

SOME FEATURES OF THE GAS-PHASE SATURATION OF A TWO-PHASE BOUNDARY LAYER

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**ABSTRACT:** In [1] the author reported that, as follows from the hydrodynamic theory of burnout, the processes of boiling and bubbling are physically related with respect to the general development of the critical transition from a nucleate to a film boundary layer structure. This paper presents certain results of a study of the variation of the gas content of a two-phase boundary layer in both boiling and bubbling through a porous plate over a wide range of loads.

1. The process of saturation of the wall layer with vapor in boiling and with gas in bubbling was studied on an apparatus similar in design to the described in [1]. The only difference was that in this case it was possible to conduct both boiling and bubbling experiments simply by changing the working section. The method of measuring the quantities required for calculating the gas content close to the heating surface in boiling or the porous plate in bubbling was based on the relationship between the electrical conductivity of a two-phase mixture and the concentration of vapor (gas) bubbles.

As a pickup we used a constantan wire probe 20 microns in diameter, which was placed at a distance  $\sim D_0/2$  above the heating surface or the porous plate. Alternating voltage at audiofrequency was supplied to the probe and the porous plate (in boiling, the heating plate).

By measuring the electrical conductivity of the two-phase wall layer we were able to obtain data on the change in gas (vapor) content over the entire load interval. Bubbling and boiling experiments were performed on distilled water, ethanol, methanol, and acetone.

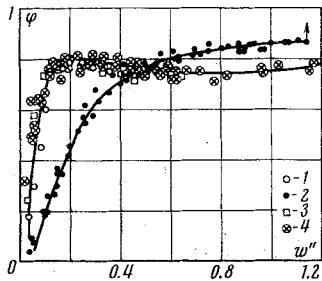


Fig. 1. Boiling: 1) ethanol; 2) water; bubbling through a porous plate: 3) ethanol; 4) water.

Figure 1 shows typical curves of the variation of gas content  $\varphi$  for boiled and bubbled ethanol (these correspond with the data obtained for methanol and acetone) and distilled water. The reduced velocity  $w''$  m/sec (for boiling  $w'' = q/\gamma''$ ) is plotted along the x axis, and the gas content  $\varphi$  along the y axis.

Clearly, the variation of the gas content during bubbling is qualitatively the same and quantitatively similar. A certain difference is observed in boiling water. The gas content curve corresponding to the boiling and bubbling of, for example, is characterized by an increase to a maximum followed by a slight fall, whereas the curve representing the variation of  $\varphi$  during the boiling of water displays a monotonic increase over the entire load interval and has no extrema.

However, in spite of the somewhat different variation of  $\varphi$  (the reasons for this effect will be discussed below), both in boiling and in bubbling it is possible to distinguish two stages of saturation of the two-phase wall layer. The first stage is a region of free rise of the bubbles without appreciable interaction, the second stage a region of intense interaction and combining of the bubbles.

The similarity of the variation in gas content and the existence of two saturation regions of different intensity becomes more obvious if the experimental data are presented in dimensionless form (Fig. 2).

Here  $\varphi$  and  $w''$  are the gas content and reduced velocity of the light component corresponding to the conditions of transition from a nucleate to a film structure. It is clear that the bubbling and boiling data are satisfactorily grouped about a single curve. The only exceptions are certain points for boiling water, which in the region of the "hump" on the curve lie somewhat lower (connected by broken line).

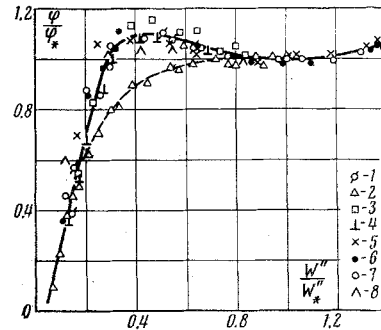


Fig. 2. Boiling: 1) ethanol; 2) water; 3) acetone; 4) methanol; bubbling through a porous plate: 5) water; 6) ethanol; 7) methanol; 8) acetone.

The experimental data indicate that the change in gas (vapor) content is mainly determined by two quantities: the specific density of the active sites (sources of bubbles)  $n/F$  and the diameter of the rising bubbles  $D_0$ .

In fact, if we restrict ourselves to an arbitrary rectangular volume of height  $D_0$  and area  $F$  near the porous plate or heating surface, then

$$\varphi = \frac{V''}{V' + V''} = \frac{\pi}{6} \frac{n}{F} D_0^2. \quad (1)$$

Since in the first region  $D_0 = \text{const}$ ,  $\varphi$  is a linear function of  $n/F$ , which, in its turn, is determined by the vapor or gas load. The variation of  $\varphi$  departs from linearity when the combining of bubbles begins to play an important part. When the agglomeration of bubbles becomes the dominant process, the quantity  $n/F$  approaches its maximum value, and the variation of  $\varphi$  is determined by the size of the rising bubbles.

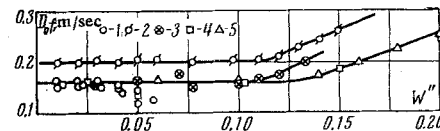


Fig. 3. Bubbling through perforated sheets: 1) mercury-water; 2) water-air,  $26.5 \cdot 10^5$  N/m<sup>2</sup>; 3) water-air  $40.0 \cdot 10^5$  N/m<sup>2</sup> (Central Boiler-Turbine Institute experiments); bubbling through a porous plate: 4) water-nitrogen; boiling: 5) ethanol.

During boiling, in the region of intense interaction when all the heat is expended in the generation of steam

$$\frac{n}{F} = \frac{6q}{r\gamma''} \frac{1}{\pi D_0^3 f} = \frac{6w''}{\pi D_0^3 f}. \quad (2)$$

Substituting (2) in (1), we obtain

$$\varphi = w'' / D_0 f, \quad (3)$$

Thus, in the second region the vapor (gas) content is determined by the ratio of the reduced vapor (gas) velocity to the product of the bubble diameter  $D_0$  and the bubble frequency at the given point. The product  $D_0 f$  has the dimension (m/sec) and is identical with the relative bubble rise velocity.

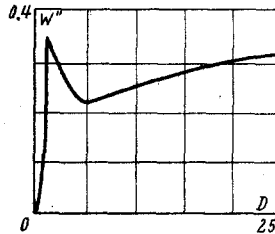


Fig. 4. The relation  $w''_0 = f(D_0)$ .

Values of  $D_0 f$  (m/sec) calculated from the experimental data using equation (3) are shown in Fig. 3 in the form of a graph of  $D_0 f = F(w'')$ . This figure includes data on bubbling through perforated sheets in the systems water-air (various pressures) and water-mercury, on the bubbling of air into water through a porous plate, and on the boiling of ethanol. It is clear that in the free-rise region  $D_0 f$  also remains constant (i.e., the bubbles rise in isolation), while in the region of intense interaction the same quantity increases linearly with the load. It is also clear that over the entire load interval  $D_0 f$  is greater than the reduced velocity.

In the first region the amount by which  $D_0 f$  exceeds the reduced vapor (gas) velocity decreases with increase in load and at the end of this region assumes a certain value, which subsequently (in the second region) remains unchanged.

Since in the free-rise region  $D_0 f = \text{const}$ , the gas content can be determined from Eq. (3) in this case, too. The quantity  $\varphi$  ceases to be proportional to the reduced velocity only as the process of bubble combination develops, when  $D_0 f \neq \text{const}$ .

The gas content at which combining of the bubbles begins to have an appreciable effect on the saturation process is easily determined from the following consideration: at the load which causes intense agglomeration the quantity  $n/F$  becomes so large that the growing bubbles almost cover the entire surface. In this case

$$\frac{n}{F} \approx \frac{4}{\pi D_0^2}.$$

Substituting this value in (1) gives

$$\varphi \approx 2/3. \quad (4)$$

This value of  $\varphi$  is close to that obtained experimentally. Consequently, in the region  $0 \leq \varphi \leq 2/3$  the heat transfer process during boiling under conditions of natural conduction depends mainly on the specific density of the vaporization sites  $n/F$ , which form, as it were, heat sinks.

In the second region the gas content changes little (10–15%) and may be taken equal to  $\varphi \approx 0.8$ . Since in this region  $n/F$  approaches its maximum value, while the fraction of the flow cross section occupied by liquid remains almost constant, it is obvious that heat transfer in the second region is determined by the intensity of turbulent washing of the heating surface by liquid from the pool.

2. Above, we noted a certain singularity of the saturation of the two-phase boundary layer in boiling water. The reasons for this effect are examined below.

In the first region the gas content depends on the quantity  $n/F$ , which can be determined from relation (2). From the latter it is

clear that  $n/F$  for different liquids is inversely proportional to the heat of vaporization  $r$  and the breakaway diameter of the bubble

$$D_0 \sim \sqrt{\sigma/(\gamma - \gamma')}.$$

For water  $r$  and  $\sigma$  have considerably higher values than for alcohols and a number of other liquids. Therefore, the number of vaporization sites in boiling water is relatively small, and their number increases more slowly with the load, since each individual site is a more powerful heat sink. The slowness of the growth of  $n/F$  considerably weakens the rate of increase of gas content with increase in load.

In boiling alcohols and other liquids, on the other hand, a larger number of vaporization sites is formed to carry away the same amount of heat (since  $r$  and  $\sigma$  have lower values). In this case the growth of the number of vaporization sites with increase in heat load is more intense, which leads to a sharper increase in  $\varphi$ . Therefore, for boiling water the curve  $\varphi = f(w'')$  has a flatter slope in the first region. The difference in the sizes of the primary bubbles in different boiling liquids also has an effect on the nature of the variation of the gas content. The effect of bubble size is expressed through the rise velocity.

Figure 4 shows the well-known relation  $w''_0 = f(D_0)$ . It is clear that this is quite complex in character and can be divided into three regions: a region of Stokes velocities, an intermediate or transition region, and a region of fluctuating motion of the bubbles. The dimensions of the rising bubbles vary with increase in heat flux; therefore, each value of  $q$  corresponds to a definite rate of removal of the bubbles from the wall region. However, as may be seen from (3), the gas content in the boundary layer depends on the bubble rise velocity.

It is known from experiments that in boiling ethanol the overwhelming majority of the bubbles formed are less than 2 mm in diameter. Numerous small bubbles rapidly fill the boundary layer and even at comparatively small loads create the conditions for maximum occupation of the wall region by the gaseous medium. As  $\varphi_{\text{max}}$  is approached, the motion of the bubbles is constricted; therefore they begin to combine, forming larger secondary bubbles. The velocity of the newly formed bubbles will differ from the rise velocity of the original bubbles and, depending on size, will correspond either to the intermediate region (then the rise velocity will decrease, and  $\varphi$  will increase) or to the fluctuation region (when the rise velocity increases somewhat, while the gas content decreases). The dimensions of the secondary bubbles and, hence, their velocity will depend on the dimensions of the primary bubbles and the number of primary bubbles that combined to form a new bubble.

At first, since, when alcohols boil the dimensions of the primary bubbles are small, combination produces new bubbles with dimensions corresponding to the intermediate region of the graph  $w''_0 = f(D_0)$ ; therefore the gas content increases not only as a result of an increase in  $n/F$ , but also as a result of a decrease in the rate of removal of the vapor phase. Hence, for alcohols  $\varphi_{\text{max}}$  is reached at loads remote from the critical regime. However, when the heat load increases to the value at which not only primary but also secondary, etc. bubbles begin to combine, the conditions exist for the production of bubbles with a diameter of 5 mm or thereabouts. Then the bubble rise velocity begins to increase again, while the gas content decreases. The existence of such changes in the velocity of the rising bubbles is also a reason for the presence of a sort of "hump" on the  $\varphi = f(w'')$  curve.

In boiling water, as already mentioned, the bubbles are much larger but more thinly distributed over the heating surface. Therefore, the process of bubble growth is protracted and not so intense as the boiling of alcohols. Moreover, the formation of new bubbles close to 5 mm in diameter requires a much smaller number of primary bubbles (for boiling water the diameter of the primary bubbles is 2.5–3.0 mm), i.e., the transition to the fluctuation region is more rapid.

For these reasons the effect of a change in bubble rise velocity is much weakened, and in boiling water  $\varphi$  increases monotonically. The accumulation of vapor in the boundary layer takes place slowly, without fluctuations, and does not lead to the formation of a "hump" on the  $\varphi = f(w'')$  curve.

When various liquids, including water, are bubbled through a porous plate, the  $\varphi = f(w)$  curves are qualitatively quite analogous to the curve characterizing the boiling of alcohols. This is because the gas was blown into all the liquids through the same porous plate. In this case the breakaway diameter is given by [2]

$$R_0 = \left( \frac{3\sigma R_1}{2(\gamma' - \gamma'')} \right)^{1/2}, \quad (5)$$

i. e., the effect of surface tension forces is much weaker and proportional to  $\sigma^{1/3}$  (the bubbling process takes place without phase transitions).

It was established experimentally that for the different liquids the average dimensions of the bubbles formed at the micropores of the plate employed varied within the range 0.2–1.5 mm. The experiments also showed that in bubbling the ratio  $n/F$  increases with the load somewhat more rapidly than even for boiling alcohols (Fig. 1).

The decisive effect of the primary bubble size is also clear from a consideration of the experimental data on bubbling through perforated sheets. In these cases, as a rule, perforated sheets with openings not smaller than 2 mm are employed. The breakaway diameter of the bubbles formed at such openings is so great that the combination of no more than two bubbles may be sufficient to form a larger bubble more than 5 mm in size. Therefore in bubbling through perforated sheets the  $\varphi = f(w)$  curves vary smoothly. A decrease in the size of the openings in the perforated sheet leads to the appearance of a maximum of "hump" on the curve.

This is confirmed by the data of [6], in which it was established that, beginning with openings 0.5 mm or less in size, the  $\varphi = f(w)$  curves acquire a characteristic "hump."

## REFERENCES

1. I. G. Malenkov, "Critical phenomena in bubbling and boiling processes," PMTF, no. 6, 1963.
2. S. S. Kutateladze and M. A. Styrikovich, *Hydraulics of Two-Phase Systems* [in Russian], Gosenergoizdat, 1958.
3. G. B. Wallis, "Some hydrodynamic aspects of two-phase flow and boiling," *International Developments in Heat Transfer*, part II, 1961.
4. G. E. Sims, V. Aktürk, and Evans-Zutterodtko, "Simulations of pool boiling transfer by gas injection at the interface," *Internat. J. Heat and Mass Transfer*, vol. 6, no. 3, 1963.
5. N. Zuber, "Nucleate boiling. The region of isolated bubbles and the similarity with natural convection," *Internat. J. Heat and Mass Transfer*, vol. 6, no. 1, 1963.
6. N. Zuber, "The problem of hydrodynamic diffusion in two-phase flow," *Proc. All-Union Conf. on Heat and Mass Transfer* [in Russian], Minsk, 1964.

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