetical liquid-cooled radome.

vapor mixing with the external flow will create a long region in which the heat transfer to the radome decreases while the temperature rises gradually toward the adiabatic wall value. Hence, cooling the front part of the radome with ablating copper might lower the temperature of the entire radome to acceptable levels. In practice, a lump of solid copper could be placed within a porous section of a conducting metal with a higher melting point, such as a steel alloy. When aerodynamic heating is conducted to the copper, the copper melts and seeps through the porous material. At the surface, the copper solidifies and cools the radome by ablating. The ablated copper is continuously replaced by liquid from melting of the original lump of copper. Estimates of copper-ion concentration indicate that the electric field conductivity would not interrupt the radar signal.

Another possible application of this freezing-melting technique might be the cooling of the throat region of hypervelocity wind-tunnel nozzles or of rocket nozzles. Transpiration of gaseous coolants has previously been applied to nozzle throats. The use of a freezing liquid (possibly copper) as the coolant would benefit from the heat of vaporization of the phase change while maintaining a nearly constant geometry. The coolant could be supplied, for example, by a replaceable copper ring retained by a ring of porous steel placed upstream of the throat.

A third possible application of cooling by a freezing liquid ablator would be for the protection of the nose of re-entry vehicles. In cases where the change of shape due to ablation is unacceptable, the freezing liquid (again, copper might be suitable) could provide the necessary cooling in a shape-stable configuration. Transpiration cooling by a liquid metal has been previously investigated[4] as a possible means for cooling re-entry vehicle nose tips. In that application, the objective was to develop an erosion-resistant, shape-stable nose. Techniques for containing and injecting a melting metal coolant were successfully demonstrated.

Concluding Remarks

The significant results of this investigation can be summarized as follows:

1) A liquid coolant may freeze when injected into a high-temperature boundary layer.

2) The freezing apparently results from the loss of the heat of vaporization from the liquid as it evaporates.

3) The phenomenon might be applied, with further development, to produce the equivalent of a shape-stable ablative coolant.

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Microstructure Effects on the Conjugate Heat Transfer Along a Vertical Circular Pin

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Nomenclature

B, Δ, λ = dimensionless material parameters, $[B = R^2/j$, $\Delta = \kappa/\mu$, $\lambda = \gamma/(\mu j)]$
C_p = specific heat
F = dimensionless stream function
G = dimensionless microrotation function
Gr = Grashof number
h = heat transfer coefficient
h = dimensionless heat transfer coefficient
j = microinertia per unit mass
k = thermal conductivity
L = length of the pin
N = angular velocity
N_c = convection-conduction parameter
Pr = Prandtl number
Q = overall heat transfer rate
q = local heat flux
R = radius of the pin
Re = Reynolds number, (UR/ν)
r = radial coordinate
T = temperature
U_∞ = freestream velocity
u, v = velocity components in x and r directions, respectively
x = streamwise coordinate
α = thermal diffusivity
η, ξ = pseudosimilarity variables
θ = dimensionless temperature
μ, κ, γ = material constants
ρ = density of fluid
σ = surface curvature parameter, $(4L/R)\, Re^{-1/2}$
ψ = stream function
Ω = buoyancy parameter, (Gr/Re^2)

Subscripts

f = properties of the fluid
w = properties of the solid pin
0 = conditions of root of the pin
∞ = conditions at freestream

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Introduction

The problem of conjugate convection and conduction for a vertical plate fin has been studied by Sparrow and Acharya[1] and Sparrow and Chyu.[2] Quite recently, Gorla[3] presented an analysis for the heat transfer characteristics of a laminar forced convective flow of a Newtonian fluid over a circular pin by the conjugate convection-conduction theory including radiative effects under optically thick limit approximation. The problem of conjugate natural convection from a vertical fin to micropolar fluids was studied by Lien and Chen.[4] The heat transfer characteristics of a moving cylinder in a quiescent micropolar fluid were studied by Gorla.[5] Moutsoglou[6] investigated the effects of the stretching of filaments on the cooling of fibers during the melt-spinning process.

In the present paper, consideration is given to a circular pin fin extending from a wall and transferring heat to a surrounding micropolar fluid. The temperature of the fin is not known a priori. The heat transfer coefficient along the circular pin is not prescribed but will be determined from a solution of the boundary-layer equations and its interaction with the pin conduction. Numerical results are presented for the local heat transfer coefficient and distribution of temperature along the length of the pin.

Analysis

Let us consider a uniform freestream flow of a micropolar fluid, with velocity U_∞ and temperature T_∞, approaching a circular pin of radius R and length L. The pin is attached to a wall of temperature T_0. The thermal conductivity of the pin is κ_w. The temperature of the pin, T_w, varies along its length. The axial and radial coordinates are taken to be x and r, respectively. The conservation equations, within Boussinesq approximation, are given in Ref. 5, and, therefore, will not be repeated to conserve space.

Preceding with the analysis, we now introduce the following variables:

$$\xi = \frac{x}{L}, \qquad \eta = \left(\frac{r^2 - R^2}{4RL}\right)\left(\frac{Re}{\xi}\right)^{1/2}$$

$$\psi(x,r) = R(\nu U_\infty x)^{1/2} F(\xi,\eta)$$

$$N(x,r) = \frac{R}{r}\left(\frac{U_\infty \nu}{R}\right)^{1/2} \frac{\rho}{4\kappa} G(\xi, \eta) \tag{1}$$

$$\theta = [T(x,r) - T_\infty]/[T_0 - T_\infty]$$

The transformed governing equations may be written as

$$(1 + \xi^{1/2}\sigma\eta)F''' + (F + \xi^{1/2}\sigma)F'' + \xi^{1/2}G' + 8\xi\Omega\theta = 2\xi\left[F'\frac{\partial F'}{\partial \xi} - F''\frac{\partial F}{\partial \xi}\right] \tag{2}$$

$$\lambda(1 + \xi^{1/2}\sigma\eta)G'' + (2F + \xi^{1/2}\sigma)G' + \eta F'G = \Delta\xi^{1/2}(1 + \xi^{1/2}\sigma\eta)ReF'' + \frac{8\Delta B\xi}{Re}G + \frac{4\xi^{1/2}}{Re^{1/2}}[1 + \xi^{1/2}\sigma\eta]^{-1}\left[FG + \xi G\frac{\partial F}{\partial \xi} - \frac{\eta}{2}GF'\right] + 2\xi\left[F' + \frac{\partial G}{\partial \xi} - G'\frac{\partial F}{\partial \xi}\right] \tag{3}$$

$$\frac{(1 + \xi^{1/2}\sigma\eta)\theta''}{Pr} + \left(F + \frac{\xi^{1/2}\sigma}{Pr}\right)\theta' = 2\xi\left[F'\frac{\partial \theta}{\partial \xi} - \theta'\frac{\partial F}{\partial \xi}\right] \tag{4}$$