payload delivery increase even when structural mass penalties are accounted for.

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Design Considerations for Space Chamber Cryopanels

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Nomenclature

A = cross-sectional area of fin tube, cm^2
a = radius of the test specimen, cm
d_1 = inner diameter of the fin tube, cm
d_2 = outer diameter of the fin tube, cm
F_{12} = shape factor
f = factor defined in Eq. (20)
K = thermal conductivity, w/cm-K
L = length of the fin, cm
L_1 = length of the fin to the point of tangent, cm
n = number of tubes per meter length
R = radius of the cryopanel, cm
t = thickness of rectangular fin, cm
t_1 = tip thickness of trapezoidal fin, cm
t_2 = base thickness of trapezoidal fin, cm
T = temperature, K
T_1 = temperature of test specimen, K
X = defined in Eq. (12), cm^2
Z = coordinate axis, cm
θ, ϕ = angles, °
σ = Stefan's constant, $w/cm^2\text{-}K^4$
ε = emissivity

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Introduction

LIQUID nitrogen cooled cryopanels are used in space simulation chambers for simulating heat sink effects of the outer space. The design criteria for cryopanels are: a) optical tightness, b) provision of high conductance paths for evacuating the test volume, and c) minimum cooldown mass. Many fin tube configurations were used in the past for meeting these criteria.[1] The selection of a particular fin configuration has been mainly arbitrary. In this analysis the heat-transfer characteristics of cryopanel sections are studied for a given temperature drop, base and tip thicknesses of fin. A method of calculating other parameters of the cryopanel geometry is presented. A selection criteria for fin configuration is evolved.

Physical Model

The physical models for the fin analysis and geometry parameters are shown in Figs. 1 and 2, respectively. It is assumed that the test specimen is spherical and its diameter is equal to one half the diameter of cryopanel, which is assumed to be cylindrical. The maximum temperature at any point on the fin is assumed to be 100 K. The spacecraft and cryopanel emissivities are taken as 0.2 and 0.9, respectively. Radiant exchange between the fin and its base or other parts of the cryopanel is neglected. The temperature perpendicular to the fin length is lumped. Constant thermal properties of the fin material are assumed. The maximum heat flux incident on the test specimen is taken as 1.4 solar constants.

Location of Fin for Maximum Heat Transfer

In radial and tangential fin cases, the base heat flux is the same for a given configuration. The heat transfer area available is proportional to OX in a radial fin and to OY in

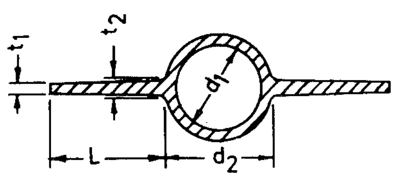

Fig. 1a Radial fin tube.

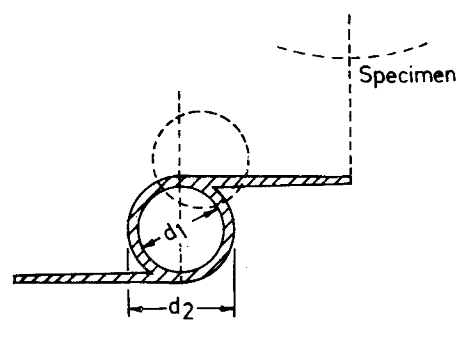

Fig. 1b Tangential fin tube.

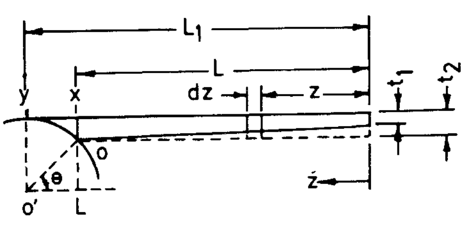

Fig. 1c Physical model for heat-transfer analysis.

a tangential fin (Fig. 1c). Approximating the arc OY to a chord, one obtains

$$OY = OX/\cos\theta \tag{1}$$

θ attains a maximum value as the point O approaches Y. Tangential fin satisfies this condition better than a radial fin. In view of higher heat-transfer area available, tangential fin tube has better heat-transfer characteristics.

Formulation of Governing Equation and Solution

a) Rectangular fin

Considering an element dZ at a distance Z from fin tip (Fig. 1c) the energy balance may be written as follows:

$$-Kt\frac{dT}{dZ} + \varepsilon\sigma F_{12}(T_1{}^4 - T^4)\,dZ + 1.96\times 10^{-1}0.8\,dZ = -Kt\frac{dT}{dZ} + \frac{d}{dZ}\left(-Kt\frac{dT}{dZ}\right)dZ \tag{2}$$

From Eq. (2) the governing differential equation may be derived as

$$\frac{d^2T}{dZ^2} + \frac{\varepsilon\sigma F_{12}(T_1{}^4 - T^4)}{Kt} + \frac{0.1568}{Kt} = 0 \tag{3}$$

F_{12} for a sphere-cylindrical strip geometry is given by[2]

$$F_{12} = a^2R/(R^2+Z^2)^{3/2} \tag{4}$$

Since the fin is designed for maximum heat load for which a is one half of R, the shape factor F_{12} per unit length reduces to

$$F_{12} = R^2/8\pi(R^2+Z^2)^{3/2} \tag{5}$$

Substituting Eq. (5) in Eq. (3) the relative magnitudes of second and third terms are found to be 10^{-4} and 7000×10^{-4}, respectively, even at $Z = 0$ and $T = 77.4K$. Consequently for design purposes the differential equation may be written as

$$(d^2T/dZ^2) + (0.1568/Kt) = 0 \tag{6}$$

The boundary conditions for Eq. (6) are derived from the following considerations: 1) from the assumption

$$T(0) = 100K \tag{7}$$

2) the fin is in vacuum environment, and heat transfer from the fin tip to the surroundings is negligible; thus,

$$(dT/dZ)(0) = 0 \tag{8}$$

The solution of this equation is

$$100 - T = 0.0784Z^2/Kt \tag{9}$$

b) Trapezoidal fin

If t_1 and t_2 are fin tip and base thicknesses, respectively, the energy balance for an element dZ at a distance Z from fin tip

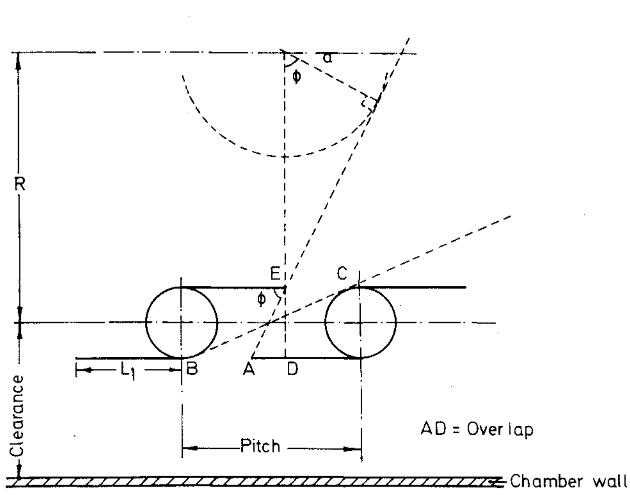

Fig. 2 Physical model for cryopanel geometry.

may be written as in case a. The governing differential equation is found to be

$$K\left(t_1 + \frac{t_2-t_1}{L}Z\right)\frac{d^2T}{dZ^2} + \frac{K(t_2-t_1)}{L}\frac{dT}{dZ} + 0.1568 = 0 \tag{10}$$

The boundary conditions are the same as given in Eqs. (8) and (9). The solution of Eq. (10) is

$$100 - T = \frac{0.1568L}{K(t_2-t_1)^2}\left[X - t_1L\left(\ln\frac{X}{t_1L} + 1\right)\right] \tag{11}$$

where

$$X = Z(t_2-t_1) + t_1L \tag{12}$$

The relation between fin length L and base temperature is obtained by substituting t_2L for X in Eq. (11) and is

$$100 - T = \frac{0.1568L^2}{K(t_2-t_1)^2}\left(t_2 - t_1 - t_1\ln\frac{t_2}{t_1}\right) \tag{13}$$

Determination of Cryopanel Array Parameters

Equations (9) and (13) give a relation between the length of fin and fin base temperature for rectangular and trapezoidal profiles, respectively. In any particular application the fin base temperature can be fixed depending on the condition of liquid nitrogen inside the tube, which in turn depends on heat received by the fluid while being transferred from the main storage tank to the cryopanel. Usually the liquid nitrogen in the cryopanel is in a pressurized or subcooled state. Consequently fin base temperature is in the range of 82–90K. The fin length may be estimated for different base and tip thicknesses for a given base temperature.

The cryopanel array parameters are: a) length of fin, b) overlap of fin array, c) pitch of the tubes, and d) number of tubes needed to make the array. The problem of determining these parameters is to be optimized between the following two conditions:

1) If the fin thickness is small, the length of fin over which given temperature drop occurs is small. This means closer spacing of the tubes, thereby increasing the number of tubes.

2) If fin thickness is large and heat-transfer characteristics are better, but the cooldown mass is large.

Overlap of the Tube Array

The fin overlap has to be so selected that, the array provides for high conductance paths for evacuating the test volume though it is optically tight. The tangential fin tube satisfies both these conditions with the arrangement shown in Fig. 2. Optical tightness requires that no part of the test specimen can see the highly polished chamber wall. Referring to Fig. 2 only the radiation falling between the lines BC and AE will be transmitted to the chamber wall without being obstructed by the fins. If the fins are so spaced that no part of the test specimen lies in this path, optical tightness can be ensured. This condition requires that the line AE can only be tangential to the test specimen even in the most pessimistic case. The pessimistic case occurs at a point on the Z-axis from which the tangent to the test specimen has least length. This implies that the point E lies just below the center of test specimen. The overlap AD can be calculated as

$$AD = DE/\tan\phi \tag{14}$$

Since DE is equal to d_2 and ϕ is 60° for a/R value of 0.5

$$\text{overlap} = d_2/(3)^{1/2} \tag{15}$$

Pitch of Tube Array

The length L_1 (Fig. 1c) is given by

$$L_1 = L + [t_2(d_2 - t_2)]^{1/2} \tag{16}$$

The pitch of the tube array is now given by

$$\text{pitch} = 2L_1 - \text{overlap} \tag{17}$$

Fin Performance

The number of tubes per meter length of the cylindrical portion of the cryopanel can be calculated as follows:

$$n = (100/\text{pitch}) + 1 \tag{18}$$

The cooldown mass is proportional to the cross-sectional area of the tube section. The cross-sectional area of the tangential fin tube can be calculated from the geometry given in Fig. 1b. It is as follows:

$$A = \frac{\pi}{4}(d_2{}^2 - d_1{}^2) + (t_1 + t_2)L + 2\left[(d_2/2)[t_2(d_2 - t_2)]^{1/2} - 0.5[t_2(d_2 - t_2)]^{1/2}\left(\frac{d_2}{2} - t_2\right) - \frac{d_2{}^2}{8}\sin^{-1}\frac{[t_2(d_2 - t_2)]^{1/2}}{d_2/2}\right] \tag{19}$$

The optimum array is one which has the lowest cooldown mass and yet the smallest number of tubes that go to make the cryopanel. Thus a factor "f" is defined such that

$$f = A \cdot n \tag{20}$$

The factor f can be calculated for various base and tip thicknesses and fin length. The configuration that gives the lowest value of factor f is the optimum fin for a given temperature drop across the fin.

Conclusions

For cryopanels which are away from the test specimen the angle ϕ used in Eq. (14) may be greater than 90°. Thus overlap in Eq. (15) will be negative. Equation (17) predicts a pitch which will be more than $2L_1$, thus providing for wide spacing of the tubes without violating the condition of optical tightness. It is possible to economize by way of reduction of number of tubes due to wider spacing and reduction of cooldown mass. This fact suggests that the entire cryopanel can be assembled in five or six parts. Pitch of tubes in different parts can be different though pitch in one part remains the same. The denser part can be placed nearer to the test specimen.

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