PHASE TRANSFORMATIONS IN A STREAM OF EVAPORATING LIQUID

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An equation is derived describing the kinetics of phase transformations, in dimensionless variables, for the adiabatic nonequilibrium flow of an evaporating liquid.

The adiabatic nonequilibrium flow of an evaporating liquid has been dealt with in many theoretical and experimental studies [1-6]. However, the similarity criteria characterizing the kinetics of phase transformations during the discharge of a saturated liquid have not yet been sufficiently explored. With the rate of change in the number of active vapor generating centers [8] and with a law governing the bubble buildup [1, 4, 5, 7] known, the equation of vapor generation becomes

$$\varkappa' = \frac{1}{m}\int_{z_0}^{z} \frac{P^2 v^*}{[kT]^2}\sqrt{\frac{2\sigma}{\pi m^*}}\exp\left[-\frac{4\pi\sigma r_{cr}^2}{3kT}\right]4\pi r^2\lambda\,\frac{\rho''\Delta TF}{\rho' Lw}\sqrt{\frac{3w}{\pi al}+\frac{2\Delta w}{3\pi ar}}\,dz^2. \tag{1}$$

Equation (1) must be integrated from section z_0, where the system crosses the saturation line, to the given section whose coordinate is z.

We introduce new scale factors, denoting them with the superscript 0, and denote the dimensionless variables with a tilde. Equation (1) becomes then

$$\varkappa' = \frac{P^{02}v^{0*}F^0 l^{02}}{[k^0T^0]^2 m^0}\sqrt{\frac{\sigma^0}{m^{0*}}}\,r_{cr}^{02}\lambda^0\,\frac{\rho^{0''}\Delta T^0}{\rho^{0'}L^0w^0}\sqrt{\frac{w^0}{a^0l^0}+\frac{\Delta w^0}{a^0r^0}}$$

$$\times\int_{z_0}^{z}\frac{\tilde P^2\tilde v^*}{(\tilde k\tilde T)^2}\sqrt{\frac{2\tilde\sigma}{\pi\tilde m^*}}\exp\left[-\frac{4\pi\tilde\sigma\tilde r_{cr}^2}{3\tilde k\tilde T}\cdot\frac{\sigma^0 r_{cr}^{02}}{k^0T^0}\right]4\pi\tilde r^2\tilde\lambda\,\frac{\tilde\rho''\Delta\tilde T}{\tilde\rho' \tilde L\tilde w}\sqrt{\frac{3\tilde w}{\pi\tilde a\tilde l}+\frac{2\Delta\tilde w}{3\pi\tilde a\tilde r}}\,\tilde F\,d\tilde z^2. \tag{2}$$

This yields the scale factor for the rate of phase transformation, when both phases flow at the same velocity:

$$\varkappa = \frac{P^2 v\,\lambda\Delta T d^3}{k^*TL\sqrt{m^*\sigma}}\cdot\frac{\sigma r_{cr}^2}{kT}\left(\frac{w\tau}{d}\right)^2\cdot\frac{1}{\sqrt{\frac{a\tau}{d^2}}} = NK(\mathrm{Ho})^2\frac{1}{\sqrt{\mathrm{Fo}}}. \tag{3}$$

At the same time, the constancy conditions must apply to the system energy and the nucleation energy of the new phase:

$$\frac{\sigma r_{cr}^2}{kT} = K = \mathrm{idem}. \tag{4}$$

The phase transformation rate was determined experimentally from the absorption of β-rays by the saturated liquid flowing through a cylindrical Venturi tube. As a source of β-rays the authors used the Sr^{90} isotope with an energy of 2.27 MeV inside a lead cylinder. The cavity in the latter had a diameter equal to that of the Venturi tube and a 10 times greater depth. On the opposite end of the Venturi tube was placed a face-type halogenide-crystal STS-5 counter in a lead shell. The cavities in both cylinders were aligned precisely coaxially with the Venturi tube and could be displaced along the latter by means of a worm-gear

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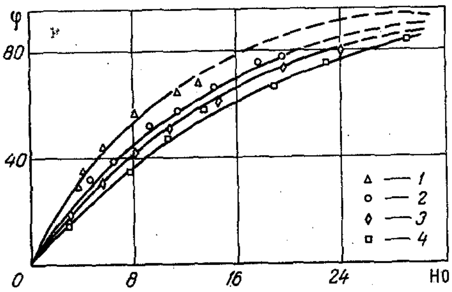

Fig. 1. Vapor generation (%) as a function of the homochronicity number and the dimensionless complexes: $k = 74.5 \cdot 10^3$ and $N = 1.3 \cdot 10^5$ (1), $k = 49.5 \cdot 10^3$ and $N = 1.6 \cdot 10^5$ (2), $k = 31.4 \cdot 10^3$ and $N = 2.4 \cdot 10^5$ (3), $k = 10.72 \cdot 10^3$ and $N = 4 \cdot 10^3$ (4).

drive. A few Venturi tubes for this test had been made of acrylic glass and brass with a 0.1-0.2 mm wall thickness. Pulses from the counter were fed to a model PP-12 converter. Before the test, the entire instrumentation was tared out by irradiating the Venturi filled with liquefied gas, with vapor at various pressures, or with a homogeneous medium whose absorptivity was known. According to a subsequent data evaluation, the total error in measuring the vapor content along the Venturi tube did not exceed 5%.

The pressure of saturated liquid propane before entering the cylindrical tube and then along the tube inside was measured during the test with class 0.4 manometers, while its mass flow rate was measured by the weighing method.

Performing a test series with the same Venturi tube at constant inlet and back pressures of saturated liquids with invariable hydrogen–carbon compositions has made it possible to establish a relation between the actual vapor content and the hydrodynamic as well as the thermal homochronicity.

The results of this experimental study are shown in Fig. 1. For our data evaluation in terms of the homochronicity criterion, the time parameter has been replaced through the Strouhal number by the distance from the Venturi inlet to the point of measurement. The curves in Fig. 1 indicate a distinct dependence of the actual vapor content in a nonequilibrium stream on the homochronicity number and that, furthermore, the curves are different for different values of the dimensionless K and N complexes, with the thermal homochronicity implicitly affecting each test point as a result of the Fourier number changing as a function of the actual vapor content and of the Ho number.

The graph also indicates that the stream velocity decreases with increasing Venturi length, i.e., the longer the liquid particles remain inside the Venturi, the more complete becomes the evaporation process in the boiling stream. From the difference between the curves for different values of the dimensionless K complex, one can conclude that a decrease in the energy of generating critical-size vapor nuclei will result in an increase in the actual vapor content in the stream.

According to a statistical analysis of the test data, the latter are fitted best on the following curve:

$$\varphi = 1 - \exp\,(K^{-0,2627} N^{0,011332}\,\mathrm{Ho}).$$

This equation has, therefore, been selected as the best approximation of the sought relation.

The variance of test points from Eq. (5) is within ±10%. This inaccuracy can be attributed to the inaccuracy of the approximation and to the error in measuring the vapor content during a test. The formula may be used, however, for calculating the mass transfer of saturated liquid through cylindrical Venturi tubes of different relative lengths.

NOTATION

ρ is the density;
v is the specific volume;
P is the pressure;
T is the temperature;
m is the mass;
V is the volume;
σ is the surface tension;
r is the radius;
k is the Stefan–Boltzmann constant;
w is the mean velocity;
l is the length;

τ is the time;
Q is the thermal flux;
a is the thermal diffusivity of the liquid;
λ is the thermal conductivity of the liquid;
L is the heat evaporation;
F is the cross section area;
φ is the actual vapor content;
β is the vapor content in discharge;
$\varkappa$ is the rate scale of phase transformation;
J is the rate of critical-size bubbles generation.

Superscripts

' denotes liquid;
" denotes vapor;
s denotes saturation;
cr denotes critical state;
* denotes molecules.

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