SOLID-PHASE TEMPERATURE IN THE COMBUSTION OF CARBON UNDER FLUIDIZED-BED CONDITIONS

A. A. Belyaev, G. N. Delyagin,
and V. G. Slutskii

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A method is proposed for the calculation of the surface temperature of carbon particles burning in a fluidized bed agitated by a mixture of oxygen and nitrogen; the method is based on the analogy between the processes of heat and mass transfer.

One of the basic parameters characterizing the combustion of carbon in a fluidized bed is the surface temperature of the burning carbon particles, T^W. The value of T^W determines the aggregate state (liquid or solid) of the ashes forming in the combustion of carbon particles and is the basic factor in the design of reactors using "liquid" or "dry" ash removal. Nevertheless, the presently available models of the process [1-3] do not include the calculation of the solid-phase temperature. Only in [4] is an outline scheme proposed for the calculation of the temperature of carbon particles burning in a fluidized bed; this scheme is based on a two-phase model of the fluidized bed [5]. However, no numerical calculation of T^W was possible in [4] because the calculations require quantities that are difficult to determine, such as the heat- and mass-transfer coefficients between the gas bubbles and the dense phase of the fluidized bed and the gas–solid transfer coefficients in the dense phase itself.

It is assumed that the heat liberation is localized on the surface of the burning solid phase, the oxidation rate at the surface is infinitely large, and the reaction product is carbon dioxide, CO_2.

The overall size of the fluidized bed considered is much larger than the fluidized particles of which it is composed. The decrease in the mass of the carbon in the bed due to combustion is replenished by further supply of fuel. It is assumed that the time for the incoming particles to be heated to the temperature at which intensive heat liberation begins on the surface is much less than the total combustion time, so that the concentration of nonreacting particles is small, and the whole solid phase of the fluidized bed may be regarded as burning.

Consider a sufficiently small "elementary" area of the gas–solid interface dS_p (Fig. 1). In a coordinate system fixed in this interface, the conservation equations for the mass and energy fluxes are of the form

$$m_g = m_C, \tag{1}$$

$$m_g h_g^w + q + q_w = m_C Q_C + m_C h_C^w. \tag{2}$$

In Eq. (1) the equality of the mass fluxes m_C and m_g of the solid and gas phases at the interface is taken into account; in Eq. (2), the total heat liberation from dS_p due to convective and conductive heat fluxes $m_g h_g^W$ and q

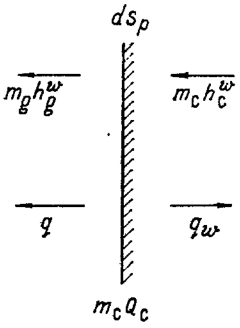

Fig. 1. "Elementary" combustion surface.

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in the gas phase, and also the heat liberation q_W due to the conductive flux in the solid phase, are related to the mass flow rate of oxygen m_O and the heat liberation per gram of oxygen Q_O by the stoichiometric relations

$$m_C = km_O, \quad Q_C = Q_O/k. \tag{3}$$

To estimate q_W, note that for a constant mass flow rate of combustion (m_C = const)

$$q_w = m_C (h_C^w - h_C^1) \tag{4}$$

and hence

$$q_w/m_C Q_C = (h_C^w - h_C^1)/Q_C \ll 1, \tag{5}$$

since the specific heat required to raise carbon to the characteristic combustion temperature $T^W = 1000$-2000°C is $h_C^W - h_C^1 = 0.5$-1.0 kcal/g, which is significantly less than the heat of combustion $Q_C \sim 8$ kcal/g. In accordance with Eq. (5), an estimate may be formed of the value of q_W in Eq. (2). Taking Eq. (4) as a first approximation for q_W and using Eqs. (1) and (3), an expression is obtained for the gas enthalpy h_g^W at the particle surface:

$$kh_g^w = kh_C^1 + Q_O - q/m_O. \tag{6}$$

In accordance with Eq. (6), the surface temperature of the burning particles is determined by the thermal effect of the oxidation Q_O and the ratio between the conductive heat transfer to the gas phase and the flux of oxidizing agent in the direction toward the particle surface q/m_O.

To calculate q/m_O it will now be shown that for constant enthalpy of the gas at the burning-particle surface

$$h_g^w = \text{const}, \tag{7}$$

which is the case, as follows from Eq. (12), below, the enthalpy and oxygen-concentration profiles are analogous:

$$H = \frac{h_g - h_g^w}{h_g^1 - h_g^w} = \frac{c_O}{c_O^1} = C. \tag{8}$$

In fact, taking into account that h_g^W, h_g^1, and c_O^1 are constant and that there is no chemical reaction in the gas phase, the equations describing the variation in H and C are identical:

$$\frac{\partial (H;\ C)}{\partial t} + u_x \frac{\partial (H;\ C)}{\partial x} + u_y \frac{\partial (H;\ C)}{\partial y} + u_z \frac{\partial (H;\ C)}{\partial z} = \frac{1}{\rho} \operatorname{div} [\rho D \operatorname{grad} (H;\ C)] \tag{9}$$

(it is assumed that the Lewis number $\text{Le} = a/D = 1$) and the boundary conditions at the particle surface S_p and at the surface of fluidizing-agent input to the bed S_1 are

$$H|_{S_p} = C|_{S_p} = 0, \quad H|_{S_1} = C|_{S_1} = 1. \tag{10}$$

Turning to the boundary conditions at the reactor "shell," note that, for reactors of an overall size much larger than the particles of which they are composed, the shell surface is negligibly small in comparison with the solid-phase surface, and so the conditions at the shell have little effect on the gas parameters. As a result, H and C are described by the same equations – Eqs. (9) – with the same boundary conditions – Eqs. (10) – and so satisfy Eq. (8).

Taking Eq. (8) into account, q/m_O takes the form

$$\frac{q}{m_O} = \frac{-\rho D\, \partial h_g/\partial n}{\rho D\, \partial c_O/\partial n} = \frac{h_g^w - h_g^1}{c_O^1}. \tag{11}$$

Substituting Eq. (11) into Eq. (6) for h_g^W, and using the relations $c_O^1 = 1/(1+N)$ and $h_g^1 = c_O^1 h_O^1 + (1 - c_O^1) h_N^1$, the following equation is obtained:

$$h_g^w (1 + N + k) = h_O^1 + N h_N^1 + k h_C^1 + Q_O. \tag{12}$$

As follows from Eq. (12), the enthalpy of the gas at the particle surface is constant – as assumed in Eq. (7) – and equal to the enthalpy of the products in the stoichiometric combustion of carbon in the fluidizing-agent mixture.

Likewise, the composition of the products at the particle surface, determined from the conditions at the gas–particle interface

$$m_{\mathrm{O}} = \rho D\,\partial c_{\mathrm{O}}/\partial n,\quad m_g c_{\mathrm{N}}^w - \rho D\,\partial c_{\mathrm{N}}/\partial n = 0,$$
$$m_g c_{\mathrm{CO_2}}^w - \rho D\,\partial c_{\mathrm{CO_2}}/\partial n = m_{\mathrm{O}} + m_{\mathrm{C}} \tag{13}$$

and the similarity of the concentration profiles

$$\frac{c_{\mathrm{O}}}{c_{\mathrm{O}}^1} = \frac{c_{\mathrm{N}} - c_{\mathrm{N}}^w}{c_{\mathrm{N}}^1 - c_{\mathrm{N}}^w} = \frac{c_{\mathrm{CO_2}}^w - c_{\mathrm{CO_2}}}{c_{\mathrm{CO_2}}^w}, \tag{14}$$

which follows from the same considerations as the similarity of the enthalpy and oxygen-concentration profiles in Eq. (8), is also constant and corresponds to stoichiometry:

$$c_{\mathrm{N}}^w = \mathrm{N}/(1+\mathrm{N}+k),\quad c_{\mathrm{CO_2}}^w = (1+k)/(1+\mathrm{N}+k). \tag{15}$$

The temperature at the particle surface is then the temperature T^{st} of stoichiometric combustion of carbon in the fluidizing-agent mixture:

$$T^w = T^{st}\,; \tag{16}$$

in deriving Eq. (16), no constraints are placed on the character of the fluidizing-agent flow and the motion of the solid phase.

Thus, under the given assumptions with regard to the oxidation mechanism, it is found that the surface temperature of the burning particles is constant over the height of the fluidized bed, is determined by parameters independent of the presence of gas bubbles and the intensity of solid-phase agitation, and is equal to the temperature of stoichiometric combustion of the fuel in the fluidizing gas mixture.

NOTATION

T, temperature; S_1, surface of fluidizing-agent input; S_p, dS_p, total and "elementary" areas of gas–solid interface; n, external normal to dS_p; m, mass flux; q, q_w, conductive heat flows to the gas and solid phase; Q, specific heat liberation; h, enthalpy; H, dimensionless enthalpy; c, concentration; C, dimensionless concentration; k, stoichiometric carbon–oxygen weight ratio; N, nitrogen–oxygen weight ratio in incoming gas mixture; ρ, u_x, u_y, u_z, density and velocity components of gas; D, diffusion coefficients; a, thermal diffusivity. Indices: 1, fluidized-bed inlet; w, solid-phase surface; g, gas; C, carbon; O, oxygen; N, nitrogen; CO_2, carbon dioxide.

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