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ON THE MECHANISM OF BOILING HEAT TRANSFER (VAPOUR BUBBLES GROWTH RATE IN THE PROCESS OF BOILING OF LIQUIDS, SOLUTIONS, AND BINARY MIXTURES)

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Аннотация—Выполнено кинематографическое исследование механизма процесса кипения в большом объеме различных по своим физическим свойствам жидкостей (вода, этиловый спирт, четырёххлористый углерод, фреон-12), водных растворов (углекислого натрия, хлористого натрия, сахара) и бинарных смесей (вода—этиловый спирт, вода—метиловый спирт, этиловый спирт— бензол, этиловый спирт—нормальный бутиловый спирт).

Приведены, полученные в результате большого количества наблюдений, достоверные данные об отрывных диаметрах d_0, частотах отрыва f и скорости роста паровых пузырей w чистых жидкостей и о влиянии на w давления, материала и тепловой нагрузки смачиваемой поверхности нагрева.

Впервые получены систематические данные о скорости роста паровых пузырей при кипении водных растворов и бинарных азеотропных и неазеотропных смесей.

NOMENCLATURE

C',	concentration of highly volatile liquid component [per cent];
ΔC,	excessive concentration of highly volatile vapour component [per cent];
d_0,	vapour bubbles diameter at departure [mm];
f,	frequency of the vapour bubbles departure [s^{-1}];
q,	specific heat flux [W/m^2];
r,	latent heat of vaporization [J/kg];
Δt,	temperature difference [degC];
w,	growth rate of vapour bubbles [mm/s];
W,	reduced vapour velocity [m/s];
z,	actual number of vaporization nuclei [$1/m^2$];
α,	heat-transfer coefficient [W/m^2 degC];
ρ'',	vapour density [kg/m^3].

HIGH INTENSITY heat transfer in nucleate boiling is accounted for by the specific mechanism of the process associated with the generation and growth of vapour bubbles on the heating surface. Irrespective of which mechanism of intensive heat removal from a heating surface may prevail during the boiling process under various conditions (piston mechanism, turbulization of the liquid layer at the wall, heat removal by vapour bubbles), the growth rate of vapour bubbles w is always of great importance. w is the product of the diameter of a vapour bubble leaving the surface d_0 and of the frequency f of the vapour bubbles departure from the surface $w = d_0 f$.

The relation of the reduced vapour velocity $W = (q/r\rho'')$ to $w = d_0 f$ is proportional to the actual number of vaporization nuclei z on the heating surface.

For the further development of the theory it is necessary that the study of the process mechanism should be intensified which requires, first of all, a systematic experimental determination of w under various conditions and for various liquids.

Though the first investigation of this problem was carried out by Jakob and Linke long ago [1] the data on the kinetics of the growth of vapour bubbles reported so far are few and for the greater part inaccurate.

1. METHODS AND APPARATUS

The study of the process mechanism was effected with the help of high-speed photography of the nucleate boiling of a pool of liquid heated to the saturation temperature. A high-speed CKC-1M photocamera capable of taking 4000 pictures per second was supplied with a timer which permitted determination of the duration of the process observed.

Experiments showed that the photography speed up to 1000 pictures per second was sufficient to obtain reliable data on the growth rate of vapour bubbles at normal boiling of the liquid (without subheating).

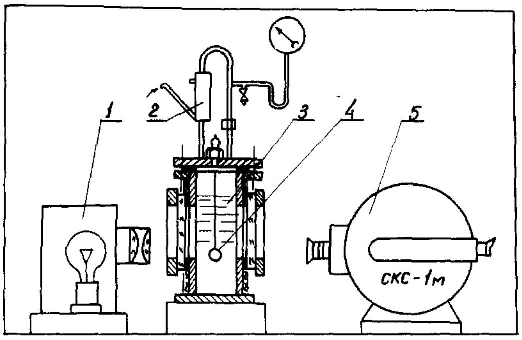

FIG. 1. Installation drawing.
1. Source of light. 2. Condenser-cooler. 3. Working chamber. 4. Test element. 5. High-speed camera.

The liquid being investigated was boiled on the test element enclosed in a stainless steel chamber. Special windows of heat resistant glass were provided for observation and photography (Fig. 1). When experiments were carried out under atmospheric pressure the chamber was supplied with a condenser-cooler having a controlled cooling surface which (and this) permitted a constant pressure and constant composition of the liquid under investigation to be maintained in the case of boiling of solutions and binary mixtures.

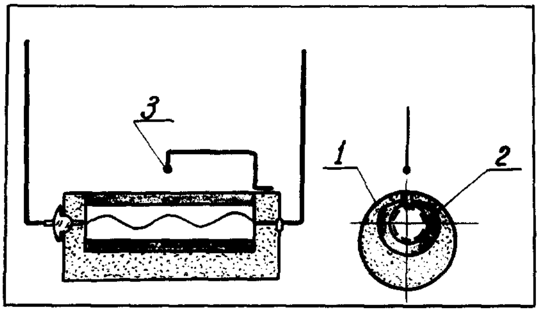

FIG. 2. Test element.
1. Body. 2. Copper rod with heater. 3. Calibre.

The test element (Fig. 2) made of sheet metal (0·1–0·15 mm) had the form of a horizontal hermetic cylinder of 20 mm in diameter and 50-mm long. The heating surface of the test element was a narrow strip along the upper generating line of the cylinder. This was achieved as follows. A hollow copper rod with a wedge-shaped upper edge 1·5-mm wide and a nichrome heater was brazed within the cylinder.

The cylinder inner space was filled with calcinated sand which allowed to be used the test element at pressures up to 10 bar. Nichrome or copper ball 1–2 mm in diameter placed above the heating surface of the test element served as a calibre for determining the scale of the photographs.

This construction of the test element made it possible to obtain in the focal plane a narrow heating surface on which boiling occurred, thus eliminating possible distortions of vapour bubble diameter at departure as compared with the calibre. To determine the effect of the material of the wetted heating surface of the test elements were made of different metals (brass, copper, permalloy).

Boiling of Freon-12, which has a low boiling temperature at atmospheric pressure was studied either in a chamber enclosed in a special thermostat filled with "dry ice" (solid CO_2) or in a Dewar vessel, its lower part having transparent walls, which made additional cooling unnecessary.

To obtain stable results the heating surface of the test element was subjected to preliminary "forming" which resulted from boiling of the investigated liquid on this particular heating surface for a long time.

Specific heat flux on the test element heating surface was chosen in such a way that the maximum possible number of vaporization nuclei could be observed and optical superposition of individual nuclei could be avoided. The test element was kept under this flux for 20–30 min after which the photographs were taken.

Special calibration experiments were carried out to determine the values of the specific heat flux of the heating surface. Special apparatus controlled the heat flux.

Photography was also carried out at a reduced heat flux on the heating surface when several (3–5) centers of vaporization could be seen in the field of vision.

The diameter of the vapour bubbles leaving the surface was determined by comparing it with the calibre photographed on the same film. The frequency of vapour bubbles departures was defined for each active vaporization nucleus by counting the number of pictures taken during the time which elapsed between the successive departures of two bubbles, observed at a known shooting speed this being defined by measuring the time intervals.

2. RESULTS

1. Results of our cinematographic investigations of the boiling process mechanism for a number of pure liquids boiling on wetted heating surfaces at atmospheric pressure are listed in Table 1. The experimental data were obtained on more than 5000 vapour bubbles which were investigated.

Table 1

Liquid	Heating surface									Average		
	permalloy			brass			copper					
	d_0 (mm)	f (1/s)	w (mm/s)	d_0 (mm)	f (1/s)	w (mm/s)	d_0 (mm)	f (1/s)	w	d_0 (mm)	f (1/s)	w (mm/s)
Water	2·5	61	153	2·3	67	154	2·8	56	157	2·5	62	155
Freon-12	0·7	84	59	0·7	99	69	0·7	91	64	0·7	91	64
Tetrachloromethane	1·1	110	121	1·1	108	119	1·1	106	117	1·1	108	119
Ethyl alcohol, 96·5 %	1·0	114	114	1·1	112	123	1·2	98	118	1·1	108	119
Normal butyl alcohol	1·05	106	111	—	—	—	—	—	—	1·05	106	111
Benzene	1·0	99	99	—	—	—	—	—	—	1·0	99	99

Observations were carried out at the following specific heat fluxes:

(a) for water from $15 . 10^3$ to $60 . 10^3$;
(b) for Freon-12 from $3 . 10^3$ to $12 . 10^3$ and
(c) for other liquids from $10 . 10^3$ to $50 . 10^3$ W/m^2.

In Fig. 3 are presented distribution curves of the diameter at departure, departure frequency and growth rate of vapour bubbles in the process of water boiling (from 970 observations) and in the process of ethyl alcohol boiling (from 1460 observations).

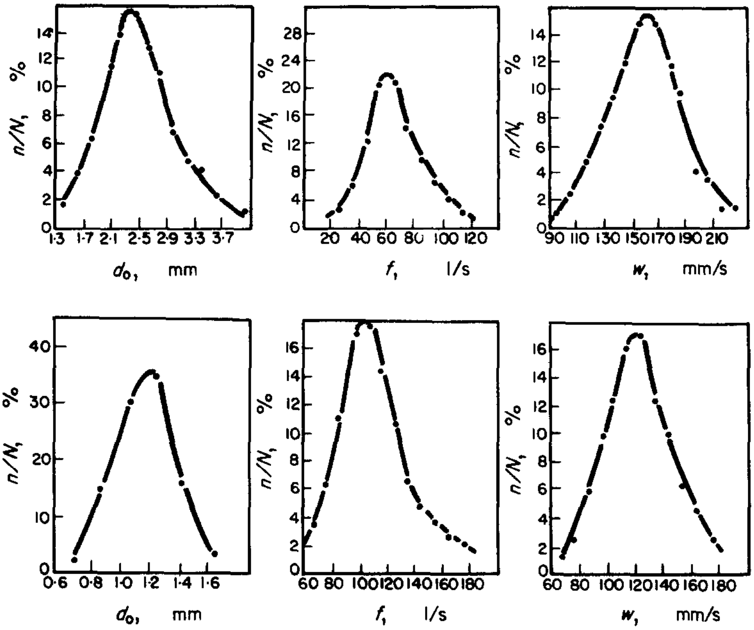

FIG. 3. Probability distribution curves of diameter at departure d_0 departure frequency f and vapour bubble growth rate w for boiling of (a) water, (b) ethyl alcohol.

As it is seen from Table 1 and Fig. 3 the investigations carried out at atmospheric pressure lead to the following conclusions:

(a) the average growth rate of vapour bubbles $w = d_0 f$ depends on physical properties of the liquid and its vapour, and is practically independent of the material of the wetted heating surface.

(b) for the majority of the vapour bubbles the frequency increases with the decrease of the diameter at departure, w being constant. It is proved that the average $w = d_0 f$ is really characteristic value of the given liquid and its vapour.

(c) values of w for tested liquids except Freon-12 being about 400 m/h do not differ greatly from the values of w for water. Taking into account that these liquids differ considerably in their properties, it may be assumed that the values of w do not vary greatly over a wide range of liquids.

(d) vapour bubble growth rate for Freon-12 proved to be 2·5 times less than that for water. This accounts for the difficulty in the generalization of the experimental data heat-transfer coefficient α for boiling Freon-12 when using formulae which do not contain w explicitly. In many cases there is a great discrepancy between theoretical and experimental values of α. Yet when the effective values of w for Freon-12 were used, the experimental data on heat-transfer intensity in boiling of Freon-12 and other liquids could readily be generalized.

(e) probability distribution of diameter at departure, departure frequency and growth rate of vapour bubbles are close to the normal probability distribution. This conclusion greatly simplifies data treatment as the most probable meanings of the values under study are close to the arithmetic mean values.

The experiments did not reveal any influence on the average w of the changes (4–5 times) of heating surface heat flux.

These results correspond to the previously reported data for methyl alcohol boiling obtained by J. W. Westwater with co-workers in one of their experimental works [2].

When vapour bubbles generate and begin to grow in the liquid pool, their growth rate greatly depends on the liquid superheat Δt. Theory and experiments make it evident.

The fact that w does not depend (or has a slight dependence) on q may be explained by the following considerations:

(1) Δt changes essentially less than q, (2) high Δt occurs only close to the heating surface and it influences only a portion of the vapour bubble surface, (3) there is a compensating influence of time interval necessary for the temperature field regeneration in the liquid near the heating surface after the vapour bubble departure. This may be explained by the fact that w here considered is related to the whole period of time between two departures of the vapour bubbles including the induction period.

2. To determine the influence of pressure on the growth rate of vapour bubbles experiments were carried out with pure liquids within the pressure range from 1 to 10 bar.

To obtain comparable data series of experiments were carried out with each heating surface in turn, covering successively all experimental pressures beginning with 1 bar.

The experimental relationship of the average vapour bubble growth rate for water and ethyl alcohol are plotted in Fig. 4. To compare the data, the ordinate represents the relative values of vapour bubble growth w/w_1 viz. relative to w_1 at the atmospheric pressure.

As it is seen from the diagram, w for ethyl alcohol decreases with pressure growth much more rapidly than for water. So for boiling water at pressure 9 bar, w is 6·6 times smaller less that w_1 at 1 bar, and for boiling ethyl alcohol at the same pressure it is 9 times less. It agrees with the observed greater relative growth of boiling heat transfer intensity for ethyl alcohol than for water.

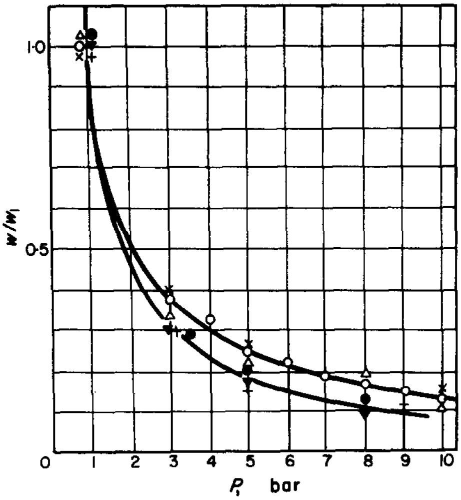

FIG. 4. w/w_1 vs. pressure for boiling on different heating surface:
Water: ×, permalloy, ○, brass, △, copper.
Ethyl alcohol: +, permalloy, ●, brass, ▼, copper.

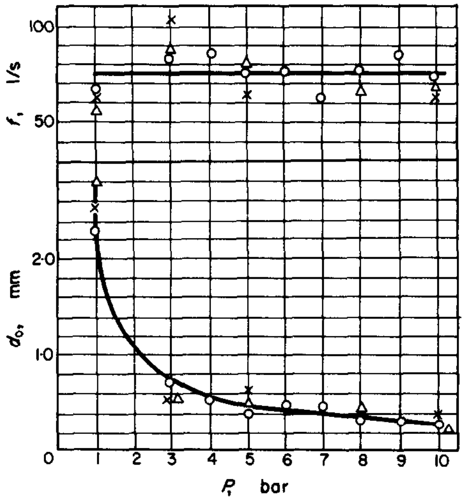

FIG. 5. d_0 and f vs. pressure for boiling water (nomenclature as in Fig. 4).

Comparison of the changes of vapour bubble diameter at departure given in the diagram (Fig. 5) for boiling water with the diagram of the changes of w/w_1 (Fig. 4) shows that the variation in the vapour bubble growth rate is almost solely due to the decrease of bubble diameter at departure.

The number of active vaporization nuclei increases with the pressure increase under constant heating surface heat flux.

Experiments with tetrachlormethane at pressures 3 and 5 bar as well as with Freon-12 at 6 and 7 bar showed analogous dependences of w/w_1.

3. Of interest, along with the study of pure liquids boiling, is the study of solutions and mixtures boiling.

Boiling of aqueous solutions of sugar, sodium chloride and sodium carbonate was studied for concentrations near saturation. Taking into consideration that in industry sugar solutions boil at subatmospheric pressure experiments were carried out with pressure ranging from 0·2 to 1 bar. For comparison similar investigations were made with water.

For the studies of viscous sugar solutions the test element (Fig. 6) was drop-shaped. Special guide baffles were provided at either side of the test element to improve the flow of the solution to the heating surface. The solution was heated up to the boiling temperature. An additional tube closed-type heater was placed under the test element. All these arrangements were made to provide the necessary heating of the solution boiling on the heating surface of the test element. This aim was achieved.

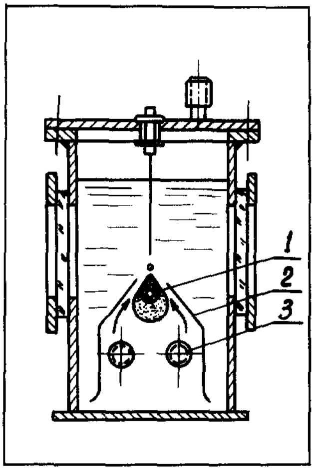

FIG. 6. Working chamber for rests with sugar solutions. 1. Wedge-shaped test element. 2. Guiding baffles. 3. Additional heater.

Diagrams (Fig. 7) show the results of tests with sugar solutions and water boiling at 0·2–1 bar. Table 2 presents data on boiling solutions of NaCl and Na_2CO_3 at atmospheric pressure.

Table 2

	d_0 (mm)	f (1/s)	w (mm/s)
Water	2·5	62	155
NaCl solution, 25%	2·4	64·5	155
Na_2CO_3 solution, 29%	2·4	65	156

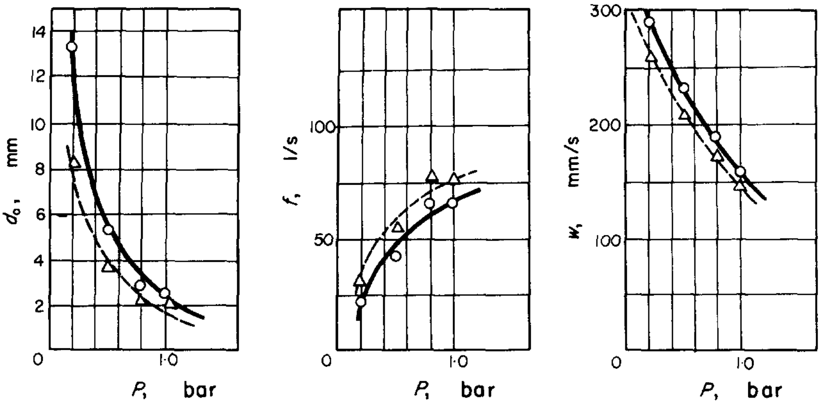

FIG. 7. d_0 and f vs. pressure at boiling of water and sugar solution (72% dry matter) in vacuum:
○, water; △, sugar solution.

From diagrams (Fig. 7) it can be seen that when highly concentrated (70–72% dry matter) solutions are boiled in vacuum, vapour bubbles growth rate does not differ greatly from that in water boiling. At the same time viscosity of sugar solutions and Prandtl number for them is much higher (1–2 orders of magnitude). It can be concluded that the influence of viscosity and Prandtl number on w is insignificant.

Experiments with boiling highly concentrated solutions on NaCl and Na_2CO_3 showed that vapour bubbles growth rate for these solutions was the same as for water.

Thus, tests with boiling aqueous solutions showed that vapour bubbles growth rate in the process of boiling solutions was predetermined by the solvent (water) and its vapour properties and that the influence of the matter properties is insignificant. Hence w for aqueous solutions boiling is practically equal to w for water boiling.

4. Vaporization process of mixtures differs greatly from that for a pure monocomponent liquid, due to the presence of a concentration gradient between the liquid and the newly formed vapour phase.

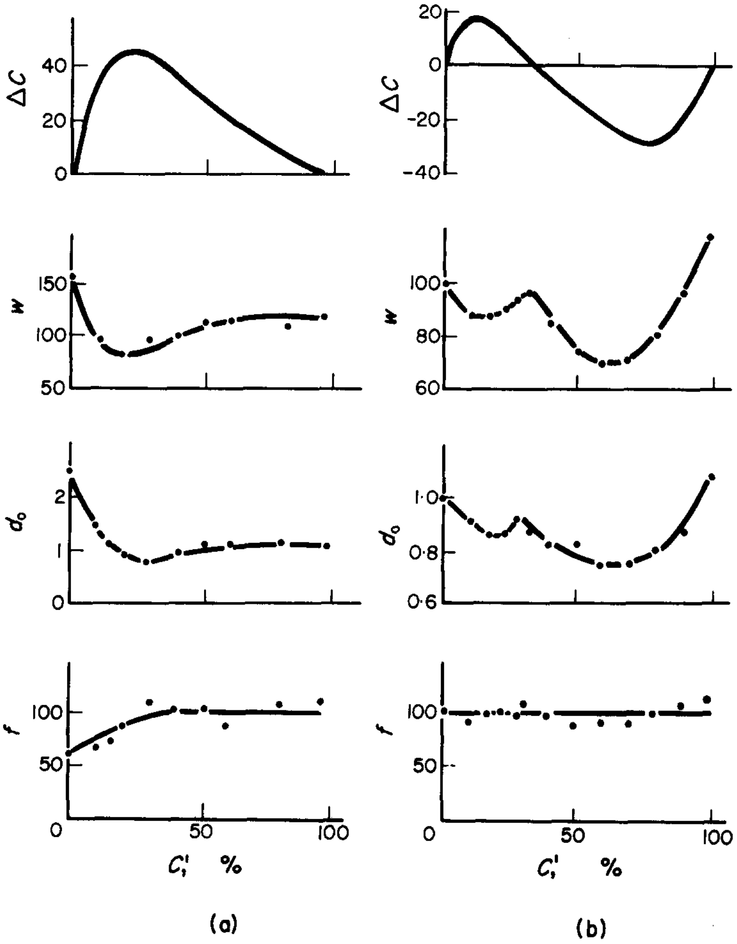

FIG. 8. $d_0 f$ and w vs. concentration for boiling of binary mixtures (C', ethyl alcohol concentration.
(a) water–ethyl alcohol; (b) benzene–ethyl alcohol.

An excessive concentration of a highly volatile component in the vapour influences both the mechanism of the boiling process of mixtures and the intensity of heat-transfer process.

From the investigations of the mechanism of the binary mixture boiling carried out at atmospheric pressure (for results see Fig. 8) the following conclusions can be made: (binary mixtures of two types were taken: without the aseotropic point—ethanol–water—and with the aseotropic point—ethanol–benzene):

(a) there exists a pronounced relationship between the average growth rate of vapour bubbles w and excessive concentration of highly volatile vapour component ΔC,

(b) for mixtures without aseotropic point w drops with the increase of ΔC reaching its minimum at ΔC maximum,

(c) with the aseotropic point there are two minima corresponding to two extremal points on the curve $\Delta C = f\ (C')$ and an intermediate maximum at the aseotropic point,

(d) bubble diameter at departure decreases reaching its minimum in the zone of extremal values of ΔC,

(e) frequency of bubble departure for ethanol–benzene mixtures in almost constant while for ethanol–water mixture increases with the growth of ethanol concentration.

The theoretical considerations describing the laws of vaporization in binary mixtures and experimental data reported in this paper make it possible to explain qualitatively the character of intensity changes in boiling heat transfer depending on the composition of binary mixtures.

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Résumé—On a réalisé une étude cinématographique du mécanisme de l'ébullition dans un grand volume avec des fluides de propriétés physiques très différentes: liquides (eau, alcool éthylique, tétrachlorure de carbone, Fréon-12), solutions aqueuses (carbonate de sodium, chlorure de sodium, sucre) et mélanges binaires (eau–alcool éthylique, eau–alcool méthylique, alcool éthylique–benzol, alcool éthylique–alcool butylique normal).

A l'aide d'un grand nombre d'observations, on a obtenu des résultats certains sur les diamètres d_0, les fréquences de détachement f et la vitesse de croissance des bulles de vapeur w de liquides propres et sur l'influence de la pression, du matériau et de la charge thermique de la surface chauffante mouillée sur w.

Pour la première fois, on a obtenu des données systématiques sur la vitesse de croissance des bulles de vapeur pendant l'ébullition de solutions aqueuses et de mélanges binaires azéotropiques et non azéotropiques.