LITERATURE CITED

1. White and Maceligot, "Theoretical bases of engineering calculations," Proc. AIME, Ser. D, 92, No. 3, 7-15 (1970).
2. Hoyt, "Theoretical bases of engineering calculations," Proc. AIME, Ser. D, 94, No. 2, 1-31 (1972).
3. P. Peyser and R. C. Little, J. Appl. Polym. Sci., 15, No. 11, 2623-2637 (1971).
4. A. N. Shabrin, in: Hydromechanics [in Russian], No. 21 (1972), pp. 80-83.
5. I. L. Povkh et al., Inzh.-Fiz. Zh., 37, No. 5 (1979).
6. J. Furukawa and T. Sayegusa, Polymerization of Aldehydes and Oxides, Krieger (1963).
7. A. A. Tager, Physical Chemistry of Polymers [in Russian], Khimiya, Moscow (1978).
8. A. A. Tager et al., Vysokomol. Soed., A16, No. 1, 9-14 (1974).
9. Yu. F. Ivanyuta and L. A. Chekalova, Inzh.-Fiz. Zh., 18, No. 6 (1970).
10. R. J. Hansen and R. C. Little, Nature, 252, No. 5485, 690 (1974).
11. I. L. Povkh, V. G. Pogrebnyak, and A. I. Toryanik, Inzh.-Fiz. Zh., 37, No. 4 (1979).

EXPERIMENTAL STUDY OF DYNAMIC EFFECTS IN BUBBLE BOILING OF LIQUIDS

V. M. Tokarev and A. A. Bogovin

UDC 536.423.1

Results of an experimental study of the principles of the transient processes in vapor bubbles for a steplike increase in thermal load are presented.

In [1, 2] boiling was studied by use of a kinetic equation, the derivation of which was based upon consideration of the two-phase boiling layer as a set of gas bubbles, appearing and growing on the heating surface. The properties and evolution of the set of gas bubbles on the heat liberating surface were studied as a function of the conditions under which they appeared and the heat-exchange regime. It was found that in the solutions of the kinetic equations the sensitivity of parameters (mean values of current and separation radii, bubble frequency and distribution) were sensitive not only to external conditions, but also to the dynamics of change of these conditions. It develops that for a standard perturbation in the form of a steplike increase in thermal flux, the bubbles respond with a transition from an initial established state to a final one, which is not monotonic for all parameters. For example, the vapor content, which is an important characteristic of the boiling regime, passes through a maximum in the transition. The time at which maximum vapor content is achieved is related to the time at which the modal value of the separation radius is achieved by the expression

$$\tau(\varphi_{\max})/\tau_s = 3.5, \tag{1}$$

in which the purely collective properties of the boiling process appear.

In calculating equipment operating with a boiling heat exchange liquid this effect is not considered. Nevertheless, one should not neglect the possible effects of flares in vapor content in transition regimes for heat-exchange devices which operate with high stresses on the heat-liberating surfaces. In particular, nonstationary heat liberation at the heated wall has been found to affect the value of the first critical thermal flux [1, 3, 4].

The purpose of the present study is an experimental verification of the theoretically predicted existence of a maximum in vapor content for steplike increase in thermal flux, quantitative measurement of the maximum parameters, and comparison with theoretical values.

The experimental technique used consisted of illuminating the layer of boiling liquid adjacent to the heat-liberating surface by a parallel light beam. With such illumination of the two-phase layer the attenuation of the light beam at the output due to intense scattering on bubbles is proportional to the total area of the projections of such bubbles intersecting the beam. If the size of the surface upon which boiling occurs is taken sufficiently small in the direction of light propagation, then mutual overlap of bubble projec-

---

Chelyabinsk Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 37, No. 6, pp. 1015-1020, December, 1979. Original article submitted February 23, 1979.

0022-0841/79/3706-1420$07.50

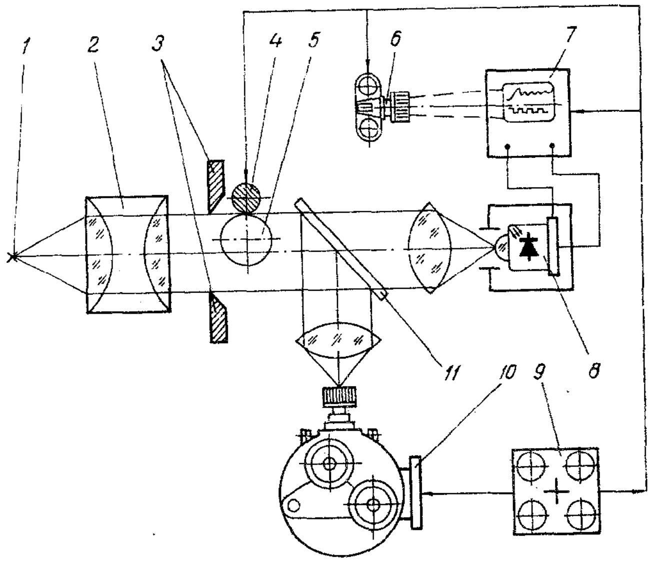

Fig. 1

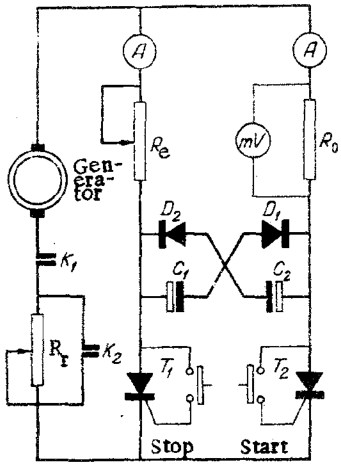

Fig. 2

Fig. 1. Schematic diagram of experimental apparatus: 1) light source; 2) condenser; 3) slit diaphragm; 4) wire heated by electric current; 5) vapor bubble on lower edge of wire; 6) photo equipment; 7) S1-18 oscilloscope; 8) FD-1 photodiode; 9) programmable clock; 10) SKS-1M cine camera; 11) semitransparent mirror.

Fig. 2. Schematic diagram of electrical circuit used to supply experimental heater with silicon controlled rectifiers.

tions may be neglected, and the degree of light attenuation will be practically linearly related to the vapor content of the boiling layer being illuminated. A direct photographic method could be used, but would not give a direct integral evaluation of the bubble mass, and obtaining such a value from the photo would require additional cumbersome processing. Moreover, in boiling in the isolated vapor bubble regime the desired effect is difficult to perceive visually. Only in intense boiling regimes does the effect become perceptible, but for other reasons, which are beyond the scope of the present study.

Figure 1 shows a schematic diagram of the experimental apparatus. Its major component is a cylindrically shaped volume containing a copper wire 0.35 mm in diameter. The cylinder was formed of stainless steel, and provided with temperature stabilizing devices and observation windows. The wire was mounted in holders which also served as current leads, installed in the lid of the cylinder. A slit diaphragm was located near the wire. The relative position of the wire and diaphragm could be adjusted by a mechanism with a micrometer screw thread. The light source was a filament type projection lamp supplied by dc current. After passage through the experimental cylinder, the light flux was focused on an FD-1 photodiode. By doing this, the two-dimensional picture of the two-phase boiling layer was converted to a signal proportional to the integral vapor content of the boiling layer. The bias on the photodiode was set within the linear portion of the device characteristic. The signal from the photodiode was displayed on an oscilloscope and photographed on the oscilloscope screen.

In the theoretical model of [1, 2] groups of vapor bubbles which grow upon but do not break away from the heating surface are considered. Bubbles which have separated and are ascending are not considered. Under actual experimental conditions ascending bubbles also appeared in the field of view, creating an interference source. To minimize this problem, the upper edge of the slit diaphragm was aligned with the lower edge of the wire, so that only bubbles growing on this lower edge appeared in the field of view. The time in which separated bubbles remain in the field of view was thus reduced to a minimum. Optimum sensitivity was achieved with a diaphragm slit width close to the most probable bubble separation radius.

The mean vapor bubble lifetime on the heat liberating surface $\langle\tau\rangle$, in water heated to the saturation temperature at atmospheric pressure is a value of the order of 1 msec, according to estimates made in preliminary experiments. The experimental heater element was supplied from a dc generator. Generator settling time to a steady-state regime after connection of the element was of the order of 30 msec. Theoretical estimates indicate that the duration of

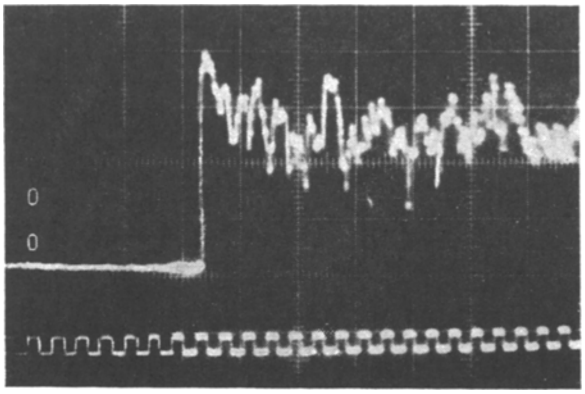

Fig. 3

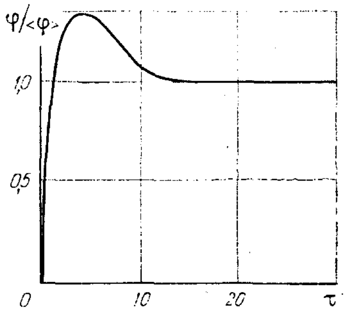

Fig. 4

Fig. 3. Oscillogram of transition process obtained in water heated to saturation temperature at atmospheric pressure (steady-state thermal flux, $2 \cdot 10^5$ W/m^2).

Fig. 4. Theoretical curve of transition process for $\langle \tau \rangle = 1.57$ msec.

the transient collective process does not exceed $20\langle \tau \rangle$, so that direct connection of the experimental heater into the generator circuit could lead to distortion of the transition process and significant smoothing of the expected effect. To eliminate the effect of the generator, the electrical circuit of [4] was replaced by a contactless switch using VKDU-150 silicon controlled rectifiers (Fig. 2). This switch ensured rapid (not more than 1 msec) switching of the current from the reference element R_0 to the load equivalent resistor R_e and back with no change in the load on the generator. Current switching is produced by discharge of the capacitors C_1 and C_2. When the nonoperating rectifier fires, the capacitor discharge current from that rectifier switches off the previously operating rectifier. Switching time can be varied by adjusting the values of C_1 and C_2. Among the advantages of this circuit, aside from high speed, is the simplicity of control. The switch can be triggered from the synchronization contact of the photo equipment, and the heater element can be switched off in the crisis regime without using intermediate mechanical relay devices to which high inertia is intrinsic.

The experiments were performed with distilled water at atmospheric pressure. Air was removed from the water by boiling before the experiments were performed. Then the thermostat system was used to establish and maintain the necessary temperature in the experimental cylinder, and the resistances R_0 and R_e were equalized. The change in vapor content after a rapid (~1 msec) increase in thermal flux was recorded. The operating sequence of the various equipment was controlled by a programmable clock. The experiment commenced with the triggering of the oscilloscope sweep. After 50-80 msec the photo shutter electromagnet was energized. When the shutter curtain was completely opened, the camera sync contact switch on the operating rectifier and switched off the equivalent load, so that the vapor content over a time period of 150-200 msec was recorded on the film. An oscillogram of the transition process is shown in Fig. 3. Due to the limited size of the sample (the number of vapor formation centers appearing in the field of view was of the order of magnitude of 10), the vapor content value measured experimentally revealed fluctuations. The relative value of the fluctuations can be determined by

$$\delta\varphi \sim \frac{1}{\sqrt{N}} 100\% = \frac{100\%}{\sqrt{10}} \approx 30\%.$$

This estimate agrees satisfactorily with the experimental results. Despite such strong fluctuations, all the oscillograms clearly showed passage of the vapor content through a maximum. With moderate thermal fluxes (in the nuclear boiling regime) the ratio $\varphi_{\max}/\langle\varphi\rangle$ was close to the theoretical value of 1.35. The average of the oscillograms reduces to the theoretical curve. With a graph of the transition process (Fig. 4), corrected to the actual experimental conditions and time scale, using Eq. (1) the mean time for attainment of most probable separation radius can be evaluated, or by considering the relationship

$$\langle \tau \rangle = \frac{\pi}{2} \tau_s,$$

the mean lifetime of a vapor bubble on the heat-liberating surface can be found. For the given experimental conditions these values proved equal to $\tau_s \approx 1$ msec and $\langle\tau\rangle \approx 1.57$ msec.

At high thermal fluxes the ratio $\varphi_{max}/\langle\varphi\rangle$ increases, reaching, in individual cases (at thermal fluxes close to critical) values close to four. This intensification of the effect at higher thermal fluxes can be obtained by studying a more complex model which considers coalescence of vapor bubbles on the surface. Coalescence leads to distortion of the bubble distribution over current and separation radii. Moreover, the vapor films which thus appear can accumulate the contribution to vapor content of the short-lived vapor bubbles, which also encourages intensification of the observed effect.

It can thus be assumed that the theoretical conclusions obtained on the basis of elementary statistical theory of collective phenomena in boiling do not contradict the experimental results. The divergence which appears in regimes close to critical should stimulate the development of a theory which can be applied in the region of regimes which have the greatest practical interest.

NOTATION

τ, time; τ_s, time required for attaining most probable separation radius; $\langle\tau\rangle$, mean lifetime of vapor bubbles on heater surface; φ, vapor content; φ_{max}, maximum vapor content achieved in transition process; $\langle\varphi\rangle$, mean vapor content in steady state; N, number of vapor formation centers acting on surface; R_0, resistance of experimental heater element; R_e, resistance of equivalent load.

LITERATURE CITED

1. V. M. Tokarev, "Nonthermodynamic aspects of the theory of boiling systems as applied to the boiling crisis," Author's Abstract of Candidate's Dissertation, Ural Politechnical Institute, Sverdlovsk (1975).
2. V. M. Tokarev, in: Heat-Mass Exchange in Phase Transitions. Proceedings of the Fifth All-Union Conference on Heat-Mass Exchange [in Russian], Vol. 3, Pt. 1, Minsk (1976), pp. 41-50.
3. V. M. Borishanskii and B. S. Fokin, "Degradation of the temperature regime upon sudden increase in thermal load on a heating surface located in a large liquid volume," Tr. TsKTI, No. 58, 58-63 (1965).
4. V. M. Borishanskii and B. S. Fokin, "Development of a heat liberation crisis with nonstationary increase in thermal flux," Tr. TsKTI, No. 78, 31-62 (1967).

CALCULATION OF INSTALLATIONS FOR DRYING GAS SUSPENSIONS

V. K. Maskaev and A. P. Baskakov

UDC 66.047

A method is given for calculating drying installations where an air suspension of finely dispersed particles is used as the drying agent.

In convective dryers the drying intensity is increased either through an increase in the coefficients of heat exchange between the material being dried and the drying agent or through an increase in the temperature of the latter. In the second case, even in the drying of fine particles, a significant temperature difference often develops between their surface and center, which leads to worsening of the quality of the finished product [1]. An increase in the coefficients of heat exchange requires considerable velocities of motion of the heat-transfer agent and corresponding expenditures of electrical energy. In the drying of finely dispersed particles in a fluidized bed the values of the coefficients of heat exchange play almost no role owing to their large specific surface area [2]. Here the amount of heat, proportional to the velocity and excess temperature of the gas, becomes the limiting factor. However, the

---

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 37, No. 6, pp. 1021-1027, December, 1979. Original article submitted February 5, 1979.

0022-0841/79/3706-1423$07.50