RADIATION HEATER WITH DISPERSE HEAT CARRIER

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The article contains calculations of the temperature profile of a radiation tube with disperse heat carrier by Fourier's equation of heat conduction and by a system of equations taking the disperse structure of the bed into account. The obtained results are compared with the experimental data. The article sheds light on the influence of the diameter of the heat carrier particles on the temperature profile of the radiation tube.

A heating device known by the name radiation tube is being widely used in industry. Various types of radiation tubes are used: vertical, horizontal, blind, etc. The temperature of the wall, which is made of metal with large nickel content, is maintained at the level of 1000-1100°C. A common shortcoming of these tubes is that in the region of the flame, the wall temperature of the radiator is the higher, the further the spot is away in the direction of the gas motion. In consequence, there is a temperature gradient of up to 250°C along the tube [1]. As a result, the useful surface of the radiation tube is insufficient, and endeavors to utilize it more fully by raising the temperature lead to the metal being burned. Moreover, if an injection burner with active gas jet in a radiation tube 1100-1200 mm long is used and efforts are made to distribute the temperature evenly over the entire working length by controlling the length of the flame, the gaseous fuel is not completely burned. In that case, chemical underfiring amounts to 55-60% [2]. Various ways of equalizing the temperature along the radiation tube are known [3-5] but they have not found widespread application.

Combustion of gaseous fuel in a bed of disperse material placed in the radiation tube and use of the particles of disperse material for the heat transfer from the combustion products to the walls of the tube make it possible successfully to overcome the shortcomings inherent in flame combustion. The principle of such a tube was described in [3].

Let us examine the temperature profile along a radiation tube with a circulating disperse heat carrier.

In [6], in the calculation of the temperature distribution along a radiation pipe with a disperse heat carrier it was assumed that the disperse material moving in an annular slit may be approximately viewed as a continuum with specified effective thermophysical properties. In that case, the classical Fourier equation of heat conduction may be used for calculating the temperature profile.

It is known that the effective thermophysical properties of a disperse medium practically do not depend on the particle diameter. Therefore, the theoretical temperature profile along the radiation tube was found to be independent of the selected particle diameter of the disperse heat carrier. Yet experiments show [3] that the selection of the particle diameter has a substantial effect on the temperature profile along the radiation tube.

Previously, it was shown [7, 8] that in short-time thermal actions, the Fourier equation of heat conduction does not describe the heat transfer in disperse media. In our case short-time thermal actions are realized at the initial (inlet) section of the radiation tube. It may be assumed that the experimentally discovered dependence of the temperature on the particle diameter may be explained by the specific conditions of heat exchange in the intake section. These specific conditions, associated with the thermal inertia of the particles, are taken into account by the previously suggested system of equations of heat transfer in a disperse medium [7, 8]

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$$c_1\rho_1\varepsilon\left(\frac{\partial}{\partial\tau}+\mathbf{v}\frac{\partial}{\partial\mathbf{r}}\right)t_1=\lambda_{ef}\,\Delta t_1+\alpha^*S(t_2-t_1), \tag{1}$$

$$c_2\rho_2(1-\varepsilon)\left(\frac{\partial}{\partial\tau}+\mathbf{v}\frac{\partial}{\partial\mathbf{r}}\right)t_2=\alpha^*S(t_1-t_2). \tag{2}$$

Since the annular slit is narrow, and the length of the radiation tube is much greater than its diameter, we may examine the one-dimensional plane problem.

For the sake of simplicity we examine heat transfer on the boundary with a semibounded medium, taking the coefficient of external heat transfer as constant. Then, if we neglect the thermal resistance of the wall of the radiation tube and the longitudinal heat transfer along the tube, the problem reduces to the determination of the temperature profile along the conditional boundary around which the disperse material flows.

The heat transfer from the moving bed to the wall through contact of the particles may be neglected. We take it that the wall temperature is equal to the temperature of the continuous phase at the boundary. We disregard the dependence of the thermophysical properties of the continuous and the disperse phases on the temperature, because the temperatre along the radiation tube changes only slightly. The change in heat content of the continuous phase may be neglected because its density is much smaller than the density of the particles of the disperse phase. The motion of the bed of disperse material is assumed to be rodlike.

We introduce the dimensionless coordinates and parameters

$$\xi=\frac{X}{d},\quad \mathrm{Fo}=\frac{\lambda_{ef}L}{c_2\rho_2(1-\varepsilon)\,d^2v},\quad \vartheta_i=\frac{t_i-t_c}{t_0-t_c},$$

$$A=\sqrt{\frac{\alpha^*Sd^2}{\lambda_{ef}}},\quad \mathrm{Bi}=\frac{\alpha d}{\lambda_{ef}},$$

where the criterion Fo is expressed through the effective characteristics of the dense disperse bed [9], and the time of its dwelling in the annular slit is $\tau = L/v$.

The dimensionless parameter A characterizes the interphase heat exchange and is equal to the limit value of the dimensionless coefficient of convective heat exchange. The parameter A does not depend on the thermophysical properties of the continuous and disperse phases and the particle diameter. It was shown in [8] that $A = \sqrt{6(1-\varepsilon)\mathrm{Nu}^*} = 2$.

Taking the above-said into account, in a system of coordinates associated with a moving bed of disperse material, the system of equations (1), (2), and the boundary conditions are written in the form

$$\frac{\partial^2\vartheta_1}{\partial\xi^2}=A^2(\vartheta_1-\vartheta_2), \tag{3}$$

$$\frac{\partial\vartheta_2}{\partial\,\mathrm{Fo}}=A^2(\vartheta_1-\vartheta_2), \tag{4}$$

$$\vartheta_2(\xi,\,0)=1,\quad \frac{\partial\vartheta_1(0,\,\mathrm{Fo})}{\partial\xi}-\mathrm{Bi}\,\vartheta_1(0,\,\mathrm{Fo})=0,\quad \left.\frac{\partial\vartheta_1}{\partial\xi}\right|_{\xi\to\infty}=0.$$

The expressions for the temperatures of the continuous and the disperse phases at the boundary with the radiation tube have the form

$$\vartheta_1(0,\,\mathrm{Fo})=\frac{2A\,\mathrm{Bi}}{\pi}\int\limits_0^1\frac{\sqrt{1-u^2}\exp(-A^2u^2\,\mathrm{Fo})}{(A^2-\mathrm{Bi}^2)\,u^2+\mathrm{Bi}^2}\,du, \tag{5}$$

$$\vartheta_2(0,\,\mathrm{Fo})=\frac{2A\,\mathrm{Bi}}{\pi}\int\limits_0^1\frac{\exp(-A^2u^2\,\mathrm{Fo})}{\sqrt{1-u^2}\,[(A^2-\mathrm{Bi}^2)\,u^2+\mathrm{Bi}^2]}\,du. \tag{6}$$

We find the values of Fo at which the solution for a semibounded medium can be used in calculating the temperature profiles. For this, we examine the rodlike motion of the bed of disperse material in a slit with width R. The problem reduces to solving the system of equations (3), (4) with the boundary conditions

$$\vartheta_2(\xi,\ 0) = 1,\quad \frac{\partial \vartheta_1(0,\ \mathrm{Fo})}{\partial \xi} - \mathrm{Bi}\,\vartheta_1(0,\ \mathrm{Fo}) = 0,\quad \vartheta_1(\delta,\ \mathrm{Fo}) = 1,$$

where $\delta = Rd$.

Solution of the Problem with the Aid of the Laplace Transform. In the region of the images we have for the temperature of the continuous phase, with $\varepsilon = 0$, that

$$T_1(0,\ S) = \frac{AP}{S\,[AP + \mathrm{Bi}\,\mathrm{th}(AP\delta)]}, \tag{7}$$

where $P = \sqrt{S/(S + A^2)}$.

Taking it that with $AP\delta \geqslant 3$ $\mathrm{th}(AP\delta) = 1$, and applying the theorem of inversion, we obtain an expression coinciding with (5). The obtained solution is correct when $\mathrm{Fo} \leqslant \delta^2/9 - 1/A^2$. Consequently, when $\mathrm{Fo} \leqslant \delta^2/9 - 1/A^2$, the temperature profiles along the radiation tube can be calculated by using the solution for a semibounded medium.

Below we present the results of the computer calculation of the temperature profiles by expression (5). In [8] it was shown that for a dense bed of disperse material, A = 2. According to [9, 10], the theoretical values of the magnitudes α, λ_{ef}, and v for the conditions of the experiment with particles of chrome–magnesite (MgO) were: α = 80 W/m²·°C, λ_{ef} = 0.83 W/m·°C, v = 0.1 m/sec. The calculations were carried out for t_0 = 660°C and t_c = 515°C.

Figure 1 shows the temperature distribution along the radiation tube in dependence on the particle diameter of the disperse material. It also shows the temperature distribution calculated by the Fourier equation of heat conduction. According to the system of equations, the uniformity of temperature distribution along the radiation tube improves with increasing particle diameter.

In Fig. 2 the theoretical and experimental temperature distributions along the radiation tube are compared for d = 1.12 mm. The temperature calculated by the Fourier equation of heat conduction is also plotted in the figure.

The graph in Fig. 2 illustrates the substantial divergence of the calculated data. This discrepancy is due to the fact that at the initial section, the heat exchange is much less intense than its theoretical value calculated by the Fourier equation [7, 8]. It is interesting that in solving problems of a similar type it is impossible to neglect the effect of the initial section, no matter how far from it the examined temperature profile lies.

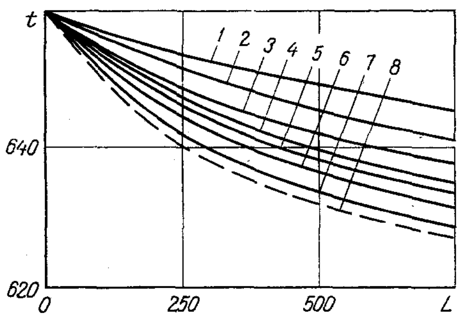

Fig. 1

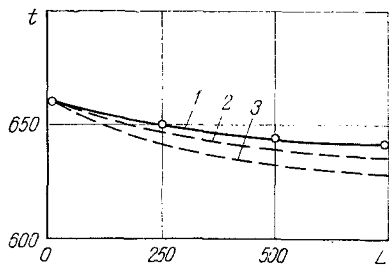

Fig. 2

Fig. 1. Temperature distribution of the radiation tube in dependence on the particle diameter of the material: 1) d = 3 mm; 2) 2.0; 3) 1.5; 4) 1.0; 5) 0.75; 6) 0.5; 7) 0.1; 8) calculated by the Fourier equation of heat conduction. L, mm; t, °C.

Fig. 2. Comparison of the theoretical and experimental temperatures along the radiation tube: 1) experimental curve; 2) theoretical curve calculated by the system of equations for particles with d = 1.12 mm; 3) curve calculated by the Fourier equation of heat conduction.

The system of equations (3), (4) may be used for calculating the temperature profile of a radiation tube with circulating disperse heat carrier in connection with any and every technological process.

The results of industrial operation of radiation tubes with circulating disperse heat carrier in a muffleless installation for chemical and heat treatment at the Minsk Tractor Plant showed that their use made it possible fully to eliminate chemical underfiring of the fuel, to intensify the heat exchange inside the tube, to reduce their number to one half, and as a result, to cut in half the expenditure of natural gas for heating.

NOTATION

c, heat capacity; ρ, density; ε, porosity of the bed; λ_{ef}, effective heat conductivity of the bed; α^*, coefficient of interphase heat exchange; α, heat-transfer coefficient; L, length of the working section of the radiating surface of the radiation tube; d, particle diameter of the heat carrier; v, velocity of the particles of the bed in the annular slit; θ, dimensionless temperature; t_0, temperature of the bed in the insert and initial temperature of the heat carrier in the annular slit; t_c, temperature of the furnace space; t_1, temperature of the continuous phase; t_2, temperature of the disperse phase; S, surface of the particles per unit volume.

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