# CONCENTRATION OF SOLIDS IN A DUST SUSPENSION FLOW

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A study has been made of the problem of the concentration of solid particles suspended in a viscous fluid flow under conditions of unsteady motion of the particles. An account is given of the results of an experimental determination of the concentration. It is shown that the unsteady dust concentration in a high-speed dust suspension flow may exceed the calculated value for steady motion by 10-20 times.

The concentration of solid or liquid dispersed material in the heterogeneous systems used in various kinds of heat and mass transfer processes must be considered one of their most important parameters. This is particularly true of such processes as the burning and gasification of pulverized fuel, since it has been shown [1, 2] that, in view of the strict relation between the mass flow rates of air and fuel, crushing the latter does not in practice lead to much intensification of the two processes mentioned, because the concentration of the dust suspension is low.

Some recent experiments on burning and gasification, especially the data of [3-5], indicate that burning rates in a dust suspension flow may greatly exceed the values previously obtained under conditions of steady burning.

An explanation of these results must evidently be sought in the fact that burning and gasification of pulverized material in the flow took place in the stage of aerodynamically unsteady particle motion, when a great difference is possible between the velocities of motion of the particles and the gas. Consequently, there may also be a large difference in particle concentration, in comparison with the values usually determined as the ratio of solid to gas flow.

This was the basis for the present study of the concentration of pulverized material entrained by viscous flow. Non-equilibrium states of particle motion are of particular interest. We examine one possible problem of this kind, namely, that relating to the conditions of tests [5] on the burning of a dust suspension.

Apparatus was built to examine the concentration of dust along the flow under the aerodynamic conditions of the above experiments. Because of the complexity of an experimental solution of the problem in a burning flow, observations were made on nonburning and cold flows, while maintaining the same Re number range for the particles used.

The method employed to determine the actual dust concentration was to rapidly isolate a certain volume of the tube in which the dust suspension was flowing. This was done by means of a pair of automatic shutters 2 mm thick [6]. Of course, the values of the concentration determined by simply weighing the dust in the isolated section of the tube were averages for the volume concerned.

The experimental apparatus consisted of a vertical sectionalized tube 15 mm in diameter and 100 cm long. Starting from the top, the tube could be divided into a total of 12 sections, each 50 mm in length. The pulverized material was fed into the tube by a horizontal screw conveyor, as in [5]. The air flowed downwards through the tube and was supplied through a mixer from a laboratory blower. A given section of the tube, called the "working section," could be rapidly shut off by the above-mentioned special system of shutters, one at each end. These shutters were actuated by a special common spring and the operating time was controlled by the tension; in practice, this time was 0.0047 sec, as determined by the method of illuminating a moving film, allowing for flash lag [6]. The relative closing time, of course, depended on the flow velocity and amounted to 10-15% of the mean residence time of the particles in the tube. The working section could be set up in any part of the tube over a length of 0.6 m, and therefore a complete picture of the distribution of dust concentration along the tube could be obtained, beginning from the point of its introduction into the flow.

The measurements were made in the following successive stages. First the shutters were adjusted; then the supplies of air and pulverized material were switched on. When steady-state conditions were attained, the shutters were operated by a special tribber mechanism, and the amount of material in the isolated volume was determined.

The pulverized material was shredded-peat coke, and, as in [5], the mean particle size was 125 and 200 $\mu$. In the course of the course of the tests, the flow velocity $w_0$ was varied over the range 15-40 m/sec, and the loading ratio or "reference concentration" $c_s^0$ over the range 0.25-0.5 kg/m$^3$. The unknown value of the concentration $c_s$ was determined as the arithmetic mean of 3-5 separate determinations of the amount of material collection in the isolated section.

The results obtained are illustrated graphically in Fig. 1, which shows the dependence of the relative concentration $c_s/c_s^0$ on the distance along the tube. The data show that the values of the actual dust concentration at the beginning of the tube are 17-23 times greater than the so-called "reference concentrations" corresponding to the case of zero particle slip relative to the gas flow. It is also clear that in practice the regime $c_s/c_s^0 \approx 1$ could not be approached under the conditions of the tests, and that this ratio was still 3-5 at the end of the investigated section of the tube. Thus, it turns out that in this case the motion of the particles is essentially unsteady. This has great practical importance, primarily from the point of view of intensifying mass transfer processes in a flow of pulverized material.

The basic relation for the particle concentration in a gas flow may be obtained from elementary considerations, if it is assumed that there is no transverse velocity distribution either for the particles or for the medium [1, 2].

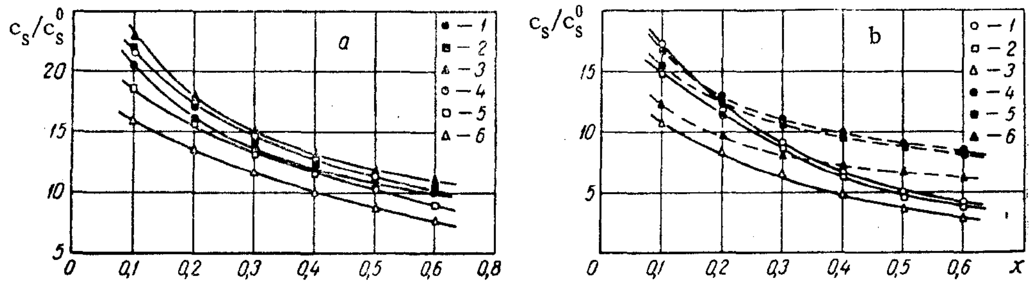


Fig. 1. Variation of relative concentration $c_s/c_s^0$ with distance along the flow, x(m): a) 1) w = 40 m/sec; 2) 35.0; 3) 32.5; 4) 25.0; 5) 20.0; 6) 15.0 with $G_k$ = 1.48 kg/hr; b) 1) w = 35 m/sec; 2) 25.0; 3) 15.0 with $G_k$ = 1.68 kg/hr; 4) w = 35 m/sec; 5) 25.0; 6) 15.0 with $G_k$ = 0.9 kg/hr

We shall consider that the process of motion as a whole is steady, i.e., that the flow picture does not vary with time and that the velocities and concentrations are functions only of the distance along the flow. If the mass flow rate of particles of size $d_i$ per unit cross section of the flow is $g_i$, their velocity at a given section is $v_i$, and the volume rate of gas flow per unit cross section, i.e., the flow velocity, is $w_0$, then, since under steady conditions $g_i$ = const at each section of the flow, we may write

$$g_i = c_s^i v_i = c_s^{i0} w_0, \tag{1}$$

where $c_s^i$ and $c_s^{i0}$ are concentrations of the solid phase: the variable concentration $c_s^i$ and the "reference" value $c_s^{i0} = g_i/w_0$. Therefore, from (1), we have

$$c_s^i = c_s^{i0}\, w_0/v_i \quad \text{or} \quad c_s^i/c_s^{i0} = w_0/v_i. \tag{2}$$

These relations indicate that, for each fraction, depending on the local particle velocity, different concentration levels, other than the reference concentration, are established.

When the dust is monodisperse, the same relation (2) holds, but should now be written:

$$c_s/c_s^0 = w_0/v. \tag{2'}$$

For a polydisperse dust, relation (2) is applicable to each of the fractions, and, by analogy, for the total concentration $c_s = \sum_i c_s^i$ we may write

$$c_s = w_0 \sum_i (c_s^{i0}/v_i). \tag{2''}$$

If, moreover, the size distribution of the particles in the original dust is known and is given by the function $f(d)$, then

$$c_s = w_0\, c_s^0 \sum_i (f(d)/v_i). \tag{3}$$

or in integral form

$$c_s = w_0\, c_s^0 \int_{d_1}^{d_2} \frac{f(d)}{v}\, \delta d. \tag{3'}$$

The specific form of the dependence of $c_s$ on the aerodynamic conditions is thus determined by the behavior of the characteristic parameter $v_i$. It should be noted that after a long enough time the system (at a sufficient distance along the flow), the solid establishes dynamic equilibrium with the flow, characterized by a constant particle velocity relative to the flow. When there is no interaction of the particles with each other and with the tube walls, this velocity represents the limiting value of the slip velocity $v_s$. If this value is very small compared to $w_0$, then $v_i \simeq w_0$ and $c_s \simeq c_s^0$, i.e., the concentration in the flow equals the reference concentration.

In other cases of equilibrium systems the general expression for a single-fraction dust is the even simpler expression:

$$c_s = c_s^0 w_0/(w_0 \pm v_s), \tag{3''}$$

where $v_s$ may be determined by known methods of calculation [7].

It follows from (2'') that determining $c_s/c_s^0$ reduces to obtaining corresponding solutions for v. These may easily be obtained for the idealized case – motion of spherical particles without interaction between each other or with the walls. This motion is described by the known equation

$$m\frac{dv_i}{dt} = \zeta\frac{\pi d_i^2}{4}\,\frac{\gamma(w_0 - v_i)^2}{2} \pm mg. \tag{4}$$

Alternatively, taking into account that $m = \frac{\pi d^3}{6}\gamma_p$, where $\gamma_p$ is the specific weight of the particle, and considering that the motion is steady, i.e., $\frac{dv}{dt} = v\frac{dv}{dx}$, we obtain

$$v\frac{dv}{dx} = \frac{3}{4}\,\frac{1}{d}\,\frac{\gamma}{\gamma_p}\,\zeta(w_0 - v)^2 \pm g. \tag{4'}$$

We make one more transformation, introducing the dimensionless velocity $\omega = v/v_\infty$ where $v_\infty = w_0 \pm v_s$. We then obtain the form

$$\omega\frac{d\omega}{dx} = \frac{3}{4}\,\frac{1}{d}\,\frac{\gamma}{\gamma_p}\,\zeta\left(\frac{w_0}{v_\infty} - \omega\right)^2 \pm \frac{g}{v_\infty^2},$$

or, setting $w_0/v_\infty = \varepsilon$ (generally speaking, $\varepsilon$ is close to unity), we obtain

$$\omega\frac{d\omega}{dx} = \frac{3}{4}\,\frac{1}{d}\,\frac{\gamma}{\gamma_p}\,\zeta(\varepsilon - \omega)^2 \pm \frac{g}{v_\infty^2}. \tag{5}$$

The type of solution of Eq. (5) depends on the properties of the quantity $\zeta$.

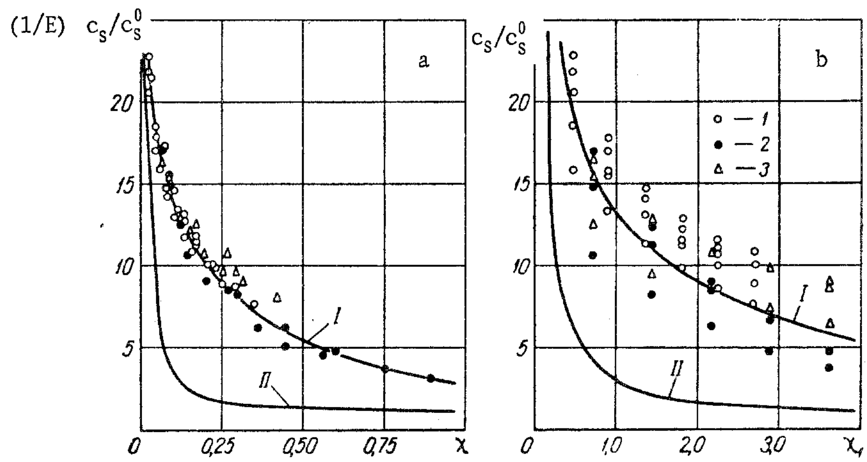


Fig. 2. Dependence of relative concentration $c_s/c_s^0$ on the dimensionless quantities $\chi$ (a) and $\chi_1$ (b): I) experimental curve: 1) $d_{eq}$ = 200 μ, $G_K$ = 1.48 kg/hr; 2) 125 μ and 1.68 kg/hr; 3) 1.25 and 0.9; II) theory.

It is desirable to examine two limiting cases of motion: a) when the Re number is small (Re ≤ 1) and $\zeta$ = A/Re, and b) when the Re number is such that $\zeta \simeq$ const. There are no ready solutions to the problem of obtaining an expression for $c_s/c_s^0 = w_0/v = \varepsilon/\omega$, since this problem has not previously been examined, and also because solutions for $\omega$ are not obtained in explicit form. Generally speaking, specific solutions of this kind are not necessary, since the first task is essentially to find the complex that controls the process. It follows from (5) that dimensionless complexes of this kind must have the form:

when $\zeta = A/Re$

$$\chi = \frac{3}{4} A \frac{\nu}{d^2} \frac{\gamma}{\gamma_p} \frac{1}{v_\infty} x, \tag{6}$$

when $\zeta = \zeta^* = \text{const}$

$$\chi_1 = \frac{3}{4} \frac{1}{d} \frac{\gamma}{\gamma_p} \zeta^* x. \tag{7}$$

Hence these two complexes should be used to analyze the experimental results and their practical usefulness judged from the outcome.

For the conditions of the above tests we may put $\varepsilon = 1$, and therefore $v_\infty = w_0$.

Taking into account that for small Re, according to [7], $\zeta = 27/Re$, we have

$$\chi = 20.2\, \nu\gamma\, x/d^2 \gamma_p w_0. \tag{8}$$

For large Re we take $\zeta^* = 0.46$, and therefore

$$\chi_1 = 0.345\, \gamma\, x/\gamma_p d. \tag{8'}$$

The results of corresponding calculations of $c_s/c_s^0$ for small and large Re are shown in Fig. 2 (curve I). The value of d was taken as the arithmetic mean of the corresponding mesh cell sizes, and x was taken as the distance along the flow from the point where the dust was introduced to the center of the working section of the tube (isolated section). The different symbols correspond to different test conditions, as described in the caption.

The graphs indicate that the best generalization of the test data in terms of the dimensionless quantities $c_s/c_s^0$, $\chi$ and $\chi_1$ is obtained when $\chi$ is chosen as the characteristic parameter. Moreover, it appears that for both variants of the calculation, the experimental data are not in quantitative agreement with the theoretical curves II for $c_s/c_s^0$ (Fig. 2). These curves were constructed on the basis of corresponding solutions of Eq. (5) and subsequent determination of the form of the functions $\omega = f(\chi)$ and $\omega = f_1(\chi_1)$ by a graphical method. The graphs show that agreement between the theoretically derived relation for $c_s/c_s^0$ and the established complexes can only be obtained by assuming considerably smaller values of $\zeta$ than for the case of flow over an isolated sphere. Thus, although the result obtained does not give quantitative agreement between $c_s/c_s^0$ and the parameters $\chi$ and $\chi_1$, it does make it possible to take one of these parameters, namely, $\chi$, as a characteristic parameter of the motion of a dust suspension for the nonequilibrium stage of motion of the particles, and to use this parameter accordingly for calculating the concentrations under other conditions, in particular under the conditions of the tests [5, 8]. Knowing the value of $c_s/c_s^0$ also allows one to find the corresponding values of relative velocity of particles in the flow and hence to evaluate such important parameters, as the diffusion Nusselt number, which is necessary for calculating transfer processes.

A suitable approximation to the relation between $c_s/c_s^0$ and $\chi$ is in this case

$$c_s/c_s^0 = \text{const}\, \chi^{-2/3}. \tag{9}$$

Here the constant should take the value 5.0.

Finally, we note that this relation, as well as the curves of Fig. 2, was obtained purely by experiment, and has significance only within the limits of variation of the parameters measured in the above-mentioned tests, so that the question of possible extension of the experiment still remains. As far as the disagreement between theory and experiment is concerned, a probable cause may be a factor not taken into account in the calculations, namely, interaction of the particles with one another and with the walls of the tube. Qualitatively, this interaction should lead to a delay in the establishment of equilibrium between the particles and the gas. This point requires special investigation. It may be assumed that the interaction effect will finally be found to depend on the relation between the constant $c_s^0$ and the diameter of the chamber.

## NOTATION

$w_0$ – flow velocity; $c_s^0$ – reference concentration of solids; $c_s$ – actual concentration of solids; d – mean particle diameter (reduced); $g_i$ – flow rate of particles per unit cross section; v – particle velocity; $v_s$ – limiting value of slip velocity; $\gamma$ – specific weight of medium; $\zeta$ – drag coefficient of particles in medium; m – particle mass; $\gamma_p$ – specific weight of particles; g – acceleration due to gravity; x – distance along flow; w – relative velocity of particle; $\nu$ – kinematic viscosity of medium; $\chi$ – dimensionless parameter.

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