Journal of Engineering Physics and Thermophysics, Vol. 79, No. 2, 2006

HETEROGENEOUS CONDENSATION OF A STEAM ON NANOPARTICLES IN A LAMINAR DIFFUSION CHAMBER

A. A. Brin' and S. P. Fisenko

UDC 536.423.4

The heterogeneous condensation of a steam on nanoparticles introduced into a laminar diffusion chamber has been investigated numerically. It has been shown that we can have a growth of droplets with a nanoparticle inside to a radius of the order of a micron even in the case of a moderate temperature difference. The time of droplet growth occurring virtually in a free-molecular regime is nearly 10^{-5} *sec.*

A laminar diffusion chamber (LDC) is widely used at present for experimental investigation of the process of homogeneous nucleation [1–3]. At the same time, it is common knowledge that any device in which a nonequilibrium medium and, in particular, a supersaturated steam, is used acts, in fact, as an amplifier of weak signals [4]. We can single out, among them, a Wilson chamber, where a supersaturated steam acts as the nonequilibrium medium, and a bubble chamber, in which a superheated liquid is used.

In the present work, we numerically investigate the possibility of detecting nanoparticles from a gas flow (by the amplification of the signal upon their appearance) due to the condensation of a supersaturated steam in the LDC condenser. Nanoparticles, in particular, those obtained in a plasmachemical reactor [5], can easily be delivered to the LDC. Heterogeneous droplets with a radius of ~1 μm grow on the nanoparticle surface as a result of the subsequent condensation of the steam. It is noteworthy that the condensation of the supersaturated steam is much more rapid on charged nanoparticles [6]. Extraction of micron particles from a gas flow has adequately been developed in the technology of aerosol systems [7].

To calculate the growth of heterogeneous water droplets formed on nanoparticles one must know the supersaturation and temperature fields occurring in the LDC, when a mixture of steam and air is used. The supersaturation of the steam must not be very high lest the homogeneous nucleation of the steam begin. Carbon nanoparticles well wettable with water [8] can be used as the center (nucleus) of condensation of the steam. For joint calculation of the temperature and density fields of the steam and the growth of droplets we use a new mathematical model of operation of the LDC [9].

The structure of an LDC is diagrammatically represented in Fig. 1. The principle of operation of the LDC is as follows: a hot steam-gas mixture with a high content of the steam enters a vertical cylindrical chamber with cold walls on which a condensed-liquid film has been preformed. The steam-gas mixture moves along a vertical channel; the processes of diffusion of the steam and heat conduction occur simultaneously in the radial direction. Since the density of the saturated steam is exponentially dependent on temperature, even a slight cooling of the mixture with a small decrease in the steam density gives rise to a metastable supersaturated medium.

In this work, we have selected a steam, with which the air flow is saturated in the LDC saturator, as the working medium (use can also be made of the vapor of organic substances: propanol and butanol) and air as the carrier gas (use of helium, argon, and hydrogen is possible). It is assumed that the LDC operates at atmospheric pressure. The mathematical model proposed enables us to operate with any combinations of these substances.

Mathematical Model. In the LDC, the flow of a steam-carrier gas mixture is laminar; the velocity profile $u(r)$ of the flow at entry into the chamber has the form

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A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 79, No. 2, pp. 10–13, March–April, 2006. Original article submitted March 28, 2005.

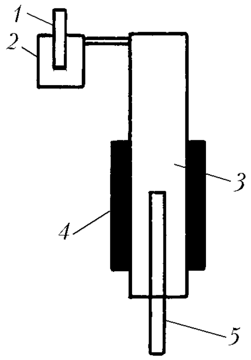

Fig. 1. Diagram of the setup: 1) introduction of nanoparticles; 2) saturator; 3) condenser; 4) water cooling of the walls; 5) removal of the waste material.

$$u(r) = 2u_0\left[1 - \left(\frac{r}{R}\right)^2\right]. \tag{1}$$

The temperature field $T(r, z)$ is described by the equation of convective heat conduction

$$u(r, z)\frac{\partial T(r, z)}{\partial z} = \frac{1}{\rho_m c_m}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(r, z)\, r\frac{\partial T}{\partial r}\right)\right], \tag{2}$$

where $\lambda(r, z)$, ρ_m, and c_m are the thermal conductivity, the density, and the heat capacity of the mixture of the carrier gas and the steam.

The field of number density of the steam in the mixture $n(r, z)$ in the chamber is described by the equation of convective diffusion

$$u(r)\frac{\partial n(r, z)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(D(T(r, z))\, r\frac{\partial n}{\partial r}\right). \tag{3}$$

Here $D(T(r, z))$ is the binary coefficient of diffusion of the steam, which is dependent on the local temperature of the mixture.

Boundary conditions for the steam on the wall, which allow for the influence of a thin film of the condensed liquid on the condenser wall, have the form

$$T(R, z) = T_w \quad \text{and} \quad n(R, z) = n_s(T_w), \tag{4}$$

where T_w is the temperature of the cold wall. At the center of the flow, we set two standard conditions:

$$\frac{\partial T(0, z)}{\partial r} = \frac{\partial n(0, z)}{\partial r} = 0. \tag{5}$$

To describe the growth of droplets in a supersaturated steam we use the equation

$$\frac{\partial R_d(z)}{\partial z} = L(R_d(z))\frac{n(r, z) - n_s(T(r, z))}{u(r)}, \tag{6}$$

which accurately describes the growth of droplets in free-molecular and diffusion regimes [10]; for intermediate Knudsen numbers, it is approximate, even if quite exact.

The initial conditions for the steam-gas mixture are the uniform distributions of the density and temperature of the steam at entry into the chamber:

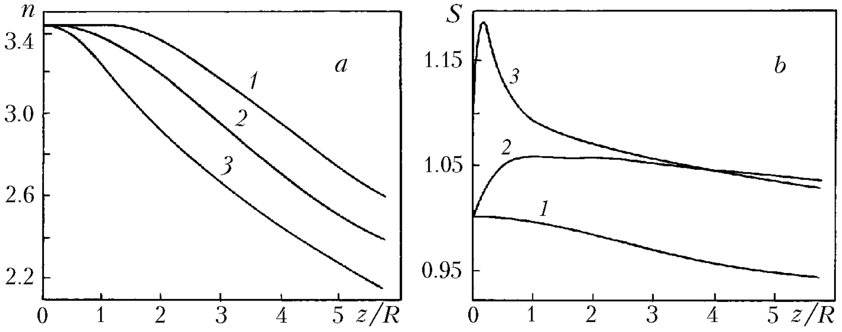

Fig. 2. Variation in the number density of the steam (a) and in the supersaturation (b) with condenser length: 1) on the condenser axis; 2) r/R = 0.714; 3) 0.857.

$$T(0, r) = T_{\text{str}}\,, \quad n(0, r) = n_{\text{s}}(T_{\text{str}})\,, \tag{7}$$

where T_{str} is the temperature of the LDC saturator. The initial value of the nanoparticle radius is prescribed at entry into the LDC condenser.

The system of partial derivative equations with variable coefficients (1)–(7) has been transformed to a system of ordinary differential equations using the method of lines [11, 12]. The partial derivatives in the radial direction were replaced by the central differences. The resulting system of ordinary differential equations was solved numerically by the Runge–Kutta adaptive method of fourth order.

Discussion of Results. Figures 2 and 3 give results of numerical modeling with the following initial and boundary conditions: R = 5 mm, T_{str} = 310 K, T_{w} = 288 K, and u_0 = 0.15 m/sec. The thermophysical properties of the steam have been taken from [13].

Figure 2a shows a variation in the dimensionless density of the steam with LDC-condenser length for different radial positions. The number density of the saturated steam at the cold-wall temperature has been selected as the density scale. In the figure, it is seen that the steam density drops with distance from the chamber inlet, and it decreases exponentially nearly from 1.5R. Since the Le number is less than 1 in our case, the values of the dimensionless temperature decrease analogously, even if somewhat more slowly. In the course of the solution, we selected the cold-wall temperature as the scale of making the temperature field dimensionless. Figure 2b shows a variation in the supersaturation $S(r, z)$ with LDC-condenser length; for different radial positions, it is determined as $S(r, z) = n(r, z)/n_{\text{s}}(T(r, z))$. From an analysis of the data it follows that supersaturation for the steam-air mixture occurs only near the cold chamber walls. The reason is that the Lewis number is $\text{Le} = \dfrac{\lambda}{\rho_{\text{m}} c_{\text{m}} D} < 1$ for this mixture, i.e., the diffusion of the steam is more efficient than the heat conduction virtually on the entire cross section of the condenser. We have a growth of droplets only in the regions where the supersaturation is more than unity, i.e., near the cold wall ($r/R > 0.7$). Consequently, for the mechanism of initiation of droplet growth on nanoparticles to work efficiently, one must introduce the nanoparticles into the wall region of the condenser. Simple calculation shows that, with a uniform distribution of nanoparticles over the channel cross section, nearly 30% of the total consumption of the nanoparticles is in the region with $r/R \geq 0.7$.

When helium or hydrogen are used as the carrier gas (for Le > 1), the supersaturation zone covers the entire cross section at entry into the LDC condenser. It can be shown that the supersaturation will be maximum at the center of the channel.

Figure 3 shows the dependence of the radius of droplets formed on nanoparticles on their position in the LDC condenser. It is seen that the droplets that are closer to the cold wall grow to a larger size (of the order of a micron), since the supersaturation is higher here. As the chamber length exceeds 6R (for the flow velocity given above), the droplet radius remains virtually constant, since the supersaturation of the steam disappears at large distances. The time of growth of the droplets is of the order of 10^{-5} sec, since it occurs virtually in a free-molecular regime. Numerical calculations have shown that the initial radius of the particles, if it is less than 10^{-7} m or more than $2{\cdot}10^{-9}$ m, does not influence the final size of a droplet grown in the LDC, which confirms the conclusion drawn in [14] based on

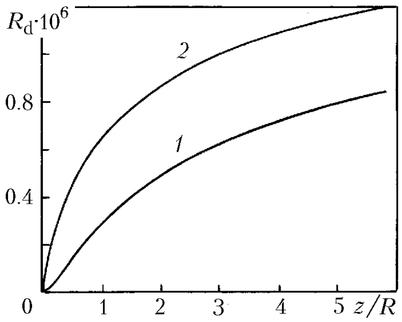

Fig. 3. Variation in the radius of heterogeneous droplets with condenser length: 1) r/R = 0.714; 2) 0.857.

experiments. Naturally, the initial shape of nanoparticles is also of no importance in the free-molecular regime of droplet growth.

As our calculations have shown, when the difference between the saturator temperature and the condenser-wall temperature is relatively small (of the order of 20°C), the supersaturation zone developed is sufficient for the droplets to grow to a micron in it. The gradients of temperature and density of the steam in the channel grow with decrease in the channel radius. As a result, as can be shown, the vapor supersaturation grows, and the droplets increase. The approximate integration of Eq. (6) yields the following estimate of the radius of droplets grown in the LDC condenser:

$$R_d(z) \sim \sqrt{\left(\frac{n_s(T_s)}{n_s(T_w)} - 1\right)\frac{m}{\rho}} .$$

It follows that increase in the saturator temperature leads to an increase in the final radius of particles, which is consistent with experimental results [15]. Also, it is noteworthy that the efficiency of application of the laser-ablation method to micron particles is substantially higher than that of its application directly to nanoparticles [4].

This work was carried out with support from the Belarusian Republic Foundation for Basic Research, project No. T04R-021.

NOTATION

c, heat capacity, J/(kg·K); D, binary diffusion coefficient, m^2/sec; Le, Lewis number; L, function, $m^4 \cdot sec^{-1}$; m, molecular weight, kg; n, number density of the steam, m^{-3}; R, radius of the LDC channel, m; R_d, radius of a droplet, m; r, radial coordinate, m; S, supersaturation; T, temperature, K; u, velocity of the flow, m/sec; u_0, average velocity of the flow, m/sec; z, axial coordinate, m; λ, thermal conductivity of the mixture, W/(m·K); ρ, density of water, kg/m^3. Subscripts: 0, average value; str, saturator; d, droplet; m, mixture; s, saturated; w, wall.

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