HEATING OF COAL PARTICLES SUSPENDED IN A VERTICAL GAS FLOW

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In the continuous coking of low-caking coals and gas an important part is played by the uniform and sufficiently rapid heating of coal particles of different sizes to a temperature close to the softening point.

![Fig. 1. Logarithm of slip velocity of spherical coal particles (a) and Bi number (b) (for free fall in nitrogen) as a function of diameter. 1) Values [10-13] obtained from experimental data for particles of irregular shape.]

In this paper an attempt is made to analyze the heat transfer processes in a tubular chamber with a parallel gas flow. Special attention has been paid to computations that take into account the actual heat conductivity of the coal, since there is reason to suppose that the internal thermal resistance of large particles may make it impossible substantially to reduce the heating time by forcing the process of heat transfer from the gas flow (e.g., by swirling in a cyclone). In previous calculations [1-3] the heat conductivity of the suspended particles has generally been taken equal to infinity.

The model employed and the calculation scheme were as follows. The heated gas used as heat transfer agent moves from bottom to top of a vertical tube at constant velocity. The coal particles are introduced into the bottom of the tube and are entrained by the gas flow. The flow velocity is selected so that it is greater than the slip velocity of the largest coal particles. From the moment of their introduction into the tube the motion of the particles is assumed to be steady, i.e., such that their velocities relative to the gas flow and the tube remain constant throughout their residence time in the tube. The neglected nonstationarity in the initial section should increase the particle heating rate somewhat, since in this case we get increased convective heat transfer, and, moreover, the time taken by the particles to pass through this section is greater than the time they take to pass through it under stationary conditions. The degree of heating of the particles calculated for the stationary model is necessarily ensured.

In the calculation the temperature of the heat transfer agent is assumed to be almost constant and close to the temperature to which the coal particles should be heated. If the initial temperature of the heat transfer agent is higher than the end temperature and falls appreciably during the heat transfer process, the duration of the process is only slightly reduced thereby.

The stationary velocity of the particles relative to the gas flow (slip velocity) is computed from the condition of equality of the gravity force to the aerodynamic drag; the latter is determined by the drag coefficient. In this case the particles are assumed to be small spheres. Having determined the slip velocity we can compute the value of the Reynolds number for these particles, which is required to determine the corresponding convective heat transfer coefficient from the empirical criterial equations. The heat transfer coefficients thus obtained are then used in computing the temperature rises of particles of different diameters as a function of time. The basic calculations have been made for carbon \((\rho = 1.4 \text{ g/cm}^3, \ c = 0.23 \text{ cal/g.deg}, \ \lambda = 7.8 \cdot 10^{-4} \text{ cal/cm} \cdot \text{sec} \cdot \text{deg})[4]\) and nitrogen at 500°C [5].

The motion of a particle relative to the tube is described by the equation

\[
m \cdot \frac{dv}{dt} = C \frac{1}{2} \rho_0 v^2 S - mg.
\]

Here \(m\) is the mass of the particle, \(v\) the velocity of the particle relative to the gas-heat transfer agent, \(S\) the cross-sectional area, \(\rho_0\) the density of the heat transfer agent, \(C\) the drag coefficient, whose value varies with variation in the particle velocity relative to the gas, and \(g\) the acceleration of gravity.

The first term on the right side of (1) is the aerodynamic drag force, which decreases with decrease in the velocity of the particles relative to the gas. The second term (gravity force) remains constant during the motion. Under stationary conditions these two forces are equal, \(dv/dt\) becomes equal to zero, and to determine the stationary slip velocity needed in the subsequent calculations we get the equation

\[
C \frac{1}{2} \rho_0 v^2 S = mg.
\]
However, the slip velocity $v$ can be obtained by means of a simple solution only in the case of very small particles, whose drag force is proportional to the velocity $v$.

In the general case a solution can be obtained from (2) only by special methods [6, 7], since the drag coefficient $C$ depends on $Re$. The stationary slip velocity was determined graphically from equation (2) (Fig. 1), which may be regarded as the condition satisfied by the drag coefficient of a sphere falling freely in the gas. It can be rewritten in the form:

$$C = \frac{mg}{\frac{1}{2} \rho g v^2} = \frac{4}{3} \frac{d^2 g}{\rho g v^2} \frac{1}{Re^2} = \frac{A}{Re^2}$$

where $v$ is the kinematic viscosity coefficient, and in log form

$$lgC = lgA - 2lgRe.$$  

On the other hand, the value of the drag coefficient must satisfy the experimental relation $lgD = f(lgRe)$ [8, 9]. Obviously, the abscissa of the point of intersection gives the value of the logarithm of the Reynolds number corresponding to stationary motion of a particle of a given radius. From this we compute the velocity of a particle falling freely in the gas

$$v = \frac{\gamma g d^2}{18 \eta},$$

where $\eta$ is the dynamic viscosity coefficient of the heat transfer agent.

In spite of the fact that the literature contains quite a large amount of data on the heat transfer between particles and a gas flow [6, 14-19], the value of the heat transfer coefficient can only be estimated. The fact is that to a large extent experiments have been conducted under different conditions, so that the results of different authors differ considerably.

Accordingly, the heat transfer coefficients needed in the calculations were computed from the Khudyakov formula [18]

$$Nu = 0.15 \frac{Re^{0.85} + 0.26 \frac{Re}{100}}{(20 < Re < 1000)},$$

obtained as a result of experiments under conditions similar to the model investigated. The only difference is in the direction of the flows: in the case described the particles and the gas are supplied to the bottom of the tube, in Khudyakov's experiments to the top. The diameter of the quartz sand particles varied in the range from 0.075 to 2.3 mm.

![Fig. 2. Time dependence of temperature for a spherical coal particle 0.074 cm in diameter (Bi = 0.4). 1] Value of temperature of spherical particle with infinitely high heat conductivity.

For values of the Reynolds number less than 20 we used the Sokol'skii formula [14]

$$Nu = 2 + 0.16 \frac{Re^{0.67}}{(0.5 < Re < 300)},$$

based on experiments on the evaporation of a single droplet in an air flow, which, unlike Khudyakov's formula, provides for a transition to a limiting value of the Nusselt number equal to two as $Re \to 0$.

For direct thermal calculations we require the Blot number $Bi = (\phi / \rho A)$. It is easy to see that it is proportional to the Nusselt number. The proportionality factor is determined from the following relation

$$Bi = \frac{\frac{s R}{2} = \frac{s 2R}{\rho g 2x} = Nu \frac{g}{2x}.$$  

The heating of particles falling freely in a hot gas is calculated from formulas representing the solution of the problem of convective heating of a sphere [20]. The relative dimensionless temperature $\theta (r, t)$ at time $t$ and point $r$ will be

$$\theta (r, t) = \frac{T(r, t) - T_0}{T_0 - T_0} = 1 - \sum_{n=1}^{\infty} A_n \frac{\sin \frac{\pi n r}{R}}{\sin \frac{\pi n R}{R}} e^{-\frac{n^2 \pi^2}{\eta}},$$

where

$$A_n = \frac{2 (\sin \mu_n - \mu_n \cos \mu_n)}{\mu_n - \sin \mu_n \cos \mu_n},$$

and the eigenvalues $\mu_n$ are found from the equation

$$\cot \mu_n = \frac{1}{1 - Bi \mu_n} (n = 1, 2, \ldots).$$