NOTATION

σ, liquid surface tension; r, capillary radius; h, capillary ascent height; ρ, density, kg/m^3; g, acceleration of gravity; η, dynamic viscosity; τ, outflow time; t, temperature, °C.

LITERATURE CITED

1. S. S. Voyutskii, Course in Colloidal Chemistry [in Russian], Moscow (1964).
2. Protocol on Ozone-Destroying Materials, Montreal (1987).
3. J. Squires, Practical Physics [Russian translation], Moscow (1971).
4. K. F. Zhigach, Zavod. Lab., No. 6, 699-703 (1937).
5. É. Gatchek, Viscosity of Liquids [in Russian], Moscow—Leningrad (1935).
6. Handbook of Chemistry, Volume 1 [in Russian], Moscow—Leningrad (1962).
7. I. I. Perel'shtein, Methods for Experimental Study of the Properties of Cooling Agents [in Russian], Moscow (1963).

OPTIMAL STARTUP CONDITIONS OF FLUIDIZED-BED BOILER

S. G. Ruzhnikov, O. V. Yangolov, M. L. Shchipko, and S. L. Gritsko

UDC 662.62:66.096.5

A mathematical model is developed permitting optimization of the startup of fluidized-bed equipment in which an exothermal reaction is occurring, by numerical-experiment method. The results obtained are tested for a semicommercial 8-MW power boiler.

Startup of power boilers with a fluidized bed (as well as gas generators, calcination furnaces, and steam boilers) from the cold state is sufficiently complex and, as a rule, includes the operation of heating the bed material and the apparatus to a definite temperature using an auxiliary (startup) fuel [1-3].

The aim of the present investigation is to optimize the startup conditions (on account of reduction in length of the operation and the consumption of startup fuel) by numerical experiment on a specially developed model. The stage of loading a portion of startup fuel in the fluidized bed heated to 460-680 K and the subsequent fuel burnup is analyzed here.

Analysis of the experimental data obtained on a 20-kW laboratory boiler [4] and on an 8-MW experimental commercial boiler [3] allows the following simplifying assumptions to be made in modeling the given process: the hydrodynamics of the apparatus with respect to the solid phase is described by an ideal-mixing model; the change in mass of the fluidized bed in the startup period is determined solely by the consumption of the component which is burning up; the volume of exhaust gases is equal to the volume of air suppplied; the mean diameter of the bed particles in the startup period remains constant; and the only combustion products are H_2O and CO_2.

Taking account of these assumptions, the mathematical model describing the startup of the fluidized-bed equipment in the case of an exothermal reaction is written as follows.

The balance of solid material is determined by the coal burnup in the bed and the loss by entrainment

$$dM_c/dt = -KM_c - K(\bar{d})\,M_c. \tag{1}$$

Institute of Chemistry and Chemical Technology, Siberian Branch, Academy of Sciences of the USSR, Krasnoyarsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 1, pp. 126-131, July, 1990. Original article submitted May 24, 1989.

0022-0841/90/5901-0923$12.50

The constant of particle entrainment $K(\overline{d})$ is calculated in accordance with the relation in [5], and the first critical rate of fluidization in this relation is determined from the well-known criterial dependence [6].

The heat balance for the fluidized-bed equipment, taking account of the given assumptions, is written in the form

$$Q_1 = Q_2 - Q_3 + Q_4 + Q_5,$$

where Q_1 is the change in heat content of the bed; Q_2 is the heat arriving with the air; Q_3 is the heat removed with the waste gases and entrainment; Q_4 is the heat liberated as a result of combustion; Q_5 is the heat sink or source from the heat exchangers, the burners, and the remainder of the equipment.

Neglecting the heat content of the gases in the medium, it is found that

$$dT/dt = [W_c H_p + W_c C_c T + G\rho_v C_v T_v + \alpha F (T_p - T) - G\rho_g C_g T + \lambda_w F_w dT_w/dx|_{x=0}]/[M_c C_c + M_I C_I]. \quad (2)$$

On reaching some temperature in the apparatus, the rate of chemical reaction – coal combustion – is limited by the quantity of air supplied. If this is so, it is assumed that $W_c = W_c^*$.

The heat-transfer coefficient is calculated from the conventional criterial equation [6]; for particles with $\overline{d} > 0.15$ mm, $\alpha = 0.8\alpha_{max}$ is assumed.

In startup conditions, the slowest thermal process in the fluidized-bed equipment is heating of the heat insulation, the thickness of which is 0.5-1 m for commercial equipment. Therefore, in the course of startup, it is not completely heated, as a rule. Taking this into account, it may be assumed that the temperature at the internal surface of the heat-insulation wall is equal to the temperature in the appartus T and the temperature of the external wall is equal to the ambient temperature T_A. For commerical equipment, the wall thickness is usually significantly less than its linear dimensions, and therefore, in determining the temperature profile at the wall, consideration may be confined to the one-dimensional heat-conduction equation

$$\frac{\partial T_W}{\partial t} = a \frac{\partial^2 T_W}{\partial x^2} \quad (3)$$

with boundary conditions of the first kind

$$T_W(0, t) = T(t); \; T_W(l, t) \triangleq T_A = \text{const} \quad (4)$$

and initial conditions

$$T_W(x, 0) = T_W(0) + \frac{T_A - T_W(0)}{l} x. \quad (5)$$

The problem in Eqs. (3)-(5) is solved by the grid method using an explicit difference scheme [7], for which $a\tau/h^2 \leq 0.5$, where τ, h are the grid steps with respect to the time and spatial coordinates, respectively. From the known temperature profile $\tau(i\tau, jh)$, the heat flux from the bed to the wall at time $i\tau$ may be determined

$$\lambda_W F_W \frac{dT_W|_{x=0}}{dx} = \lambda_W F_W \frac{T_W(i\tau, 0) - T_W(i\tau, h)}{h}.$$

Experimental thermograms (Fig. 1) are obtained in boiler startup with a rate of fluidizing air in front of the lattice of 0.6 m/sec, a particle diameter of the bed of 0.5-3 mm, and an input temperature of the fluidizing air of 30°C for the laboratory boiler and 100°C for the semicommercial boiler. It is evident from Fig. 1 that the evolution of the thermal conditions of the boiler startup may occur in one of the following versions: rapid heating of the fluidized bed to temperatures above 1300 K (case 1); normal heating of the fluidized bed of the boiler (case 2); spontaneous cessation of bed heating at a certain point, with subsequent cooling of the boiler (case 3 for the experimental boiler).

The first and third cases of boiler startup are unacceptable. The type of filler has a great influence on the boiler startup. The results of startup of laboratory and commer-

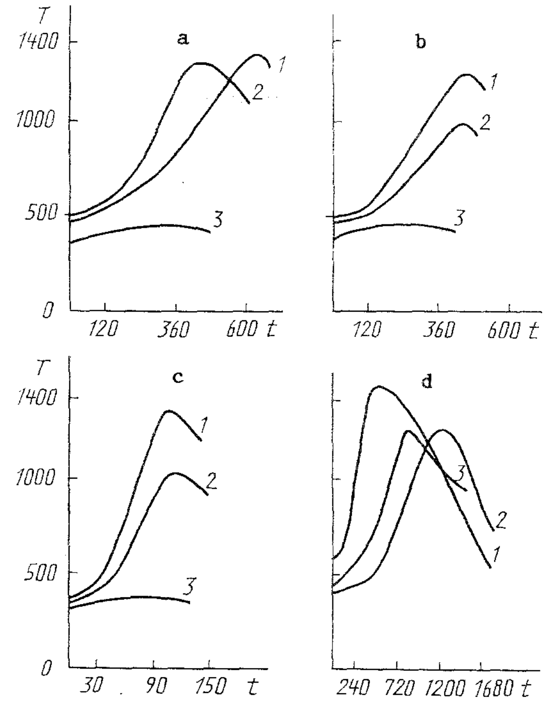

Fig. 1. Variation in mean temperature of fluidized bed in boiler startup: a) laboratory boiler, slag filler, mass 9 kg; Irsha–Borodinsk coal, mass 3 (1) and 2 (2, 3) kg; b) Berezovsk coal mass 2 (1) or 1 (2, 3) kg; c) filler, IK-12-70 catalyst, mass 10 kg; Irsha–Borodinsk coal, mass 2 (1) and 1 (2, 3) kg; d) semicommercial boiler, slag filler, mass 800 kg; Irsha–Borodinsk coal, mass 600 (1), 300 (2), and 150 (3) kg.

cial boilers with slag filler are shown in Fig. 1a, d. If IK-12-70 catalyst is used as the filler, this permits 40-60°C reduction in the initial bed temperature in startup and reduction in the time for the boiler to reach the operating temperature conditions.

The experimental data obtained permit refinement of the mathematical model. The identification problem is solved here by numerical methods. Varying the preexponential factor and the activation energy determining the rate constant of coal combustion, as well as the entrainment coefficient of coal particles from the bed, the refined parameters are determined from the condition of a minimum of the discrepancy function

$$\Phi(K_0,\ E,\ K') = \sum_{j=1}^{n} \sum_{i=1}^{m} (T_{ji}^{e} - T_{ji})^2 \to \min_{K_0, E, K'},$$

where T_{ji}^{e}, T_{ji} are the i-th experimental and theoretical values of the bed temperature for the j-th case of startup.

The search for a minimum of the function $\Phi(K_0,\ E,\ K')$ is by the Nelder–Mead algorithm [7], and numerical integration of Eqs. (1) and (5) is by a method of Rozenbrok type of second-order accuracy [8].

Realization of the given algorithm on an EC-1061 computer permits the determination of the most reliable values of the variable parameters (Table 1).

Note the good agreement of the constants K_0 and E obtained as a result of identification of the model from experimental data on the startup of laboratory and semicommercial boilers when working with the same fuel, which proves the possibility of using a scale model of the process. The difference in the entrainment constants K' is due to different geometric parameters of the equipment (the height of the furnace chamber of the laboratory boiler is 0.5 m, and that of the semicommercial boiler is 6.25 m).

TABLE 1. Results of Identification

Equipment	Startup coal (deposit)	Filler	Identification parameters		
			$K_0 \cdot 10^{-7}$	E	K'
Laboratory boiler ($S = 0.05\ m^2$)	Irsha–Borodinsk	Boiler slag	2,3668	12456	$0{,}3 \cdot 10^{-4}$
The same	Berezovsk	IK-12-70 catalyst	2,8012	10812	$0{,}3 \cdot 10^{-4}$
»	Berezovsk	Boiler slag	2,2661	12762	$0{,}3 \cdot 10^{-4}$
Semicommercial boiler ($S = 2\ m^2$)	Irsha–Borodinsk	Boiler slag	2,4617	12670	$1 \cdot 10^{-7}$

The deviation of the theoretical bed-temperature values from the experimental values is no more than 15%.

The choice of optimal startup conditions of power equipment is determined as a result of solving the following optimization problem

$$t,\ T_0 \to \min, \tag{6}$$

$$G \in [G_1,\ G_2], \tag{7}$$

$$T_0 \in [T_0^{(1)},\ T_0^{(2)}], \tag{8}$$

$$M_c \in [M_c^{(1)},\ M_c^{(2)}], \tag{9}$$

$$T_{p_{\min}} \leqslant T(t) \leqslant T_{p_{\max}},\ \dot{T} < 0, \tag{10}$$

$$T(t) < T_{\max},\ \forall t. \tag{11}$$

This is a two-criterion problem. The first optimizing criterion is the startup time of the equipment from the instant of bed fluidization in the instant at which the working bed temperature is reached (1073-1173 K). The time of bed heating t_c in the steady state is not taken into account by this criterion, since t_c is uniquely determined by the construction of the apparatus and the power of the heat source. There is an explicit dependence between t_c and the bed temperature at the instant of fluidization T_0. Therefore, reduction in T_0 leads to reduction in t_c. In addition, the temperature T_0 has a significant influence on the thermal evolution of the boiler in startup conditions. Thus, decrease in T_0 below some limiting values makes boiler startup impossible at any values of the mass of startup fuel M_c and the flow rate of fluidizing agent G. Therefore, the second optimizing criterion chosen is the temperature T_0.

The optimization problem in Eqs. (6)-(9) is solved by scanning the variables G, T_0, M_c. In the first stage of the calculations, the mass of startup fuel M_c is fixed. Then, varying the flow rate of fluidizing air in the interval G_1, G_2, the minimum initial temperature of the bed at which boiler startup occurs is determined. The startup conditions are regarded as acceptable if the constraints in Eqs. (10) and (11) apply. Thus, the first point of the set of compromises (the Pareto set) such that T_0 is minimal but the startup time is not minimal is determined.

Increasing the temperature T_0 to $T_0^{(2)}$ and varying the flow rate within the limits G_1, G_2, the boiler startup conditions in which the startup time is a minimum but the initial bed temperature is not the minimum possible (the second point of the set of compromises) is determined.

Varying the mass of startup fuel M_c within the limits $M_c^{(1)}$, $M_c^{(2)}$ permits the construction of the whole set of compromises characterizing the relation between the initial bed temperature T_0 and the startup time. The calculation results obtained show that, with increase in the initial bed temperature T_0 to some values T_0', the startup time of the apparatus t decreases, which corresponds to the physical concept of the given process. If T_0 exceeds the value T_0', there is increase in the startup time t. This is associated with overshooting of the bed temperature beyond the maximum working value and hence longer cooling of the bed to the working temperature (case 3 in Fig. 2). Case 1 in Fig. 2 corresponds to the first point of the set of compromises ($T_0 \to \min$) and case 2 to the second point ($t \to \min$).

As a result of numerical solution of the given optimization problem, regions of stable startup are plotted for the laboratory (Fig. 3) and semicommercial boilers with respect to

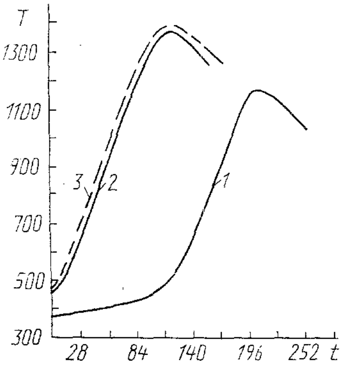

Fig. 2

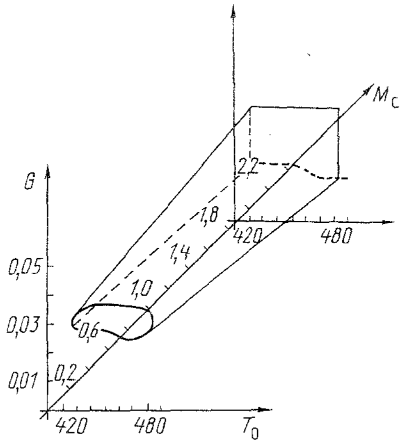

Fig. 3

Fig. 2. Variation in mean temperature of the fluidized bed boiler startup for the extreme points of the set of compromises: 1) T_{0min}; 2) t_{min}; 3) $T_0 > T_0'$.

Fig. 3. Region of stable startup of laboratory boiler: G is the flow rate of fluidizing air, m^3/sec; T_0 is the mean bed temperature at the instant of fluidization, K; M_c is the initial mass of coal in the bed, kg.

the basic controlling parameters: the mass of startup fuel M_c, the flow rate of fluidizing air G, and the bed temperature at the instant of fluidization T_0. Any combination of parameters M_c, G, T_0 from the given set permits startup of the apparatus by the proposed scheme.

NOTATION

a, thermal diffusivity of wall material of lining; C, specific heat; $\bar{d}=1/\sum_{i=1}^{N}(x_i/d_i)$, surface-mean diameter of bed particles; d_i, diameter of bed particles of i-th dimensional group; E, activation energy; F, surface area; g, acceleration due to gravity; G, flow rate of fluidizing air; h, integration step with respect to spatial coordinate; H, efficiency of coal; $K = K_0 \exp(-E/RT)$, rate constant of combustion; K_0, preexponential factor; K', empirical constant; $K(\bar{d})$, entrainment constant, $K(\bar{d}) = K'(U_e - U_{cr})M_c/\bar{d}$; ℓ, thickness of the lined wall; M, mass; R, gas constant; S, cross-sectional area of boiler; t, time of process; T, temperature; T_{pmin}, T_{pmax}, minimum and maximum working temperatures of bed; T_{max}, maximum attainable bed temperature; $U_e = G/S$, velocity of gas calculated in the free cross section of the equipment; U_{cr}, first critical rate of fluidization; $U_{cr} = g\bar{d}^2(\rho^* - \rho_g)/[1400\mu_g + 5.22\sqrt{\bar{d}^3 g\rho_g(\rho^* - \rho_g)}]$; V, volume; V_c, air volume required theoretically for the ignition of 1 kg of the organic mass of coal; $W_c = KM_c$, rate of chemical reaction; W_c^*, maximum possible combustion rate at air flow rate G, $W_c^* = G/V_c$; x, spatial coordinate; x_i, mass proportion of particles in the i-th fraction; α_{max}, heat-transfer coefficient, $\alpha_{max} = (0.85Ar^{0.19} + 0.006Ar^{0.5}Pr^{0.33})\lambda_c/\bar{d}$; β, γ, coefficients; λ, thermal conductivity; ρ, density; τ, integration step with respect to the time coordinate; Ar, Archimedes number; Nu, Nusselt number; Pr, Prandtl number.

LITERATURE CITED

1. V. V. Kafarov, A. I. Kobyakov, V. P. Meshalkin, and V. D. Toropchin, Teor. Osn. Khim. Tekhnol., 21, No. 5, 675-682 (1987).
2. I. N. Shteiner, N. S. Rassudov, I. S. Gol'braikh, et al., Teploénergetika, No. 4, 32-35 (1985).
3. S. G. Ruzhnikov, E. P. Tarasov, M. L. Shchipko, and O. V. Yangolov, in: Heat and Mass Transfer in Power Equipment: Abstracts of the Proceedings of the Minsk International Forum on Heat Transfer, May, 1988 [in Russian], Minsk (1988), Sec. 10, pp. 85-87.
4. M. L. Shchipko, N. A. Azhishchev, S. L. Gritsko, and B. N. Kuznetsov, Khim. Tverd. Topl., No. 4, 119-123 (1986).

5. L. Eits, Principles of Fluidization Mechanics with Applications [Russian translation], Moscow (1986).
6. I. P. Mukhlenov, B. S. Sazhin, V. F. Frolov, et al., Calculations of Boiling-Bed Equipment (Handbook) [in Russian], Leningrad (1986).
7. D. Himmelblau, Applied Nonlinear Programming [Russian translation], Moscow (1975).
8. A. A. Samarskii, Theory of Difference Schemes [in Russian], Moscow (1977).
9. V. A. Novikov, Zh. Vychisl. Mat. Mat., No. 3, 385-390 (1987).

COLLECTOR HEAT EXCHANGER WITH VARIABLE COOLANT PROPERTIES

V. A. Babenko

UDC 536.48

A mathematical model of the cooling of a porous heat-liberating tube between a coaxial tube and a channel of annular cross section is proposed and realized.

The delivery of heat carrier through the lateral wall of one channel and its collection in another coaxial channel is a widely used method in heat exchangers, chemical reactors, and power plants [1, 2]. On cooling extended porous elements, the use of a transverse filtration scheme ensures multiple reduction in hydraulic expenditures in comparison with the longitudinal scheme.

One possible deficiency of the transverse-filtration scheme (the so-called collector scheme) is nonuniformity of filtration over the length of the apparatus, which reduces its effectiveness and may facilitate the development of an emergency. Reducing the nonuniformity entails rational choice of the cross sections of the delivery and collection channels, as well as the wall porosity.

The method of heat-exchanger calculation is to solve the parabolic momentum and energy equations in the channels and in the porous wall, matching the solutions at the boundaries of the calculation regions in accordance with external and internal boundary conditions.

Four regions of radius variation are isolated (Fig. 1) in the cylindrical coordinate system (r, x): a) the central tube, $r \in (0, a)$; b) the internal region of the annular channel, $r \in (b, f)$; c) the outer region of the annular channel, $r \in (f, c)$; d) the porous wall, where $r = f$, the radius of maximum velocity in the annular channel.

The equations of mass, momentum, and energy balance are now written in one of the flow regions a, b, or c in the channels

$$\frac{\partial (r\rho u)}{\partial x} + \frac{\partial (r\rho v)}{\partial r} = 0, \quad (1)$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = -\frac{dP}{dx} + \frac{1}{r}\frac{\partial (r\tau)}{\partial y}, \quad (2)$$

$$\rho u \frac{\partial h}{\partial x} + \rho v \frac{\partial h}{\partial r} = \frac{1}{r}\frac{\partial}{\partial y}(rq), \quad (3)$$

where $y = |r - r_w|$ is the distance from the corresponding wall; the shear stress τ and heat-flux density q are defined as follows

$$\tau = \rho \nu \nu_{\mathrm{eff}} \frac{\partial u}{\partial y}, \quad (4)$$

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 1, pp. 131-140, July, 1990. Original article submitted October 21, 1988.

 0022-0841/90/5901-0928$12.50