Engineering Notes

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Thermal Scale Modeling of Multilayered Insulation

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THE work of Gabron[1] has shown that thermal similitude can be retained in model and prototype if the temperature preservation technique is used in modeling multilayer insulations (MLI). This result is applicable for one-dimensional heat flow, and it provides a distorted thickness for the insulation in the model for the case in which the same foil is used in model and prototype. Below it is shown that the temperature and material preservation technique derived by Shih[2] can eliminate that distortion of MLI thickness.

We start with the two dimensionless groups of Gabron,

$$(CT/nq'')_m = (CT/nq'')_p \tag{1}$$

$$(\epsilon\sigma T^4/nq'')_m = (\epsilon\sigma T^4/nq'')_p \tag{2}$$

where subscripts m and p mean model and prototype, respectively, C is thermal conductance between foils, T is temperature in the MLI at homologous locations, n is the number of MLI foils, q'' is heat flux, ϵ is foil emissivity, $\ll 1$, and σ is the Stefan-Boltzmann constant. By taking $q''_m = q''_p$, Gabron showed that, for MLI built up from the same foil with the same spacing in both model and prototype, then $n_m = n_p$. That is, the model MLI thickness had to be the same as that of the prototype. The distortion thus introduced would be of no consequence in one-dimensional heat flow. However, in a three-dimensional small scale model, the MLI thickness distortion could seriously distort its surface area and thus perturb its temperatures enough to invalidate the model results. Then the temperature preservation technique, which requires that $q''_m = q''_p$, may not be suitable for such models.

If both temperature and material are preserved in model and prototype by the surface control technique derived by Shih, the ratio of heat fluxes is inversely proportional to the scale ratio, or $q''_m = q''_p/R$, where $R = L_m/L_p$, and L is length. Then, Eq. (1) becomes

$$(C_m TR/n_m q''_p) = (C_p T/n_p q''_p) \tag{3}$$

$$n_m/n_p = R \tag{4}$$

The previous result follows wherever $C_m = C_p$, or the same foil and spacing is used in both model and prototype. Evidently, the total MLI thickness will be properly scaled and not distorted in the model. A similar result follows from Eq. (2)

$$(\epsilon_m \sigma T^4 R/n_m q''_p) = (\epsilon_p \sigma T^4/n_p q''_p)$$
$$n_m/n_p = R \tag{5}$$

It should be noted that $\epsilon_m = \epsilon_p$ only in the MLI. Surface control for all radiating surfaces requires that $\epsilon_m = \epsilon_p/R$, otherwise. This would mean that the model MLI external surface emissivity should be increased. Fortunately, that is the one possible way in which the emissivity of the foil can practically be changed.

The explanation for the apparent departure from the scaling laws on emissivity for foil in MLI, when the surface control technique of Shih is used, lies in an understanding of the fact that these laws have their origin in the requirement that rates of heat transfer by each mechanism should be held in fixed ratio to each other. With temperature and material preservation, fluxes should be in inverse ratio to the scale. However, a foil in the model is radiating to an adjacent foil at a temperature different from that of a foil adjacent to the homologous location in the prototype. Figures 1 and 2 may make this more easily seen for a half-scale model and prototype. The difference in the fourth power of adjacent temperatures is twice as much in the model as in the prototype. Then heat flux because of the radiation in the model is twice as much as in the prototype, without any change to the emissivity of the foil in the model. Heat flux because of the conduction in the model is also twice as much since, with half as many joints, the model MLI has twice as much conductance.

A more obvious, but less practical, means of modeling MLI with surface control and without geometric distortion would be to obtain thinner foil with increased surface emissivity for the model. The model MLI would then consist of as many layers of foil as the prototype MLI. The difficulty here would be in attempting to provide twice the conductance between foils in the model. As indicated immediately previous, for temperature and material preservation,

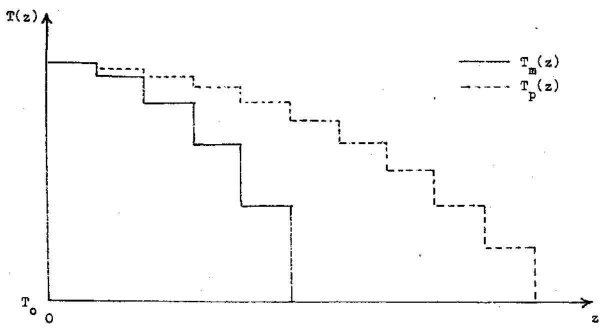

Fig. 1 Temperature vs foil thickness.

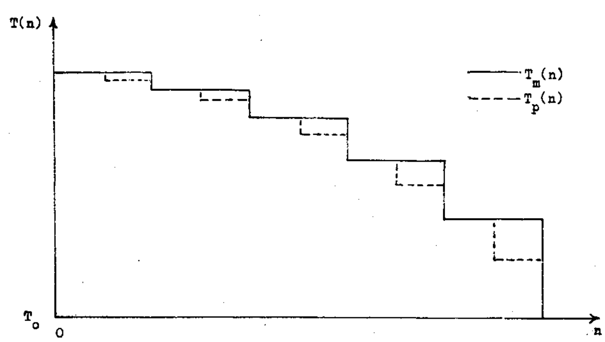

Fig. 2 Temperature vs homologous location.

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heat flux by both radiation and conduction should be twice as much in the half-scale model as in the prototype. Since temperature differences between homologous foils must be the same in both model and prototype, the increased fluxes in the model must be provided by increased emissivity and conductance in the model. The emissivity is easily increased by such means as black dots on the surface, but accurate changes to the conductance would be much more difficult. The model foil may not actually need to be thinner, since the temperature drop across each foil is usually neglected; and this need not necessarily introduce distortion if the increased model conductance is to be obtained by greater compression of the model MLI. However, the uncertainty in conductance values is large enough, especially when different means of construction are used, that this method is actually less attractive than the more convenient one discussed previously.

To summarize, surface control techniques allow thermal modeling of MLI without geometric distortion or modification of the foil used to build up the MLI, except the surface emissivity of the outermost layer, where normal scaling laws again control the emissivity. Both temperature and material can be preserved, provided the number of layers of foil on the prototype is an integral multiple of $1/R$, the reciprocal of the scale ratio.

References

[1] Gabron, F., "Thermal Scale Modeling Techniques for Voyager-Type Spacecraft," Rept. 951417, Arthur D. Little Inc., Cambridge, Mass.

[2] Shih, C., "Thermal Similitude of Manned Spacecraft," AIAA Paper 66-22, New York, 1966.

Newtonian Aerodynamic Coefficients for an Arbitrary Body, Including "All Shadowed" Areas

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Introduction

NEWTONIAN hypersonic aerodynamic theory, based on the assumption of a thin shock layer, has been widely used because of its inherent simplicity. The main assumption is that local pressure coefficient C_p, varies only with local body angle of attack, θ, as long as the freestream can impinge directly on the point in question. Where the local point does not "see" the flow, $C_p = 0$. Applying these two concepts is straightforward and forms the basis of most applications today. The principal computational difficulty in making Newtonian calculations arises when one part of the body with $\theta < 90°$ is shielded from the freestream (shadowed) by a portion of the body upstream of it. In previous work this problem has either been ignored,[1] or has been solved by requiring that the body be specified by a series of mathematical surfaces bounded by space curves.[2] A simpler approach was sought, in which the body could be described by a series of planar cross sections, and each defined by a finite number of points. A technique has been developed for rapidly determining whether each body point is "shadowed" and for determining unambiguously the elemental surface areas, and associated local body normals.

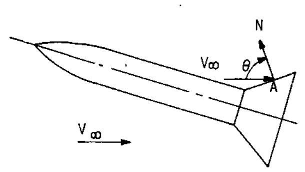

Fig. 1 Shading of a point by body upstream.

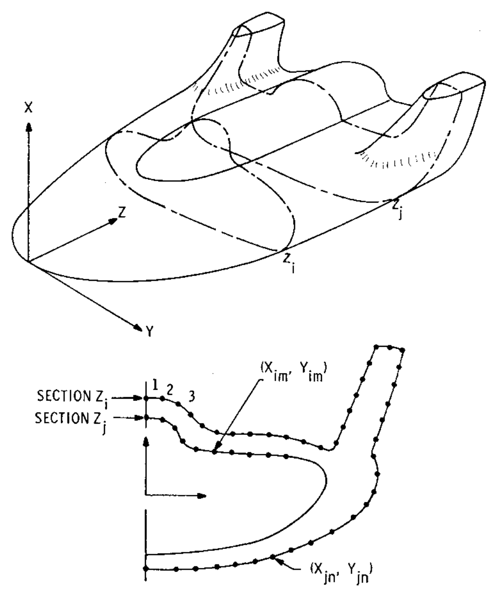

Fig. 2 Arbitrary body definition.

Shadow Area Determination

The basic equation of Newtonian flow theory $C_p = K \cos^2\theta$ yields the local C_p in terms of θ and a constant K, a function of Mach number. This equation is valid only for surface areas that "see" the flow (Fig. 1), for which $|\theta| \leq 90°$, where $\cos\theta = -\mathbf{V}_\infty \cdot \mathbf{n}/|V_\infty|$, $\mathbf{V}_\infty$ = freestream velocity vector, and $\mathbf{n}$ = local normal unit vector. For simple shapes (sphere, ellipsoid, cone, etc.) the shadow areas that don't "see" the flow, (for which $C_p = 0$) are determined simply by $|\theta| > 90°$. For more complex shapes, typified by flared bodies of revolution or complex lifting re-entry vehicles, a point on the surface may have $|\theta| < 90°$ and yet have $C_p = 0$ because it is shadowed by an upstream portion of the body, e.g., point A of Fig. 1.

Let us define the body in a Cartesian coordinate system (Fig. 2) by transverse sections normal to the z axis (z_i, z_j, etc.), and points in each cross section (x_{im}, y_{im}), (x_{jn}, y_{jn}), etc. In

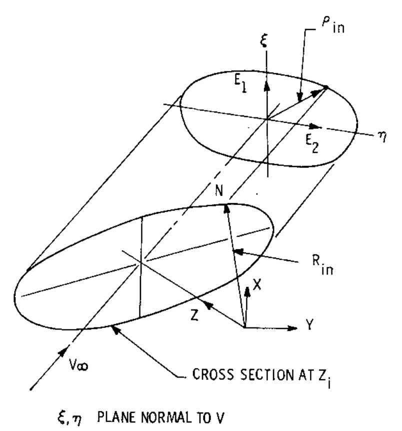

Fig. 3 Projection of z_i cross section onto ξ,η plane.

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