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RADIANT HEATING OF A FLUIDIZED BED

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The authors examine the heat transfer between a radiating roof and the surface of a fluidized bed through the transparent gas medium in a cylindrical furnace.

The radiant heating of a fluidized bed is appropriate, for example, in the infrared drying of polydisperse materials [1, 2]. Radiant heating is very effective at temperatures above 1300° K, when a gaseous heat supply is impossible owing to the low heat resistance of the distributor and the agglomeration of the particles.

The exact calculation of the radiative heat transfer in a cylindrical furnace with a fluidized bed, including heat transfer between the roof, the bed and the wall lining, leads to very clumsy expressions, not given in the literature. We will find an expression for the heat flux on the simplifying assumption that the lining plays only a small part in the heat transfer and may be regarded simply as a reflecting surface in the process of heat transfer between the roof and the bed.

For simplicity, instead of the emission of the roof and the bed we consider the emission of their centers. As far as the roof is concerned, this assumption is reasonable, since the burner is located in the center of the roof; for the bed it is rough approximation, justified by the fact that the temperature at the center of the bed is always much higher than the temperature of the parts of the bed adjacent to the furnace walls.

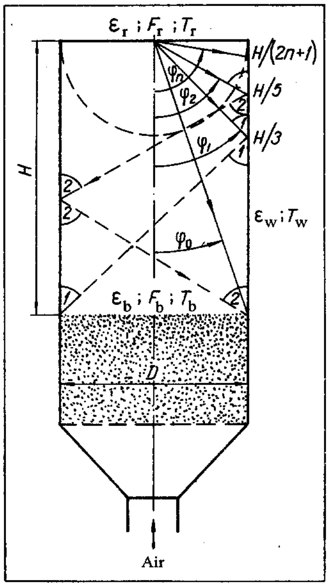

Fig. 1. Model of furnace with radiating roof. The radiation leaving the center of the roof in a cone with angle φ_0 between the generator and the furnace axis reaches the bed without reflection, the radiation between generators with angles φ_n and φ_{n-1} undergoes n-fold reflection from the lining.

We divide all the radiation from the roof and the bed into a part that does not undergo reflection and parts that undergo one-, two-, ..., and n-fold reflection from the furnace walls (we neglect the roughness of the lining, assuming that the angle of incidence is equal to the angle of reflection). In this connection, we note that if we describe (Fig. 1) cones with lines joining points H, H/3, H/5, ..., H/(2n + 1), ..., as generators, and axes coinciding with the furnace axis, they divide a hemisphere of radius D/2, described from the center of the roof, into a sequence of annular segments (the n-th segment is between the generators with angles φ_n and φ_{n-1}), and the radiation entering the solid angle of the n-th annular segment undergoes n-fold reflection from the furnace walls. The fraction of the heat transmitted to the solid angle of the n-th annular segment:

$$q_n = (S_n - S_{n-1})/S,$$

where S is the surface of the hemisphere, and S_n is the curved surface of the n-th segment. Substituting $S = \pi D^2/2$, $S_n = \pi D^2 \sin^2(\varphi_n/2)$, we obtain*

$$q_n = \cos\varphi_{n-1} - \cos\varphi_n.$$

As a result of n-fold reflection from the walls, instead of Qq_n an amount of heat $Qq_n\hat{\varepsilon}^n$, $\hat{\varepsilon} = 1 - \varepsilon_w$ is the reflectivity of the lining, reaches the bed. Thus, the total amount of heat from the roof reaching the bed:

$$Q_\Sigma = \sum_{n=0}^{\infty} Qq_n \hat{\varepsilon}^n = Q \sum_{n=0}^{\infty} \hat{\varepsilon}^n (\cos\varphi_{n-1} - \cos\varphi_n). \tag{1}$$

Since

$$\varphi_n = \operatorname{arctg}\left[\frac{2n+1}{2}\frac{D}{H}\right]$$

$$\cos\varphi_n \equiv \cos\operatorname{arctg} x_n = (1 + x_n^2)^{-1/2},$$

we can rewrite (1) as

$$Q_\Sigma = Q \sum_{n=0}^{\infty} \hat{\varepsilon}^n \left[(1 + x_{n-1}^2)^{-1/2} - (1 + x_n^2)^{-1/2}\right].$$

Noting that $x_{-1} = 0$ and in Q_Σ

$$\sum_{n=0}^{\infty} \hat{\varepsilon}^n (1 + x_{n-1}^2)^{-1/2} = 1 + \hat{\varepsilon} \sum_{n=0}^{\infty} (1 + x_n^2)^{-1/2} \hat{\varepsilon}^n,$$

we finally have

$$Q_\Sigma = Qf(\varepsilon_w,\ D/H), \tag{2}$$

$$f(\varepsilon_w,\ D/H) = 1 - \varepsilon_w \sum_{n=0}^{\infty} \frac{(1-\varepsilon_w)^n}{\left(1 + \left[\frac{2n+1}{2}\frac{D}{H}\right]^2\right)^{1/2}}. \tag{3}$$

The heat reaching the roof from the bed

$$Q'_\Sigma = Q' f(\varepsilon_w,\ D/H), \tag{4}$$

where in (2) and (4)

$$Q = \sigma \varepsilon_r T_r^4 F_r;\quad Q' = \sigma \varepsilon_b T_b^4 F_b.$$

Thus, noting that $F_b = F_r = F$, we have

$$\Delta Q = Q_\Sigma - Q'_\Sigma = \sigma F f\left(\varepsilon_w,\ \frac{D}{H}\right)\left[\varepsilon_r T_r^4 - \varepsilon_b T_b^4\right]. \tag{5}$$

*$\varphi_{-1} = 0$ corresponds to the vertical axis of the furnace (treated as a "cone").

For $T_b/T_r \leq 0.5$, correct to 1–2%, we can rewrite (5) in the form:

$$\Delta Q \simeq \sigma_{red} F [T_r^4 - T_b^4], \tag{5'}$$

where

$$\sigma_{red} = \sigma f \left(\varepsilon_w, \frac{D}{H} \right) \varepsilon_r . \tag{6}$$

For ε_w not too close to zero, the series in (3) converges quite rapidly, and to find f in (5) and (6), it is sufficient to confine oneself to the first few terms. For the case of an ideally reflecting lining $\varepsilon_w = 0$ the series diverges. However, in the limit as $\varepsilon_w \to 0$ the entire second term in (3) vanishes, which is obvious when one notes that for n greater than a certain number N the series in (3) is majorized by the series

$$\sum_{n=N}^{\infty} (1 - \varepsilon_w)^n / [(D/H)\, n],$$

and according to L'Hôpital's rule

$$\lim_{\varepsilon_w \to 0} \varepsilon_w \sum_{n=1}^{\infty} (1 - \varepsilon_w)^n / n = \lim_{\varepsilon_w \to 0} \frac{- \sum_{n=0}^{\infty} (1 - \varepsilon_w)^n}{- 1/\varepsilon_w^2} = 0.$$

Thus,

$$f(\varepsilon_w = 0,\ D/H) = 1. \tag{7}$$

For $(D/H) \to 0$

$$f(\varepsilon_w,\ D/H) \to 1 - \varepsilon_w \sum_{n=0}^{\infty} (1 - \varepsilon_w)^n = 0. \tag{8}$$

In Fig. 2, using (7) and (8), we have plotted graphs of f as a function of D/H for various values of ε_w. The value of σ_{red} increases with increase in the ratio D/H, i. e., when the roof is close above the bed, and when a highly reflective lining material is used.

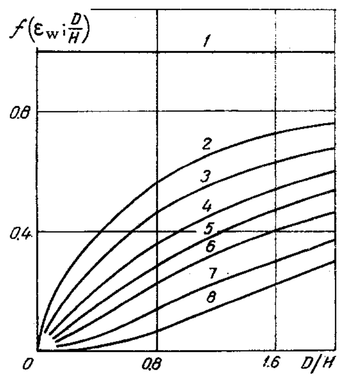

Fig. 2. $f(\varepsilon_w, D/H)$ as a function of D/H at various values of ε_w: 1) $\varepsilon_w = 0$; 2) 0.2; 3) 0.3; 4) 0.4; 5) 0.5; 6) 0.6; 7) 0.8; 8) 1.0.

The radiant heating process was tested on an experimental device (Fig. 3), in which sand (0.5–1 mm fraction) was fluidized with air. At a radiating-roof temperature of 1573° K and a bed temperature of 500° K the heat flux was 35 000 W/m^2. The reduced radiation factor $\sigma_{red} = 0.41 \cdot 10^{-8}$ W/m$^2 \cdot$ °K^4. The discrepancy between this value and the calculated σ_{red} from (6) and Fig. 2 is attributable to the large temperature drop between the roof and the bed, in which case the lining plays an important part in heat transfer. If the temperature gradient is not large, our assumptions correspond to reality [3].

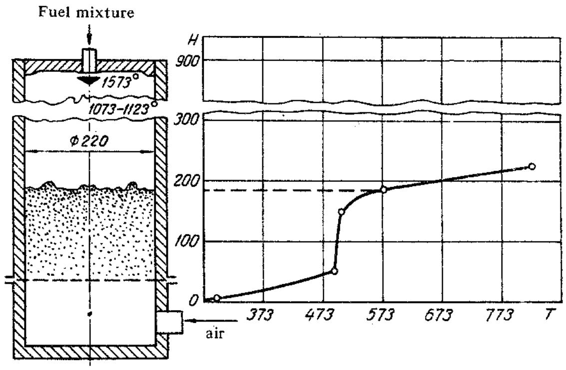

Fig. 3. Variation of the temperature (T, °K) over the height (H, mm) of a furnace with a radiating roof.

We trust that our simplified analysis will be found useful in a more accurate investigation of the problem in which the role of the lining is taken into account.

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