

DEPTH OF PENETRATION OF SOLID- OR LIQUID-PHASE PARTICLES IN OPPOSING GAS-SUSPENSION JETS

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The depth of penetration of particles in systems of opposing gas-suspension jets has been investigated theoretically and experimentally.

One of the promising methods of intensifying heat- and mass-transfer processes in a gas suspension is the opposing jet method [1].

This method, in addition to being used in drying, mixing, and homogenizing equipment, is now being introduced into furnace technology in connection with the combustion of fuel oil containing sulfur at low air-fuel ratios.

To determine certain design parameters of equipment using the opposing jet principle and to clarify the processes involved, it is important to determine the depth of penetration and flight time of the solid or liquid particles in the opposing flow.

Let two opposing gas-suspension jets leave tubes of the same diameter and move toward each other at the same velocity (Fig. 1). The flow is symmetrical both with respect to the tube axis and with respect to the plane in which the jets meet. The diameter and specific weight of the particles are constant. If we assume that a particle moves strictly along the tube axis, drift effects are eliminated. We further assume that the velocities of the two gas flows are constant and equal to v_g for any x , except the point $x = 0$, where the velocities are zero. The particle velocity at $x = 0$ is assumed equal to the velocity of the carrier gas at the tube outlet. * To simplify the calculations we neglect gravitational forces. With the above assumptions the differential equation of the forces acting on the particle can be written in the form

$$-m_p \frac{dv_p}{d\tau} = c_x \frac{(v_g + v_p)^2}{2g} \gamma_g E_p. \quad (1)$$

If we regard the particle as a spherical body, after expanding the expressions

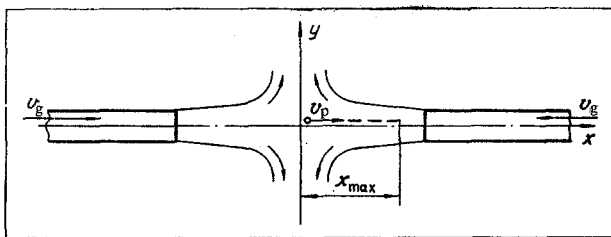


Fig. 1. Two-phase opposing jets.

$$m_p = \frac{\pi d^3}{6} \frac{\gamma_p}{g} \text{ и } F_p = \frac{\pi d^2}{4}$$

and canceling, we can represent the differential equation (1) in the following form:

$$-\frac{dv_p}{dx} = 0.75 \frac{c_x (v_g + v_p)^2}{v_p d} \frac{\gamma_g}{\gamma_p}. \quad (2)$$

The Wieselsberger curve giving the relation $c_x = f(Re)$ for flow over a sphere can be divided into three regions: a) Stokes region $Re < 0.4$; b) transition region $0.4 < Re < 1000$; c) self-similar region $10^3 < Re < 10^5$. With an accuracy sufficient for practical purposes these intervals can be approximated by suitable formulas. Let us then determine the maximum depth of penetration of the particles into the counterflow for all these regions.

a) Stokes region. $c_x = 24/Re = 24\nu/(v_g + v_p)d$.

We substitute the value of c_x into Eq. (2):

$$-\frac{dv_p}{dx} = 0.75 \frac{24\nu\gamma_g(v_g + v_p)}{d^2 \gamma_p v_p}. \quad (3)$$

Integrating Eq. (3) with the condition that at $x = 0$, $v_p = v_g$, we obtain

$$x = \frac{d^2 \gamma_p}{18\nu\gamma_g} [v_g \ln(v_g + v_p) - v_p + v_g - v_g \ln 2v_g]. \quad (4)$$

The maximum depth of penetration can be determined starting from the fact that in this case the particle velocity is equal to zero:

$$x_{max} = 0.0166 \frac{d^2 \gamma_p v_g}{\nu \gamma_g}. \quad (5)$$

b) Transition region. In the general case for the transition region

$$c_x = \frac{A}{Re^n} = \frac{A v^n}{(v_g + v_p)^n d^n}$$

Substituting the value of c_x into Eq. (2) and integrating with the same conditions as in a) above, we obtain

*We are concerned with the case in which the particles are preaccelerated (e.g., by a nozzle) to the velocity of the gas flow.

$$x_{\max} = \frac{d^{(n+1)} \gamma_p v_g^n}{0.75 A v^n \gamma_g} \left[\frac{1}{n 2^{-n}} + \frac{1}{(1-n) 2^{(1-n)}} - \frac{1}{n} - \frac{1}{1-n} \right] \quad (6)$$

For $10 < Re < 10^3$ the drag coefficient of the particle can be determined from Vyrubov's formula [2] $c_x = 12.5/Re^{0.5}$; i.e., $A = 12.5$, and $n = 0.5$. In this case

$$x_{\max} = 0.0245 \frac{d^{1.5} \gamma_p v_g^{0.5}}{v^{0.5} \gamma_g} \quad (7)$$

c) Self-similar region. In this region at $10^3 < Re < 10^5$

$$c_x = \text{const} \approx 0.4.$$

Substituting the value of c_x into Eq. (2) and integrating with the same boundary conditions as in a) above, we obtain

$$x_{\max} = 0.744 \frac{d \gamma_p}{\gamma_g} \quad (8)$$

It follows from (8) that in the self-similar region the maximum depth of penetration does not depend on the velocity of the carrier flow.

In the same way we can determine the particle flight time:

for $Re < 0.4$

$$\tau_{\max} = 0.0384 \frac{d^2 \gamma_p}{v \gamma_g} \quad (9)$$

for $10 < Re < 10^3$

$$\tau_{\max} = 0.061 \frac{d^{1.5} \gamma_p}{v_g^{0.5} v^{0.5} \gamma_g} \quad (10)$$

for $10^3 < Re < 10^5$

$$\tau_{\max} = 1.66 \frac{d \gamma_p}{v_g \gamma_g} \quad (11)$$

Equations (5), (7), (8)–(11) were obtained for the above-mentioned simplifying assumptions, whose validity was verified experimentally.

The experimental apparatus is shown schematically in Fig. 2. Air from blower 1 was fed to two opposing glass tubes 2. By means of regulating valves 9, the plane in which the jets meet was adjusted so as to be symmetrical relative to the ends of the tubes. Light source 4 was a high-pressure mercury-vapor lamp of the "Igar" type. The process was photographed in an absolutely dark room. As they entered the light beam, particles introduced into one of the gas flows became visible and left tracks on the film. Knowing the distance between the ends of the tubes, we were able to determine the depth of penetration of the particles into the counterflow.

It is clear from the trajectories shown in Fig. 3 that the particles execute damped oscillatory motions. Since gas-discharge tubes emit an intermittent light

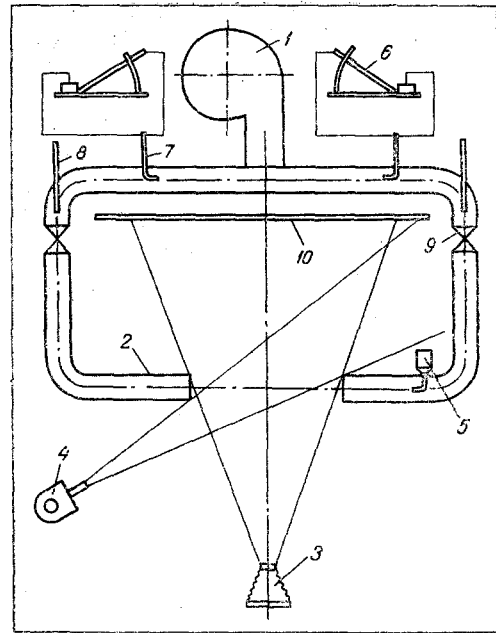


Fig. 2. Diagram of experimental apparatus for the photographic study of two-phase opposing jets: 1) blower; 2) glass tubes; 3) camera; 4) illuminator; 5) feeder; 6) micromanometer; 7) Prandtl tube; 8) thermometer; 9) regulating valve; 10) screen.

flux, whose frequency is equal to twice the frequency of the electric current, the photographed trajectories are intermittent. This method of photography gives, as it were, a trajectory with a time scale superimposed. From the length, frequency, and number of the streaks it is possible to determine the velocity and acceleration of the particles and also the time taken by the particle to cover the investigated part of the trajectory.

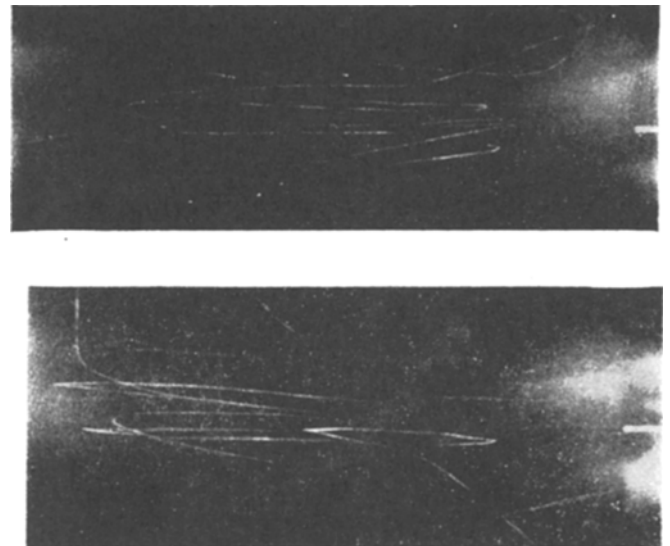


Fig. 3. Photographs of particle trajectories in opposing jets.

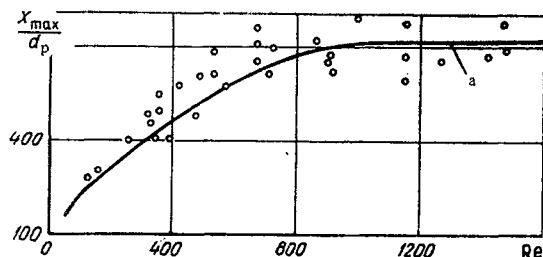


Fig. 4. Relative depth of penetration of the particles into the counterflow as a function of Reynolds number: a) calculated curve.

When the depth of penetration became so great that the particles entered the opposite tube, it was determined by trapping the particles on a rod 0.8 mm in diameter coated with adhesive.

The experiments were performed with particles of Amberlite IRA-401 anion-exchange resin of regular spherical shape. The diameter of the particles was varied from 75 to 500 μ .

The experimental results are presented in Fig. 4, where the relative penetration depth x_{max}/d is plotted as a function of Reynolds number. The Reynolds number was calculated with respect to the particle diameter. Clearly, the experimental points lie quite close to the calculated curve. The distance between the ends of the tubes was varied from 1 to 9 tube diameters. In this L/D range the distance between the ends of the tubes did not have much influence on the depth of penetration into the counterflow.

The experiments showed that the formulas derived are valid at $x_{max} > 2D$, i.e., when the zone of varia-

tion of the carrier flow velocities at the jet interface is less than the depth of penetration of the particles.

The results of our experiments to determine the depth of particle penetration in opposing jets are in satisfactory agreement with the data of [3] for the range of Reynolds numbers $10^2 < Re < 10^3$.

NOTATION

v_g is the gas velocity; v_p is the particle velocity; m_p is the particle mass; g is the acceleration of gravity; γ_g is the specific weight of gas; γ_p is the specific weight of the particle; F_p is the maximum cross section of the particle; c_x is the particle drag coefficient; ν is the kinematic viscosity of the gas; d is the particle diameter; D is the tube diameter; τ is the time; L is the distance between the ends of opposing tubes; x_{max} is the maximum depth of penetration of the particle into the counterflow.

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