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LOAD CONTROL IN LOW-POWER FLUIDIZED BED BOILERS

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A thermal engineering analysis of a new method of load control in low-power fluidized bed boilers is cariied out. The method ensures smooth control and does not require heat-transfer surfaces to be located inside the furnace.

As is known [1], design and operation of power-producing fluidized bed boilers are associated with the problem of rational load control. As a rule, any changes in the load are usually accompanied by changes in the height of the fluidized bed caused by variation of the rate of blast or the weight of the bed [1]. This control has some disadvanges, which are most pronounced in low-power boilers ($\leq$3 MW), where fluidized beds of a rather low height ($H \leq 0.3$ m) are used. Because of this, smooth load control is impossible. Therefore, the search for alternative methods of load control is very important for perfection of boiler equipment employing the fluidization technique.

In the present work a new method of load control is considered that does not require heat-transfer surfaces located within the bed and ensures smooth load control of the boiler [2].

A schematic of the furnace is shown in Fig. 1. The grate of the main bed is manufactured with apertures and is connected with additional cooled beds that serve as external finning and function to remove heat from the main fluidized bed. This method does not require conventional heating surfaces located within the layer. The principle of the control is based on changing the hydrodynamic conditions in one or several additional layers by changing the rate of gas filtration [2]. In this case the disperse material of the additional layer can be fluidized ($u \geq u_0$) or fixed ($u < u_0$). In the former case the additional layer functions as a fin cooling the main bed and in the latter it works as a cooled area of the gas distributor.

In a thermal engineering analysis of the method of load control suggested, first, two main steady-state operating regimes of an additional bed will be considered, namely, a fluidized bed regime and a fixed aerated bed regime.

Steady-State Fluidized Bed Regime. As has been stated above, in this kind of operation the additional bed works as a fin cooling the main bed. With the heat release from combusion of coal neglected, the heat conduction equation describing the temperature field in the fin has the form

$$\mathrm{Pe}\,\frac{d\theta}{d\xi} = \frac{d^2\theta}{d\xi^2} - 2\,\mathrm{Bi}\,\theta \tag{1}$$

with the boundary conditions

$$-\frac{d\theta}{d\xi} + \mathrm{Pe}\,(\theta - \theta_0) = 0\,, \quad \xi = 0\,; \quad \theta = 1\,, \quad \xi = 1\,. \tag{2}$$

The solution (1) and (2) will be written as

$$\theta = \frac{(\mathrm{Pe} - p_2 - \mathrm{Pe}\,\theta_0 \exp p_2) \exp (p_1\xi) + (\mathrm{Pe}\,\theta_0 \exp p_1 - (\mathrm{Pe} - p_1)) \exp (p_2\xi)}{(\mathrm{Pe} - p_2) \exp p_1 - (\mathrm{Pe} - p_1) \exp p_2}\,, \tag{3}$$

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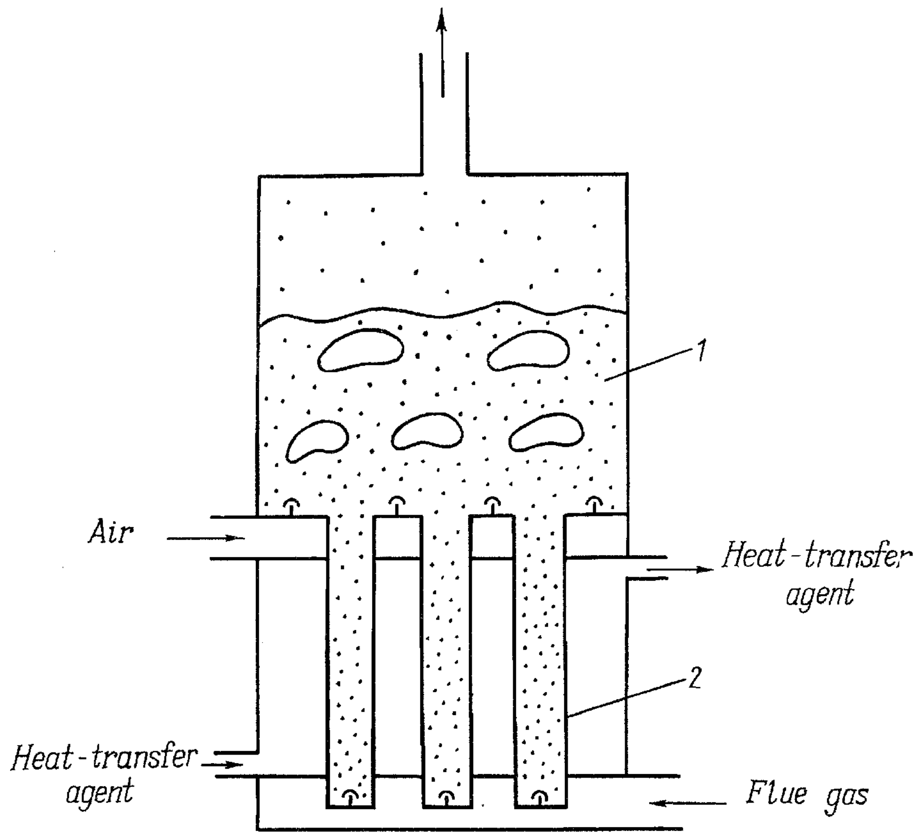

Fig. 1. Schematic of the fluidized bed boiler: 1) main bed; 2) additional bed.

where

$$p_{1,2} = \frac{\mathrm{Pe}}{2} \pm \sqrt{\left(\left(\frac{\mathrm{Pe}}{2}\right)^2 + 2\,\mathrm{Bi}\right)}.$$

The quantity of heat transferred from the main bed to the additional one per unit time is

$$Q_{\mathrm{FB}} = \frac{\pi R^2 \lambda_{\mathrm{ef}}^{\mathrm{v}} (T_b - T_w)}{H} \left(\frac{d\theta}{d\xi}\bigg|_{\xi=1} - \mathrm{Pe}\,\frac{T_b}{T_b - T_w}\right). \tag{4}$$

The efficiency E of the fin is determined from the relation

$$Q_{\mathrm{FB}} + \pi R^2 c_f \rho_f u T_0 = 2\pi R H \alpha (T_b - T_w) E, \tag{5}$$

which gives the following expression for calculating E:

$$E = \frac{1}{2\,\mathrm{Bi}} \left(\frac{d\theta}{d\xi}\bigg|_{\xi=1} - \mathrm{Pe}\,\frac{T_b - T_0}{T_b - T_w}\right). \tag{6}$$

The quantities Q_{FB} and E were calculated for the following conditions: $H = 1$ m; $R = 0.25$ m; $d = 1.5$ mm; $\rho_s = 2000$ kg/m^3; $T_b = 800$°C; $T_w = 100$°C; $T_0 = 200$°C; $u_0|_{800°\mathrm{C}} = 0.48$ m/sec. The effective vertical thermal conductivity $\lambda_{\mathrm{ef}}^{\mathrm{v}}$ was calculated from a formula derived in [3]. The quantity $\alpha^{\max}$ defined by the following expression [4] was used as α_1:

$$\mathrm{Nu}^{\max} = 0.4\,\mathrm{Ar}^{0.16} \left(\frac{\rho_s}{\rho_f}\right)^{0.14} \left(\frac{c_s}{c_f}\right)^{0.30} + 0.0013\,\mathrm{Ar}^{0.63}\,\mathrm{Pr}. \tag{7}$$

TABLE 1. Values of the Heat Extraction Q_{FB} and the Efficiency of the Fin E in the Case of the Additional Bed Operating as a Fluidized Bed

u, m/sec	Q_{FB}, kW	E
0.5	70	0.50
0.7	126	0.88
1.0	136	0.96
1.5	128	0.92
2.0	133	0.99
2.5	137	0.99
3.0	125	0.98

TABLE 2. Values of the Heat Extraction Q_{FiB} from the Additional Bed Operating as a Fixed Aerated Bed

u, m/sec	Q^*_{FiB}, kW	Q_{FiB}, kW
0.05	0.35	0.38
0.10	0.70	0.76
0.15	1.20	1.30
0.20	1.60	1.75
0.60	5.30	5.52

It was found that $\alpha^{max} = 221$ W/(m^2·K). In Table 1, calculated Q_{FB} and E for various rates of gas filtration (based on T_b = 800°C) are presented. One can see that under developed stirring of particles in the additional bed ($u \geq 0.7$ m/sec), the heat extraction is almost constant, reaching 130–135 kW.

Steady-State Fixed Aerated Bed Regime. The additional layer functions as a section of a gas distributor of the main fluidized bed. In this case vertical dispersion heat transfer can be neglected over convective transfer by gas filtered through the bed.* In this case the heat conduction equation has the form

$$c_f \rho_f u \frac{\partial T}{\partial x} = \lambda_{ef}^{h} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right), \tag{8}$$

with the boundary conditions

$$\frac{\partial T}{\partial r} = 0, \quad r = 0; \quad T = T_0, \quad x = 0; \quad -\lambda_{ef}^{h} \frac{\partial T}{\partial r} = \alpha (T - T_w), \quad r = R. \tag{9}$$

The formal substitution $x/u \to t$ reduces two-dimensional problem (8) and (9) to the classical one-dimensional unsteady-state problem of heating (cooling) a cylinder under boundary conditions of the third kind. Therefore, it is possible to write down the solution of (8) and (9) immediately [5]:

$$\bar{\theta} = \frac{T - T_0}{T_w - T_0} = 1 - \sum_{n=1}^{\infty} A_n J_0 \left(\mu_n \frac{r}{R} \right) \exp \left(- \frac{\mu_n^2}{\mathrm{Pe}_x} \right), \tag{10}$$

where

$$A_n = \frac{2 J_1 (\mu_n)}{\mu_n [J_0^2 (\mu_n) + J_1^2 (\mu_n)]}.$$

* Under these particular conditions this suggestion is valid throughout the volume of the fluidized bed except for a thin boundary layer separating the main fluidized bed from the fixed additional bed. In this region a substantial the temperature gradient occurs that connects the temperatures of the main and additional beds.

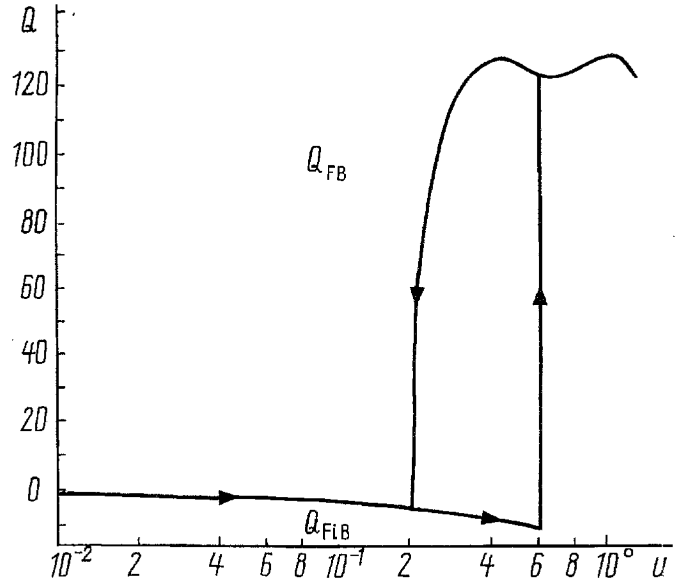

Fig. 2. Plot of the power Q_{FB} removed from the main bed and Q_{FiB} supplied to it versus the rate of gas filtration. Steady-state regimes. Q, kW; u, m/sec.

For the quantity of heat entering the main bed with the convective gas flow, we have

$$Q_{FiB} = \int_0^R 2\pi r T(H, r)\, c_f \rho_f u\, dr = 2\pi R^2 c_f \rho_f u \times$$

$$\times \left[\frac{T_w}{2} - (T_w - T_0) \sum_{n=1}^{\infty} A_n \frac{J_1(\mu_n)}{\mu_n} \exp\left(-\mu_n^2 \frac{1}{\mathrm{Pe}_H} \right) \right].$$

The quantities Q_{FiB} were calculated for the same conditions as in the first case (except the filtration rates). The heat transfer coefficient between the fixed aerated bed and the inner surface of the tube of the additional bed was calculated using the method of [6]. Table 2 contains Q_{FiB} as a function of the inlet velocity of gas (at 200°C). This table also contains the heat fluxes Q^*_{FiB} calculated from the following formula with the radial temperature profile neglected:

$$Q^*_{FiB} = \pi R^2 c_f \rho_f u\, [\exp(-2/\mathrm{Pe}^*)(T_0 - T_w) + T_w], \tag{11}$$

which follows from solution of the system*

$$\mathrm{Pe}^* \frac{d\theta}{d\xi} = -2\theta, \tag{12}$$

$$\theta = 1, \quad \xi = 1; \quad \theta = \frac{T - T_w}{T_0 - T_w}. \tag{13}$$

As can be seen from Table 2, inclusion of temperature changes over the tube radius increases slightly the heat flux entering the main bed, whose absolute value is naturally much less than Q_{FB} (see Table 1).

The results obtained are presented graphically in Fig. 2, which shows the whole set of steady thermal states of the additional bed. The velocity u is calculated at the temperature of the inlet gas $T_0 = 200$°C. The rate of initial

* The analysis has shown that the solutions of (1) and (2) for a fixed bed and of (12) and (13) coincide almost everywhere except for a thin layer at $\zeta = 1$, which is apparently a consequence of the basic difference in the boundary conditions (2) and (13).

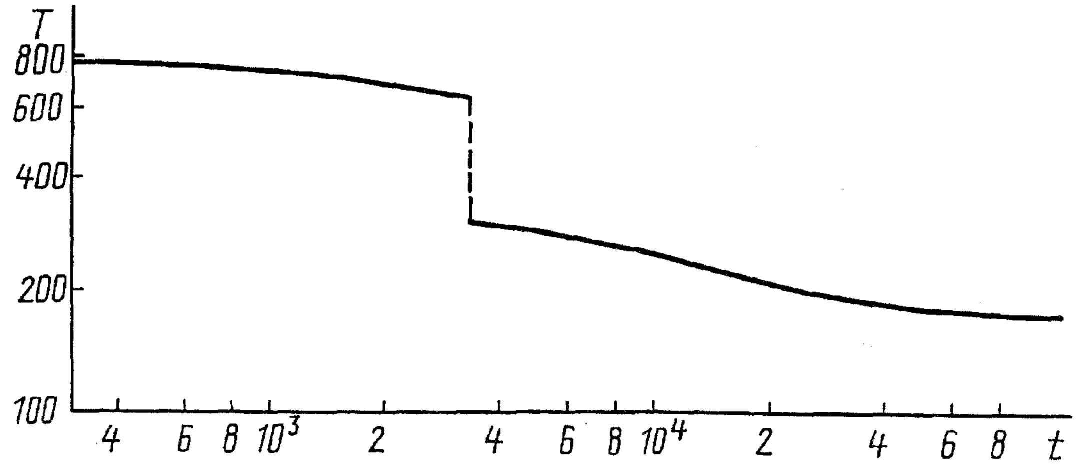

Fig. 3. Dynamics of cooling of the additional bed at the point $x = H/2$. T, °C; t, sec.

fluidization of disperse material is $u_0 = 0.60$ m/sec at 200°C and $u_0 = 0.21$ m/sec at 800°C. It is interesting to note that because of the different temperature levels of the disperse material in the fixed ($T \simeq 150-200$°C) and fluidized ($T = 800$°C) beds, hysteresis appears in the relation $Q(u)$. During operation with the positive quantity $Q = Q_{FB}$ (heat is removed from the main bed), the additional bed serves as a fin with almost ideal efficiency (due to $\lambda_{ef}^{v} \to \infty$). During operation with the negative quantity $Q = Q_{FiB}$ (heat is supplied to the main bed), the additional bed functions as an element of a gas distributor of the main bed. It is on the difference in Q_{FB} and Q_{FiB} (both in absolute value and in sign) that the present method of load control in the boiler is based.

It seems of indubitable practical interest to analyze the unsteady regime of the transition of the additional bed from the fluidized to the fixed state.*

Since the characteristics times of cooling the bed $t_1 = c_s\rho_s(1-\varepsilon)H/c_f\rho_f u$ and $t_2 = c_s\rho_s(1-\varepsilon)R/2\alpha$ exceed the characteristic time of interphase heat transfer $t_s = c_f\rho_f\varepsilon d^2/12\lambda_f(1-\varepsilon)$ by several orders of magnitude, one can reasonably suggest that the temperatures of the gas and the particles are equal at each moment; i.e., a steady process can be assumed. In this case cooling of the fixed bed is described by the following system of equations:

$$\frac{\mathrm{Pe}^*}{2}\frac{d\theta}{d\xi} + \frac{\partial\theta}{\partial\,\mathrm{Fo}} = -\theta\,, \tag{14}$$

$$\theta = \theta_0\,, \quad \xi = 0\,; \quad \theta = 1\,, \quad \mathrm{Fo} = 0\,. \tag{15}$$

It should noted here that in writing Eqs. (14) and (15) the radial temperature distribution was neglected. This neglect can lead only to an insignificant decrease in the time of cooling (see Table 2).

The solution of Eqs. (14) and (15) is obtained by the integral Laplace transformation [5] and has the form

$$\theta = \exp(-\mathrm{Fo})\,, \quad 0 < \mathrm{Fo} < 2\xi/\mathrm{Pe}^*\,;$$
$$\theta = \exp(-\mathrm{Fo}) + \theta_0\exp(-2\xi/\mathrm{Pe}^*) - \exp(-(2\xi/\mathrm{Pe}^* + \mathrm{Fo}))\,, \quad \mathrm{Fo} > 2\xi/\mathrm{Pe}^*\,. \tag{16}$$

As can be seen, function (16) describes a wave process of heat propagation with the velocity $u_{ef} = c_f\rho_f u/c_s\rho_s(1-\varepsilon)$. It is evident that within the framework of the problem formulated the presence of this "effective" velocity of the thermal front can be explained by differences in the volume heat capacities of the phases (when they are equal, $u_{ef} = u/\varepsilon$ is the real velocity of the gas in the space between the particles).

* The inverse transition from the fixed to fluidized state can be performed almost instantaneously because of a high thermal conductivity of the fluidized bed.

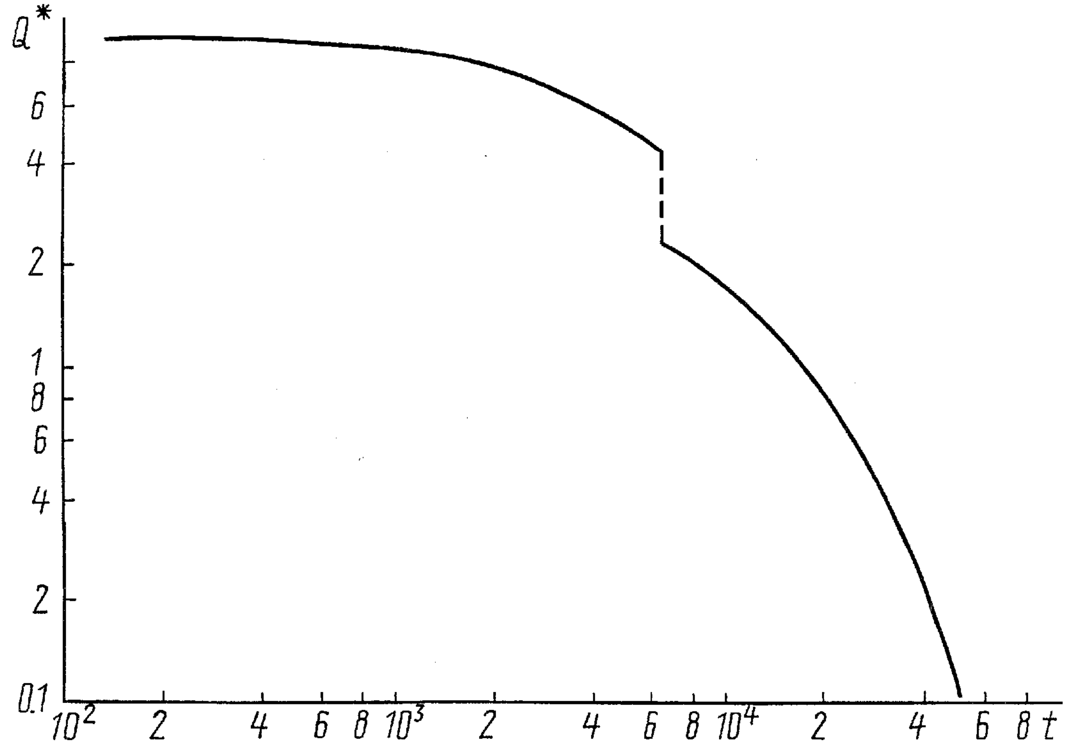

Fig. 4. Plot of the power Q^* versus time. Q^*, kW.

In Fig. 3 one can see the plot of the temperature of the bed at the point $x = H/2$ versus the time, calculated from Eq. (16) for $u = 0.2$ m/sec at $T_0 = 200^0$C and $\varepsilon = 0.4$ (the other conditions were indicated earlier). In this case the velocity of the wave front is $u_{ef} \simeq 1.5 \cdot 10^{-4}$ m/sec. In Fig. 4 the quantity of heat $Q^*(t)$ released from the additional bed per unit time calculated from Eq. (16) is shown:

$$Q^*(t) = \int_0^H 2\pi R\alpha\,(T(x) - T_w)\,dx + \pi R^2 c_f \rho_f u\,(T|_{x=\mathrm{H}} - T_0)\,,$$

$$\int_0^H T(x)\,dx = \int_0^{\frac{c_f\rho_f ut}{c_s\rho_s(1-\varepsilon)}} \left[T_w + (T_b - T_w)\exp\left(-\frac{2\alpha t}{R\,c_s\rho_s\,(1-\varepsilon)}\right) + \right.$$

$$+ (T_0 - T_w)\exp\left(-\frac{2\alpha x}{R\,c_f\rho_f u}\right) - (T_b - T_w)\,\times$$

$$\left.\times \exp\left(-\left(\frac{2\alpha x}{R\,c_f\rho_f u} + \frac{2\alpha t}{R\,c_s\rho_s\,(1-\varepsilon)}\right)\right)\right] dx \,+$$

$$+ \int_{\frac{c_f\rho_f ut}{c_s\rho_s(1-\varepsilon)}}^{H} \left[T_w + (T_b - T_w)\exp\left(-\frac{2\alpha t}{R\,c_s\rho_s\,(1-\varepsilon)}\right)\right] dx\,, \quad t < \frac{c_s\rho_s\,(1-\varepsilon)\,H}{c_f\rho_f u}\,,$$

$$\int_0^H T(x)\,dx = \int_0^H \left[T_w + (T_b - T_w)\exp\left(-\frac{2\alpha t}{R\,c_s\rho_s\,(1-\varepsilon)}\right) + \right.$$

$$+ (T_0 - T_w)\exp\left(-\frac{2\alpha x}{R\,c_f\rho_f u}\right) -$$

$$-(T_b - T_w)\exp\left(-\left(\frac{2\alpha x}{R\, c_f \rho_f u} + \frac{2\alpha t}{R\, c_s \rho_s (1-\varepsilon)}\right)\right)\Bigg]\, dx\,, \quad t > c_s \rho_s (1-\varepsilon)\, H/c_f \rho_f u\,. \tag{17}$$

As can be seen from Fig. 4, cooling (achievement of steady conditions) is a rather slow process. Slagging of the additional bed can be prevented by putting on a blast containing no oxygen (flue gases).

The method of thermal calculation suggested here predicts the main regime parameters that ensure the required load of the boiler operating following this scheme.

NOTATION

$\mathrm{Ar} = (gd^3/\nu_f^2)(\rho_s/\rho_f - 1)$, Archimedes number; $\mathrm{Bi} = \alpha H^2/R\lambda_{\mathrm{ef}}^{\mathrm{v}}$, $\mathrm{Bi}^* = \alpha R/\lambda_{\mathrm{ef}}^{\mathrm{h}}$, Biot numbers; c, heat capacity; d, diameter of particles; $\mathrm{Fo} = 2\alpha t/Rc_s\rho_s(1-\varepsilon)$, Fourier number; g, free fall acceleration; H, height of the fin (of the additional bed); $\mathrm{Nu} = \alpha_1 d/\lambda_f$, Nusselt number; $\mathrm{Pe}_x = c_f\rho_f uR^2/\lambda_{\mathrm{ef}}^{\mathrm{h}}x$, $\mathrm{Pe_H} = c_f\rho_f R^2/\lambda_{\mathrm{ef}}^{\mathrm{h}}H$, $\mathrm{Pe} = c_f\rho_f uH/\lambda_{\mathrm{ef}}^{\mathrm{v}}$, $\mathrm{Pe}^* = c_f\rho_f R/H\alpha$, Peclet numbers; $\mathrm{Pr} = c_f\eta_f/\lambda_f$, Prandtl number; r, radius; Q, heat flux; R, radius of the additional bed; T_b, temperature of the fluidized bed; T_w, temperature of cooling water; T_0, inlet temperature of gas; T, temperature; t, time; u, u_0, rates of filtration and initial fluidization; x, coordinate; α_1, α_2, heat release coefficients; $\alpha = 1/(1/\alpha_1 + \delta/\lambda_s + 1/\alpha_2)$, heat transfer coefficient; ε, porosity; ρ, density; δ, thickness of the wall; λ, thermal conductivity; $\theta = (T - T_w)/(T_b - T_w)$; $\theta_0 = (T_0 - T_w)/(T_b - T_w)$; $\xi = x/H$; μ_n, roots of the characteristic equation $J_0(\mu)/J_1(\mu) = \mu/\mathrm{Bi}^*$. Subscripts: f, gas; s, solids; ef, effective, FB, fluidized bed; FiB, fixed bed. Superscripts: max, maximum, h, horizontal; v, vertical.

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