INVESTIGATION OF THE TRAJECTORY OF MOTION OF AN AEROSOL IN AN ISOTHERMAL GASEOUS CURVILINEAR FLOW

V. E. Maslov, V. D. Lebedev,
N. I. Zverev,* and S. G. Ushakov

UDC 532.525.5

On the basis of experimental and computational investigations, the feasibility is analyzed for the mathematical and physical simulation of slightly dust-laden curvilinear flows.

Because of the widespread use of computers, a large number of papers has appeared which have been devoted to calculations of the motion of two-phase curvilinear flows [1-3].

However, in the absence of a specially arranged experiment it is not possible to show how admissible the numerical data are and for which, in order to obtain them, some or other assumptions are inevitable.

Also, until recently, it has not been completely evident which of the decisive criteria of similarity might be disregarded in a physical simulation of slightly dust-laden flows.

The trajectories of motion of an aerosol in an isothermal curvilinear flow are determined below by numerical and experimental methods.

The purpose of the paper is to attempt to show: a) the necessary and adequate conditions which will ensure, with an accuracy acceptable in practice, the feasibility of the mathematical and physical simulation of dust-laden curvilinear flows in which the concentration of dust may be neglected and b) the role and effect of the principal physical factors occurring in the differential equations of motion of the aerosol, on its behavior in a real turbulent flow.

The subject of investigation are ring-shaped channels, geometrically similar to one another (Fig. 1a). The carrier medium is air with t = 20-30°C. The aerosols are narrow-cut fractions of potassium bichromate and iron obtained by the air-sizing method [4]. The procedure for determining the experimental trajectory of the aerosol is described in [5]. The widely-known compleximetric method of analysis was used for determining the trajectory of the iron dust.

The aerodynamic pattern in the channel is determined by a five-channel ball probe method. Its self-similarity was verified over the range of Reynold's numbers from $16.5 \cdot 10^4$ to $36.7 \cdot 10^4$. The radial velocity component of the carrier stream, over the whole range of motion of the aerosol, is an order lower than the tangential component and is directed to the outer wall of the channel (Fig. 1b). The calculation of the trajectory of motion of the aerosol is carried out by a system of dimensionless differential equations [5] which were integrated on the URAL-2 computer. The decisive parameters of these equations, being from the physical point of view the defining criteria of similarity [6], are as follows: $St = \bar{\delta} V \rho_r / \mu_0 r_0$ is the Stokes criterion; $Fr = V^2/gr_0$ is the Fronde criterion; $R = \bar{\delta} V \rho_0 / \mu_0$, where V and r_0 are the flow velocity and channel radius at the point of entry of the aerosol; $\bar{\delta}$ and ρ_r are the average size and density of the aerosol; ρ_0 and μ_0 are the density and dynamic viscosity of the stream and g is the acceleration due to gravity.

* Deceased.

Eastern Branch of the F. E. Dzerzhinskii Thermotechnological Scientific Research Institute, Chelyabinsk. Translated from Inzhenerno-Fizicheskii Zhurnal, February, 1971, Vol. 20, No. 2, pp. 255-260. Original article submitted May 29, 1969.

© 1973 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for $15.00.

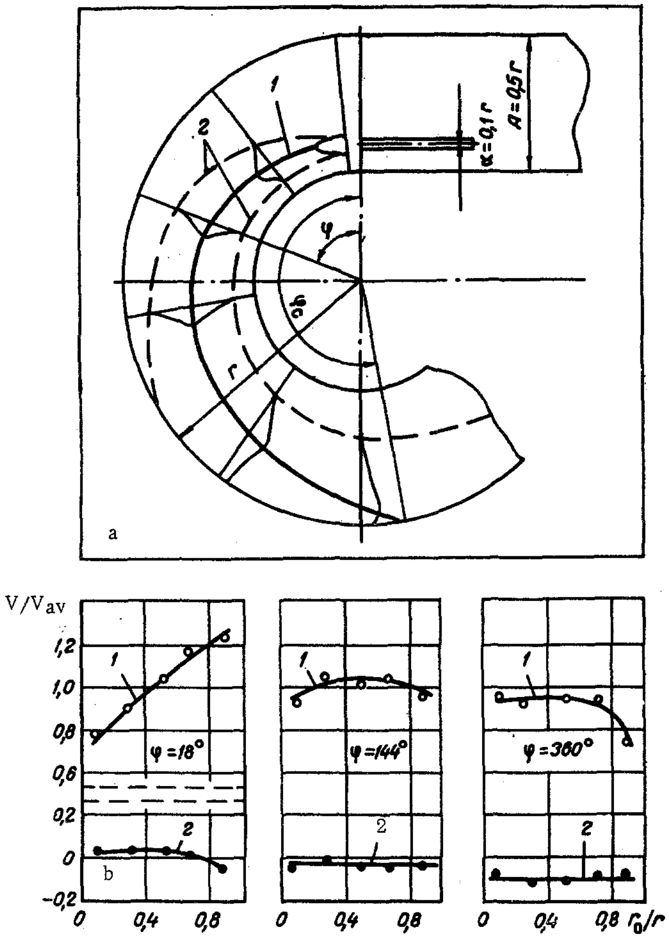

Fig. 1. Schematic diagram of the experimental section and the velocity field in it; a) experimental channel (1) trajectory of motion of aerosol; 2) curves bounding the dust jet scouring; b) flow velocity field in different sections of channel (1) curves of tangential components of flow velocity; 2) curves of radial components of flow velocity.

The following basic assumptions are made in the calculation: sphericity of the aerosol; absence of turbulent pulsations affecting the average motion of the aerosol; absence of nonstationarity effect of the relative motion of the aerosol on its drag coefficient.

The following quantities were varied in the calculation and in the experiment: $\bar{\delta}$ from 16.5 to 427 μ; V_0 from 4.6 to 20 m/sec; external channel radius r from 0.25 to 1 m; initial dimensionless aerosol velocity $W_{\varphi 0} = W_{\varphi 0}/V$ from 0 to 1.0; ρ_r from 274 to 795 kg·sec²/m⁴. The basic calculation was carried out for the actual flow velocity field occurring in the channel. In addition, three variants of the calculation were made for a potassium bichromate dust with the following additional assumptions: absence of gravity (Fr = ∞) when $W_{\varphi 0} = 1$; absence of a radial component of the flow velocity ($V_r = 0$) with a real field of tangential velocities; substitution of the real field of tangential velocities by a field which is uniform with respect to radius and angle φ (V_φ = const; $V_r = 0$).

The analysis showed that the maximum divergence between trajectories with changes of $\bar{\delta}$, V, $W_{\varphi 0}$, r_0 and ρ_r and also from comparison of calculation and experiment, occurs at the point of contact to the aerosol with the outer wall of the channel and, consequently, can be defined by the parameter $C = \varphi_c/360°$ where φ_c is the angle of separation of the aerosol (Fig. 1a).

The total number of experimental trajectories obtained during the investigation was 114. Each trajectory, as a rule, was duplicated. The degree of divergence between experiment and calculation (with

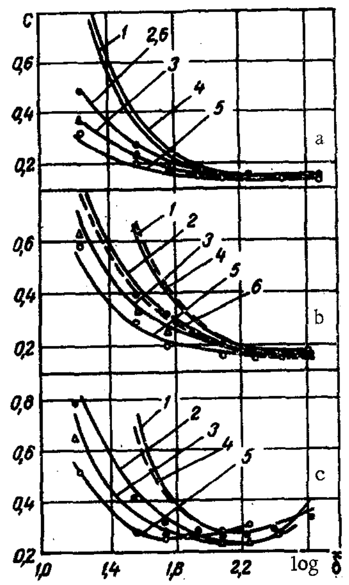

Fig. 2

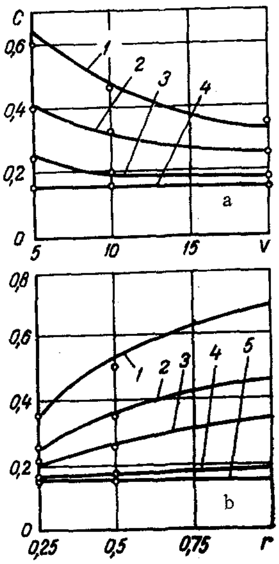

Fig. 3

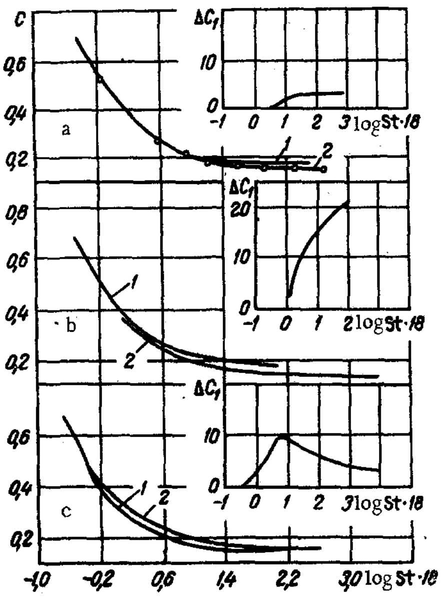

Fig. 4

Fig. 2. Dependence of angles of separation of aerosol on its size: a) V = 17.5 m/sec, $W_{\varphi 0} = 1$; b) 4.6 m/sec and 1, respectively; c) 4.6 m/sec and 0; 1) V_τ = const, $V_r = 0$; 2, 3, 5 and 6) V_τ = var, V_r = var; 4) V_τ = var; $V_r = 0$; 1, 2, 3, 4, 6) $\rho_r = 272$ kg·sec²/m⁴; 5) $\rho_r = 785$ kg·sec²/m⁴; 6) Fr = ∞.

Fig. 3. Dependence of C on: a) carrier flow velocity (r = 0.25 m) [1) $\bar{\delta} = 16.5\,\mu$; 2) 25; 3) 56; 4) 427]; b) channel radius (V = 10 m/sec) [1) $\bar{\delta} = 16.5\mu$; 2) 25; 3) 37.5; 4) 126.5; 5) 424].

Fig. 4. Effect of the criteria Fr (a and b) and R (c) on the motion of the aerosol. a: 1) r = 1 m; V = 10 m/sec; R = 10.6-410; Fr = 8.5; 2) r = 0.5 m; V = 17.5 m/sec; R = 18.5-478; Fr = 52.2; $St_1 = St_2$, $R_1 \cong R_2$, $Fr_2 = 6.1\ Fr_1$; b: 1) r = 1.0 m; V = 5 m/sec; R = 5.3-205; Fr = 2.12; 2) r = 0.25 m; V = 20 m/sec; R = 21.2-820; Fr = 136; c: 1) r = 1.0 m; V = 10 m/sec; R = 10.6-410; Fr = 8.5; 2) r = 0.25 m; V = 5 m/sec; R = 5.3-205; Fr = 8.5.

the real velocity field) defined by the quantity $\Delta C = (\varphi_c^p - \varphi_c^e)/(\varphi_c^p + \varphi_c^e) \cdot 2 \cdot 100\%$ (where φ_c^p and φ_c^e are calculation and experiment respectively) fluctuated from 0 to 8% and on the average was 1.8%. The quite good agreement between calculation and experiment can be seen from Fig. 2 and 3 (curves – calculation; points – experiment) for changes of $\bar{\delta}$, V, r and ρ_r.

If gravity is neglected in the calculation (Fr = ∞), the trajectory length of the coarse dust is decreased only when V = 4.6 m/sec or, more correctly, when Fr ≅ 6.0. When V = 17.6 m/sec (Fr = 90) the effect of gravity is almost negligible (see Fig. 2a, curves 2 and 6).

If the radial flow velocity component is neglected in the calculation, this leads to a sharp increase of the value of C for fine dust; the increase is sharper the less V and $W_{\varphi 0}$ (Fig. 2, curves 1 and 2). The effect of the real tangential velocity field in comparison with a uniform field (in both cases $V_r = 0$) has almost no influence on the length of the aerosol trajectory, independently of $\bar{\delta}$, V and $W_{\varphi 0}$ (Fig. 2, curves 1 and 4).

It can be seem from Fig. 2 that when $W_{\varphi 0} = 1$ an increase of coarseness of the aerosol is expressed in a reduction of the values of C only up to a defined value of $\bar{\delta}$ (when V = 17.5 m/sec, up to $\bar{\delta} = 126.5\mu$ and when V = 4.6 m/sec up to $\bar{\delta} = 284\mu$). With further increase of $\bar{\delta}$, the trajectory length is almost unchanged. A different situation occurs when $W_{\varphi 0} = 0$. Here, at a defined value of $\bar{\delta}$, the value of C reaches a minimum and then begins to increase again. This phenomenon, obviously, is connected with the effect of gravity on the process.

The aerosol density ρ_r also has a similar effect on C (Fig. 2, curves 2 and 5). When $W_{\varphi 0} = 1$, an increase of ρ_r affects the value of C in the direction of a reduction of the latter only for a relatively fine dust. For coarse aerosols, an increase of their density has almost no effect on the trajectory of motion.

When $W_{\varphi 0} = 0$, the trajectory length of fine aerosols decreases with increase of ρ_r and for coarse aerosols it increases. This is because in the first case inertial forces play the primary role and in the second case, gravitational forces play the primary role.

It can be seen from Fig. 3, that with increase of V and decrease of r, the value of C decreases the more sharply, the finer the aerosol.

Turbulent pulsations of the flow affect the trajectory of motion of the aerosol in the following way. On exit from the feeder, diameter 7 mm, the dust stream does not remain constant in proportion to the motion but is continuously widening (Fig. 1a, curve 2), the more sharply the finer the aerosol. At the same time, the maximum of the distribution curve of the dust over the channel height (curve 1) coincides with the corresponding point of the trajectory obtained by calculation in which pulsations were not taken into account.

Thus, in order to effect a mathematical simulation in the region checked by experiment, one can: assume the coefficient of hydrodynamic resistance of the aerosol moving in the stream to be equal to the drag coefficient ψ under stationary conditions. In this case, the value of ψ must be taken in accordance with [7]; an aerosol of irregular shape must be replaced by a spherical particle of the same hydrodynamic diameter; when $Fr \geq 40$, gravity is not taken into account; turbulent flow pulsations are not taken into account in the calculation. It is essential to have a complete aerodynamic pattern of the carrier stream, certainly including in it the magnitude and distribution of the radial velocity component and to have data on the fractional composition of the dust obtained by the air-sizing method.

It should be noted that a precise determination of the radial flow velocities is associated with considerable procedure difficulties and therefore cases when an accurate mathematical simulation is more complicated to achieve than a physical simulation are not exceptional.

Physical simulation is ensured (for self-similarity of the carrier stream) if the criteria St, Fr and R in the model and in the example are equal. However, usually it is not possible in practice to maintain this condition completely.

In order to show the effect and role of each of these criteria, the data from the investigation was processed in dimensionless form.

It can be seen from Fig. 4, where the relations between C and St ($W_{\varphi 0} = 1$) are plotted for various values of Fr and R, that the principal criterion defining the process is St.

When St = idem and R = idem, a change of magnitude of Fr is expressed in the following way. For $St \leq 0.4$ the change of Fr has almost no effect on the process. When $St \geq 0.4$, an increase of Fr from 8.5 to 52.2 (Fig. 4a) the degree of divergence $\Delta C_1 = (\varphi_{C1} - \varphi_{C2})/(\varphi_{C1} + \varphi_{C2}) \cdot 2 \cdot 100\%$ between curves 1 and 2 does not exceed 4%. A sharper effect of Fr is expressed by a change of its absolute magnitude from 2.12 to 136. In this case, ΔC_1 reaches 20% (Fig. 4b).

The effect of R is shown in Fig. 4c. When St = idem and Fr = idem and R is changed by a factor of 2, the value of ΔC_1 fluctuates from 0 to 10% and on an average amounts to about 5%.

Thus, when St = idem and R = idem, the effect of Fr is expressed more strongly the lower is its absolute value and the greater is the absolute value of St.

When $St < 0.4$, a change of Fr from 2.2 to 136 has almost no effect on the process. When $St > 0.4$, a change of Fr within the same limits leads to an error of not more than 20%. This makes it possible for the majority of inertial equipment (dust cyclones, centrifugal scrubbers, cyclone furnaces) to be limited by the conditions St = idem, R = idem and Fr ≠ idem. When St = idem and Fr = idem, the effect of R is stronger the greater is the absolute value of Fr. On the whole, for different versions, exclusion of R leads to an error not exceeding 15%. This permits limitation to the condition: St = idem, Fr = idem and R ≠ idem especially for devices where gravitational force plays the predominant role (the absolute value is small).

LITERATURE CITED

1. M. A. Gol'dshtik, A. K. Leont'ev, and I. I. Paleev, Inzh.-Fiz. Zh., No. 2 (1960).
2. I. M. Basina and A. V. Tonkonogit, Izv. AN Kazakh SSR, No. 1 (21) (1962).
3. V. A. Emel'yanov, V. N. Kuz'min, and A. D. Klyuchnikov, University Bulletin, Energitika, No. 2 (1963); No. 7 (1964); No. 4 (1966).

4. V. I. Ignat'ev and N. I. Zverev, Teploenergetika, No. 2 (1960).
5. V. E. Maslov, V. D. Lebedev, and S. G. Ushakov, Inzh.-Fiz. Zh., 15, No. 3 (1968).
6. N. I. Zverev, Teploenergetika, No. 7 (1957).
7. N. A. Fuchs, Mechanics of Aerosols [in Russian], Izd. AN SSSR, Moscow (1965).