DETERMINATION OF THE ABSORPTIVITY OF INSIDE SURFACES OF A CYLINDRICAL VACUUM CHAMBER

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A method for experimental determination of the absorptivity of the inside surfaces of a cylindrical vacuum chamber is proposed.

To calculate radiant heat transfer it is sometimes necessary to establish the absorptivity of the inside surfaces of a cylindrical vacuum chamber in a state characteristic for operating conditions. This problem can be solved if we take into account the following.

Suppose that in a system of two coaxially arranged cylindrical bodies of the same length (Fig. 1) for which $d \ll D$, body 1 is a heater, each of the surfaces 1-4 is isothermal, and the absorptivities within the limits of the surface are constant. Then the radiant balance-flux for any of the surfaces is equal to

$$X_i = \sum_{k=1}^{4} Q_{\text{ef.}k}\varphi_{k.i} - Q_{\text{ef.}i}, \tag{1}$$

and

$$Q_{\text{ef.}i} = X_i\left(\frac{1}{A_i} - 1\right) + Q_{\text{self.}0}. \tag{2}$$

Substituting (2) into (1) gives

$$X_i = \sum_{k=1}^{4} Q_{\text{ef.}k}\varphi_{k.i} - \left[X_i\left(\frac{1}{A_i} - 1\right) + \sigma_0 T_i^4 F_i\right]. \tag{3}$$

For nonconcave bodies 1, 2, 3 the terms $Q_{\text{ef.}i}\varphi_{i,i}$ are equal to zero, and therefore $\sum_{k=1}^{4} Q_{\text{ef.}k}\varphi_{k,i}$ does not include X_i. Then for bodies 1, 2, 3 we obtained on the basis of Eq. (3)

$$X_i = A_i\left[\sum_{k=1}^{4} Q_{\text{ef.}k}\varphi_{k,i} - \sigma_0 T_i^4 F_i\right], \tag{4}$$

and for body 4

$$X_4 = \frac{1}{\left(\frac{1}{A_4} - 1\right)(1 - \varphi_{4,4}) + 1}\left[\sum_{k=1}^{3} Q_{\text{ef.}k}\varphi_{k,4} - \sigma_0 T_4^4 F_4 (1 - \varphi_{4,4})\right]. \tag{5}$$

We write system of Eqs. (2)-(5) in an expanded form

$$X_1 = A_1\left\{\left[X_2\left(\frac{1}{A_2} - 1\right) + \sigma_0 T_2^4 F_2\right]\varphi_{2,1} + \left[X_3\left(\frac{1}{A_3} - 1\right) + \sigma_0 T_3^4 F_3\right]\varphi_{3,1} + \left[X_4\left(\frac{1}{A_4} - 1\right) + \sigma_0 T_4^4 F_4\right]\varphi_{4,1} - \sigma_0 T_1^4 F_1\right\},$$

$$X_2 = A_2\left\{\left[X_1\left(\frac{1}{A_1} - 1\right) + \sigma_0 T_1^4 F_1\right]\varphi_{1,2} + \left[X_3\left(\frac{1}{A_3} - 1\right) + \sigma_0 T_3^4 F_3\right]\varphi_{3,2} + \left[X_4\left(\frac{1}{A_4} - 1\right) + \sigma_0 T_4^4 F_4\right]\varphi_{4,2} - \sigma_0 T_2^4 F_2\right\},$$

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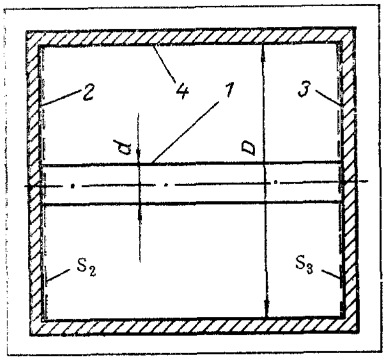

Fig. 1. Diagram for determining the absorptivity of inside surfaces of a cylindrical vacuum chamber: 1) heater; 2, 3, 4) surfaces of chamber; S_2 and S_3) shields.

$$X_3 = A_3\left\{\left[X_1\left(\frac{1}{A_1}-1\right)+\sigma_0T_1^4F_1\right]\varphi_{1,3}+\left[X_2\left(\frac{1}{A_2}-1\right)+\sigma_0T_2^4F_2\right]\varphi_{2,3}+\left[X_4\left(\frac{1}{A_4}-1\right)+\sigma_0T_4^4F_4\right]\varphi_{3,4}-\sigma_0T_3^4F_3\right\}, \qquad (6)$$

$$X_4 = \frac{1}{\left(\frac{1}{A_4}-1\right)(1-\varphi_{4,4})+1}\left\{\left[X_1\left(\frac{1}{A_1}-1\right)+\sigma_0T_1^4F_1\right]\varphi_{1,4}+\left[X_2\left(\frac{1}{A_2}-1\right)+\sigma_0T_2^4F_2\right]\varphi_{2,4}+\left[X_3\left(\frac{1}{A_3}-1\right)+\sigma_0T_3^4F_3\right]\varphi_{3,4}-\sigma_0T_4^4F_4(1-\varphi_{4,4})\right\}.$$

The irradiance coefficients figuring in (6) can be calculated according to [1] and [2].

System of Eqs. (6) can be used for substantiating the method of experimental determination of the absorptivity of the inside surfaces of a cylindrical vacuum chamber. The experiment to determine the absorptivity of the inside cylindrical surface of the chamber is carried out in the following way (Fig. 1). A heater 1 with a known high absorptivity A_1 and shields S_2 and S_3 having a known low absorptivity ($A_{S_2} = A_{S_3}$) are installed coaxially in the chamber. At a vacuum precluding convection and constant power of the heater the system is brought to a steady regime of heat transfer, after which the power of the heater and the average temperatures of the surfaces are measured. In this case the unknown quantities in (6) are X_{S_2}, S_{S_3}, X_4, and A_4. With consideration of symmetry of the system (Fig. 1) and $A_{S_2} = A_{S_3}$ the radiant balance-fluxes X_{S_2} and X_{S_3} are equal.

Equations (6), by substituting the given and experimentally measured values into them, are reduced to the form

$$\begin{aligned} a_1X_{S_2}+a_2X_4\left(\frac{1}{A_4}-1\right)&=a_0,\\ b_1X_{S_2}+b_2X_4\left(\frac{1}{A_4}-1\right)&=b_0,\\ c_1X_{S_2}+X_4\left[c_2\left(\frac{1}{A_4}-1\right)+1\right]&=c_0,\end{aligned} \qquad (7)$$

where a, b, c are numerical coefficients which depend on the given and experimentally determined values.

The solution of system (7) permits determining the absorptivity A_4 of the inside cylindrical surface 4 of the vacuum chamber. For the same state of all inside surfaces we should consider that $A_2 = A_3 = A_4$.

In the case when $A_2 \neq A_3 \neq A_4$ it is required to conduct two more experiments to determine absorptivity A_2 and A_3.

The first of them is conducted in the presence of just one of the shields. In this case X_2 and X_{S_3} are determined from system of equations (6) (if shield S_3 is left), and also the absorptivity of the end surface A_2.

The second experiment is conducted without shields. System (6) in this case will contain X_2, X_3, X_4, and A_3 as the unknowns, and on solving it absorptivity A_3 is found.

The possibility of implementing this method of determining the absorptivity of the inside surfaces of a cylindrical vacuum chamber was checked on a chamber whose inside diameter was D = 610 mm and length L = 540 mm. Along the longitudinal axis of the chamber was a cylindrical electric heater with diameter d = 35 mm and length l practically equal to L (l = 535 mm) coated with candle black, and aluminum foil shields were placed on the inside surfaces of the bottom and cover of the chamber. At a vacuum of 10^{-5} mm Hg and steady thermal regime of the entire system we measured the power dissipated by the heater and the average temperatures of surfaces 1, S_2, S_3, and 4.

The following results were obtained on conducting the experiment: $X_1 = -127$ W; $T_1 = 506.4$°K, $T_{S_2} = T_{S_3} = 323$°K; $T_4 = 303.6$°K.

The experimental results were treated in the following order.

1. Using Eq. (7) [1],

$$\varphi_{4,4} = 1 - \frac{2}{\pi} \cdot \frac{\beta}{\alpha} \operatorname{arctg} \frac{1}{\sqrt{1-\left(\frac{\beta}{\alpha}\right)^2}} + \frac{1}{\pi\alpha}$$

$$\times \arcsin\sqrt{1-\left(\frac{\beta}{\alpha}\right)^2} - \frac{\sqrt{1+4\alpha^2}}{\pi\alpha} \operatorname{arctg}\left[\sqrt{1+4\alpha^2}\ \operatorname{tg}\arcsin\sqrt{1-\left(\frac{\beta}{\alpha}\right)^2}\right],$$

where $\alpha = D/2L$ and $\beta/\alpha = d/D$, we obtain $\varphi_{4,4} = 0.5163$ and $H_{4,4} = \varphi_{4,4}F_4 = 0.5344$ m^2.

2. From Fig. 2b [7] we found $\varphi_{1,S_2} = \varphi_{1,S_3} = 0.39$ and consequently $H_{1,S_2} = H_{1,S_2} = \varphi_{1,S_2}F_1 = 0.0232$ m^2.

3. Having written the closure conditions [2] in the form

$$H_{1,4} + 2H_{1,S_2} = F_1,$$
$$H_{1,4} + H_{4,4} + 2H_{4,S_2} = F_4,$$
$$H_{1,S_2} + H_{S_2,S_3} + H_{4,S_3} = F_{S_2}$$

and having solved this system for mutual surfaces $H_{1,4}$, H_{4,S_2}, and H_{S_2,S_2}, we determine $\varphi_{1,4}$, φ_{4,S_2}, and φ_{S_2,S_3} and thereby we obtain the values of all irradiance coefficients for the system

$\varphi_{1,1} = 0$	$\varphi_{S_2,1} = 0{,}0794$	$\varphi_{S_3,1} = 0{,}0794$	$\varphi_{4,1} = 0{,}01266$
$\varphi_{1,S_2} = 0{,}39$	$\varphi_{S_2,S_2} = 0$	$\varphi_{S_2,S_2} = 0{,}0857$	$\varphi_{4,S_2} = 0{,}2355$
$\varphi_{1,S_3} = 0{,}39$	$\varphi_{S_2,S_3} = 0{,}0857$	$\varphi_{S_3,S_3} = 0$	$\varphi_{4,S_2} = 0{,}2355$
$\varphi_{1,4} = 0{,}22$	$\varphi_{S_2,4} = 0{,}835$	$\varphi_{S_2,4} = 0{,}835$	$\varphi_{4,4} = 0{,}5163$
$\sum_{k=1}^{4} \varphi_{1,k} = 1{,}0$	$\sum_{k=1}^{4} \varphi_{S_2,k} = 1{,}001$	$\sum_{k=1}^{4} \varphi_{S_3,k} = 1{,}001$	$\sum_{k=1}^{4} \varphi_{4,k} = 0{,}99996$

4. Having substituted the experimental data for X_1, T_1, T_{S_2}, and T_4, the values of A_1 and $A_{S_2} = A_{S_3}$ (on the basis of the reference data, $A_1 = 0.94$ [3] and $A_{S_2} = A_{S_3} = 0.03$ [4] are used), and the values of the corresponding irradiance coefficients into (6), after transformations we obtain system (7) in the form

$$4{,}8265\ X_{S_2} + 0{,}0119\ X_4\left(\frac{1}{A_4} - 1\right) - 51{,}5021 = 0,$$

$$-0{,}91687\ X_{S_2} + 0{,}007065\ X_4\left(\frac{1}{A_4} - 1\right) + 1{,}090 = 0,$$

$$53{,}99661\ X_{S_2} - 0{,}4837\ X_4\left(\frac{1}{A_4} - 1\right) - X_4 + 108{,}537 = 0,$$

from which we find $X_{S_2} = 8.3746$ W, $X_4 = 110.2935$ W, and the absorptivity of the polished rolled-steel surface 4 of interest to us, $A_4 = 0.0807$.

Using for the entire system the equation $\sum_{i+1}^{4} X_i = 0$ as the check equation, we have

$$-127{,}0 + 110{,}2935 + 2 \cdot 8{,}3746 = 0{,}0427 \text{ w}.$$

The 0.034% deviation with respect to the balance of the radiant balance-fluxes may be the result of errors in measuring the experimental quantities and the accumulation of calculation errors.

For a vacuum chamber with practically the same state of all internal surfaces with successive determination of A_1, A_2, A_3 by the method described we obtained close values of these quantities. Their deviation from the average value $\bar{A} = (A_4 + A_2 + A_3)/3$ was (+8.1)-(−9.5)%.

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