THE DEGENERATION OF NUCLEATE BOILING CONDITIONS UNDER CONDITIONS OF FREE CONVECTION

B. P. Avksentyuk, G. I. Bobrovich,
S. S. Kutateladze, and V. N. Moskvicheva

UDC 536.423.1

An experimental investigation was made of the effect of the degeneration of nucleate boiling conditions under conditions of natural convection for alkali metals (potassium, cesium) in working sections with diameters of 14 and 11 mm in a pressure range of 0.04-1.7 bar, and for nonmetallic liquids (ethanol, benzene, and carbon tetrachloride) in working sections with diameters from 0.1 to 10 mm in a pressure range of 0.05-2.5 bar. The regions were determined for thermal flows, with which the appearance of a vapor phase after single-phase natural convection leads to the formation of a stable vapor film. The results of high-speed moving-picture photography of this phenomenon are also given.

In the investigation of heat transfer and of critical heat fluxes in nonmetallic liquids boiling under a vacuum, a number of investigators [1-4] have observed degeneration of nucleate boiling conditions, when the first appearance of a vapor phase after conditions of natural convection without boiling led to the formation of a stable vapor film, avoiding nucleate boiling conditions. This usually occurred in small-diameter working sections (less than 3 mm) and at low pressures (less than 0.3 bar). A qualitative explanation of this phenomenon is connected with an increase in the size of the critical nuclei for vapor formation and with the large breakaway diameters of the bubbles at lowered pressures [1-3]. However, no special investigations of this phenomenon have been made.

In an investigation of the boiling of cesium under conditions of free convection the phenomenon of the degeneration of nucleate boiling conditions has been observed for alkali metals [5, 6]. A transition from conditions of natural convection to film-type boiling, bypassing nucleate boiling conditions, has been observed to pressures of ~ 1.7 bar.

The present article sets forth the results of an experimental investigation of this phenomenon, with the aim of determining the regions of heat fluxes, with which the appearance of a vapor phase after single-phase natural convection leads to the formation of a stable vapor film on the heat-evolution surface.

The experiments with liquid metals were carried out in a unit of which a schematic diagram and a detailed description are given in [7]. The tests with cesium were carried out in a working section made of stainless steel and with a diameter of 11 mm, and with potassium in a working section with a diameter of 14 mm made of molybdenum. The purity of the surface of the working sections corresponded to approximately the sixth class. The volume in which the boiling of the metal was carried out was irradiated with x-ray beams, and the x-ray image was transferred to the screen of an electron-optical converter, with which visual observations were made of the processes under investigation. The experiments with nonmetallic liquids (benzene, ethanol, carbon tetrachloride) were carried out in a unit described in detail in [8], with the sole change that the working volume was put into a thermostat. The experiments were carried out in horizontally arranged sections with diameters from 0.1 to 10 mm, whose heat-transfer surface was polished up to a purity corresponding to the tenth class. Before filling of the unit by the liquid, the working volume and the working section were carefully washed. After filling of the unit with the working liquid, it was degasified. The usual pretreatment of the working section was not carried out, to avoid the

---

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 69-73, January-February, 1972. Original article submitted August 30, 1971.

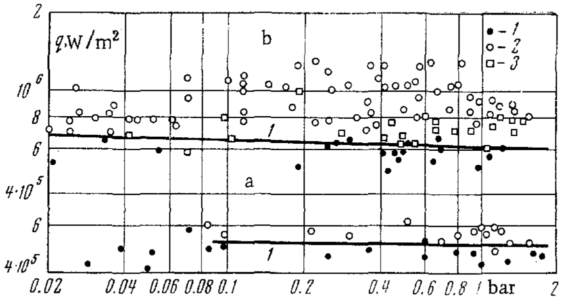

Fig. 1

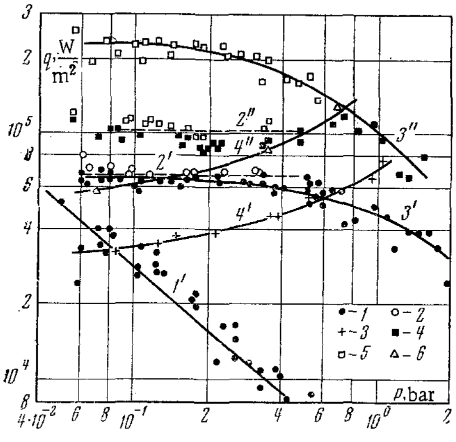

Fig. 2

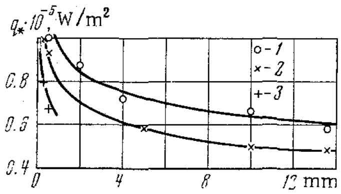

Fig. 3

formation of stable vapor-formation centers on the surface. All the measurements were made at the saturation temperature. The feed to the working sections was effected maintaining a constant flow. The working sections were charged smoothly. The formation of a vapor film was recorded from the sharp increase in the temperature of the surface of the working section and visually.

Figure 1 gives the results of experiments with cesium (a) and with potassium (b): 1) transition from single-phase convection conditions to unstable boiling; 2) transition from single-phase convection conditions to film-type boiling; 3) transition to film-type boiling after the stop of unstable boiling.

Figure 2 gives plots of the experimental data for ethanol in a working section with a diameter of 10 mm: 1) transition to nucleate boiling; 2) formation of a stable vapor film; 3) q^* and a diameter of 0.5 mm; 4) transition to nucleate boiling; 5) transition to film-type boiling; 6) q^*. In a "fresh" section, temperature superheating of the liquid, preceding the formation of a vapor phase after single-phase natural convection, was rather small, and nucleate boiling conditions were obtained. Thus, on Fig. 2, curve 1' averages data obtained in a fresh section with a diameter of 10 mm. However, as the experiments were carried out, the superheatings necessary for boiling increased (obviously as a result of the elimination of the residual gas from the microdepressions of the heating surface) until, with the attainment of determined heat fluxes, a stable vapor film was not formed after conditions of single-phase natural convection.

Values were obtained for the minimal heat fluxes, at which the appearance of a vapor phase after single-phase natural convection led to the formation of a stable vapor film q_* (curve 1 on Fig. 1a, b; curves 2', 2'' on Fig. 2). It is evident that for these curves, no significant dependence on the pressure is observed, either for alkali metals or for nonmetallic liquids. Thus, with heat loads $q < q_*$, the appearance of a vapor phase led to a system with nucleate boiling conditions, and, with $q > q_*$, to film-type boiling conditions. With treatment of the section, the temperatures of the walls and, correspondingly, the heat fluxes increased, and there was a broadening of the range of pressures at which there occurred a transition from single-phase natural convection to film-type boiling. Curves 3' and 3'' on Fig. 2 average the experimental data obtained when further operating time has practically no effect on the measured values.

During the course of the experiments, measurements were also made of the heat fluxes at which there occurs a breakdown of the vapor film q^* (curves 4' and 4'' in Fig. 2). It is evident from the curves that at lowered pressures there is hysteresis; i.e., the formation of a stable vapor film after single-phase natural convection takes place at higher heat fluxes than its breakdown. For drops a single point was measured, corresponding to the second critical density of the heat flux q^* (2.4×10^5 W/m^2 at $p = 0.023$ bar), which was also found to be considerably lower than q_*. Thus, for each working section a region was defined, bounded from below by the values of q_* (curves 2' and 2'' on Fig. 2) and on the right by the values of q^* (curves 4' and 4'' on Fig. 2), for heat fluxes for which the appearance of a vapor phase after single-phase natural convection will lead to the formation of a stable vapor film. The upper boundary is determined by the limiting degrees of superheating of the liquid at the heating surface. The formation of a vapor film after conditions of single-phase natural convection can occur also at higher pressures, but they are hydrodynamically unstable ($q < q^*$) and, with increasing from the region of unstable vapor films, their lifetime decreases.

Analogous regions for heat fluxes, at which the degeneration of nucleate boiling conditions is possible, were determined in working sections for benzene, carbon tetrachloride, and ethanol. In all cases, the curves for q_* do not exhibit any significant dependence on the pressure. Figure 3 gives values of q_* as a function of the diameter of the working section for ethanol (1), benzene (2), and carbon tetrachloride (3). It is evident that the dependences $q_* = f(d)$ are found to be identical for these liquids: the minimal heat flux at which degeneration of nucleate boiling conditions is possible increases with a decrease in the diameter of the working section.

The formation of a vapor film after conditions of single-phase natural convection at lowered pressures takes place explosively, with a characteristic noise; this is obviously explained by the large degrees of superheating preceding the formation of the vapor phase. Thus, for ethanol, in a pretreated section with a diameter of 4 mm, the temperature under these conditions was ~ 160°C, which corresponds to a pressure in an equilibrium nucleus of a bubble, before its sudden growth, of ~13 bar. The process of the formation of a vapor film, after conditions of single-phase natural convection, takes place quite rapidly, and it is impossible to detect visually the intermediate stages of its development. Thus, for alkali metals, at the moment of the formation of a vapor film, there was recorded visually only the instantaneous illumination of the whole volume of liquid around the working section irradiated by the x-ray beams; this argues for the formation of a large amount of the vapor phase, after which the temperature of the wall rose sharply, and the feed of the working section was disconnected. Visual observations of this phenomenon for nonmetallic liquids recorded only the onset of film-type boiling.

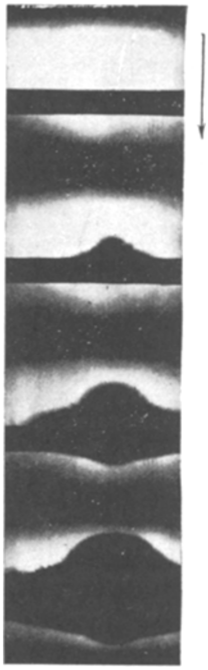

Fig. 4

High-speed moving-picture photography made it possible to follow this phenomenon in more detail. Figure 4 shows a series of consecutive photographs, illustrating the appearance of the vapor phase for benzene on the surface of a working section with a diameter of 5 mm, with $p = 0.15$ bar and $q = 0.9 \times 10^5$ W/m^2. In these photos, the light field is the liquid phase, the dark field is the vapor phase, and the dark band is the working section. The interval between frames was 5×10^{-4} sec. It is evident that the rapid growth of a vapor-formation nucleus at any point of the surface (the point of nucleation of the vapor phase varied in different tests) initiates the growth of adjacent nuclei in the heated layer of liquid near the wall, bringing about a process of foam-type boiling, propagating over the whole surface at a high velocity. After the rapid growth of the vapor cloud and its increase up to considerable dimensions (beyond the limit of a frame), it is densified and somewhat decreased in volume due to coalescence of vapor bubbles and to a decrease in the liquid interlayers in the vapor cloud. The layer of liquid remaining on the heat-transfer surface is vaporized as a result of its isolation from the main mass of the vapor cloud, and the temperature of the surface starts to increase rapidly. Therefore, after breakaway of the vapor bubble forming on the surface, film-type boiling is established. The duration of the whole process, from the nucleation of the vapor phase to the establishment of film-type boiling, is ~ 0.1 sec.

The experiments showed that the phenomenon of the degeneration of nucleate boiling can take place at pressures greater than atmospheric. For example, for carbon tetrachloride in a working section with a diameter of 0.5 mm, degeneration of nucleate boiling conditions was observed to pressures of ~ 2 bar, while for ethanol in a working section with a diameter of 4 mm, the formation of hydrodynamically unstable films after single-phase convection occurred at pressures of ~ 3 bar. This obviously permits drawing the conclusion that the phenomenon of degeneration of nucleate boiling conditions is determined not so much by the special characteristics of the boiling, characteristic of a deep vacuum, as by the special characteristics of a vapor phase in a strongly superheated layer of liquid near the wall (see Fig. 4). Earlier, for nonmetallic liquids, this type of phenomenon had been observed only at lowered pressures and in small-diameter sections. This is explained by the fact that under the above conditions, as a result of the inhibition of the process of nucleus formation, high degrees of superheating are readily achieved ($\Delta T \geq \Delta T_*$), at which the formation of a stable vapor film is more possible than in large-diameter sections and at higher pressures. In recent years, a number of authors [9, 10], in the investigation of heat transfer with the forced flow of alkali metals in tubes, have observed a sharp worsening of the heat transfer, due to the formation of a vapor phase after single-phase convection. Both phenomena are obviously of a similar physical nature.

LITERATURE CITED

1. S. J. D. Van Stralen, "Heat transfer to boiling binary liquid mixtures at atmospheric and subatmospheric pressures," Chem. Engng. Sci., 5, 290-296 (1956).
2. J. H. Lienhard and V. E. Schrock, "The effect of pressure, geometry, and the equation of state upon the peak and minimum boiling heat flux," Trans. ASME, Ser. C, J. Heat Trans., 85, No. 3, 261-272 (1963).
3. C. J. Rallis and N. N. Jawurek, "Latent heat in saturated nucleate boiling," Internat. J. Heat Mass Trans., 7, No. 10, 1051-1068 (1964).
4. N. N. Mamontova, "The boiling of liquids at lowered pressures," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3, 140-144 (1966).
5. V. N. Moskvicheva, G. I. Bobrovich, B. P. Avksentyuk, and N. N. Mamontova, "Investigation of the boiling process of alkali metals," Preprint, Institute of Thermophysics, Siberian Division, Academy of Sciences of the USSR, Novosibirsk (1968).
6. G. I. Bobrovich, "Critical heat fluxes with the boiling of liquid metals," in: Turbulence near the Wall [in Russian], Izd. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1968).
7. G. I. Bobrovich, B. P. Avksentyuk, and N. N. Mamontova, "On the mechanism of boiling of liquid metals," Papers JSME, Semi-Internat. Sympos. Tokyo, 1967, Vol. 2; Tokyo S. A., pp. 171-178.
8. G. I. Bobrovich, I. I. Gogonin, S. S. Kutateladze, and V. N. Moskvicheva, "Critical heat fluxes with the boiling of binary mixtures," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 4, 108-111 (1962).
9. K. Schleisiek, "Heat transfer and boiling during forced convection of sodium in an induction-heated tube," Nucl. Engng. and Design, 14, No. 1 (1970).
10. H. Kottowski, Über die Ausbildung einer Restschicht beim Sieden von Alkalimetallen in Kanälen. Atomkernenergie, 15, No. 2, 131-137 (1970).