INFLUENCE OF FREE CONVECTION ON THE RATE OF AEROSOL PRECIPITATION FROM A LAMINAR GAS STREAM

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Results of experiments and computational estimates are presented which show that turbulization of a stream under the influence of free convection can substantially intensify aerosol deposition on channel walls from a laminar gas stream.

The deposition of fine and moderately coarse aerosol particles from a laminar gas stream which is inhomogeneous in temperature or concentration is ordinarily associated with thermo- and diffusophoresis phenomena. The theory of thermo- and diffusophoresis has been developed most completely by Yalamov [1]. By using this theory, the coefficient of aerosol particle capture by the channel walls in a laminar gas or steam–water mixture flow can be calculated [1]. In this case the velocity, temperature, and concentration profile in the channel are assumed parabolic when calculating the "trapping coefficient." The computations yield good (up to 30%) agreement with experiments in which only the total quantity of deposited aerosol was measured. The agreement between the computed and measured total quantity of deposited particles was also noted in our preceding paper [2]. However, it has been established that a diminution in the aerosol concentration along the channel length will not occur smoothly, as follows from computations by means of the formulas in [1], but a short band exists in which a sharp (seven- to eightfold) drop in the aerosol concentration occurs. In this paper, an attempt is made to give a foundation to this phenomenon experimentally and theoretically.

The tests were performed on the apparatus described in [2]. In contrast to the previous experiments, the readings of the digital voltmeter were not recorded visually, but by a moving picture camera with frequency of 24 frames per second. This permitted investigation of the nature of the change in the value of the luminance (aerosol concentration) at this point with time (in particular, to take the average with respect to time sufficiently exactly rather than approximately).

The tests were performed only in the laminar mode in the following range of variation of the fundamental parameters: Re = 600–1200, Gr = $1.2 \cdot 10^4$–$1.8 \cdot 10^4$, and Gr/Re = 20–110. The Reynolds and Grashof numbers were determined by means of the hydraulic diameter of the channel [3]. The change in the relative aerosol concentration along the length of the channel axis had the same form as in [2].

As in the previous tests, the existence of a short (10–20 cm) band, where a sharp diminution in the aerosol concentration occurs has been established in the channel; however, it has been clarified that the steepness of the drop in concentration in this band depends not so much on the quantity Re as on the ratio Gr/Re: Tests with identical Re and different Gr/Re showed this. The dependence of the rate of aerosol concentration drop in the band of magnified deposition on the mean value of Gr/Re is shown in Fig. 1 (the quantity Gr/Re was approximately halved along the length of the condenser because of the diminution in the temperature drop between the gas and the wall). Here $\Delta\overline{C}$ is the relative dimensionless drop in concentration, and $\Delta\overline{l}$ is the relative length of the magnified deposition band. From the experimental results presented in Fig. 1 the conclusion can be drawn that the most probable reason for the phenomenon observed is stream turbulization under the effect of free convection forces. It is known that the aerosol concentration in the core of the turbulent stream

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is equalized across the section because of transverse velocity pulsations, and deposition on the walls occurs under the effect of thermo- and diffusophoresis forces in the viscous sublayer. The rates of particle thermo- and diffusophoresis are proportional to the vapor temperature and concentration gradients [1], and since the temperature and concentration in the core of the turbulent stream are constant (distributed according to the profile 1/7, for instance), the gradient in the viscous sublayer is approximately an order of magnitude greater than the mean in the laminar stream. Consequently, fog deposition on the walls increases sharply during stream turbulization (with the mean velocities conserved), which indeed results in a "jump" in the concentration. The expression for the "trapping coefficient" in a turbulent gas flow has been obtained in [2].

We try to give a foundation to the turbulization assumption. Let us consider two tests with minimum and maximum gas velocities (Table 1). Since the gas flow is completely built-up, the inertial terms can be neglected in the equation of motion, and, moreover, all the physical properties of the gas (except the density) can be considered constant because of the small temperature drop:

$$\frac{\partial^2 w_x}{\partial y^2}+\frac{g\beta(T_0-T)}{\nu}+\frac{1}{\mu}\frac{dp}{dx}=0, \tag{1}$$

where β is the coefficient of volume expansion, T_0 is the temperature on the stream axis, and ν and μ are the kinematic and dynamic viscosities of the steam-gas mixture. Since the thermal and hydrodynamic stabilization sections precede the experimental section, the velocity profile is parabolic at the entrance to the experimental section and the mean temperature almost agrees (at least it is not higher) with the temperature on the axis $T \triangleq T_0$. It is seen from Table 1 that the maximum temperature drop varies between 16 and 7°C for the first test and from 25 to 15°C for the second. For the flows under consideration it can be assumed with great accuracy that $dp/dx = \Delta p/l$ [3], where l is the length of the experimental section. Furthermore, $\Delta p = \xi(\rho w_x^2/2)(l/d_{eq})$, and since we are interested in only the upper bound of the quantity $|dp/dx|$, we then take the value of ρw_x^2 at the entrance section, and the friction coefficient ξ will therefore be determined by the Poiseuille law. If the quantity $(1/\mu)(dp/dx)$ is taken as being maximum (at the beginning of the experimental section) and the quantity $g\beta(T_0 - T_W)/\nu$ as being minimum in absolute value (at the end of the experimental section), then after substituting the numerical values we obtain for both tests

$$\frac{g\beta(T_0-T_W)}{\nu}+\frac{1}{\mu}\frac{dp}{dx}>0. \tag{2}$$

The inequality (2) includes the upper bound of the quantities $T_0 - T$ and $|dp/dx|$. Since for all x, $dp/dx < 0$ and $T \to T_0$ as $y \to h/2$ (h is the channel width), then there exists a pair of values x and y for which

$$\frac{g\beta(T_0-T)}{\nu}+\frac{1}{\mu}\frac{dp}{dx}<0 \tag{3}$$

Therefore, $\partial^2 w_x/\partial y^2 = 0$ in one of the channel sections, and in conformity with the Rayleigh theorem the flow becomes unstable under the effect of the free convection forces. Here the stabilizing effect of the transverse stream of condensing vapor can be neglected because of the small volume vapor content $(\varepsilon_{V.V})\ j_W/w_X < 10^{-3}$ [4].

Therefore, the dependence shown in Fig. 1 actually characterizes the flow in the transition domain. For small Gr/Re the transition domain is stretched downstream, while for high Gr/Re flow reversal occurs right after the loss of stability.

The nature of the change in aerosol concentration with respect to time at different points on the channel axis is of great interest. Examples of histograms of the aerosol density (luminance) fluctuation as well as of the change in the relative root-mean-square fluctuation along the channel length are shown in Figs. 2, 3, and 4 for tests Nos. 1 and 2:

$$\frac{\sigma}{M}=\frac{1}{M}\sqrt{\frac{\sum_{i=1}^{N}(M-E_i)^2}{N}}, \tag{4}$$

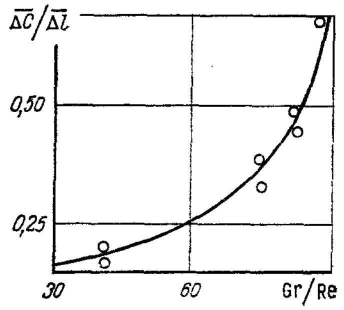

Fig. 1. Dependence of the rate of aerosol concentration drop in the magnified deposition band on the mean value of Gr/Re: ΔE is the drop in luminance in the magnified deposition band; E_0 is the aerosol luminance at the beginning of the band; Δl is the length of the magnified aerosol deposition band; $\overline{\Delta C} = \Delta E/E_0$; $\overline{\Delta l} = \Delta l/l$.

TABLE 1. Parameters at the Entrance and Exit Sections of the Experimental Part ($x = 0$, $x = l$) for Two Tests with Minimum and Maximum Gas Velocities

Test no.	w_x, m/sec	$\bar{T}$, °K	T_w, °K	Re	Gr	$\varepsilon_{v.v}$
1	0,329 0,305	299 286	283 279	674 677	76800 36100	0,0548 0,0188
2	0,630 0,571	308 293	283 278	1225 1212	108000 76200	0,0821 0,0268

where N is the number of measurements; $M=\frac{1}{N}\sum_{i=1}^{N}E_i;$ E_i; and E_i is the instantaneous value of the luminance, which is proportional to the numerical concentration of the aerosol. These two tests exhibit two characteristic types of changes in the fluctuation histograms along the channel length. For Re > 1000 the quantity σ/M increases smoothly and not very strongly, but the histograms have the form of a normal distribution "deliquescing" downstream. For Re = 600-700 a definite "intermittency" in the fluctuations holds. The distribution densities then have several distinct maxima, acquire a Gaussian shape, and the relative root-mean-square fluctuation is large in absolute value.

It must be noted that no change in the nature of the histogram was noted before and after the magnified deposition band in all the modes (at least qualitatively). This in some sense contradicts the results in [5], where the time of water flow turbulization in a vertical channel under the effect of free convection forces was determined by the beginning of wall temperature fluctuations. For the case of free and forced convection in agreement at the wall, the authors obtained an empirical formula for the distance from the entrance to the experimental section to the section in which turbulization occurs:

$$x_{cr} = 4.25\,\mathrm{Ra}^{-0.8}. \tag{5}$$

The distance from the entrance to the experimental section to the band of magnified deposition in our tests agrees to ±30% accuracy with those computed by this formula.

The time for each measurement was 15 sec on the average; i.e., each histogram contains 300-400 measurements, and more than 100 histograms in all were processed.

The noted nature of the aerosol density fluctuation histograms is associated with the singularities of interaction between the free and forced convection and requires a further study in this plan.

In conclusion, let us discuss the question of the explanation of the agreement between the measured total quantity of deposited aerosol and that computed without taking account of the influence of free convection. As the results of our experiments showed, this is related to the sufficiently long length of a slot channel. According to computations by the method

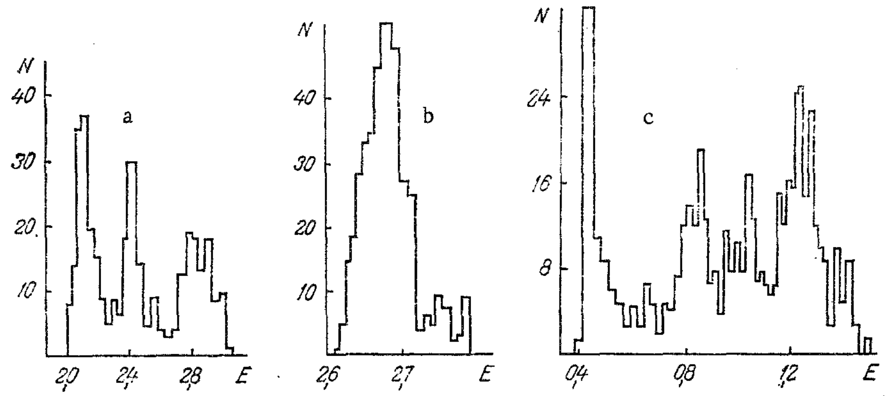

Fig. 2. Examples of histograms for test No. 1: a) x = 15 cm; b) x = 30 cm; c) x = 80 cm.

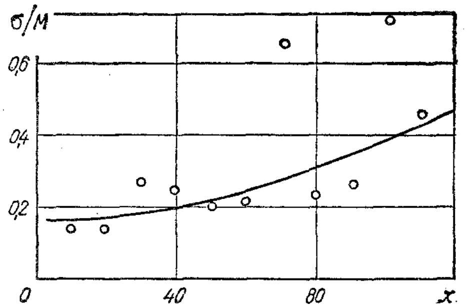

Fig. 3

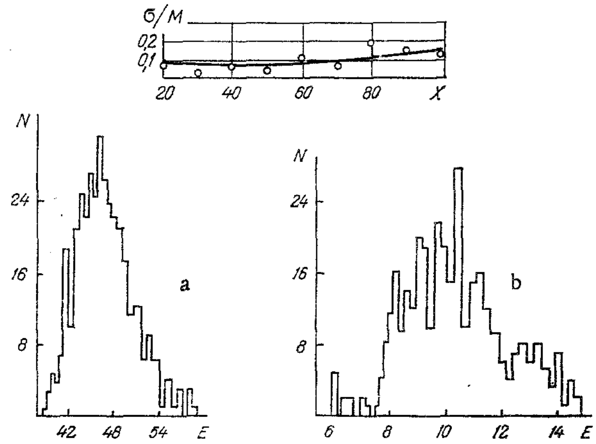

Fig. 4

Fig. 3. Change in the relative root-mean-square deviation of the aerosol concentration along the channel length for test No. 1.

Fig. 4. Examples of histograms and change in the relative root-mean-square deviation of the aerosol concentration along the channel length for test No. 2: a) x = 15 cm; b) x = 100 cm.

in [1], up to 70% aerosol can be deposited in a channel several hundred calibers long; hence, the excess of the experimental quantity over the computed values lies within the limits of experimental accuracy. For short slot channels with a length slightly different from the size of the loss of the stability band, a computation of the drop deposition without taking account of free convection can yield a reduction of severalfold.

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