ABOUT RADIATION TRANSFER IN COMBUSTION OF A FILLER IN A POROUS BODY

V. V. Levdanskii and Khoang Wan Viet UDC 536.3

The influence of the depth of a filler surface in a porous body on the radiation flux emerging from the porous body is considered.

In many technological processes there emerge problems of heat exchange by radiation of porous bodies with the ambient medium (drying of porous bodies at high temperatures, their combustion, use as heatproof coverings, etc.). This brings up the question of the conditions for the radiation flux on a porous body–ambient medium boundary. The presence of pores (capillaries) in the radiating body gives rise to special features in the mentioned boundary conditions, enhancing the nonuniformity of the process of heat exchange by radiation. It is common knowledge that in the regime of radiation slip the gas temperature near the surface, onto which the radiation is incident, is not equal to the temperature of the surface proper, i.e., there is a so-called temperature jump [1]. For a porous body, the formation of the gas temperature near the body surface is substantially affected by such parameters as porosity, the geometry of capillaries, the optical characteristics of the frame of the porous body, and the filler (given the latter). As the filler burns out from the porous body, the unfilled portion of the capillaries will increase and the temperature of the system will vary, which will also affect the radiation flux emerging from the porous body.

The porous body structure may manifest itself in the expression describing the radiation slip near the surface of a capillary-porous body, by which the temperature jump near the body surface is also determined.

For the density of the radiation flux near the porous body surface in the approximation of a gray medium we can write the expression [2]

$$e(0)=\frac{\varepsilon e_1(1-\Pi)+I\Pi}{\varepsilon(1-\Pi)+\Pi}-\frac{2}{3}\,\frac{\Pi+\varepsilon(1-\Pi)-2}{\varepsilon(1-\Pi)+\Pi}\left(\frac{de}{d\tau}\right)_{\tau=0}, \tag{1}$$

where e is the density of the radiation flux of the medium above the body; ϵe_1 is the density of the radiation flux of the porous body frame at the boundary with the external medium; ϵ is the emissivity factor of the frame; Π is the porosity; I is the density of the radiation flux, emerging from the capillary averaged over radii and lengths.

The expression (1) as $\Pi \to 0$ becomes the expression for an impermeable surface [1]. From (1) it is obvious that the radiation flux density (and correspondingly the temperature of the medium at the boundary with the body, the expression for which is obtained in the transition from e to T) depends on the radiation flux emerging from the body via capillaries (i.e., on the value of I), which, in turn, is related to the temperature distribution within the body. When using the model of "dust-laden gas" the calculation for e(0) can be performed by the approach described in [3]. As the filler surface in the porous body moves deeper, the value of I will vary, which will also involve a variation in e(0) and correspondingly in T(0).

Apart from the above-mentioned effect, the conditions at the boundary of the porous body with the external medium will also depend on the spatial (angular) distribution of radiation emerging from the capillaries. When the capillaries are filled completely the radiation emerging from the surface may be considered to be distributed according to the cosine law. However, in the process of deepening of the filler in the porous body (for example, in the process of its burning out) the directional diagram of the emerging radiation can be modified. The character of the angular distribution

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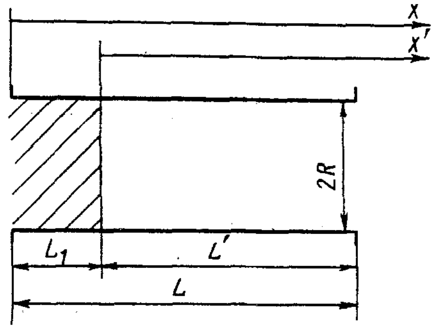

Fig. 1. Geometric scheme of the problem.

will be affected both by the size of the burned out (empty) zone in the capillaries and the temperature on the flame front (or the phase transition). If the temperature of the filler surface increases with moving into the body, the angular distribution will shrink (increasingly differing from the cosine law). The capillaries emerging on the porous body surface may be distributed nonuniformly (they can be more numerous on some sections and less numerous on others). The places of "thickening" of the capillaries' emergence (with a considerable difference of the angular distribution of radiation emerging from them from the cosine law) will enhance the nonequilibrium of the system.

In the special case in which the radiation wavelength is much smaller than the geometric dimensions of the capillary, modeled further by a cylindrical channel with length L and radius R, the angular distribution of radiant energy $\gamma(\theta)$, characterized by the ratio of the quantity of this energy emerging from the channel at the angle θ to its axis to the quantity of the radiant energy leaving it in the direction of the axis, when the channel is filled with the burning out substance to $X = L_1$ (Fig. 1) can be represented as

$$\gamma(\theta) = W(\theta)\cos(\theta),$$

where the function $W(\theta)$ by analogy with [4] is expressed in the following manner:

$$W(\theta) = \frac{4l'}{\pi I_{L_1}} \int\limits_0^{\frac{\mathrm{tg}(\theta)}{2}} I(x')(1 - l'^2\xi^2)^{\frac{1}{2}}\, d\xi + 1 - \frac{2}{\pi}\left[\arcsin(u) + u(1-u^2)^{\frac{1}{2}}\right] \quad \text{for} \quad \theta \leqslant \mathrm{arctg}\left(\frac{2}{l'}\right), \tag{2}$$

$$W(\theta) = \frac{4l'}{\pi I_{L_1}} \int\limits_0^{\frac{1}{l'}} I(x')(1 - l'^2\xi^2)^{\frac{1}{2}}\, d\xi \quad \text{for} \quad \theta \geqslant \mathrm{arctg}\left(\frac{2}{l'}\right),$$

$$l' = \frac{L}{R} - \frac{L_1}{R} = l - l_1, \quad x' = \frac{X'}{L'} = \frac{x - l_1/l}{1 - l_1/l}, \quad \xi = \frac{(1-x')\,\mathrm{tg}(\theta)}{2}, \tag{3}$$

$$u = \frac{l'\,\mathrm{tg}(\theta)}{2} = \frac{(l - l_1)\,\mathrm{tg}(\theta)}{2};$$

here $l' = L'/R$, where $x = X/L$ and $x' = X'/L$ are the corresponding dimensionless coordinates; $I(x')$ is the density of the energy flux emerging from the lateral surface of the channel; I_{L1} is the density of the energy flux, emerging from the filler surface. We will further assume the external medium temperature to be fairly low, so the radiation entering the channel at $x = 1$ may be neglected. The values for I and I_{L1} are found from the equations [1, 5]

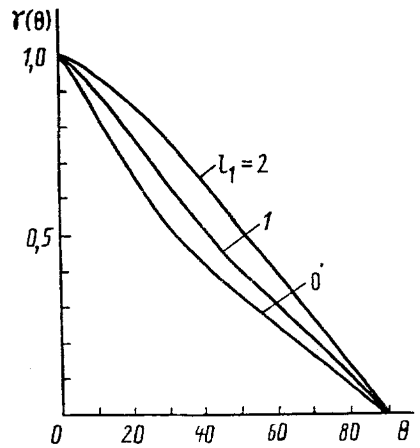

Fig. 2

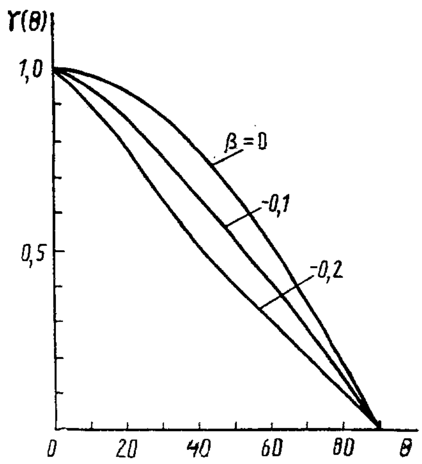

Fig. 3

Fig. 2. Angular distribution of the radiation flux emerging from a cylindrical channel at various values of l_1; $l = 4$, $\epsilon_1 = \epsilon_2 = 1$, $\beta = -0.2$. θ, deg.

Fig. 3. Angular distribution of the radiation flux emerging from a cylindrical channel at various values of the parameter β; $\epsilon_1 = \epsilon_2 = 1$, $l_1 = 1$.

$$\begin{gathered} I(x') = \varepsilon_2 \sigma T^4(x') + (1-\varepsilon_2)\left[I_{L_1} K(x') + \int_0^l I(\chi) K_1(|x'-\chi|)\, d\chi\right], \\ I_{L_1} = \varepsilon_1 \sigma T^4_{L_1} + 2l'(1-\varepsilon_1) \int_0^l I(x') K(x')\, dx', \end{gathered} \tag{4}$$

where ϵ_1 and ϵ_2 are respectively the emissivity factors of the filler and the channel lateral surface; $K(x')$ and $K_1(x')$ are the angular coefficients, characterizing the probabilities for the radiation to fall from one element of the inner surface to the another [1]; T_{L1} is the filler surface temperature. The approximate solution of Eq. (4) is given in [5].

For definiteness we infer that the temperature at $x = 0$ is maintained constant (T_0), and $T(x)$ varies according to the law

$$T(x) = T_0 \exp(\beta x) = T_0 \exp\left\{\beta\left(1 - \frac{l_1}{l}\right) x' + \frac{l_1}{l}\right\}.$$

We will consider the case $\epsilon_1 = \epsilon_2 = 1$; in doing so, for $W(\theta)$ we have

$$W(\theta) = \frac{4l'}{\pi} \int_0^{\frac{\mathrm{tg}(\theta)}{2}} \exp\left\{4\beta\left(1 - \frac{l_1}{l}\right) x'\right\} (1 - l'^2\xi^2)^{\frac{1}{2}}\, d\xi + 1 -$$

$$- \frac{2}{\pi}\left[\arcsin(u) + u(1-u^2)^{\frac{1}{2}}\right] \quad \text{for} \quad \theta \leqslant \mathrm{arctg}\left(\frac{2}{l'}\right);$$

$$W(\theta) = \frac{4l'}{\pi} \int_0^{\frac{1}{l}} \exp\left\{4\beta\left(1 - \frac{l_1}{l}\right) x'\right\} (1 - l'^2\xi^2)^{\frac{1}{2}}\, d\xi \quad \text{for} \quad \theta \geqslant \mathrm{arctg}\left(\frac{2}{l'}\right).$$

From the expression for $W(\theta)$ it follows that at $\epsilon = 0$ or $L = L_1$ the cosine law is satisfied. Figure 2 shows the dependence of the angular distribution of the radiation flux emerging from the channel on the location of the flame front (or the phase transition) with β, differing from 0. It is evident that as the filler front moves into the channel $\gamma(\theta)$ shrinks when $\beta < 0$.

Figure 3 gives the dependence of the angular distribution of the radiation flux emerging from the channel on the parameter β. It can be seen from the figure that the larger the temperature drop, the narrower the directional diagram at the outlet from the channel ($\beta < 0$).

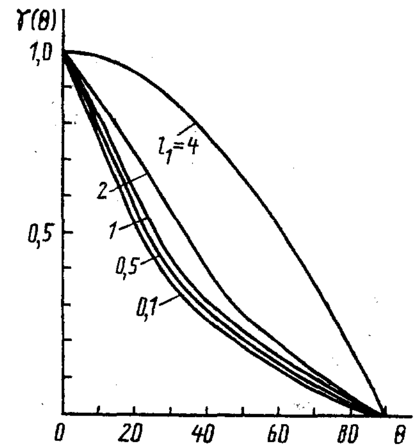

Fig. 4. Angular distribution of the energy flux removed from a cylindrical channel by a molecular beam (the isothermal case, the conditions of vacuum at the outlet from the channel), curve l_1 = 4 corresponds to the cosine law).

We will point out that with the energy removal from the capillaries both the energy flux removed by radiation and the energy flux removed by a molecular beam will take place. In this case, as the filler front moves deeper in the capillary the spatial distribution of these fluxes can vary in different ways. Thus, for example, as has been mentioned above, with $\epsilon_1 = \epsilon_2 = 1$ and $\beta = 0$, the angular distribution of the radiation energy will not vary as the filler moves deeper, and the angular distribution of the energy removed by the molecular beam, calculated analogously to [6] for the scheme shown in Fig. 1, will shrink, provided that the system is isothermal and the channel lateral surface is impermeable (Fig. 4).

Thus, from the aforesaid it follows that both the radiation density jump above the porous body (1) and the angular distribution of the radiation emerging from the capillary may substantially depend on the position of the filler surface in the porous body. In this case the indicated parameters will be affected by the variation in the geometry of the system as the filler surface moves deeper into the body and the variation (in particular, an increase) in the temperature of the filler surface itself.

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