INFLUENCE OF SPECULAR REFLECTION COMPONENT OF SURFACES ON THE RADIATION CHARACTERISTICS OF A HERRINGBONE CAVITY

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The Monte Carlo method is used to compute the reflection and transmission coefficients of a herringbone cavity on the basis of a homogeneous specular-diffuse model of surface reflection.

Cavities of different shape are used extensively in apparatus where radiation heat transfer predominates. For instance, lattice cooling radiation screens are used in cryogenic vacuum chambers [1]. An individual cell of the screen formed by two adjacent ribbed tubes of herringbone type, for instance, is a cavity whose radiation characteristics (radiant energy reflection and transmission characteristics) govern the efficiency of the screen to a significant extent.

The traditional approach to analyzing the radiation characteristics of a cavity is based on using an ideal diffuse model of reflection, and its corresponding experimental values of the hemispherical reflection coefficients of surfaces forming the cavity. Investigations executed [2-5] to estimate the influence of the directional properties of surface reflection on radiation heat transfer in different systems indicate a complex interaction between the surface reflection model taken and the accuracy of the analysis performed. Mostly this interaction is determined by the specific conditions of the problem, however, the following can be extracted from the general situations: taking account of the directional properties of surface reflection raises the accuracy of the analysis in those cases when the radiant flux reflected from these surfaces is governing for the system domain under investigation. This is especially manifest in the exposure of a system to an external collimated flux [3,5].

In this paper, the total radiant flux emerging from a cavity through the entrance and exit surfaces, referred to the external flux, i.e., hemispherical integrals with respect to the spectrum of the cavity reflection and transmission coefficients averaged over the surface, is the result of considering the radiant heat transfer in a herringbone cavity. The cavity can be exposed to both diffuse and collimated external radiant flux, where the natural radiation of the surface and the external radiation from the back side are negligibly small in comparison. A homogeneous specularly diffuse model of reflection [6] is used in the research, according to which the hemispherical reflection coefficient can be represented as the sum of the specular and diffuse components

$$R = R_d + R_s. \tag{1}$$

The magnitude of the components is independent of the angle of incidence of the irradiating flux, and the direction of R_s corresponds exactly to specular reflection. The degree of specularity of the surface reflection will be characterized by the parameter $\rho_s = R_s/R$. The range of ρ_s from 0 to 0.5 is considered in the present paper.

The Monte Carlo method is used to solve the formulated problem. The basic principles and practical methods of modeling the radiation heat transfer process have been worked out well enough [7-9]. Only certain peculiarities of the analysis of the reflection and transmission coefficients of an individual cell of the screen are reflected briefly below. Let each batch (particle) inserted in the cavity possess unit energy. (therefore, for the total number of particles being followed in the cell N, an energy equal to N units is introduced.) In each collision with some surface of the cavity the particle loses a fraction of the energy proportional to the absorption coefficient of this surface, and is reflected with the remaining energy. The direction of particle reflection is determined taking the relationship (1) into account, i.e., the probability of specular reflection equals the degree of specularity of the reflection ρ_s. If the particle is reflected in conformity with a diffuse law

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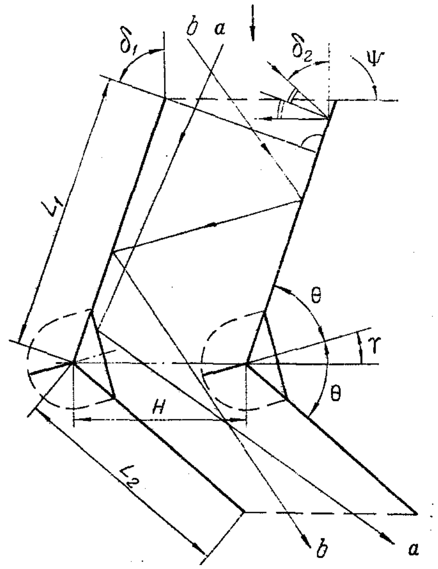

Fig. 1. Herringbone cavity (computational diagram).

(the probability density of reflection at an angle η to the normal is P(η) = cos η), then the connection of the random variable η with the random variable M_η distributed uniformly in the interval (0, 1) is accomplished by means of the cumulative function

$$M_\eta = \int_{-\infty}^{\eta} P(\eta)\, d\eta = \int_{0}^{\eta} \cos\eta\, d\eta = \sin\eta, \tag{2}$$

$$\eta = \arcsin M_\eta. \tag{3}$$

The particles are tracked until they emerge from the cell of the screen through the entrance or exit surfaces. Let a particle undergo z collisions prior to emergence from the cavity, it will leave the surface with the energy

$$W = R_1 R_2 \ldots R_z, \tag{4}$$

where the subscripts 1, 2, ..., z indicate the value of the reflection coefficient of those surfaces with which the 1, 2, ..., z-th collisions, respectively, occurred. Therefore, the reflection and transmission coefficients equal

$$\alpha = \frac{1}{N} \sum_{i=1}^{N_{\text{en}}} W_i, \quad \xi = \frac{1}{N} \sum_{j=1}^{N_{\text{ex}}} W_j. \tag{5}$$

The mentioned "energy" approach affords good possibilities when all the cavity surfaces possess identical reflectivity. In this case, it is sufficient to compute the number of particles emerging from the cavity through the entrance and exit surfaces as a function of the number of collisions by the Monte Carlo method, and the radiation characteristics of the cavity are easily determined for any value of R by the dependences

$$\alpha = \frac{1}{N} \sum_{z=0}^{n} R^z N_{\text{en}_z}, \tag{6}$$

$$\xi = \frac{1}{N} \sum_{z=0}^{n} R^z N_{\text{ex}\,z}, \tag{7}$$

where n is the number of collisions to be taken into account.

Let us consider the radiation characteristics of a cavity as a function of the system optical-geometric parameters (Fig. 1). For all the versions examined: Θ = 55°; $L_1/H = 1.6$; $L_2/H = 1.3$.

Reflection Coefficient of a Herringbone Cavity

It can be assumed that the reflection coefficient of a cavity under collimated exposure depends strongly on the magnitude and direction of the specular component of the first

TABLE 1. Ranges of External Radiant Flux Entrance Angles in a Herringbone Cavity

Ψ, deg	δ_1, deg	δ_2, deg	Range			Fraction of external diffuse flux within the range limits		
			I	II	III	I	II	III
40	40	—10	50	80	50	0,179	0,413	0,408
50	50	10	40	100	40	0,117	0,587	0,296
60	60	30	30	120	30	0,067	0,750	0,183
70	70	50	20	140	20	0,030	0,882	0,088
80	80	70	10	160	10	0,008	0,970	0,022
90	90	90	0	180	0	0	1	0

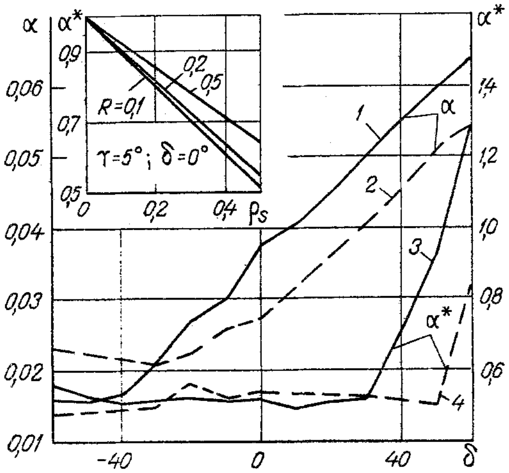

Fig. 2. Absolute and relative reflection coefficients of a cavity exposed to a collimated flux. R = 0.1; 1) $\rho_s = 0$, $\gamma = 5°$; 2) 0 and 15°; 3) 0.5 and 5°; 4) 0.5 and 15°.

reflection $R_s^{(1)}$, on the (leading) edges nearest to the entrance surface. Three ranges of entrance angles exist (let $\delta < 0$ to the right of the normal to the entrance surface in Fig. 1):

1. $\delta_1 \leq \delta < 90°$, $R_s^{(1)}$ emerges completely from the cavity through the entrance surface;
2. $-90° < \delta \leq \delta_2$, $R_s^{(1)}$ is incident on the other inner surfaces, i.e., does not emerge from the cavity;
3. $\delta_2 < \delta < \delta_1$, $R_s^{(1)}$ emerges partially from the cavity through the entrance surface.

The limit values of the ranges correspond to the following conditions: $\delta_1 = \Psi$, the external flux is incident along the normal to the cavity edge; $\delta_2 = 2\Psi - 90°$, the direction of $R_s^{(1)}$ is parallel to the cavity entrance surface where $\Psi = \Theta + \gamma$ (Fig. 1).

The presence of the specular component within the first range evidently magnifies the cavity reflection coefficient as compared with completely diffuse surface reflection. Let us note that this and the transition ranges diminish as Ψ increases and become zero for Ψ = 90° (Table 1). Most extensive is the second range, where as the slope of the edge increases, the edge grows and encloses all possible entrance angles for Ψ = 90°. For a cavity exposed within the limits of this range of angles, we note the following:

An increase in the fraction of specular reflection for invariant R will cause a significant decrease in the cavity reflection coefficient by approximately a linear law, where the influence is stronger for smaller values of R (Fig. 2).

Depending on the entrance angle δ (for constant R and ρ_s for all surfaces), the absolute values of the coefficient α can be highly varied, but the relative decrease of the cavity reflection coefficient, induced by the specular component, is practically identical for the entire width of the interval; this holds for various angles of the rotation of the profiles forming the herringbone cavity (Fig. 2).

In the case of diffuse exposure of the cavity, the external flux can be represented provisionally as a combination of individual collimated fluxes whose relative intensity is subject to the Lambert law. Therefore, the reflection coefficient of the cavity in the presence of a specular reflection component depends on the angular distribution of the external flux

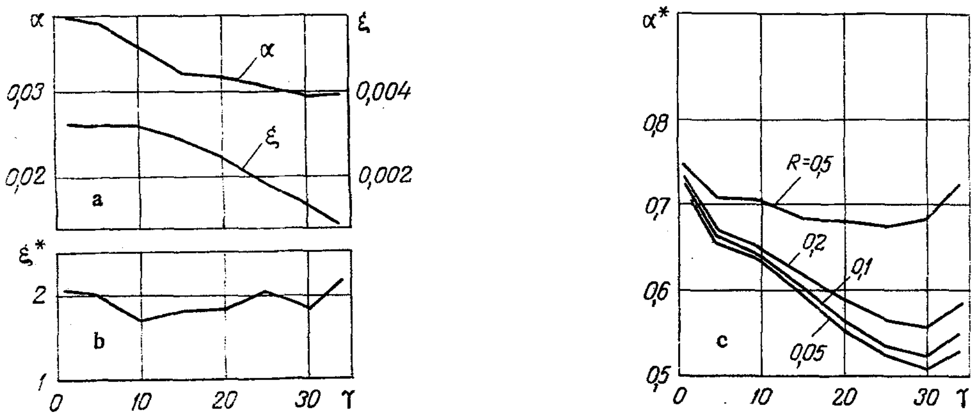

Fig. 3. Dependence of the cavity radiation characteristics on the angle of profile rotation under diffuse exposure: a) $\rho_s = 0$, $R = 0.1$; b and c) $\rho_s = 0.5$.

in the ranges noted above. The predominant fraction of the energy in the whole range of real values of the angle Ψ is introduced into the cavity (Table 1) at angles within the range II. Therefore, on the whole the cavity reflection coefficient diminishes with the increase in the degree of specularity of the surface reflection. (By analogy with the collimated exposure, this effect is magnified with the diminution in R.) Rotation of the profiles (growth of Ψ because of γ for Θ = const) results in an increase in the fraction of the external flux arriving in the second range, and correspondingly, in a stronger diminution in the cavity reflectivity for the identical values of ρ_s (Fig. 3). For larger values of R, this effect is attenuated because of the increase in the compensating role of the flux re-reflected from the outer edges of the cell.

Transmission Coefficient of a Herringbone Cavity

The results of computations in the case of cavity exposure to collimated radiant flux, represented in Fig. 4, show that depending on the entrance angle of the external flux, the transmission coefficient ξ can be increased (ξ* > 1) or decreased (ξ* < 1) in the presence of a specular component of surface reflection. In conformity with the physical model of the Monte Carlo method, this can evidently be explained by particle redistribution according to the number of reflections needed passing through the cavity. If the increase in the ρ_s of the surfaces results in an increase in the number of particles with small numbers of reflections (for optically opaque cavities, principally particles with one reflection), then the quantity ξ hence increases. The three surfaces forming the left side of the herringbone cavity contour afford the external flux particles the opportunity to slip through the cavity with one reflection from one of these surfaces (a–a in Fig. 1). In this case (in the neighborhood of $\delta = \Psi - 90°$) the presence of the specular reflection component increases the cavity transmission coefficient sharply (Fig. 4).

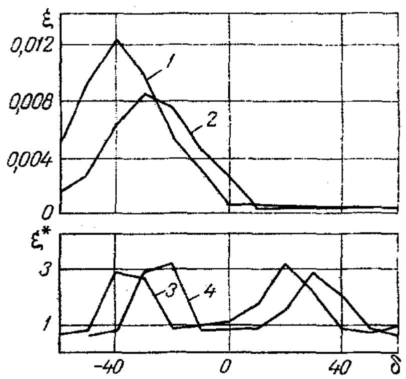

Fig. 4. Absolute and relative transmission coefficients of the cavity exposed to a collimated flux, R = 0.1. Notation the same as in Fig. 2.

There exists still another range of external flux entrance angles (in the neighborhood of δ = +20° in Fig. 4), where the specular component also influences the quantity ξ strongly. In this case the number of particles having two reflections from opposite edges (b–b in Fig. 1) increases. However, this range is less essential for cavities with highly absorbing walls because of the quite low absolute values of the transmission coefficient ξ.

The increase in the ρ_s of the surface under diffuse exposure of a herringbone cavity results in a growth of the cavity transmission coefficient. For instance, the presence of a specular reflection component ρ_s=0.5 increases ξ approximately twofold for practically all γ as compared with ideal diffuse surface reflection (Fig. 3). Taking account of the angular distribution of the external diffuse flux, the growth of the coefficient ξ in the ranges noted above apparently considerably exceeds its diminution for all other entrance angles.

Herringbone cavities with highly absorbing walls are considered in the paper. If the wall coverings possess definite diffuse-specular reflection properties, then this must quite definitely be taken into account in computing the cavity radiation characteristics. This latter is valid upon exposure of the herringbone cavity to both collimated and isotropic (diffuse) radiant flux.

NOTATION

α, ξ, hemispherical integral coefficients of radiant energy reflection and transmission of a herringbone cavity; R, hemispherical integral coefficient of surface reflection; ρ, ratio of the appropriate reflection component to the total surface reflection; δ, angle between the direction of ray (particle) entrance into the cavity and the normal to the entrance surface of the cavity; M, random variable distributed uniformly in the range (0,1); $P(\eta)$, probability density of reflection from a surface at the angle η to the normal. Subscripts: s, specular reflection; d, diffuse reflection; en, ex, entrance and exit openings of the herringbone cavity surface; i, j, particles leaving the cavity through the entrance and exit surfaces; z, number of particle collisions with walls prior to emergence from the cavity; asterisk (*) is the ratio between the value for specular-diffuse surface reflection and the value for ideal diffuse reflection for identical R.

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