INTENSIFICATION OF HEAT TRANSFER AND STABILIZATION OF THE BOILING PROCESS IN THE VERY LOW PRESSURE REGION

V. V. Yagov and D. A. Labuntsov

UDC 536.246:536.423.1

Various processes of intensifying heat transfer and stabilizing the boiling process for liquids in the very low pressure region are analyzed and studied experimentally. The great effectiveness of using thin hydrophobic screens attached to the surface to be heated was discovered.

The well known tendency toward reduction in heat transfer with decrease in pressure (see, for example, [1, 2]) is based mainly on experimental data in the region $p_s \geq 1$ bar. Recently there has been an increase in interest in the problem of conducting boiling at very low pressures. Experimental observations have shown the unique peculiarities of boiling under high vacuum. Thus, in [3], as earlier in [4-8], it was noted that for pressures lower than 0.2-0.3 bar, boiling takes on an ever increasing unstable character as pressure is lowered. Under the conditions existent in [3] (a significant volume of the boiling vessel, planar horizontal heating surface), pauses in the process of generating vapor bubbles attained values of the order of tens of seconds. The pauses were interrupted by short-term pulses of boiling, wherein a noticeable amount of kinetic energy was transferred to the liquid in the process of forming vapor volumes, which produced intensive pulsations, hydraulic shocks, and splattering. At the same time a significant fluctuation in surface temperature of the liquid was observed. Reduction in pressure led to significant increase in surface superheating, a condition necessary for such unstable boiling. Thus, for $p_s = 0.036$ this superheating reached 25-28°K for water, and 38-40°K for ethanol.

In practice the features of unstable boiling noted above are most undesirable. Hence there is a need to examine methods of stabilizing the boiling process in a vacuum and simultaneously intensify heat transfer.

Methods of Stabilizing Boiling and Intensifying Heat Transfer. We will examine possible methods of solving this problem, starting with an analysis of the conditions for generation of the vapor phase in a liquid on a solid heated surface. In accordance with [9] the change in thermodynamic potential of a system upon generation of a vapor nucleus is presented in the following form:

$$\Delta\Phi = (f'' - f')V\rho'' + \sigma S\left[1 - \frac{S_{st}}{S}(1 - \cos\theta)\right]. \quad (1)$$

The value of $\Delta\Phi$ is in actuality the energetic barrier for development of a viable vapor nucleus. The engineering problem of stabilizing the boiling process and intensifying heat transfer in boiling in a vacuum corresponds physically to a search for methods of lowering this barrier, i.e., methods for decreasing the value of the second term of Eq. (1).

In practice this may be attained by acting upon the value of the liquid surface tension σ, on the microsmoothness of the heated surface (thereon depends the value of the ratio S_W/S), or on the wettability of the surface (on the value of the marginal wettability angle θ). We will examine these three possibilities.

1. It was established in [10] that the addition of surface-active substances to boiling water, reducing the surface tension of the liquid by a factor of 2-3, leads to the creation on the heated surface of a layer of

---

Energy Institute, Moscow. Translated from Izhenerno-Fizicheskii. Zhurnal, Vol. 20, No. 6, pp. 973-981, June, 1971. Original article submitted September 28, 1970.

fine vapor bubbles and increases the heat transfer coefficient. However, as was shown in [11], the effect of surface tension on intensity of heat transfer is not very significant and may be represented empirically by the relationship $\alpha \sim \sigma^{-1/3}$.

2. In [9] it was shown that the ratio S_w/S is increased with transition from a protuberant to a plane boundary, and increased yet further by various depressions, cavities, and abrasion on the surface. The latter usually serve as centers of vapor formation in boiling. In general it can be maintained that heat transfer intensity is increased with transition from polished to coarsely finished surfaces. However, the data of various authors on the quantitative effect of surface smoothness are quite contradictory. It was shown in [12] that the effect of surface finish on heat transfer intensity with boiling water was small, and appeared only at low levels of heat flow (up to 120 kW/m^2). In [13] great differences (by a factor of 3-4) were discovered in heat transfer coefficients for boiling of n-pentane on surfaces with various finishes. Similar results on the effect of surface smoothness in n-pentane boiling are presented in [14].

3. From analysis of Eq. (1) it is clear that a change in marginal wetting angle θ significantly influences the value of the vapor phase formation energy barrier.

In [15] a noticable increase in heat transfer coefficients was discovered for boiling water with an increase in marginal angle θ from 45° to 90°; with an increase in θ from 90° to 135° the heat transfer level remained practically constant.

In [9] the principal difference between vapor formation on wettable ($\theta < \pi/2$) and nonwettable ($\theta > \pi/2$) heating surfaces was shown. In fact, for the case $\theta > \pi/2$ for certain microgeometries of the heated surface the vapor phase formation energy barrier can go to zero, and in such a case boiling is in principle possible immediately upon attainment by the liquid of the saturation temperature T_s. In [12] it was established that on the surface of a steel tube coated by a thin layer of "Vapor" brand turbine oil, vapor formation commenced at $\Delta T = 1\text{-}2$°K. However, even at $q = 112$ kW/m^2 a heat transfer crisis arose, which fact indicates the inapplicability in practice of employing continuously hydrophobic heating surfaces as vapor generators.

In [16], the deposition (by a special method) of Teflon spots on a steel ribbon produced a succession of wettable and nonwettable spots, which on the one hand ensured a reduction in the vapor nucleus activation energy, and on the other hand excluded the early onset of a boiling crisis. Such a method permitted significant reduction in the temperature head for onset of boiling (ΔT_{BH}) and produced an increase in heat transfer coefficients for water, boiling under atmospheric conditions, in the low and moderate heat transfer rate range (10-150 kW/m^2) by a factor of approximately five.

Experimental Results and Evaluation. All of the studies mentioned above [10-16], which examined the effects of σ, θ, and heating surface smoothness on heat transfer in boiling, did so for atmospheric or higher pressures. Our study, using an apparatus described in [3], examined various methods of stabilizing the boiling process and intensifying heat transfer in boiling of water and ethanol under reduced pressures. It should be noted that the heat transfer surface was quite large (a horizontal nickel disk with diameter of 56 mm), being at least of the same order of magnitude as the breakaway diameter of the vapor bubbles, whereas in the majority of other studies of boiling in vacuo the dimensions of the heating surface were significantly smaller than the breakaway dimensions of the vapor bubbles.

1. In accordance with the analysis presented above, the effect of surface tension σ on heat transfer intensity is insignificant and, moreover, connected with the admixture of various adulterants to the liquid, which a given technological process may not permit. In the present study the effect of surface tension σ on boiling intensity in vacuo was not examined.

2. The experimental data of [3] were obtained for boiling on a polished surface (9th-10th class cleanness by All-Union State Standard 27-89-59). In the present study, experiments were conducted with water boiling on a surface with 4th class cleanness (surface finished with coarse grain emery paper or coarse file). No qualitative changes in the boiling of water at pressures of 0.036 bar and 0.100 bar on such a surface in comparison with a "clean" surface were noted, long pauses in generation of vapor bubbles were observed, as were significant oscillations in the heated surface temperature, vapor formation had an explosive character and led to expulsion of liquid from the experimental vessel into the condenser.

As regards quantitative changes, the effect of surface finish was observed only at pressures above 100 mbar. As may be seen from Fig. 1a, the transitional heat transfer regime with the coarse surface corresponds to a lower temperature head than is the case with boiling on a polished surface (14 and 21°K respectively). The character of the function $q = f(\Delta T)$ is identical for both surfaces. At a pressure of 36 mbar the surface finish had no effect whatever on heat transfer intensity. Fig. 1b indicates that experimental points for both surfaces approximate the same function in coordinates $(q, \Delta T)$.

As follows from Fig. 1, the creation of conical depressions with a diameter of 0.2-0.4 mm and the same depth on the heated surface did not lead to the appearance of stable vapor formation centers. Eleven depressions were formed in the 56 mm round plate using a punch with point angle of 60°. In accordance with [9], at such a conical angle, and with values of $\theta = 40-50°$, most probable for the water–nickel combination, the vapor phase formation energy barrier is close to minimum.

In summing up, one may assume a quite weak influence of surface finish on heat transfer and character of boiling under reduced pressure conditions, whereby there is a basis to assume that this influence will become yet weaker with further reduction in pressure. In any case, it is scarcely practical to recommend creation of artificial surface roughness as a method of stabilizing and intensifying boiling under low pressure conditions.*

3. In accordance with the above analysis, a promising method of boiling intensification seems to be the creation on the heated surface of areas with reduced local wettability. Our study reproduced, in particular, the methodology of [16] for lowered pressure conditions. About 100 spots of hydrophobic substances were deposited on a surface with area of 25 cm^2. In various series of experiments silicone resins (lacquers), industrial hydrophobic agents (type GKZh), paraffin, and a polyfluoroethylene resin were employed.

The effect of such artificially created vapor formation centers proved to be different at different pressures. Thus, spots of polymerized polymethylphenylsiloxane resin (K-55) applied to the heated surface changed the character of boiling quite significantly at a pressure of 0.2 bar: vapor formation centers were fixed and no pauses were observed in their operation, significant oscillations in heating surface temperature disappeared. The heat transfer coefficients rose noticeably, as compared with boiling on a smooth surface, as is evident from Fig. 2a. The temperature head at boiling onset was reduced to 10°K (as compared to 17°K for the clean surface). The breakaway diameter of bubbles was 5-8 mm (as opposed to 40-50 mm for boiling on the clean surface). However, as pressure was reduced below 0.1-0.2 bar boiling on the surface with hydrophobic spots gradually took on all the characteristics of an unstable explosion-like process, and upon reaching pressures of 0.05-0.06 bar could not be distinguished qualitatively or quantitatively from boiling on a clean surface.

At sufficiently low pressures only surfaces with spots of polyfluoroethylene resin emulsion produced stable boiling, since this resin has the best hydrophobic properties, which produce the necessary lowering in the vapor phase formation energy barrier. Figure 2b, which compares the experimental data for boiling of water on such a surface (pressure 0.036 bar) with results for a clean surface (curve 2), illustrates the positive effect of employing spots of polyfluoroethylene, deposited on the heat transfer surface. The approximation curve drawn through the points of the first three days of experiment corresponds to a heat transfer coefficient three or four times as great as on a clean surface. The boiling process was stabilized and no pauses in bubble generation were noted.

In engineering practice, the question of effective lifetime of a vapor generating surface with hydrophobic coating is quite important. In [16] this problem was not studied, the length of the experiments not exceeding four hours. In our study, this question was given special examination. The experiment was conducted such that over the course of 10-12 hours, the boiling process was studied, with the surface remaining below liquid the remainder of the day. Thus, for various series of experiments, the average service time of the heat transfer surfaces was 120-330 h. Curve 2a was obtained in the course of five days, during which time no deterioration of the process was observed. In the case of water boiling at a pressure of 36 mbar on a surface with polyfluoroethylene emulsion spots, beginning with the fourth day of experiment, some reduction in heat transfer coefficient was noted (see Fig. 2b). However, over the course of the entire experiment (8 days) the heat transfer coefficients remained significantly higher than for boiling on a clean surface.

Nevertheless, the poor adhesion properties of the resin on metallic surfaces are a shortcoming of this method. Thus a new method of stabilizing the intensifying boiling in a vacuum was developed and investigated. The method employed a perforated hydrophobic screen, placed on the heating surface.

---

*In [17] stabilization of alkali metal boiling was attained by creation on the heated surface of depressions of a special configuration, so-called "mushroom-like" depressions. However it is difficult to evaluate the practicability of such a method in engineering practice.

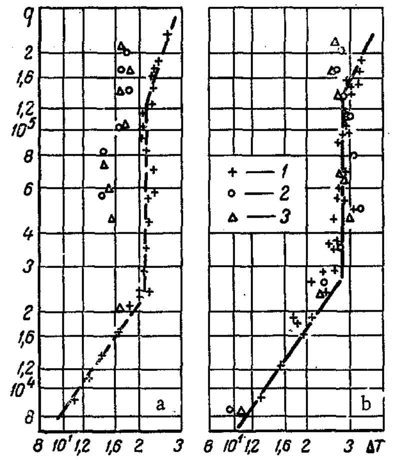

Fig. 1

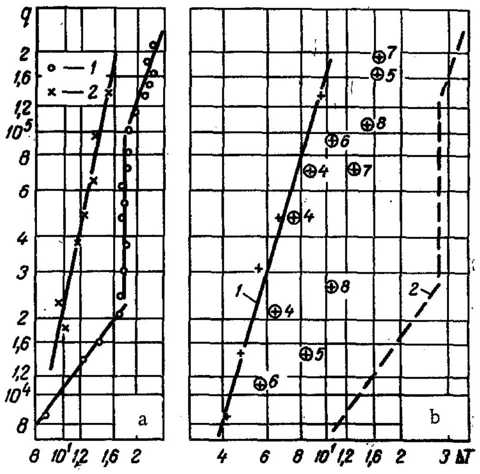

Fig. 2

Fig. 1. Effect of heating surface finish on heat transfer in boiling water at pressures of $p_s = 100$ mbar (a) and $p_s = 36$ mbar (b). 1) Polished surface; 2) rough surface (to 4th class finish); 3) surface with conical depressions. q, W/m^2; ΔT, °K.

Fig. 2. Boiling of water on surfaces with spots of hydrophobic substances: a) spots of polymethylphenylsiloxane resin, $p_s = 200$ mbar [1) clean surface, 2) surface with spots], b) spots of polyflouroethylene resin emulsion, $p_s = 36$ mbar [1) results of first three days; within circles are points from fourth to eighth day of experiment, numbers alongside points indicating day number]; 2) clean surface with $p_s = 36$ mbar.

Polyfluoroethylene screens 0.1-0.3 mm in thickness with square or round openings with nominal diameters from 0.6 to 2.5 mm were employed. The area of the openings comprised 25-35% of the total heating surface area (for example in 1 cm^2 of screen area there were 18 openings with diameter of 1.5 mm). The screen was pressed flat against the heating surface and attached at the perimeter with a stainless steel ring.

The use of these screens changed the characteristics of boiling and heat transfer over the entire pressure range studied (to 0.016 bar) in a radical manner. The boiling process over the surface covered by the polyfluoroethylene screen was practically indistinguishable in external appearance from boiling under atmospheric conditions. For low heat loads ($q \leq 20$ kW/m^2) a small number of vapor formation centers acted, the number increasing quickly with increasing thermal flux, and even at $q = 40$ kW/m^2 "colonies" of vapor bubbles formed a continuous ascending vapor–water column above the surface.

The effectiveness of using such screens is due, in our opinion, to two factors. First, the introduction of a hydrophobic material into the superheated liquid boundary lowers the work necessary to form phase division surfaces. In this way the screen placed on the heating surface acts in the same manner as spots of polyfluoroethylene emulsion on the surface, while at the same time the technological difficulties of introducing the hydrophobic covering are simplified. Secondly, the formation of stable vapor regions between the polymer screen and the metallic surface is possible, i.e., there may be some analogy here with the "mushroom-shaped" depressions of [17]. The hydrophobic property must further the stability of vapor formation between the screen "skeleton" and the heating surface, while the liquid can pass freely to the surface through the openings.*

Figure 3a presents the experimental data obtained for water boiling on a surface covered by a polyfluoroethylene screen, with openings 1.5 mm in diameter (at pressure of 36 mbar). Under these conditions onset of boiling took place at $\Delta T = 3.5$°K, i.e., ΔT_{BH} was reduced by a factor of eight as compared with a bare surface, and the heat transfer coefficients for thermal fluxes up to 100 kW/m^2 were increased by a factor of 4-6, even exceeding the value of the heat transfer coefficient for water boiling on a clean bare

---

*A metallic screen, geometrically identical with the polyfluoroethylene one, had practically no effect on water boiling at low temperatures (its effect was analogous to increasing roughness of the heating surface).

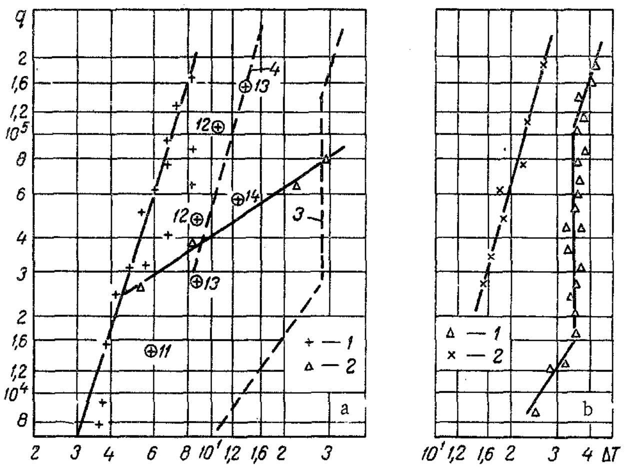

Fig. 3. Boiling on a surface covered by a polyfluoroethylene screen: a) water, $p_s = 36$ mbar [1) mesh diameter 1.5 mm (numbers alongside points indicate day of experiment); 2) hole diameter 0.6 mm; 3, 4) bare surface with $p_s = 0.036$ and 1.0 bar, respectively]; b) ethanol, $p_s = 60$ mbar [1) bare heating surface; 2) surface covered by polyflouroethylene screen with square openings 2.5 × 2.5 mm)], q, W/m^2; ΔT, °K.

heating surface at atmospheric pressure. The experimental data obtained over the course of 10 days approximate the function $q \sim \Delta T^{3.33}$. Only in the last four days of the two-week-long experiment was some reduction in the heat transfer coefficients observed, although as before, they exceeded the values characteristic of a bare surface by a factor of 2-3. Also, over the entire course of the experiment there were no signs of instability in boiling.

The question of the optimum dimensions of the orifices in the screen is of great practical interest. A reduction in this diameter increases the "degree of discreteness" of the coating, which should produce a positive effect. However, at the same time the role of capillary effects increases, hindering the penetration of the liquid to the very heating surface and creating the danger of a premature "steaming" or boiling crisis. These factors set a limit to the range of orifice diameters possible.

The fact that such a limit exists is supported by the curve presented in Fig. 3a, obtained with the use of a polyfluoroethylene screen with openings 0.6 mm in diameter. Although boiling over such a screen appeared stable and intense, heat transfer coefficients decreased with an increase in temperature head due to deterioration in conditions for approach of the liquid to the heating surface. At $q \approx 105$ kW/m^2 there occurred a "steaming" of the surface; an unstable thermal regime developed, characterized by steady increase in heating surface temperature.

The results of our study indicate that, in the heat transfer rate range up to 250 kW/m^2, in the case of water boiling at pressures down to 0.016 bar, a screen with orifices 1.5-2.5 mm in diameter is to be recommended.

Experiments also showed the effectiveness of a polyfluoroethylene screen for boiling of ethanol under vacuum conditions. Figure 3b presents curves for ethanol (96%) boiling under a pressure of 0.06 bar on a bare heated surface and with use of the screen. There is evidently a significant increase in heat transfer with use of the screen, with which complete stabilization of the boiling process occurred.

NOTATION

T_W	is the temperature of heating surface;
T_S	is the saturation temperature of liquid;
$\Delta T = T_W - T_S$	is the temperature head;
ΔT_{BH}	is the temperature head at onset of boiling;
q	is the specific heat flux;
ΔΦ	is the change in thermodynamic potential of system;
f" and f'	are the specific (per unit mass) thermodynamic potentials of vapor and liquid phases respectively;
V	is the volume of vapor phase generated;
ρ''	is the vapor density;
σ	is the surface tension coefficient on vapor–liquid boundary;
S	is the total surface area of vapor phase generated;
S_W	is the portion of S over which vapor phase contacts walls;
θ	is the marginal angle of wettability;
α	is the heat transfer coefficient;
p_s	is the pressure on surface of boiling liquid.

LITERATURE CITED

1. V. P. Isachenko, V. A. Osipova, and A. S. Sukomel, Heat Transfer [in Russian], Energiya, Moscow (1965).
2. S. S. Kutateladze, Fundamentals of the Theory of Heat Exchange [in Russian], Mashgiz (1962).
3. V. V. Yagov, A. K. Gorodov, and D. A. Labuntsov, Inzh. Fiz. Zh., 18, No. 4 (1970).
4. N. N. Mamontova, Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3, 140 (1966).
5. C. J. Rallis and H. H. Jawurek, Int. J. Heat Mass Transfer, 7, No. 10, 1051 (1964).
6. V. I. Deev, V. V. Gusev, and G. P. Dubrovski, Teploenergetika, No. 8, 73 (1965).
7. J. Rabin, R. Beaubouef, and G. Commerford, Chem. Engng. Progr. Sympos. Series, 62, No. 64 (1966).
8. N. G. Styushin and L. M. Elinzon, Inzh. Fiz. Zh., 16, No. 1 (1969).
9. D. A. Labuntsov, Izv. Akad. Nauk SSSR, OTN. Energ. i Transport, No. 1, 58 (1963).
10. A. I. Morgan, L. A. Bromley, and C. R. Wilke, Industr. and Engng. Chem., No. 12, 2767 (1949).
11. E. K. Averin and G. N. Kruzhilin, Izv. Akad. Nauk SSSR, OTN, No. 10, 131 (1955).
12. E. K. Averin, Izv. Akad. Nauk SSSR, OTN, No. 3, 116 (1954).
13. B. J. Berenson, Int. J. Heat Mass Transfer, 5, No. 10, 985 (1962).
14. C. Corty and A. S. Foust, Chem. Engng. Progr. Sympos. Series, 51, No. 17, 1 (1955).
15. E. I. Aref'eva and I. T. Alad'ev, Inzh. Fiz. Zh. 1, No. 7 (1958).
16. R. K. Young and R. L. Hummel, Chem. Engng. Progr. Sympos. Series, 61, No. 59, 264 (1965).
17. P. J. Marto and W. M. Rohsenow, Teploperedacha, 88, No. 2, 38, 51 (1966).