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DEPOSITION OF ULTRAFINE AEROSOLS IN A PLANE CHANNEL FROM A LAMINAR VAPOR–GAS FLOW OF NONUNIFORM CONCENTRATION

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UDC 533.72:66.074

The deposition of a high-dispersity aerosol in a water-vapor concentration gradient field in a thermal diffusion chamber with a control element [1] has been experimentally investigated.

One of the most complex problems of the separation of aerosol impurities from gas streams is the trapping of ultrafine aerosols with a particle size of less than $1 \cdot 10^{-6}$ m [2, 3]. In a number of studies [3-6] problems of this kind are solved by using the directional motion of the aerosol particles in the concentration gradient field of one of the components of the gas mixture on the basis of the fact that for fine aerosol particles the velocity of this motion, which is equal to the Stefan flow velocity and the rate of diffusiophoresis, depends only weakly on the size and shape of the particles, the physical properties of the material of which they are composed, and the phase transitions at their surface [7-9]. Since the rate of diffusiophoresis and the Stefan flow velocity are determined by the concentration gradient and the content of the active (diffusing) component of the gas mixture [7], in most cases various designs of thermal diffusion chamber (TDC) are used as the filter apparatus.

In order to improve the gas purification rate at high aerosol particle concentrations, the authors have proposed a filter model in the form of a TDC with a control element [1]. However, the study of the operation of this filter [10] is far from complete, since accurate

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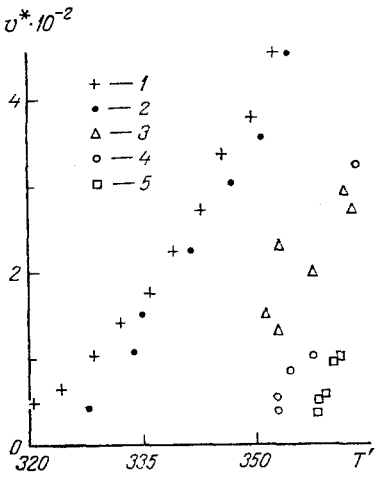

Fig. 1

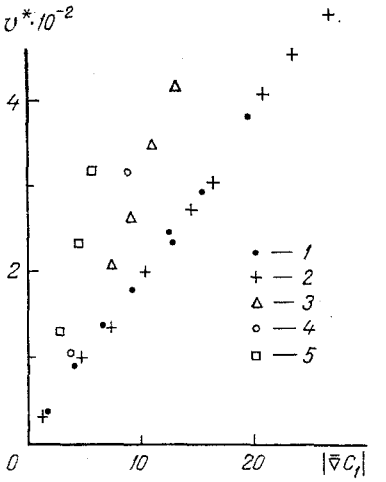

Fig. 2

Fig. 1. "Critical" velocity v*, m/sec, as a function of the TDC heater temperature T', K, at a constant cooler temperature T", K, for a channel 0.475 m in length: 1, 2) results of our experiments for $r_g = 1 \cdot 10^{-8}$ m [1) T" = 313 K; 2) 322]; 3-5) experimental data of [3] [3) T = 341.5 K; 4) 349.8; 5) 356.2].

Fig. 2. "Critical" velocity v* as a function of the water-vapor concentration gradient $|\nabla C_1|$, m^{-1}, for a channel 0.475 m in length: 1, 2) results of our experiments for $r_g = 0.85 \cdot 10^{-8}$ and $1 \cdot 10^{-8}$ m, respectively [1) $C_1 \in$ (0.28...0.36); 2) $C_1 \in$ (0.28... 0.40)]; 3-5) experimental data of [3] [3) $C_1 \in$(0.36...0.48); 4) $C_1 \in$(0.44...0.55); 5) $C_1 \in$(0.56...0.59)].

experiments have been carried out only for a very narrow region of particle sizes at low concentration gradients and vapor contents. We therefore set ourselves the task of making a more detailed investigation of the ultrafine aerosol filtration process in TDC-type devices with a control element over a broad interval of chamber thermal regimes and aerosol parameters.

The experiments were carried out on the apparatus described in detail in [10], the measuring technique consisted in determining the maximum flow rate of the air suspension through the working zones† of the filter at which all the particles are trapped. This quantity has been called the "critical" flow rate Q* [10]. In the experiments we used a sodium chloride aerosol with a narrow particle size spectrum (standard geometric deviation no worse than 1.5), obtained by homogeneous condensation of the vapor as a result of the mixing of two streams at different temperatures [11]. In order to exclude the condensation growth of the aerosol particles in the working zone of the chamber, in all the experiments the temperature of the control element was kept equal to the heater temperature [10]. During the experiments we measured the "critical" flow rate Q*, the temperatures of the heater T', the cooler T" and the TDC control element and, moreover, the size r_g and concentration of the aerosol particles.

The rigorous theoretical analysis of the heat and mass transfer processes and the motion of the aerosol particles in a TDC with a control element is a complex problem. Estimates [12] have shown that changes in the geometric parameters of the control element can affect the water vapor concentration distribution in the channel and hence the quantity Q*. At the same time, experimental measurements of Q*, made for a constant filter thermal regime and constant aerosol particle size but various nickel gauze parameters (in the experiments we used gauze with a rectangular mesh measuring $(75 \times 75) \cdot 10^{-12}$ and $(159 \times 159) \cdot 10^{-12}$ m^2 and individual fiber diameters of $50 \cdot 10^{-6}$ m and $108 \cdot 10^{-6}$ m, respectively), gave the same results.

An important characteristic of the filter investigated, needed, for example, for its engineering design, is the "critical" velocity v*, which is equal to the ratio of Q* to the

†The working zone is the space between the heater and the control element of the TDC.

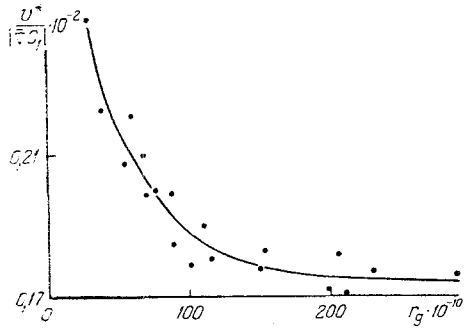

Fig. 3

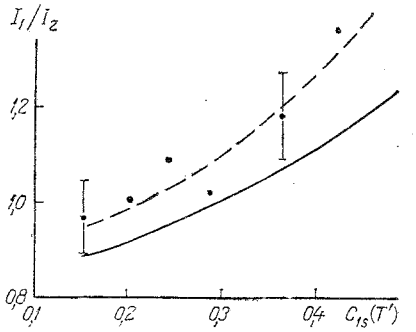

Fig. 4

Fig. 3. "Critical" velocity reduced to unit concentration gradient, $v^*/|\bar{\nabla}C_1|$, m^2/sec, as a function of the dimensions of the aerosol particles r_g, m, at the constant vapor content $C_1 = 0.10$. The curve is the result of a least squares analysis of the experimental data.

Fig. 4. Specific vapor flow rate I_1/I_2 as a function of the saturated water-vapor concentration at the heater surface $C_{1s}(T')$ for constant saturated vapor concentration at the cooler $C_{1s}(T'') = 0.12$ and an aerosol particle size $r_g = 1 \cdot 10^{-8}$ m.

cross section of the chamber working zone. A similar quantity can easily be calculated from the data of [3], in which the precipitation of a tobacco smoke aerosol (mean particle size $\langle r \rangle \approx 0.4 \cdot 10^{-6}$ m) in a plane flow-type TDC, with a distinctive method of creating the water-vapor concentration gradients, was experimentally investigated. It is useful to compare the results of the two studies.

Some of the results of our experiments are shown in Fig. 1 in the form of a plot of v^* against T' at constant T". Clearly, as the temperature difference between the heater and the cooler increases, so does the "critical" velocity. In fact, an increase in the absolute value of T' is accompanied by increases in, firstly, the saturation vapor concentration at the heater surface, and hence the vapor concentration gradient $|\bar{\nabla}C_1|$, and, secondly, the mean vapor molecule content of the gas mixture C_1. This, in its turn, leads to an increase in the particle deposition rate, which, in the case of a high-dispersity aerosol and particle deposition purely as a result of diffusiophoresis and Stefan flow, has the form [7]:

$$u = \frac{m_1^{1/2}}{m_1^{1/2}C_1 + m_2^{1/2}C_2} \frac{D_{12}}{1 - C_1} |\bar{\nabla}C_1| \qquad (1)$$

and acts in a direction opposite to that of the concentration gradient. At the same time, as follows from simple physical considerations, the variation of u also determines the behavior of the "critical" velocity.

The small difference with respect to v^* at the same T' in our two series of experiments is associated with the difference in cooler temperatures.

The same figure also contains the experimental data of [3] which, clearly, are governed by the same laws. The fact that the absolute values of v^* obtained in [3] and in our study do not coincide is attributable to the fact that in [3] the maximum temperature difference was 21°, whereas in our experiments it reached 40°. Moreover, by using a porous plate as the TDC heater, the authors of [3] artificially reduced the vapor molecule concentration near the heater, which leads to a decrease in $|\bar{\nabla}C_1|$ and C_1 and hence in u and v^*.

As follows from (1), the aerosol particle deposition rate is proportional to the vapor–gas mixture concentration gradient. Therefore it is useful to establish experimentally the dependence of v^* on $|\bar{\nabla}C_1|$. The values of $|\bar{\nabla}C_1|$ in the TDC were calculated on the assumption of a linear vapor concentration profile in the channel [12].

In Fig. 2 we have reproduced some typical results of our experiments and the data of [3]. Clearly, both can be satisfactorily approximated by straight lines drawn from the origin at various angles of inclination. The observed difference in the slope of the straight lines and the associated quantitative discrepancy in the results of the experiments are attributable to the difference in the experimental conditions (principally in the vapor content). In fact, according to the authors' calculations, the corrections to the velocity v^* determined by the

thermophoretic and gravitational deposition of particles in the apparatus [3] amount to not more than 10%. At the same time, a twofold increase in C_1 (in the region $C_1 \in (0.1...0.6)$) leads to an increase in u by approximately the same factor.

It should be noted that in all the experiments an increase in $|\bar{\nabla}C_1|$ is accompanied by an increase in C_1. However, the linearity of the dependence of v* on $|\bar{\nabla}C_1|$ is not affected. This is because on the interval $C_1 \in (0.1...0.6)$ the function $1/1 - C_1$ (see Eq. (1)) is only slightly nonlinear.

The theory of diffusiophoresis of high-dispersity aerosols [7-9] and the experiments [3, 6, 13, 14] indicate that the velocity of fine particles in a binary gas mixture of nonuniform concentration does not depend on their size. Therefore, the monotonic growth of v* with decrease in particle size observed in Fig. 3 can only be attributed to the additional contribution to the total deposition rate of Brownian diffusion of the particles. The Brownian particle deposition is determined by the Brownian diffusion coefficient, which for aerosol particles with $r_g \leq 1 \cdot 10^{-8}$ m is proportional to $1/r_g^2$ [2]. Thus, the contribution of this effect to the deposition rate and hence v* is nonlinear, as is also apparent from Fig. 3.

In the region $r_g \geq 1.5 \cdot 10^{-8}$ m the Brownian motion is insignificant and for our experimental conditions, according to estimates, increases v* by not more than 5%.

An analysis of Fig. 3 indicates that the critical gas flow velocity in filters of similar design does not depend on the degree of polydispersity of the aerosol supplied to the working zone of the filter if $r_g \geq 1.5 \cdot 10^{-8}$ m. For smaller particles the Brownian diffusion makes a substantial contribution to deposition. Moreover, the experiments showed that v* does not depend either on the aerosol particle concentration on the interval $10^8...10^{14}$ m^{-3} or on the nature of the particles.

The energy capacity of the TDC can conveniently be estimated from the amount of vapor released in the filter for cleaning unit mass of air I_1/I_2. The theoretical† and experimental values of this quantity were calculated from the expressions given in [10]. The results of the calculations for one series of experiments are shown in Fig. 4. The continuous curve is the theoretical curve, the broken curve the experimental one, obtained by a least squares analysis of the experimental data. Clearly, the curves are similar in character. At the same time, as $C_{1s}(T')$ increases, a gradual increase in the difference between the values of $(I_1/I_2)_{theor}$ and $(I_1/I_2)_{exper}$ is observed. This cannot be attributed to measuring errors since the maximum error of $(I_1/I_2)_{exper}$ does not exceed 10%, and in individual experiments the difference between the theoretical and experimental results reaches 20%. One reason for this discrepancy may be the assumptions made by the authors in constructing the theory [15]. However, comparison of the results of the analytic calculations [15] and the exact solution of the analogous problem obtained on a computer [3] indicates satisfactory agreement (discrepancy not more than 8% [15]).

A careful analysis of the results obtained in [15] shows that for trapping aerosols in an ordinary plane-parallel channel with wettable walls the optimum operating regime from the energy standpoint is that with a small temperature difference between heater and cooler and a high average temperature in the channel. Precisely these conditions were realized in the apparatus investigated in [3] and the results obtained confirm the existence of an optimum regime. Since in our experiments we observed qualitative agreement both with the results of [3] and with the conclusions of the theory [15], clearly the regime described above may also be considered optimal for a TDC with a control element.

The results of our experimental investigation of an aerosol filter based on a TDC with a control element indicate that filters of this type can be used for the high-efficiency separation from gases of ultrafine aerosol particles of any kind (including radioactive) over a broad range of particle sizes and concentrations.

NOTATION

T' and T", temperatures of the heater and the cooler of the TDC with control element; $C_{1s}(T')$, $C_{1s}(T")$, molar saturated water-vapor concentrations at the surfaces of the heater and the cooler of the TDC; $\langle r \rangle$ and r_g, mean and geometric mean radii of the aerosol particles; $|\bar{\nabla}C_1|$, modulus of the water-vapor concentration gradient; Q*, "critical" rate of flow through the working zone of the TDC with control element; v*, "critical" velocity of the aerosol in

†For determining $(I_1/I_2)_{theor}$ we used the theory of aerosol particle deposition in a plane channel with a temperature difference and wettable walls [15].

the working zone; u, rate of deposition of the aerosol particles in the water-vapor concentration gradient field; C_1 and C_2, relative concentrations of the vapor molecules (vapor content) and air; m_1 and m_2, masses of the vapor molecules and the air; I_1 and I_2, mass fluxes of water vapor and air; D_{12}, interdiffusion coefficient of the air–water vapor mixture.

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HEAT EXCHANGE AND BOILING CRISIS IN SLOT CHANNELS UNDER THE ACTION OF AN ELECTRIC FIELD

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UDC 537.248.2

The results of an experimental and analytical investigation of the effect of electric fields on the boiling of dielectric liquids with low thermal conductivity under constrained conditions are given.

Experimental and analytical investigations of heat transfer during boiling and condensation in an electric field [1-3] provide convincing evidence that, under certain conditions, its effect on the phase transition and the vapor–liquid flow causes considerable quantitative and qualitative changes in the thermal and hydrodynamic phenomena. The field-induced perturbations in a two-phase medium, which are accompanied by the development of large-amplitude electrodynamic waves, cause a restructuring of the flow. The development of electroconvection, changes in the structure of the two-phase medium, an increase in the interphase contact surface area, and reduction in the characteristic dimensions of films, drops, bubbles, etc., lead under certain conditions to vigorous intensification of the heat and mass exchange in an electric field. The specific features of the thermal and hydrodynamic phenomena in a two-phase flow resulting from the imposition of an electric field make it possible to devise highly efficient electrohydrodynamic heat transfer devices. However, the practical application of these features in designing closed electrohydrodynamic (EHD) heat-transfer devices (heat pipes or thermosiphons) is basically at the stage of technical proposals. The factors

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