# THE ENTRAPMENT FACTOR PERTAINING TO MEDIUM-SIZE VOLATILE PARTICLES IN SLOT CHANNELS

Yu. I. Yalamov and E. R. Shchukin

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The theory of precipitation is applied to medium-size particles under the influence of thermo- and diffusophoretic forces in gas streams through slot channels. A formula for the aerosol entrapment factor is then derived.

When a binary gaseous mixture (consisting, for example, of water vapor and air) is passed through a slot channel [1], with nonuniform temperature and concentration distributions, then medium-size volatile particles forming around dry condensate nuclei in a stream supersaturated with vapor will precipitate on the channel walls under the influence of diffuso- and thermophoretic forces [1, 4].

The velocity of particles suspended in a gas (shown in x, y coordinates in Fig. 1 with symmetry with respect to the z-axis)

$$\mathbf{v} = \mathbf{V} + \mathbf{v}_D + \mathbf{v}_T, \tag{1}$$

with $\mathbf{V}$ denoting the stream velocity, $\mathbf{v}_D$ denoting the diffusophoretic velocity [2], and $\mathbf{v}_T$ denoting the thermophoretic velocity of volatile particles, was determined first by Yu. I. Yalamov and E. R. Shchukin [3] and later more accurately by Yu. I. Yalamov, B. V. Deryagin, and V. S. Galoyan [4] (the Yalamov—Deryagin—Galoyan formula will be used here).

By solving the equation

$$\frac{dx}{v_x} = \frac{dz}{v_z}, \tag{2}$$

one can determine the extreme trajectory of a particle, i.e., the trajectory which passes through the channel exit ($x = d/2$, $z = l_c$) and which bounds the region adjacent to the channel wall where all particles of a given kind precipitate.

The entrapment factor, defined as the ratio of the number of particles precipitating on the wall per unit time to the number of particles entering the channel during that time (we assume that aerosol particles are uniformly distributed in a gas at the channel entrance), is

$$\delta = \frac{\left(\frac{d}{2} - |x_H|\right)}{\frac{d}{2}} = 1 - \frac{2|x_H|}{d}, \tag{3}$$

with $x_H$ denoting the coordinate of the extreme trajectory at $z = 0$.

In practice one may use the model of a slot condenser where the temperature and the concentration of the vapor of the volatile substance (for example, of water vapor in air) $n_1$ are given at the entrance and at the walls of the channel [1], under the condition that $n_1 < n_2$:

$$T(x = 0,\ z = 0) = T_{\mathrm{in}};\quad n_1(x = 0,\ z = 0) = n_{1\mathrm{in}}; \tag{4}$$

$$T\left(x = \pm\frac{d}{2},\ z\right) = T_{\mathrm{w}};\qquad n_1\left(x = \pm\frac{d}{2},\ z\right) = n_{1\mathrm{w}} \tag{5}$$

The distributions of mass velocity, concentration, and temperature in such a channel are

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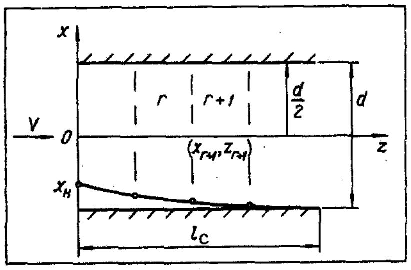


Fig. 1. Schematic diagram of a slot condenser.

$$V_z = V_0\left[1 - \frac{(2x)^2}{d^2}\right], \tag{6}$$

with $V_0 = (3/2)\bar{V}$ denoting the maximum stream velocity ($\bar{V}$ denoting the mean stream velocity),

$$V_x = -D\frac{n}{n_1 n_2}\cdot\frac{\rho_1}{\rho}\,\mathrm{grad}\,n_1, \tag{7}$$

D denoting the mutual diffusivity of the mixture components, $\rho_i = m_i n_i$, $\rho = \rho_1 + \rho_2$, $m_i$ denoting the mass of a molecule of the i-th kind, $n_i$ denoting the number of molecules of the i-th kind per unit time,

$$n_1(x, z) = n_{1\mathrm{w}} + (n_{1\mathrm{in}} - n_{1\mathrm{w}})\exp\left\{-\left(\frac{3.4}{d}\right)^2\frac{Dz}{V_0} - 0.85\left(\frac{2x}{d}\right)^2\right\}$$
$$\times\left[1 - 0.6\left(\frac{2x}{d}\right)^2 - 0.27\left(\frac{2x}{d}\right)^4 - 0.115\left(\frac{2x}{d}\right)^6\right]; \tag{8}$$

$$T(x, z) = T_\mathrm{w} + (T_\mathrm{in} - T_\mathrm{w})\exp\left\{-\left(\frac{3.4}{d}\right)^2\frac{a^2 z}{V_0} - 0.85\left(\frac{2x}{d}\right)^2\right\}$$
$$\times\left[1 - 0.6\left(\frac{2x}{d}\right)^2 - 0.27\left(\frac{2x}{d}\right)^4 - 0.115\left(\frac{2x}{d}\right)^6\right], \tag{9}$$

and $a^2$ denoting the thermal diffusivity.

For the velocity of particles we have

$$V_z = V_0\left[1 - \left(\frac{2x}{d}\right)^2\right], \tag{10}$$

$$V_x = -D\frac{m_1}{m_2}\cdot\frac{1}{n_2}\left[1 + \frac{\left(1 + 6C_m\frac{\lambda}{R}\right)}{\left(1 + 2C_m\frac{\lambda}{R}\right)}\right]\mathrm{grad}\,n_1$$
$$-\frac{2\delta\left[K_{sl} + \frac{m_1}{m_2}\left(1 + 6C_m\frac{\lambda}{R}\right)\right]\varkappa_e\,\mathrm{grad}\,T_\infty}{n\left[2\varkappa_e + \left(\varkappa_i + \frac{2Lm_1\delta D}{1 + 2K_s\frac{\lambda}{R}}\right)\left(1 + 2C_t\frac{\lambda}{R}\right)\right]\left(1 + 2C_m\frac{\lambda}{R}\right)\left(1 + 2K_s\frac{\lambda}{R}\right)}$$
$$-\frac{2K_{Tsl}\nu\left[\varkappa_e + \left(\varkappa_i + \frac{2Lm_1\delta D}{1 + 2K_s\lambda/R}\right)C_t\frac{\lambda}{R}\right]\mathrm{grad}\,T_\infty}{T\left[2\varkappa_e + \left(\varkappa_i + \frac{2Lm_1\delta D}{1 + 2K_s\frac{\lambda}{R}}\right)\left(1 + 2C_t\frac{\lambda}{R}\right)\right]\left(1 + 2C_m\frac{\lambda}{R}\right)}. \tag{11}$$

In expression (11) $n_2 = n - n_1$, $n = p/kT$, $C_m$, $K_{sl}$, $K_{Tsl}$ are the coefficients of diffusive, isothermal, and thermal sliding, $\lambda$ is the mean-free-path length, $\varkappa_e$ and $\varkappa_i$ are the thermal conductivity of the gas and of a droplet respectively, L is the specific heat of evaporation, $\nu$ is the kinematic viscosity $\delta = dn_{1s}(T)/dT$ with $n_{1s}(T)$ denoting the density of saturated vapor of the volatile component in the mixture at temperature T, $C_t$ and $K_s$ are the coefficients associated respectively with the temperature jump and the concentration jump of the volatile component at the droplet surface, T and n are respectively the temperature and the density of the gas at a given point, and k is the Boltzmann constant. Equation (2) has no analytical solution when

$$\frac{|\overline{\Delta n_2}|}{n_{2\mathrm{w}}} > 0.6, \qquad \frac{\overline{\Delta T}}{T_\mathrm{w}} > 0.6, \tag{12}$$

where

$$\overline{\Delta n_2} = n_2(x_\mathrm{H}, z = 0) - n_{2\mathrm{w}}, \quad \Delta T = T(x_\mathrm{H}, z = 0) - T_\mathrm{w}.$$

In that case we find the extreme trajectory by subdividing the channel into several segments along the z-axis so that the coefficients associated with grad $n_1$ and grad T in (11) may be assumed constant within

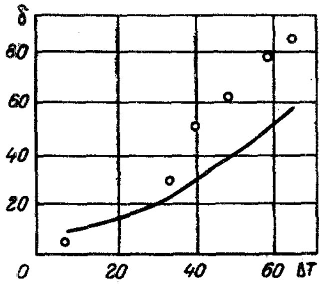


Fig. 2

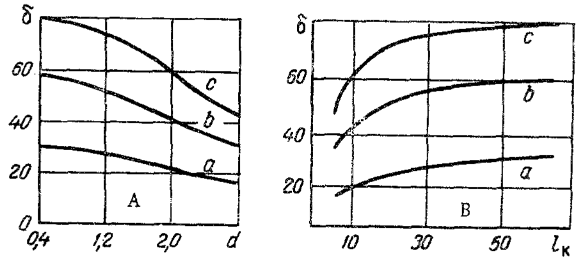


Fig. 3

Fig. 2. Theoretical and test values of the entrapment factor $\delta$ (%) as a function of the temperature difference $\Delta T = T_{in} - T_W$ (°C), for $T_W = 285°K$ and $\lambda/R = 0.1$.

Fig. 3. Theoretical curves of the entrapment factor as a function of (A) the channel width $\delta = f(d)$ and (B) the channel length $\delta = f(l_c)$: d(cm), $l_c$(cm), $\delta$ (%), $\lambda/R = 0.1$.

each segment, and by successively determining the particle trajectories within each segment from the channel exit ($x = \pm d/2$, $z = l_c$) to the channel entrance (the end of the trajectory in segment r + 1 being also the beginning of the trajectory in segment r).

If condition (12) is satisfied, then substituting $\bar{n}_2 = n_{2W} + \overline{\Delta n_2}/2$ and $\bar{T} = T_W + \overline{\Delta T}/2$ in (11) will yield an analytic solution for the entrapment factor, without the need to subdivide the channel into segments:

a) when the effect of thermophoretic forces is negligible, i.e. when $v_D \gg V_T$; solution (2) with the initial condition ($x_0 = d/2$, $z_0 = l_c$) and $x_H = d(1-\delta)/2$ will then yield the following analytic expression for the entrapment factor:

$$-\ln(1-\delta) - 0.425(1-\delta)^2 - 0.09(1-\delta)^4 - 0.017(1-\delta)^6 + \frac{\exp[0.85(1-\delta)^2]}{1.7} = \frac{\Delta n_1}{\bar{n}_2} \cdot \frac{m_1}{m_2}\left[1 + \frac{1 + 6C_m\frac{\lambda}{R}}{1 + 2C_m\frac{\lambda}{R}}\right] \times \left[1 - \exp\left\{-\left(\frac{3.4}{d}\right)^2 \frac{Dl_c}{V_0}\right\}\right] + 0.86; \quad (13)$$

b) when the effect of volatility is negligible, i.e., when $\varkappa_e \ll (\varkappa_i + (2Lm_1\delta D/(1 + 2K_S\lambda/R))$ and the second term on the right-hand side of (11) may be omitted; we then have

$$-\ln(1-\delta) - 0.425(1-\delta)^2 - 0.09(1-\delta)^4 - 0{,}017(1-\delta)^6 + \frac{\exp\{0.85(1-\delta)^2\}}{1.7} = \frac{\Delta n_1}{\bar{n}_2} \cdot \frac{m_1}{m_2}\left[1 + \frac{1 + 6C_m\frac{\lambda}{R}}{1 + 2C_m\frac{\lambda}{R}}\right]\left[1 - \exp\left\{-\left(\frac{3{,}4}{d}\right)^2 \frac{Dl_c}{V_0}\right\}\right] + \frac{\Delta T}{\bar{T}} \cdot \frac{2K_{Tsl}\nu C_t\frac{\lambda}{R}}{a^2\left(1 + 2C_m\frac{\lambda}{R}\right)\left(1 + 2C_t\frac{\lambda}{R}\right)}\left[1 - \exp\left\{-\left(\frac{3.4}{d}\right)^2 \frac{a^2 l_c}{V_0}\right\}\right] + 0.86. \quad (14)$$

Formulas (13) and (14) have been derived for a laminar flow of gases with approximately defined boundary conditions (the gas temperature and the density of the vapor of the volatile component in the mixture are stipulated not across the entire entrance section but only at the initial point $x = 0$, $z = 0$) without considering the possibility of gas turbulization or that large particles may precipitate under their own weight.

Although relations (13) and (14) have been derived for a laminar flow, a comparison with the test data obtained by A. N. Terebenin [5] indicates their applicability within the range $Re \leq 500$, inasmuch as the theoretical values for the entrapment factor are on the low side and differ, within this range of the Reynolds number, by 5-30% from the test values (Fig. 2).

There are no other data available in the scientific literature besides the test data pertaining to the aerosol entrapment factor as a function of the temperature difference ($\Delta T = T_{in} - T_W$), obtained by A. N. Terebenin and A. P. Bykov [5-7] with a semiindustrial condenser-diffusion filter passing a binary air and water vapor mixture.

Measured and calculated values of the entrapment factor $\delta$, as a function of the temperature difference ($\Delta T = T_{in} - T_W$), are compared in Fig. 2 ($d = 0.6$ cm, $l_c = 92$ cm, $V_0 = 120$ cm/sec) with $n_{1in}$ and $N_{1W}$ equal to the densities of saturated water vapor at temperatures $T_{in}$ and $T_W$ respectively. According to the graph, the theoretical values of the entrapment factor differ from its test values within 30%.

Owing to the lack of test data, in Fig. 3 A, B are shown only theoretical curves of the entrapment factor $\delta$ as a function of the channel width d($l_c = 92$ cm; $V_0 = 120$ cm/sec; $T_W = 285$°K; $\Delta T = 38°$ (*a*); $\Delta T = 63°$ (b); $\Delta T = 80°$ (c)) and as a function of the channel length $l_e$ ($d = 0.6$ cm) at $V_0 = 120$ cm/sec, $T_W = 285$°K, and $\Delta T = 38°$ (*a*); $\Delta T = 63°$ (b); $\Delta T = 80°$ (c)) in each case, with $n_{1in}$ and $n_{1W}$ equal to the densities of saturated water vapor at temperatures $T_{in}$ and $T_W$ respectively. According to Fig. 3, a narrowing of the channel or a lengthening of the plates will cause the entrapment factor first to increase fast up to a certain limit and then to remain almost constant, which is important to consider in the design of slot condensers.

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