KINETICS OF MOISTURE FORMATION IN A PERTURBED FLOW

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The effect of fluctuations of the parameters of state of a vapor flow on the initial condensation kinetics is investigated.

Multiphase disperse flows are presently used to a large extent in heat engineering, aviation, and chemical technology. The initial development of such a flow occurs in a very wide range of the vapor phase parameters. Thus, e.g., moisture drops in the last stages of high-power steam turbines are formed under conditions of a rather high vacuum, while, in atomic power turbines, they develop while the steam has an elevated density. The relaxation phenomena of condensation connected with the passage of compression and rarefaction waves in supersonic flows are important processes in the nozzles of rocket or aircraft motors. Condensation in turbulent jets are characteristic for chemical technology processes, etc.

A very important feature of the multiphase flows in question is the fluctuation of the parameters of state, which, in turn, determine the kinetics of heat and mass exchange and the dynamic interaction between phases in the initial condensation region.

According to the fundamental concepts of the kinetics of moisture formation in a vapor flow, the degree of supersaturation of the vapor phase [1] is one of the most important quantities determining the development of the initial condensation process. It affects materially the dimension of the critical-size condensation nuclei developing in the flow, the nucleation rate, the subsequent growth rate of nuclei, etc. Therefore, investigation of the degree of supersaturation in perturbed flows as a function of the amplitude of parameter fluctuations and of the spectral characteristics of the parameters by direct analysis of the equations of the heat and mass exchange kinetics and the dynamic interaction between phases constitutes a pressing problem.

Three regions can be singled out with respect to the relaxation time of interaction between phases. The first is connected with the presence of low-frequency oscillations in the flow. It is characterized by the fact that the oscillation periods of fluctuations are much longer than the relaxation times. The temperature difference and the relative velocities of phases are negligibly small (quasiequilibrium conditions). The second region encompasses medium-frequency oscillations. In this region, the oscillation periods of the parameters and the relaxation times are quantities of the same order. The third region comprises high-frequency oscillations, for which the oscillation periods are markedly shorter than the relaxation times. Considerable discrepancies between the temperatures and relative velocities of phases are observed in this zone (relaxation conditions).

The quasiequilibrium and the relaxation regions are amenable to adequate theoretical analysis.

Degree of Supersaturation of the Vapor Phase. In correspondence with the kinetic theory of liquids and gases [2], the numbers of condensing α and evaporating β molecules per unit area of a plane interface between phases are equal to

$$\alpha=n_1\sqrt{RT_1/2\pi}, \tag{1}$$

$$\beta=n_g\sqrt{RT_g/2\pi}\exp(-\lambda_s/RT_g). \tag{2}$$

Under steady-state conditions of the dynamic equilibrium of phases ($T_1 = T_g = T$ and $\alpha = \beta$), the equilibrium volume concentration of vapor is equal to

$$n_1=n_{1,s}=n_g\exp(-\lambda_s/RT). \tag{3}$$

If the equation of state for the vapor phase is used as for an ideal gas [1], the equilibrium vapor pressure corresponding to the temperature T is given by

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$$p_s = RT\rho_g \exp(-\lambda_s/RT_1). \tag{4}$$

For the region of small perturbations ($u'/\bar{u} \ll 1$) in a quasistationary isentropic vapor flow, the relationships between the pressure, the temperature, and the velocity fluctuations are given by the following expressions in the first approximation:

$$p = \bar{p}\gamma^{\frac{k}{k-1}}, \tag{5}$$

$$T = \bar{T}\gamma, \tag{6}$$

where

$$\gamma = \left[\frac{1 + (k-1)\bar{M}^2 \dfrac{u'}{\bar{u}}}{1 + \dfrac{k-1}{2}\bar{M}^2}\right]^{-1}. \tag{7}$$

Using (4)-(7), we write the degree of supersaturation in the following form:

$$\Pi = \frac{\bar{p}}{p_s}\varphi, \tag{8}$$

where

$$\varphi = \gamma^{\frac{1}{k-1}} \exp\left[\frac{\lambda_s}{RT}\,\frac{(k-1)\bar{M}^2\dfrac{u'}{\bar{u}}}{1 + \dfrac{k-1}{2}\bar{M}^2}\right]. \tag{8a}$$

Critical Dimension of Condensation Nuclei. Under conditions of thermal and dynamic interaction between phases, the critical-size nuclei must be determined directly on the basis of the equation of mass exchange between phases,

$$dg/dt = \alpha_g - \beta_g. \tag{9}$$

In correspondence with the kinetic theory of gases, the flux of molecules condensing on a drop with the radius r is equal to

$$\alpha_g = \alpha\sqrt{(1+g)/g}\,(1 + \sqrt[3]{1/g})^2\, 4\pi r^2 F(\eta), \tag{10}$$

where

$$F(\eta) = \frac{1}{2}\exp(-\eta^2) + \left(\eta + \frac{1}{2\eta}\right)\int_0^{\eta} \exp(-\eta^2)\, d\eta; \tag{11}$$

$$\eta = v/\sqrt{2RT}.$$

In (10) the factor $F(\eta)$ accounts for the relative velocity of phases in a two-phase flow.

The flux of molecules evaporating from the surfaces of drops is equal to

$$\beta_g = \beta \exp(\lambda/RT_g)\, 4\pi r^2. \tag{12}$$

Under conditions where the number of molecules constituting a drop is much larger than unity,

$$\alpha_g = \alpha\, 4\pi r^2 F(\eta), \tag{13}$$

while the capillary energy is given by

$$\lambda_\sigma = 2\sigma/n_g r. \tag{14}$$

The term critical-size condensation nucleus refers to a nucleus in the state of dynamic equilibrium with the vapor phase, which is determined by the condition $dg/dt = 0$.

Therefore, after simple calculations, we readily obtain

$$r_{cr} = 2\sigma/\rho_g RT_g \ln\Phi, \tag{15}$$

where

$$\Phi = \frac{n_1}{n_{1,s}}\sqrt{T/T_g}\, F(\eta) \exp[\lambda_s(T_g - T)/RTT_g]. \tag{16}$$

The derived expression (16) makes it possible to determine the dimension of the critical-size condensation nucleus under conditions of dynamic and thermal interaction between phases. The dynamic interaction is accounted for by the quantity $F(\eta)$, while the thermal interaction is taken into account by the difference between the phase temperatures.

Using the equation of state for the vapor phase as for an ideal gas, we rewrite the expression for Φ in the following form:

$$\Phi = \Pi \sqrt{T/T_g}\, F(\eta) \exp[\lambda_s (T_g - T)/RTT_g]. \tag{17}$$

If the phases are in thermodynamic equilibrium ($\eta = 0$, $T = T_g$), we have $\Phi = \Pi$, and relationship (15) is transformed into the well-known Kelvin equation [1].

The isentropic parameter fluctuations which develop in supersonic two-phase flows and also weak rarefaction and compression waves propagate at the local velocity of sound. In this case, the local relative velocity of phases is equal to [1]

$$v = a\left(1 + M\frac{v_-}{u}\right), \tag{18}$$

where

$$v_- = \bar{u} - \bar{u}_g \pm (u' - u_g'). \tag{19}$$

Then, the dimensionless velocity is given by

$$\eta = \sqrt{k/2}\left(1 + M\frac{v_-}{u}\right), \tag{20}$$

while the value of $F(\eta)$ in the first approximation is determined by

$$F(\eta) \simeq 1 + \frac{1}{6} k\left(1 + 2M\frac{v_-}{u}\right) = \psi. \tag{21}$$

The combined effect of isentropic fluctuations of the vapor parameters and of the local relative phase velocity results in the fact that the dimension of critical-size condensation nuclei is determined, with an allowance for (8) and (21), by an expression of the following form:

$$r = r_{cr} g, \tag{22}$$

where

$$r_{cr} = 2\sigma/\rho_g RT \ln \Pi; \tag{22a}$$

$$g = \left[\gamma\left(1 + \frac{\ln \varphi\psi}{\ln \Pi}\right)\right]^{-1}. \tag{23}$$

We can assume that, in the first approximation,

$$g = \left\{1 + \frac{1}{\ln\bar{\Pi}}\left[\frac{\lambda_s}{k\bar{T}}\,\frac{(k-1)M^2\frac{u'}{\bar{u}}}{1 + \frac{k-1}{2}\overline{M}^2} + \frac{1}{6}k\left(1 + 2M\frac{v_-}{u}\right)\right]\right\}^{-1}. \tag{24}$$

For instance, in the case of steam, for $M = 1.5$, $u'/\bar{u} = 0.1$, and $\ln \bar{\Pi} = 1$, we obtain $g = 0.5$.

It should be mentioned that, in accordance with expression (22), the dimension of critical-size nuclei on the saturation curve has a finite value and is determined by

$$r_{cr} = 2\sigma/\rho_g R\bar{T}\gamma \ln\varphi\psi \tag{25}$$

for $M = 1.5$, $u'/\bar{u} = 0.1$, and $\gamma \ln \varphi\psi = 1.0$, which corresponds to the degree of supersaturation $\Pi = 0$.

Nucleation Rate. A characteristic feature of the existing theories of the kinetics of condensation nucleus development is that the distribution function of molecular associations with respect to sizes under conditions of dynamic equilibrium of the system constitutes a key relationship in investigating the nucleation rate in turbulent wet-steam flows.

The rate of variation in the volume concentration N_g of molecular associations consisting of g molecules is described by an equation of the following type:

$$dN_g/dt = I_+ - I_-, \tag{26}$$

where the nucleation rate is

$$I_+ = N_{g-1}/\tau_{g-1}, \tag{27}$$

while the break-up rate is equal to

$$I_- = N_g/\tau_g^*. \tag{28}$$

Here τ_{g-1} is the mean free time of nuclei consisting of (g − 1) molecules and τ_g^* is the mean time of molecule evaporation from the surface of a nucleus consisting of g molecules.

Under steady-state conditions of dynamic equilibrium of the system, we have $dN_g/dt = 0$, and, considering (27) and (28), we obtain

$$N_g/N_{g-1} = \tau_g^* \tau_{g-1}. \tag{29}$$

With an allowance for (1) and (13), the mean free time is given by

$$\tau_{g-1} = 1/\alpha_{g-1} = \left[n_1 \sqrt{\frac{RT}{2\pi}}\, 4\pi r_{g-1}^2 F(\eta) \right]^{-1}. \tag{30}$$

By taking into account (2), (12), and (14), we find the mean evaporation time:

$$\tau_g^* = 1/\beta_g = \exp(-2\sigma/\rho_g RT r_g)\, n_{1,s} 4\pi r_g^2. \tag{31}$$

We write the left-hand side of Eq. (29) in the following form:

$$N_g/N_{g-1} \simeq N_g \bigg/ \left(N_g - \frac{dN_g}{dg} \right) \simeq \exp(d \ln N_g/dg). \tag{32}$$

After simple transformations, we obtain from (29)-(32)

$$\frac{d \ln N_g}{dg} = \ln\left[\frac{p}{p_s} F(\eta) \right] - \frac{2\sigma}{\rho_g RT_g} \tag{33}$$

or, considering (15),

$$\frac{d \ln N_g}{dg} = \frac{2\sigma}{\rho_g R\bar{T}} \left(\frac{1}{r_{cr}} - \frac{1}{r_g} \right). \tag{34}$$

After integration, we obtain the well-known Gibbs equation [3],

$$N_g = c \exp\left[\frac{2\sigma_g}{\rho_g RT} \left(\frac{1}{r_{cr}} - \frac{3}{2r_g} \right) \right], \tag{35}$$

where the constant c can be found from the boundary condition for g = 1 and $N_g = n_1$. Considering (22)-(24), we write

$$N_g = f\bar{N}_g, \tag{36}$$

where

$$\bar{N}_g = c \exp\left[\frac{2\sigma}{\rho_g R\bar{T}} \left(\frac{1}{\bar{r}_{cr}} - \frac{3}{2r_g} \right) \right], \tag{37}$$

while

$$f = \exp g \ln \varphi\phi.$$

Rate of Drop Growth. In investigating the growth rate of condensate drops, we shall use the expression (9) given earlier and write it in the form

$$dg/dt = [n_1 \sqrt{RT/2\pi}\, F(\eta) - n_{1,s} \sqrt{RT_g/2\pi}\, \exp(2\sigma/\rho_g RTr)]\, 4\pi r^2. \tag{38}$$

Using the equation of state for the vapor phase as for an ideal gas, we rewrite (38) in the following form:

$$\frac{dr}{dt} = \frac{\rho_1}{\rho_g} \sqrt{\frac{RT}{2\pi}} \left[F(\eta) - \frac{1}{\Pi} \sqrt{\frac{T}{T_g}} \exp\left(\frac{2\sigma}{\rho_g RT_g r} \right) \right]. \tag{39}$$

If the relative velocity of phases is equal to zero, we have F(η) = 1, and Eq. (39) is transformed into the well-known Langmuir equation.

After we substitute the function F(η) (21) and the degree of supersaturation (8) in Eq. (39), the latter becomes

$$\frac{dr}{dt}=\frac{\rho_1}{\rho_g}\sqrt{\frac{RT}{2\pi}}\left[1+\frac{1}{6}k\left(1+2M\frac{v_-}{u}\right)-\frac{1}{\overline{\Pi}\varphi}\sqrt{\frac{T}{T_g}}\exp\left(\frac{2\sigma}{\rho_g RT_g r}\right)\right. . \qquad (40)$$

An analysis of the derived relationships indicates that fluctuations of the state parameters and the accompanying relaxation phenomena affect to a high degrhe the initial moisture formation and determine the disperse composition of the suspended phase. It should be mentioned here that, in thermodynamic devices, especially under variable conditions, the presence of separation phenomena with strongly pronounced flow pulsation, turbulent pulsating supersonic streams, and compression and rarefaction waves leads to the development of drop moisture in spite of the fact that calculations based on the mean state parameters indicate its virtual absence.

NOTATION

n, volume concentration of molecules; R, universal gas constant; T, temperature; λ, bond energy of molecules at the interface between phases; a, velocity of sound; m, molecular mass; t, time; r, radius of a condensation nucleus; g, number of molecules in a condensation nucleus with the radius r_g; p, vapor pressure, k, isentropic exponent for vapor; u, velocity; σ, surface tension of the condensate; v, relative velocity of phases; ρ, density; M, Mach number; Π, degree of supersaturation. Subscripts: 1, vapor phase; g, disperse phase; s, equilibrium parameters on the saturation curve; 1, s, vapor parameters on the saturation curve; the prime denotes pulsations; a bar on top marks averaged parameters.

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DEHYDRATION OF SOLUTIONS AND SUSPENSIONS IN A FLUDIZED BED

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The conditions for the stability of the granulometric composition of a product for continuous operation of the granulator in the nonrecycling mode are considered. The nature of the granulation as a function of the temperature of the heat carrier is analyzed when the granulation parameters of the granules are known.

It is well known that the process of drying solutions, suspensions, and melts in a fluidized bed consists in precipitating the solid material when the dispersed media are dried on the surface of the bed granules. Depending on the physicochemical compositions of the initial solutions, the temperature conditions of the drying and other factors, an increase in the particles may be accompanied by their agglomeration and simultaneous granulation. New granulation centers may be formed, particularly due to thermal granulation of the particles.

A considerable number of publication [1-3] have been devoted to the question of the thermal granulation of granules in a fluidized bed, in which it is assumed that the main mechanisms by which granulation occurs are based on the temperature difference between the bed and the solution, and also the temperature difference between the bed and the boiling point of the solution. However, the results we have obtained in semiindustrial tests of the drying and granulation of solutions of sodium sulfate, and also on suspensions of nonphenyl coagulant in a fluidized bed [4, 5] show that this approach is unsatisfactory. These tests,

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