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HEAT TRANSFER AND THE COMBUSTION TEMPERATURE OF COKE PARTICLES IN A FLUIDIZED BED

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The temperature of carbon particles undergoing combustion in a fluidized bed is measured. Heat-transfer laws are ascertained.

In recent years power engineering has made use of coal combustion in a fluidized bed of a noncombustible, coarsely dispersed material [1]. Carbon particles burning in a fluidized bed are heat sources having a higher temperature than the surrounding particles of nonburning material. Thus, information on their temperature is of great practical interest. Such information is needed, first of all, to evaluate the particle combustion time and, second, to predict the moment of fusion of the ash portion of the fuel.

Several experimental studies have recorded the temperature of a relatively coarse carbon particle burning in a fluidized bed of a finely dispersed incombustible material [2-4]. A carbon sphere was immersed in the bed and the temperature of its center measured with a thermocouple in [2, 3]. The particle was attached to a flexible thermocouple and could thus move a little. The authors of [4] used a different method to measure particle temperature. They prepared a carbon sphere with several loops of wire with a known melting point. They then determined the temperature of the layer in which the loops melted and used this determination

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to establish the degree of overheating of the particles burning in the bed. The information available on the temperature of burning particles is fragmentary and somewhat contradictory. For example, according to the data in [2], the temperature of the particles increases during combustion. According to the data in [3], the temperature remains constant and begins to decrease only at the end of the process. It must be noted also that the experiments were conducted with fluidized beds of a finely dispersed material, whereas it is information on the temperature of carbon particles burning in a fluidized bed of a coarsely dispersed material that is of practical interest. The present work fills this gap.

The experiments were conducted on a laboratory unit. We created a fluidized bed of narrow fractions of sand (0.4 and 0.7 mm) and fireclay (1.1 and 2.15 mm) in a 40-mm-diameter quartz column heated electrically from the outside. The height of the settled bed was a constant 40 mm in all of the tests. The gas distributor was a porous ceramic plate through which was blown preheated air. The tests were conducted with roughly spherical particles of coke (moisture content 2%, ash content 9.8%, density 1.1 g/cm^3) 4-12 mm in diameter. A through hole 0.7 mm in diameter was drilled in the particle and a thermocouple inserted in the hole so that its junction was located at the center of the sphere. The diameter of the junction was roughly equal to the diameter of the hole and the junction was "wedged" in the hole. In some cases the hole was sealed with a paste of coke breeze on a silicate glue. The particle, thus secured to the thermocouple, was then submerged in a fluidized bed previously heated to a temperature of from 1023 to 1073°K. The flexible thermocouple wire (0.2-mm diameter) did not seriously impede the movement of the particles in the layer. The temperature of the particle was recorded with a potentiometer which simultaneously recorded the temperature of the bed with the aid of a second, stationary thermocouple. Measurement accuracy was 7°K.

Figure 1 shows a typical thermogram of the process of coke-particle combustion in a fluidized bed for two fractions of incombustible material. The coke particle immersed in the bed heats quickly and burns. Its temperature then stabilizes and remains roughly constant for a long time.

Figure 2 shows the range of change in overheating of the carbon particle in the fluidized bed, i.e., the difference between the temperature of the bed and the temperature of the burning particle. This temperature difference determined the moment the particle temperature became steady-state. The figures also show the data of other investigators. Included is a point taken from [2] and means and standard deviations from [4]. The data from [3] shows the range of variation of the overheating temperatures. Two regions may be distinguished on the graphs: a region of relatively fine particles, where an increase in particle size is accompanied by a sharp increase in overheating of the carbon spheres; a region of coarse particles ($d_i > 1$ mm), where this pattern is less in evidence.

The process of combustion of the carbon particle is accompanied by the liberation of heat not only on the particle surface, but also in a thin gas boundary layer. Carbon monoxide formed on the surface of the burning coke undergoes combustion in the gas layer [5]. We will evaluate the thickness of this "burning" layer and compare it with the thickness of the diffusion boundary layer. Let us write the balance equations for the carbon monoxide in the layer in dimensionless form [6]:

$$Y'' - \frac{kd_i^2}{D} Y = 0, \tag{1}$$

where $Y = Z/Z_n$; k is the combustion-rate constant for carbon monoxide, which was taken from [6].

Let us write the solution of Eq. (1) for the boundary conditions $\xi = 0$, $Y = 1$ and $\xi \to \infty$, $Y = 0$:

$$Y = \exp\left(-\sqrt{\frac{kd_i^2}{D}}\,\xi\right). \tag{2}$$

We will assume that the thickness of the "burning" gas layer is equal to the distance from the surface at which the concentration of carbon monoxide falls by one order. In this case, from (2) we obtain the following expression for evaluating the relative thickness of the burning layer:

$$\xi_0 = 2.3\sqrt{\frac{D}{kd_i^2}}. \tag{3}$$

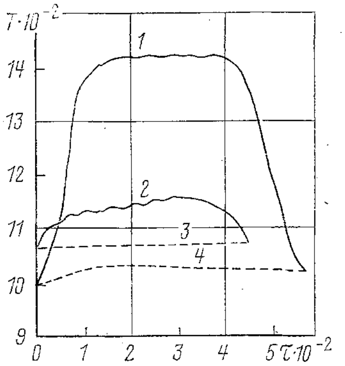

Fig. 1

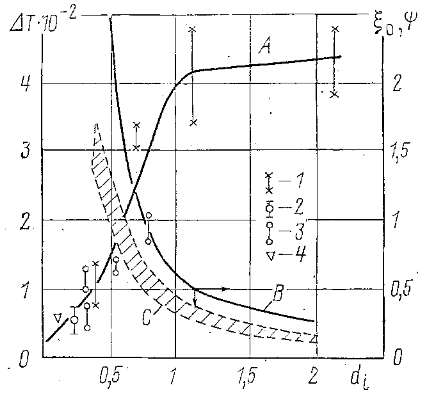

Fig. 2

Fig. 1. Change over time of the temperature of a carbon sphere burning in a fluidized bed: 1, 4) temperature of sphere of initial diameter of 9.6 mm and fluidized bed of incombustible particles of diameter of 1.1 mm; 2, 3) temperature of sphere of initial diameter of 5.3 mm and fluidized bed of particles of 0.4-mm diameter. $T \cdot 10^{-2}$, K; $\tau \cdot 10^{-2}$, sec.

Fig. 2. Dependence of overheating temperature of a carbon sphere burning in a fluidized bed on the size of the particles of incombustible material forming the bed: 1) our experiments (curve A); 2, 3, 4) data from [4, 3, 2], respectively; B) relative thickness of "burning" gas film (Eq. (3)); C) relative thickness of diffusion boundary layer (Eq. (4)). $\Delta T \cdot 10^{-2}$, K; d_i, mm.

Function (3) is shown graphically in Fig. 2 in the form of the dependence of the relative thickness of the burning layer on the diameter of the inert particles. In calculating the thickness of this layer, the temperature of the carbon particle was found from the generalizing curve A in Fig. 2. The hatched region in Fig. 2 characterizes the thickness of the diffusion boundary layer at the surface of the carbon particle in the fluidized bed. Its value was found for $5 < d < 10$ mm from the relation

$$\psi = \frac{d}{\mathrm{Sh}\, d_i}. \tag{4}$$

The Sherwood number was determined from a correlation obtained earlier by generalizing experiments on coke-particle combustion in a fluidized bed of an inert material [7]:

$$\mathrm{Sh} = 0.24\, \mathrm{Ar}^{0.33} \sqrt{\frac{d}{d_i}}. \tag{5}$$

It turned out that the thicknesses of the burning layer and the diffusion boundary layer formed at the surface of the carbon particle are nearly the same. It can be seen from Fig. 2 that, in a fluidized bed of a coarse material, the thickness of the burning layer of gas is less than the radius of the inert particles. The relative thickness of the burning layer increases with a decrease in particle diameter. This is especially the case when the inert particles are smaller than 1 mm. It is interesting to note that the greatest overheating of the burning carbon particles, reaching 400°K, is seen in the bed of coarse material — which is the type of bed of the greatest practical interest. The temperature of the burning particles increases slowly with an increase in the diameter of the incombustible particles forming the fluidized bed. An empirical correlation was constructed for this region and is graphed in Fig. 3. Also shown are standard deviations of the empirical points and their means. The correlation has the following form:

$$\Delta T = 670\, d_i^{0.23} d_0^{0.15}. \tag{6}$$

It is valid for relatively coarse particles of incombustible material ($0.07 \leqslant d_i \leqslant 0.215$ cm) and coke ($0.4 \leqslant d_0 \leqslant 1.2$ cm) and reflects the overheating of the hot carbon sphere in the fluidized bed.

Let us examine steady-state combustion, when the overheating of the carbon particle is constant. We formulate the condition for heat balance on the combustion surface as:

$$\alpha \Delta T = \beta \rho_0 q (X - X_n). \tag{7}$$

On the right is the heat flow caused by the diffusion of oxygen to the combustion surface. On the left is the heat flow from the burning particle to the fluidized bed surrounding it.

Using Eqs. (5) and (6), after several transformations we finally obtain the following expression from Eq. (7)

$$\mathrm{Nu} = 0{,}24\, B\, \mathrm{Ar}^{0.207} \left(\frac{d_i}{d_0} \right)^{0.65}, \tag{8}$$

where

$$B = \frac{q \rho_0 D (X - X_n)}{c \rho a\, 670} \left[\frac{g (\rho_4 - \rho)}{\nu^2 \rho} \right]^{0.123}.$$

Equation (8) is valid when $1.4 \cdot 10^3 < \mathrm{Ar} < 4 \cdot 10^4$, $2.3 < d_o/d_i < 14$. The coefficient B is a fairly stable quantity and reflects the relationship between the heat and mass flows through the burning gas layer at the combustion surface. We will calculate coefficient B from experimental data obtained with high concentrations of oxidant ($X = 0.21$) in the incoming flow, when the combustion process proceeds in the diffusion region ($X_n/X \to 0$). The thermophysical characteristics of the medium were assumed to conform with the temperature of the bed (1023°K) in the evaluation of the coefficient. Then, knowing the value of B ($B = 20.8$), we can simplify Eq. (8) thus

$$\mathrm{Nu} = 5\, \mathrm{Ar}^{0.207} \left(\frac{d_i}{d_0} \right)^{0.65}. \tag{8a}$$

Equation (8a) characterizes heat transfer between the burning coke particle migrating in the bed and the bed itself, comprised of incombustible material. It is similar to the empirical relation which describes heat transfer between a stationary surface and a fluidized bed of various materials ($80 < \mathrm{Ar} < 10^8$) at high temperatures (up to 1473°K) [8]:

$$\mathrm{Nu}_m = 0.88\, \mathrm{Ar}^{0.213}. \tag{9}$$

This correlation was plotted for maximum heat-transfer coefficients. Simultaneously solving Eqs. (8a) and (9), we find the relative rate of heat transfer for the surface of the burning coke particle:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_m} = 5.7 \left(\frac{d_i}{d_0} \right)^{0.65}. \tag{10}$$

The latter depends on the ratio of the sizes of the burning and nonburning particles. For the sake of illustration, Eq. (10) is graphed in Fig. 4 in logarithmic coordinates. The figure also shows experimental data from [9], which investigated heat transfer between a fluidized bed and the stationary surface of transducers of different heights. The ratio of the size of the transducer surface to the diameter of the particles of the fluidized bed ranged from 2 to 20. Experimental values of relative heat-transfer coefficient are shown for two fractions of sand (1.42 and 0.63 mm). The experimental points are quite a bit lower than Eq. (10), while the generalizing curves are shallower. We should point out that, under combustion conditions, heat transfer takes place more intensively when the carbon and inert particles are of comparable size. The role of the burning gas layer is probably important in this effect. The thickness of the gas layer increases with an increase in the diameter of the carbon sphere, and there is a corresponding decrease in the unit quantity of heat liberated in the layer. This significantly lessens the effect of such heat liberation on heat transfer to adjacent nonburning particles through gas lenses close to points of contact between the particles. It can be seen from the graph that the effect of the burning gas layer is greatly reduced even at $d/d_i > 10$. Conversely, when the carbon particles and nonburning particles are of comparable size ($d = d_i$), then all heat liberation connected with CO oxidation is concentrated in the thin gas layer near the points of contact of adjacent particles. The high unit density of this heat liberation leads to a marked increase in the temperature of the gas layers and intensifies heat transfer from the burning particle to adjacent particles. The similar form of the functions describing heat transfer in a fluidized bed to a stationary surface and to a coarse migrating particle of carbon undergoing combustion is indirect confirmation of the reliability of empirical correlation (8a). Correlation (6) reflects the conditions

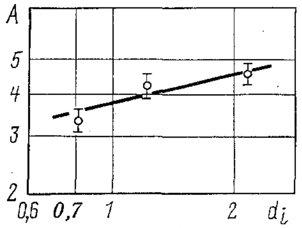

Fig. 3

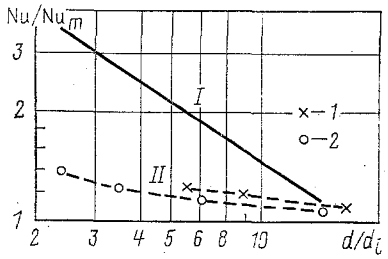

Fig. 4

Fig. 3. Temperature of overheating of a carbon sphere of initial diameter d burning in a fluidized bed of incombustible particles in relation to the size of the latter (d_i). A = ($\Delta T \cdot 10^{-2}$) $d_i^{0.15}$, K·cm$^{0.15}$.

Fig. 4. Dependence of relative heat-transfer coefficient on ratio of size of heat-transfer surface to size of particles of the fluidized bed: I) burning carbon particle; II) flat heat-transfer surface; 1, 2) particles 0.63 and 1.42 mm in diameter, respectively.

of the experiment: high concentration of oxidant X = 0.21 in the gas flow and a diffusion regime of combustion. Using the relations obtained in (5) and (8) to describe the transfer of mass (5) and heat (8) between a fluidized bed and a burning particle, it is not difficult to obtain a more general relation establishing the temperature of the burning coke particle. After several transformations and allowing for Eqs. (5) and (8a), we find the following equation from the heat-balance equation (7)

$$\frac{\Delta T}{\Theta} = 0.048\,\mathrm{Ar}^{0.127}\left(\frac{d}{d_i}\right)^{0.15}, \tag{11}$$

where $\theta = [D\rho_0 q(X - X_n)/a\rho c]$ is the effective combustion temperature of carbon. The correlation has an error no greater than 17% and is valid at $1.4 \cdot 10^3 < \mathrm{Ar} < 4 \cdot 10^4$ and $2.3 < d/d_i < 14$.

Thus, it follows from Eq. (11) that the temperature of a carbon particle burning in a fluidized bed of a coarse material is relatively weakly dependent on its size and the diameter of the particles forming the bed. At the same time, this temperature increases with an increase in the concentration of oxygen in the flow. The completed study of the temperature of a carbon particle burning in a fluidized bed allows us to make certain conclusions regarding the laws of heat transfer in the system. The heat-transfer coefficient between the particle and the fluidized bed surrounding it does not depend on the gas filtration rate and is determined only by the Archimedes number, i.e., the rate of the beginning of fluidization of the material. Carbon monoxide burning in the boundary layer intensifies heat transfer, this intensification being particularly marked when the size of the burning particles is close to the size of the incombustible particles making up the bed.

NOTATION

a, diffusivity of air; c, heat capacity of air; D, diffusion coefficient of oxygen in air; d_0, d, initial and running diameters of carbon sphere; d_i, diameter of inert particles; k, rate constant for carbon monoxide combustion; q, calorific value of carbon oxidation to CO_2; ΔT, temperature difference between burning particle and fluidized bed; X, X_n, oxygen concentration in the fluidized bed and on the surface of the burning particle; Z, Z_n, running concentration of carbon monoxide and concentration on the surface of the burning particle; α, heat-transfer coefficient between fluidized bed and burning particle; α_m, maximum heat-transfer coefficient between fluidized bed and a stationary body submerged in the bed; β, mass-transfer coefficient between fluidized bed and burning particle; λ, thermal conductivity of air; ν, kinematic viscosity of air; ρ_0, ρ, ρ_4, density of oxygen, air, and inert material; ξ, relative thickness of burning gas layer; ψ, relative thickness of diffusion boundary layer; Nusselt criterion $\mathrm{Nu} = \alpha d_i/\lambda$; Sherwood criterion $\mathrm{Sh} = \beta d/D$; Archimedes criterion $\mathrm{Ar} = [g d_i^3 (\rho_4 - \rho)]/\nu^2 \rho$.

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COALESCENCE OF COARSELY DISPERSED CONCENTRATED EMULSIONS WITH TURBULENT AGITATION

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The coalescence of drops, larger than microscale vortices, induced by velocity pulsations in concentrated emulsions is examined based on the theory of locally isotropic turbulence.

Intensification of the interaction of drops with the dispersed phase accompanying turbulent motion of fluid emulsions is widely used to increase the efficiency of different technological processes. However, under real conditions, it is difficult to establish reasonable regimes due to the nonunique relationship between the basic technological parameters. Thus, turbulent agitation increases the frequency of collisions between drops, the rate of mass transfer, the rate of chemical reactions in the dispersed phase, but, on the other hand, it decreases the dispersity and complicates the subsequent separation of phases in the emulsion system. In its turn, the dispersity of the emulsion determines the mechanisms for interaction and destruction of drops, as well as the nature of the reverse effect of the dispersed phase on the hydrodynamic parameters of the continuous medium. In this respect, the least studied are turbulent flows of unstable concentrated emulsions with a nonequilibrium dispersed phase, i.e., capable of coalescence or fragmentation.

Since the drop-size distribution in a turbulent flow of unstable emulsions is the subject of separate investigation, the effect of polydispersity is not examined in this work. It is assumed that in the range studied, changes in the concentration of the emulsion do not exhibit anomalous rheological properties, while the coalescence of drops does not create any difficulties in examining the two-phase system as a homogeneous fluid with the use of a simple quasihomogeneous model. The analysis of the coupling between the hydrodynamic and viscous characteristics of emulsions and the concentration of the dispersed phase is based on A. N.

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