Journal of Engineering Physics and Thermophysics, Vol. 83, No. 4, 2010

MODELING OF SUPERHEATED-STEAM DRYING OF BIOFUEL IN A FLUIDIZED BED

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UDC 677.057.135.2

The drying of a dispersed material in a fluidized bed has been modeled mathematically. The dependence of the bed's mass, which ensures a prescribed final humidity, on the regime parameters of the fluidized system has been established. The superheated-steam drying of wood granules in a fluidized bed has been investigated experimentally.

Keywords: *fluidized bed, biofuel, superheated steam.*

Introduction. The drying of wood raw material by a superheated steam is a promising alternative to traditional methods [1] by virtue of the well-known advantages (inert heat-transfer agent with a heat capacity nearly twice as high as the heat capacity of air, several processes carried out in one apparatus, exclusion of thermal pretreatment of the raw material in many cases, etc.). The use of the fluidized-bed technology makes it possible to most completely realize the above advantages of this method of drying and to create highly efficient compact apparatuses for a continuous process [2].

In this connection, the present work seeks to theoretically and experimentally investigate the process of drying of wood granules by a superheated steam in a fluidized bed with the aim of establishing the influence of different physical, hydrodynamic, and thermophysical factors on the intensity of the drying and determining the mass of the fluidized bed, which makes it possible to produce the dispersed material with a prescribed humidity (moisture content) in a continuous process.

Physical Model. Figure 1 diagrammatically shows the apparatus for continuous drying of a dispersed material by a superheated steam in a fluidized bed. The physical model of the process is based on the following assumptions:

(a) the process follows the regime of decreasing drying rate;
(b) the temperature of the steam escaping from particles is equal to the temperature of the particles;
(c) the drying occurs under external-problem conditions;
(d) the fluidized bed is considered as an ideally miscible medium;
(e) heating of the particles is gradient-free;
(f) the dispersed material is dried in the emulsion phase of the fluidized bed.

Calculation of Balance and Hydrodynamic Parameters. A relationship between the mass fluxes of feed (F_0) and unloading (F_{out}) can be found from the condition of equality of the flow rates of an absolutely dry dispersed material:

$$\frac{F_0}{1+\hat{c}_0}=\frac{F_{out}}{1+\hat{c}_{out}}\,. \quad (1)$$

For the relation F_0/F_{out}, we obtain, from (1),

$$\frac{F_0}{F_{out}}=\frac{1+\hat{c}_0}{1+\hat{c}_{out}}\,. \quad (2)$$

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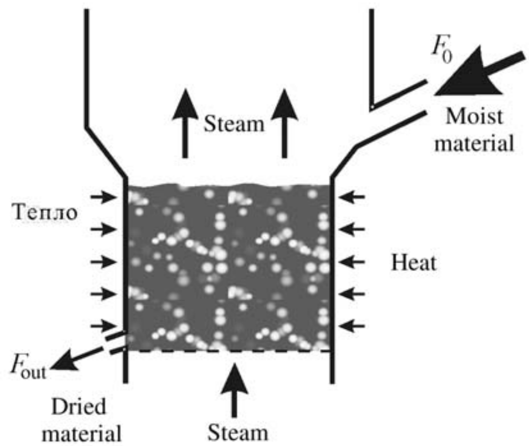

Fig. 1. Diagram of the apparatus for superheated-steam drying of a dispersed material in a fluidized bed.

The additional mass flux of the steam (ΔF), which is released when the dispersed material is dried to a prescribed humidity $\hat{c}_{out}$, is determined by the dependence

$$\Delta F = F_0 - F_{out} = \frac{\hat{c}_0 - \hat{c}_{out}}{1 + \hat{c}_{out}} F_0 \,. \tag{3}$$

The thermal power that must additionally be supplied to the bed to compensate for the energy expenditure on heating the fed dispersed material, evaporating the moisture, and heating the generated steam is determined from the heat-balance equation:

$$Q + \frac{F_0}{1 + \hat{c}_0} c_s T_0 + \frac{F_0 \hat{c}_0}{1 + \hat{c}_0} c_{liq} (T_0 - 273) = \frac{F_{out}}{1 + \hat{c}_{out}} c_s T_{out} + \frac{F_{out} \hat{c}_{out}}{1 + \hat{c}_{out}} c_{liq} (T_{out} - 273)$$

$$+ \Delta F \left(q + c_f (T_f - T_{cr}) + c_{liq} (T_{cr} - 273)\right) . \tag{4}$$

With account for (1) and (3), (4) yields the expression for Q in the form

$$Q = \frac{F_0}{1 + \hat{c}_0} \left(c_s (T_{out} - T_0) + c_{liq} (\hat{c}_{out} (T_{out} - 273) - \hat{c}_0 (T_0 - 273))\right.$$

$$\left. + (\hat{c}_0 - \hat{c}_{out}) (q + c_f (T_f - T_{cr}) + c_{liq} (T_{cr} - 273))\right) . \tag{5}$$

The velocity of initiation of fluidization is determined from the well-known Todes formula [3]

$$u_{mf} = \frac{\nu_f}{d} \frac{\mathrm{Ar}}{1400 + 5.22\sqrt{\mathrm{Ar}}} , \tag{6}$$

where $\mathrm{Ar} = \dfrac{g d^3}{\nu_f^2} \left(\dfrac{\rho_s^0 (1 + \hat{c}_{out})}{\rho_f} - 1 \right)$.

When $\rho_s = \rho_s^0 (1 + \hat{c}_{out})$ it is assumed in the expression for Ar that, in accordance with assumption (d) of the ideal mixing of particles, their mean humidity in the bed is equal to the humidity in the unloading flux $\hat{c}_{out}$. The optimum filtration velocity $u = u_{opt}$ [3] is

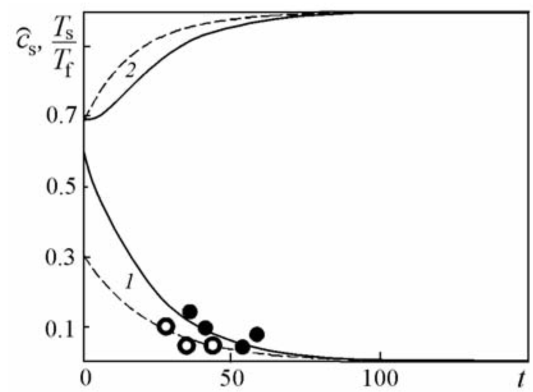

Fig. 2. Moisture content (1) and dimensionless temperature (2) of a particle vs. time; d_{eq} = 2.6 mm, T_0 = 293 K, and T_f = 423 K; $\hat{c}_0$ = 0.6 (solid curves) and $\hat{c}_0$ = 0.3 (dashed curves); points, experimental data. t, s.

$$u_{opt} = \frac{\nu_f}{d} \frac{Ar}{18 + 5.22\sqrt{Ar}} . \quad (7)$$

At this velocity, the maximum coefficient of heat exchange of the fluidized bed with the surface, which corresponds to the maximum intensity of mixing of particles, is attained.

Mathematical Model of Drying of a Single Particle. The model involves the following equations:

(a) the energy equation [4]

$$\rho_s^0 (c_s + \hat{c}_s c_{liq}) \frac{\pi d^3}{6} \frac{dT_s}{dt} = \frac{\pi d^2}{4} \alpha_* (T_f - T_s) + \rho_s^0 \frac{\pi d^3}{6} (q + (c_{liq} - c_f)(T_{cr} - T_s)) \frac{d\hat{c}_s}{dt} ; \quad (8)$$

and (b) the kinetic equation [4]

$$\rho_s^0 \frac{\pi d^3}{6} \frac{d\hat{c}_s}{dt} = -\frac{\pi d^2}{4} \beta \rho_s^0 \hat{c}_s . \quad (9)$$

The initial conditions are as follows:

$$t = 0 , \quad \hat{c}_s = \hat{c}_0 ; \quad T_s = T_0 . \quad (10)$$

Calculation of the effective drying rate β is carried out according to the procedure presented in [4]. The coefficient of interphase heat exchange α_* is calculated from the existing dependences [5]. Solution of system (8) and (9) with initial conditions (10) makes it possible to obtain evolution curves of a particle (Fig. 2).

Calculation of the Bed's Mass Necessary for Producing the Dispersed Material with a Prescribed Humidity c_{out}. The sought mass of the bed M is determined from the obtained $\hat{c}_s(t)$ curves (Fig. 2). For this purpose we use the well-known [6] distribution function of the residence times of particles in an ideally mixed system

$$E(t) = \frac{1}{\bar{t}} \exp\left(-\frac{t}{\bar{t}}\right), \quad (11)$$

where $\bar{t}$ is the mean residence time of particles in the bed, which is determined by the formula [6]

$$\bar{t} = \frac{M}{F_0} . \quad (12)$$

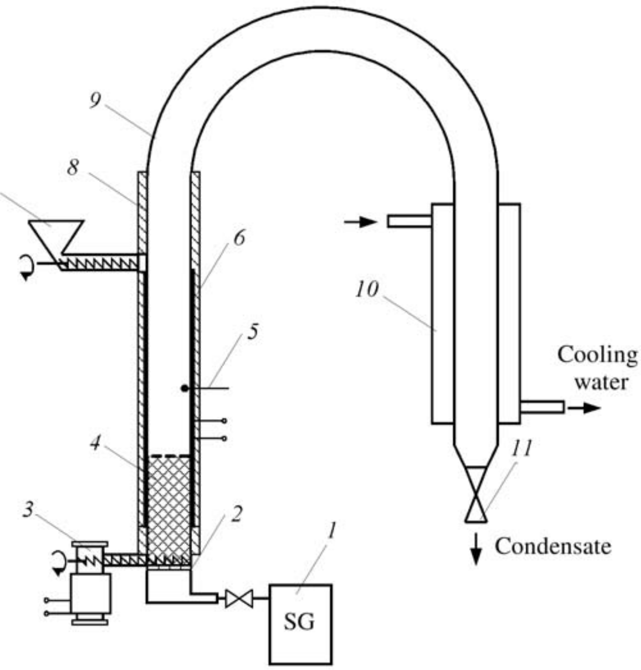

Fig. 3. Diagram of the experimental setup: 1) steam generator; 2) gas-distributing grid; 3) heated unloader; 4) bed of the fluidized material; 5) thermocouple; 6) heater of the fluidization chamber; 7) loader of the material; 8) heat insulation; 9) casing of the fluidization chamber; 10) condenser; 11) valve.

The humidity of particles in the bed (and hence in the unloading flux) $\hat{c}_{\text{out}}$ is dependent on their residence time in the system and is determined by the formula

$$\hat{c}_{\text{out}} = \frac{1}{\bar{t}} \int_0^\infty \hat{c}_{\text{s}}(t) \exp\left(-\frac{t}{\bar{t}}\right) dt \,. \tag{13}$$

For prescribed $\hat{c}_{\text{out}}$ and $\hat{c}_{\text{s}}(t)$, relation (13) represents the equation for the parameter $\bar{t}$. The sought mass of the bed is determined, from (12), as

$$M = F_0 \bar{t} \,. \tag{14}$$

Expressions (8)–(14) yield that M is a function of the following parameters:

$$M = f(F_0, \hat{c}_0, \hat{c}_{\text{out}}, q, \lambda_{\text{f}}, \nu_{\text{f}}, D_{\text{f}}, c_{\text{liq}}, c_{\text{f}}, c_{\text{s}}, T_0, T_{\text{f}}, d, u_{\text{opt}}) \,. \tag{15}$$

With the π theorem of similarity theory, we can write dependence (15) in dimensionless form

$$\frac{Mu_{\text{opt}}}{F_0 d} = f\left(\text{Ja}, \text{Ar}, \text{Re}_{\text{opt}}, \frac{T_{\text{f}} - T_0}{T_0}, \text{Pr}, \text{Sc}, \frac{D_{\text{f}}}{\nu_{\text{f}}}, \frac{c_{\text{liq}}}{c_{\text{f}}}, \frac{\hat{c}_0 - \hat{c}_{\text{out}}}{\hat{c}_{\text{out}}}\right). \tag{16}$$

With allowance for the fact that it is precisely the steam that is considered as the drying agent and for the single-valued relationship between Re_{opt} and Ar (formula (7)), we can simplify the equation:

$$\frac{Mu_{\text{opt}}}{F_0 d} = f\left(\text{Ja}, \text{Ar}, \frac{T_{\text{f}} - T_0}{T_0}, \frac{\hat{c}_0 - \hat{c}_{\text{out}}}{\hat{c}_{\text{out}}}\right). \tag{17}$$

Processing of the obtained calculated M values by the least-squares method allows the formula

$$\frac{Mu_{opt}}{F_0 d} = 9500\text{Ja}^{-1.27}\,\text{Ar}^{-0.1}\left(\frac{T_f - T_0}{T_0}\right)^{1.8}\left(\frac{\hat{c}_0 - \hat{c}_{out}}{\hat{c}_{out}}\right), \tag{18}$$

which approximates the calculated data with a mean error of 5% and a maximum one of 9% for $0.51 \le \text{Ja} \le 0.63$, $10^4 \le \text{Ar} \le 2.5 \cdot 10^5$, $0.44 \le \frac{T_f - T_0}{T_0} \le 0.78$, and $0.2 \le \frac{\hat{c}_0 - \hat{c}_{out}}{\hat{c}_{out}} \le 5$.

Experimental Investigation of the Process of Drying. A diagram of the setup is presented in Fig. 3. Cylindrically shaped pinewood granules of diameter 2 mm and height 3 mm were used as the investigated material. The height of the material's bed in the drying chamber was 50–80 mm. The initial humidity of the granules was created by uniform moistening of the absolutely dry material with a design amount of water followed by standing for 24 hours. Before the drying, fluidization chamber of the setup 9 was heated to a prescribed temperature using heater 6. The temperature in the fluidization chamber was monitored using thermocouple 5 and a TRM 101 secondary device. Before the experiment, we also heated unloader 3 to a temperature of 110–120°C. Once the prescribed temperature in the chamber 9 and that of the steam in steam generator (SG) 1 had been attained, the moist material was fed to the fluidization chamber via loader 7. The granules were heated and dried once the superheated steam had been fed to the fluidization chamber. On completion of the process of drying, the feed of the superheated steam to the fluidization chamber was cut off, the chamber's heater was switched off, and the unloader was dried by blowing with compressed air. The last portion of unloaded wood granules was investigated for humidity by the method of drying to a constant weight in the drying cabinet at 105°C. The measurement results are given in Fig. 2.

Conclusions. We have developed the model of a continuous process of superheated-steam drying of biofuel in a fluidized bed. We have established the functional dependence of the bed's mass ensuring a prescribed final humidity of particles on the regime parameters of the system. This dependence has been realized in the form of a generalized dimensionless formula that can be recommended for use in engineering practice. We have experimentally investigated the process of drying of wood granules. A satisfactory agreement between the calculated and experimental data on the mean humidity of the granules as a function of the drying time has been shown.

NOTATION

$\text{Ar} = \frac{gd^3}{\nu_f^2}\left(\frac{\rho_s}{\rho_f} - 1\right)$, Archimedes number; c_f, c_{liq}, and c_s, specific heats of the steam, water, and solid particles, J/(kg·K); $\hat{c}_s$, moisture content of particles; d, particle diameter, m; D_f, diffusion coefficient, m^2/s; F, mass particle flux, kg/s; $\text{Ja} = c_s(T_f - T_0)/q$, Jacob number; M, bed's mass, kg; Pr, Prandtl number; q, specific heat of vaporization, J/kg; $\text{Re} = ud/\nu_f$, Reynolds number; $\text{Sc} = \nu_f/D_f$, Schmidt number; t, time; T_f, temperature of the superheated steam, K; T_s, temperature of particles, K; u, filtration velocity of the steam, m/s; α_*, coefficient of interphase heat exchange, W/(m^2·K); β, effective drying rate, m/s; λ_f, thermal conductivity of the steam, W/(m·K); ν_f, kinematic viscosity of the steam, m^2/s; ρ_f and ρ_s, densities of the steam and particles, kg/m^3; ρ_s^0, density of an absolutely dry particle, kg/m^3. Subscripts: cr, critical; s, steam; eq, equivalent; liq, water; s, particle; opt, optimum; out, at exit; 0, at entry; $^{-}$, mean value.

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