MECHANISM OF COOLING OF HIGH-TEMPERATURE GAS (PLASMA) JETS IN A FLUIDIZED BED

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A mechanism accounting for the high intensity of the heat transfer of a plasma jet in a fluidized bed is described. Rough calculations are made of the maximum heating of a single particle ejected from the plasma jet.

It is well known that the cooling of high-temperature gas (initially plasma) jets in a fluidized bed is extremely rapid [1, 2]. However, as yet there is no clear understanding of the mechanism of this process.

It was argued in [2] that the role assigned to radiant transfer in [1] was exaggerated; in [2] great emphasis was placed on the importance of conductive–convective transfer at the "mobile walls" of the gas flame even in the high-temperature part of the process, although it was acknowledged that, if a high degree of emissivity is assumed, radiation may play the dominant role in the heat transfer of the initial, intrinsically plasma part of the jet. However, it was found in [3] that the emissivity of the plasma jet is low ($\varepsilon \approx 0.001$-$0.002$), and hence radiation cannot play a dominant role if there are only a few jets of particles entrained in the gas (plasma) flame radiating at the colder parts of its walls [2]. These mobile walls, as is known, form a two-phase (gas–particle) "boundary layer" of the gas flame of the jet [4]. In these circumstances, the basic mechanism of the heat transfer of a high-temperature gas jet with a fluidized bed resembles the mechanism of heat transfer of a low-temperature gas, which has been rather more adequately described. In 1975, interesting experimental data were obtained on the heat transfer of such jets with a fluidized bed, and hence the convective heat-transfer coefficient of the jet with its walls was calculated, assuming that the gas jet retains its cylindrical shape, that the specific heat of the gas is independent of temperature, and that the mean temperature of the jet over the cross section is equal to the temperature measured at its axis [5]. Heat-transfer coefficients of between 1700 and 6800 $\mathrm{W/m^2 \cdot deg}$ (rising with increase in the initial jet velocity) were calculated and recommended for use in engineering calculations. However, this information is clearly not enough to be of practical use: It is also necessary to know the restrictions, limits, or additional conditions on the applicability of these entirely conditional coefficients (for example, the minimum mobility of the particles, limitations on the bed height, etc.), and a serious search for such additional information must involve an examination in detail of the real mechanism of jet heat transfer.

Also in 1975, the idea of conductive–convective heat transfer from the jet suggested in [2] was somewhat developed [6, 7]. In particular, use was made in [6] of an earlier idea that in a dense homogeneous bed, taking only conductive transfer into account, the active heat-transfer region, where the temperature difference between the gas and the particles (the temperature differential) remains pronounced, is extremely short (no more than a few particle diameters). As emphasized in [6], this implies that in a dense homogeneous region of the inhomogeneous fluidized bed — an emulsion of interchanging particles — the heat transfer with an incoming bubble gas or jet is confined within a thin layer of material. Because of the "organized" motion of the particles along the boundaries of the gas flame and their superheating, the external surface of the active zone is not coincident with this boundary but removed some distance from it toward the end of the gas flame, so that the region $T \neq T_{fb}$ extends considerably beyond the gas flame.

In [7] the heat transfer of a low-temperature jet with a fluidized bed was again reduced basically to the heat transfer in the relatively thin two-phase boundary layer surround-

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ing the gas flame; it was noted that rapid circulation of these particles is desirable so as to avoid superheating. In [7] a semiempirical formula was also given and recommended for the determination of the degree of relaxation of the temperature differential at the end of the gas flame. This formula was derived using fewer assumptions than in [5] but again its limits of application are not clear, since it includes an empirical correction factor P_f that is obtained on the basis of a relatively small number of experiments, and no indication is given of whether this empirical factor may be regarded as a function only of the ratio between the length of the gas flame and the bed height.

On the basis of what has been said, it is assumed that the high intensity of the heat transfer of a high-temperature jet with a fluidized bed is due to the entry of gas from the gas flame in the mobile porous "walls" (in other words, in the gas—solid-particle boundary) and not simply to convective flow of the jet around these walls nor to radiation of the plasma gas. This would be expected to lead to relatively slight cooling of the gas flame on entering the bed when the expansion of the jet has not resulted in the capture of any particles and no ejected cold gas has been mixed with jet. The existence and, in some cases, the significance of such a region seem to be confirmed by experimental data [8] on the formation of NO_2 in amounts corresponding to 1900-1950°K in the combustion of a specially prepared gas—air mixture in a fluidized bed of mean temperature 1560-1700°K. These may be explained by the instantaneous ignition of the prepared (and preheated by passing through a grid) mixture and the poor heat liberation from the high-temperature combustion products that have yet to come into contact with the low-temperature particles at the beginning of the jet, issuing from the grid.

Finally, as the jet propagates, there is fairly intense cooling of the gas that is not ejected but remains in the gas flame, because the flow around the walls of the flame differs from the flow around a smooth impermeable surface and is accompanied by the recovery of a certain amount of gas from the gas—solid-particle boundary layer as a result of turbulence and deviation of the jet as it flows around the particles, similar to filtrational mixing. The cooling of the gas flame is intensified by the known instability of the gas jets which do not emerge from the fluidized bed [4], the exchange of different phases of their development in time, and the associated horizontal blunting of the jets, facilitating the inertial penetration of the gas flame by the solid particles. The presence of even small amounts of particles in the gas flame (for this reason or through ejection from the mobile walls) may lead to significant cooling because of the high volume specific heat of the particles. The volume content and, in particular, the flow rate of solid particles would be expected to increase over the length of the flame as its oscillations are of larger amplitude at the top than at the bottom. Therefore, even at a relatively low temperature differential, a considerable absolute quantity of heat may be liberated from the continuously diminishing amount of gas remaining in the gas flow. The combination of the low gas flow rate through the low-temperature (hindmost) region of the gas flame and the increase in solid-particle flow rate leads to a rapid fall in temperature in this region. Because of the gradual decrease in the gas flow rate in the gas flame, the calculation of the rate of cooling of the jet in a fluidized bed according to the longitudinal temperature profile of the gas flame is fairly arbitrary and, therefore, the assumption that the jet is identical with its gas flame is not very good. Note that the estimate of the rate of cooling of a high-temperature jet in a fluidized bed in [1] is evidently also distorted by the failure to take into account the radiation of the hot junction of the thermocouple at the colder wall of the flame, which reduces the initial value of the flame temperature.

The rate of cooling calculated from the longitudinal temperature of the gas flame does not characterize the heat liberation from the whole jet. For example, the latter may be very large even when the calculated value of the rate of cooling is zero, i.e., when the temperature remains constant along the gas-flame axis, if some high-temperature gas leaves the gas flame and is cooled beyond its limits in the two-phase boundary layer of the jet.

From the foregoing it is evident that the mechanism of the heat transfer of a high-temperature jet with a fluidized bed is complex, so that the idea of a heat-transfer coefficient has little meaning. The lack of information on the extent to which ejected and inertial particles fill the gas flame and also the inaccuracy of the information on the circulation of material in the vicinity of the gas flame have so far prevented an analytic calculation of the kinetics of cooling of a high-temperature jet in a fluidized bed. However, the proposed heat-transfer mechanism suggests the possibility of simple engineering design methods for quenching equipment with fluidized beds.

Since the gas flame does not emerge from the bed and the particles are large [6], heat transfer occurs mainly in the immediate vicinity of the gas flame, in the first layers of moving particles [2, 6, 7]; i.e., as required, the quenching of the reaction products occurs within the limits of the fluidized bed. The rapid circulational motion of particles along the flame to its low-temperature region and the radial displacement of the solid phase (its effective thermal diffusivity) ensure that the rate of exchange of particles at the gas-flame boundary is sufficient to avoid superheating and fusion of the particles. The radial displacement may be increased by increasing the flow rate of fluidizing gas. The radiant transfer with the "visible" or colder regions mentioned in [2] will play a certain role in the heat transfer from the strongly heated particles.

In the light of what has been said, the engineering, hydrodynamic, and thermal design of quenching equipment with a fluidized bed reduces to the following.

1. Calculate the range of the nonisothermal jet (the length of the gas flame l_f) in the fluidized bed so as to ensure that $H_0 \geqslant l_f/0.7$, hence avoiding the reemergence of the jet. The value of l_f may be determined from the formula of Shakhova or Minaev [4, 9-11] as in the case of an isothermal jet.

2. From the given bed temperature (the quenching temperature), and the initial temperature and flow rate of the plasma gas, the thermal balance may be used to determine the heat liberated from the circulating solid heat-tranfer agent or through the flow of the bed around the heat-transfer surface. Assuming the composition, determine by the usual kinetic calculations the size of the heat-transfer surface in the quenching chamber or the external surface cooled by the heat carrier.

Experiments show that, as a result of the fluidization conditions, it is always simple to provide conditions such that no fusion of the particles occurs. In particular, even for a small (0.095 m) chamber radius (unfavorable for the development of a high A^{g}_{eff}), a plasma-jet temperature at the inlet (the nozzle section) of up to 6000°K, bed temperatures up to 700°K, sand particles of diameter 315 μ, and fluidization number $W \geq 3.5$ fusion does not occur.

Thus, for the design of working quenching chambers, analytic calculation of the maximum heating of individual particles is unnecessary. But, as such calculations may be of interest subsequently for optimization of the equipment, some approximate estimates are given below.

Consider the motion of an individual spherical particle of quartz sand ejected by a high-temperature (initially plasma) nitrogen jet, along the boundary of a gas flame that may be approximated by a channel of constant cross section. The temperature of this particle, moving in the quenching chamber of a plasmotron in an upward gas flow, may be calculated by combined solution of the equation of particle motion in the gas flow and the equation of convective–conductive heat transfer.

For quasisteady motion of a one-dimensional flow (isothermal over the channel radius), the appropriate equations are as follows:

$$mv\frac{dv}{dx} = C_d\rho_g\frac{(v_g - v)^2}{2}S - mg, \tag{1}$$

$$v\frac{dT}{dx} = \alpha\frac{F}{C\rho V}(T_g - T). \tag{2}$$

In these conditions $Bi \leq 0.1$ and Fo is sufficiently large; accordingly, if there are no internal heat sources in the particles, the thermal resistance of the disperse particles may be neglected, a near-zero temperature gradient inside the particles may be assumed, and it may be regarded as a steady-state problem.

Interactions between particles are disregarded. As an approximation, the variation of the gas temperature over the length of the jet is represented as follows:

$$T_g = T_0\frac{d_0}{x + d_0}, \tag{3}$$

which is close to the experimentally observed variation.

A similar decrease in temperature was observed in [12] (the system was isothermal) and the velocity in the gas flame of a turbulent jet propagating in a fluidized bed in quasi-steady conditions was found to be

$$v_g = v_0 \frac{2.73 r_0}{C_1 x} . \tag{4}$$

The decrease in gas velocity is due to the expansion of the gas and "leakage" of gas through the "walls" of the gas flame. The linear velocity in the gas flame will also decrease because of the fall in temperature but in a first approximation this may be neglected, and on the basis of Eqs. (3) and (4) the linear velocity may be taken to be directly proportional to the temperature in a nonisothermal gas flow

$$v_g = v_0 \frac{T_g}{T_0} . \tag{5}$$

The subscript 0 denotes conditions at the plasmotron inlet (the nozzle cross section).

In the calculations the usual temperature dependences are used: for the gas density

$$\rho_g = \rho_0 \frac{T_0}{T_g} ; \tag{6}$$

for the dynamic viscosity

$$\mu_g = \mu_0 \left(\frac{T_g}{T_0} \right)^n . \tag{7}$$

The superscript n is calculated according to [13] and is found to be 0.81 for nitrogen in the temperature range 800-6000°K.

The values of ρ_0 and μ_0 are taken at the inlet (the nozzle cross section) for $T_0 = 6000°K$.

In the region of low Reynolds numbers (Re_s = 1-5) the aerodynamic drag of the particles C_d needed for Eq. (1) is taken from a relation obtained in [14] for a fixed smooth sphere unmoving with respect to the low-temperature isothermal flow

$$C_d = \frac{31.2}{Re_s} = 31.2 \left[\frac{(v_g - v) d_g \rho_g}{\mu_g} \right]^{-1} . \tag{8}$$

The heat-transfer coefficient between the gas and the solid particles in Eq. (2) is determined using a relation obtained in [15] for the region of low Reynolds numbers (Re_s = 0-200),

$$Nu = 2 + 0.16 Re^{0.67} . \tag{9}$$

The system of ordinary first-order differential equations in Eqs. (1) and (2) with given initial conditions was integrated on a Minsk-22M computer by the fourth-order Runge–Kutta method with automatic step selection.

Since at low temperatures the temperature dependence of the thermal conductivity of nitrogen cannot be sufficiently accurately approximated, Eqs. (1) and (2) are solved by the method of quadratic interpolation for the treatment of tabular data [13] on the thermal conductivity of nitrogen in the temperature range 800-6000°K.

Curves of the heating of quartz-sand particles in a plasma nitrogen jet are shown in Fig. 1. It is evident that the heating of the particles depends considerably on the particle diameter and the initial velocity with which the particles approach the jet aperture. Small particles (d_s = 200 μ) are heated mainly over a distance of one nozzle diameter.

Estimates of the effect of radiation by the particles show that the temperature change due to radiation is 0.3% for small particles (d_s = 200 μ) and 0.1% for larger particles.

In calculations of radiant transfer it is assumed that particles heated by the gas flame liberate heat to the next layers of particles, which are midway in temperature between the heated particles and the bed core.

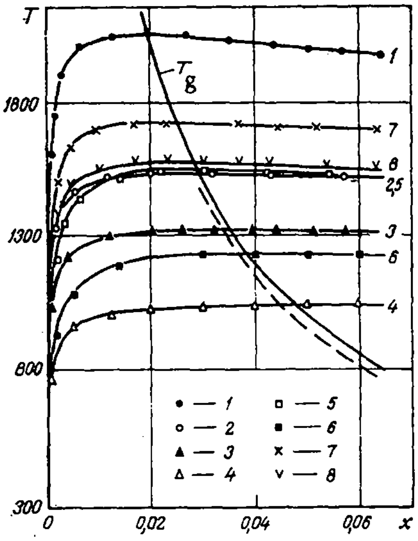

Fig. 1. Change in temperature of gas and quartz-sand particles over the length of the plasma jet when T_0 = 6000°K, d_0 = 0.01 m: 1,2,3,4) d_s = 200, 315, 400, 600 μ, respectively; v_g = 32.4 m/sec; v_{s0} = 0.1 m/sec; 5,6) v_{s0} = 1 and 2 m/sec, respectively, v_g = 32.4 m/sec, d_s = 200 μ; 7.8 v_g = 64.8 and 97.2 m/sec, respectively, v_{s0} = 0.1 m/sec, d_s = 200 μ; the curves for the gas temperature correspond to Eq. (3) (continuous curve) and experiment (dashed curve).

Note in conclusion that estimates of the heating of particles moving along the boundaries of a high-temperature gas flow are rather too high, since the exchange of particles in this region under the influence of the radial mixing of the solid phase in the fluidized bed was neglected.

NOTATION

H_0, fluidized-bed height; m, particle mass; x, current (axial) coordinate; v_g, v, velocity of gas and particles; ρ_g, ρ, density of gas and particle material; T_g, T, gas and particle temperatures; S, maximum particle cross section; C_d, aerodynamic drag of particles; C, specific heat of particle material; α, heat-transfer coefficient between gas and solid particles; F, V, surface area and volume of particle; r_0, initial radius of isothermal jet; C_1, isothermal-jet coefficient; d_0, diameter of plasmotron nozzle; d_s, particle diameter; τ_s, time of particle motion; V_{s0}, initial velocity of particle approaching jet nozzle; $Nu = \alpha d_s/\lambda_g$, Nusselt number; $Fo = 4a_s\tau_s/d_s^2$, Fourier number; $Re = (v_g - v)d_s\rho_g/\mu_g$, Reynolds number; $Bi = \alpha d_s/\lambda_s$, Biot number; a_s, thermal diffusivity of particle. Indices: g, gas; s, solid particle; f, flame; fb, fluidized bed.

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