

The diffusional retardation of phase transitions of drops in a two-component medium

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A study has been undertaken to consider the influence of an inert component on the rate of evaporation (condensational growth) of drops in a vapour-gas medium. It is found that in the presence of even small amounts of an inert gas, the rate of phase transitions on the drop surface is noticeably smaller than in the one-component case, this being connected with the diffusional retardation of phase transitions (the screening effect).

The problems of non-stationary evaporation (condensational growth) of drops in a gaseous medium had been considered by Rakhmatulina (1981) and Nigmatulin (1987). The behaviour of bubbles liquids was considered by Abdel Aziz (1988).

Let us consider the quasi-stationary state of the heat and mass transfer between the single spherical drop and the surrounding vapour-gas medium. Following Nigmatulin (1987), we accept a simplifying assumption that the variation of the composition of the gaseous phase and its temperature have an insignificant effect on the thermophysical properties of the gaseous phase, i.e.

$$\lambda_g = \text{const}, R_g = \text{const}, C_g = \text{const} \quad (1)$$

Here λ_g and C_g are the thermal conductivity coefficient and heat capacity, respectively, R_g is the gas constant. The subscript g denotes the gas-phase parameters. The above assumption is valid if the molecular masses of the vapour and gaseous components are close to one another, and a temperature change in the system is not too large. We suppose that the inter-diffusion in the system obeys the Fick's law of binary diffusion. Within the framework of the assumptions accepted, the equations of continuity, heat inflow of state in a spherical coordinate system are as follows

$$\frac{d}{dr}(\rho_g W r^2) = 0 \quad (2)$$

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$$\frac{d}{dr} r^2 \rho_g \left(K_s W - D \frac{dk_s}{dr} \right) = 0 \tag{3}$$

$$C_g \rho_g W \frac{dT}{dr} = \frac{\lambda_g}{r^2} \frac{d}{dr} \left(r^2 \frac{dT}{dr} \right) \tag{4}$$

$$P = \rho_g R_g T, P = \text{const.} \tag{5}$$

We assume that the pressure in the gas phase is uniform and therefore, constant at the quasi-stationary stage. In eqs. (2) to (5) ρ is the density, W -radial velocity, r -Euler spherical coordinate counted off from the drop centre, K_s is the concentration of the vapour, D is the coefficient of inter-diffusinn, P is the pressure and T is the temperature.

In the quasi-stationary approximation, the boundary conditions on the interface are as follows

$$r = a ; T = T_a = T_s(K_{sa}P),$$

$$jL = \lambda_g \left(\frac{\partial T}{\partial r} \right), W = W_a, J = \rho_{ga} W_a \tag{6}$$

$$(1 - K_{sa})j = -\rho_{ga} D \left(\frac{\partial K_s}{\partial r} \right)_a$$

Here a is the drop radius, L is the latent heat, j is the rate of phase transition per unit area. The subscripts a and S refer to the parameters on the drop surface and on the saturation line, respectively. In representation (6) it is assumed that the temperature profile inside the drop is uniform, and the heat of phase transitions is supplied and removed by the gas. The dependence of the pressure of the saturated gas on temperature may be approximated by the formula (Tsian 1965)

$$P_s = P_* \exp(-T_s / T_s) \tag{7}$$

where P_* , T_* are constants chosen from the conditions of the best approximation of tabular data in a given pressure interval.

The boundary conditions at infinity

$$r \rightarrow \infty W = 0, T = T_\infty, K_s = K_{s\infty}. \tag{8}$$

The solution of heat inflow eq. (4) is of the form (Nigmatulin 1987)

$$T = C_2 + C_1 \exp(-b/r) \tag{9}$$

$$C_1 = \frac{T_\infty - T_a}{1 - e^{-b/a}}, C_2 = T_\infty - \frac{T_\infty - T_a}{1 - e^{-b/a}}$$

$$\left(b = \frac{C_g \rho_{ga} W_{1a} a^2}{\lambda_g} \right).$$

The parameter b determines the intensity of injection or suction.

At low concentrations of an inert gas ($K_{1\infty} \ll 1$) asymptotic expressions are obtained (Nigmatulin 1987) for the temperature and concentration on the interface

$$T_{\infty} = T_{g\infty} \left[1 - (B-1) \frac{T_{\infty}^*}{T_{g\infty}} K_{1\infty} \right] \quad (10)$$

$$K_{2\infty} = 1 - BK_{1\infty}$$

$$B = \left[1 + (T_{\infty}^* - T_{g\infty}^*) \frac{\lambda_g R_g}{2lpD} \right]^{-1}$$

$$T_{g\infty} = T_g(K_{2\infty} p).$$

In the quasi-equilibrium approximation the rate j of phase transitions can be determined from boundary condition (6). Substituting formula (9) describing the quasi-stationary distribution of the temperature around the drop into formula (6) and taking into account relationships (10), one arrives at

$$j = \frac{\lambda_g b}{l a^2} j_0^{b/a} \frac{[T_{\infty} - T_{g\infty} + (B-1)T_{\infty} K_{1\infty}]}{1 - j_0^{b/a}} \quad (11)$$

Let us denote by j_0 the rate of phase transitions in the absence of the inert gas. Then formula (11) can be transformed into

$$j = j_0 \left[1 + \frac{T_{\infty}^* (B-1)}{T_{\infty} - T_{g\infty}} K_{1\infty} \right]$$

$$= j_0 [1 - \beta K_{1\infty}],$$

$$\beta = \frac{T_{\infty}^* (T_{\infty} + T_{g\infty}) \alpha}{1 + (T_{\infty}^* - T_{g\infty}^*) \alpha}, \quad \alpha = \frac{\lambda_g R_g}{2lpD} \quad (12)$$

In real situations the parameter β is, as a rule, large

$$\beta \gg 1. \quad (13)$$

This is connected with large values of T_{∞}^* (for instance, for a water drop at the atmospheric pressure, $T_{\infty}^*/T_{g\infty} \approx 13$). From formula (12), subject to (13), it can be seen that even a small addition of an inert gas into the vapour results in an appreciable decrease of the rate of phase transitions because of the screening effect of the gas in the vicinity of the interface.

From formula (12) it can also be seen that this effect is stronger in the case of condensation because $T_{\infty} < T_{g\infty}$, and therefore, the denominator is less as compared with the case of evaporation. Accordingly, the values of β are larger.

The influence of the component-composition of a vapour-gas medium on the rate of phase transitions on the drop surface is studied. It is found that even a very small concentration of an inert gas leads to a considerable decrease in the rate

of phase transitions, this being connected with a diffusional retardation of phase transitions due to the screening effect of the gas near the interface.

References

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