NUCLEATION OF GAS AND VAPOR BUBBLES DURING MOTION OF FLUID IN POROUS METALS

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Results are presented of an analytical and experimental study concerning the conditions under which gas and vapor bubbles nucleate during motion of a fluid in porous metals.

One effective method of intensifying the processes of heat and mass transfer is organization of the flow of the heat carrier in porous materials with a large developed intraporous surface. Either one-phase or evaporating streams of fluid can be used here. An important item in these processes is nucleation of gas and vapor bubbles. Emergence and growth of gas bubbles, for instance, results in formation of a two-phase stream with a higher drag, while nucleation and growth of vapor bubbles determine the location of the evaporation front in porous heat exchangers. Here will be presented results of a study concerning the conditions under which gas and vapor bubbles nucleate during the flow of water in porous metals.

Emergence of a vapor nucleus within the bulk of saturated liquid or at a surface element of the solid phase is fluctuational in nature. The probability of emergence of such a nucleus is proportional to $e^{-L/kT}$, where L denotes the work of bubble formation. At the liquid–solid interphase boundary the molecular bond is weaker and work of bubble formation, equal to the change in the system's thermodynamic potential $\Delta\Phi$ due to appearance of a bubble, is smaller than within the bulk of liquid. This work can be calculated [1] according to the relation

$$\Delta\Phi = (f_V - f_L)\rho V + \sigma S\left[1 - \frac{S_w}{S}(1 - \cos\theta)\right]. \tag{1}$$

Here f_V and f_L are the chemical potentials of the vaporous phase and the liquid phase, respectively; ρ, density of the vapor; V, S, respectively, the volume and the total surface area of a bubble; S_W, surface area of contact between a bubble and the solid phase; σ, coefficient of surface tension; and θ, critical wetting angle.

The second term on the right-hand side of expression (1) characterizes the work of bubble surface formation, which can depend on physicochemical properties (θ) and on geometrical properties (S_W/S) of the surface. Expression (1) defines two trends of activities affecting the nucleation process: 1) deterioration of local wettability (increase of angle θ) and 2) creation of conditions favorable to an increase of the contact surface S_W/S between a bubble and the solid phase. It has been demonstrated [1], specifically, that a deterioration of local wetting ($\theta \geq \pi/2$) and a presence of microcraters of the simplest conical shape facilitate nucleation of the vaporous phase without superheat during thermodynamic equilibrium.

Expression (1) has been derived theoretically and validated qualitatively in experiments with formation of vapor bubbles at a heated surface during boiling, but it is entirely applicable to nucleation of gas bubbles in a liquid saturated with gas as well. In the latter case, however, the process is characterized by some unique features. Firstly, nucleation of gas bubbles is more difficult, owing to the low concentration of dissolved gas. The state of equilibrium saturation of a liquid with dissolved gas is determined not only by the pressure and the temperature but also by the concentration of dissolved gas, which under usual conditions is difficult to monitor.

Porous metals most readily meet the requirements which create conditions favorable to nucleation of bubbles, in terms of geometrical structure (this is obvious) and largely in terms of numerous segments of deteriorated wettability. The technology of producing porous metals involves destroying the microstructure of the metal and formation of inhomogeneities, in terms of chemical composition, near metal particles and oxide films. It has been demonstrated [2] that such effects cause appreciable changes in the wettability. Considering that only a 0.1–1.0-μm large segment of deteriorated wettability is needed for formation of a gas bubble, one

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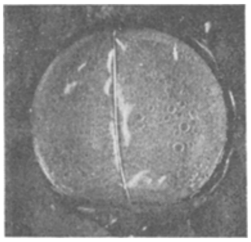

Fig. 1. Release and accumulation of air bubbles at the outside surface of a metal specimen.

can regard all points of contact between particles in a porous metal as potential bubble nucleation centers.

During formation of a gas bubble within a narrowing microcrater with poorly wettable lateral surfaces ($\theta > \pi/2$) the gas pressure can be much lower in that microcrater than in the liquid. In this case the gas bubble will remain alive even when the saturation of the liquid with dissolved gas has dropped below the equilibrium level. As the liquid returns to its saturation or oversaturation state, such a bubble will act as a permanent center of release of dissolved gas.

Experimental Procedure

The experiments for the purpose of establishing the conditions of nucleation of gas and vapor bubbles during motion of a liquid in porous metals were performed using water distillate at two levels of saturation with dissolved air: saturated water and deaerated water. Saturation with air under atmospheric pressure at 20°C was attained by lengthy stirring and subsequent standing, to remove the air bubbles. Deaeration was effected by preliminary heating of the water to 80°C and subsequent cooling in a closed tank under vacuum.

Flow of water through a specimen was produced by two methods.

1. Water was driven by a batching pump from the tank through a hydraulic test stand and heated here under pressure in the heat exchanger of a thermostat, prior to being fed to a metal specimen, whereupon it was pushed through that specimen under atmospheric pressure at the outlet. The temperature of the water was measured with a thermocouple installed inside the specimen. The mass flow rate of water was varied over the 1-10 $\text{kg/m}^2\cdot\text{sec}$ range.
2. Water from a translucent open tank under atmospheric pressure at 20°C was driven through a metal specimen by the vacuum at the outlet surface of that specimen.

Oversaturation of water with dissolved air during flow through a porous specimen occurred in both methods as a result of a drop of pressure. The pattern of water discharge at the outlet surface of metal specimens was observed visually and photographed. In the first method was recorded the water temperature at which the smallest visible single air bubbles began to appear at the outlet surface; in the second method was recorded the pressure at the outlet surface at which visible single air bubbles began to appear in the stream behind the specimen.

The test specimens in both methods had the shape of disks. The parameters of these specimens are given in Table 1. Specimens 1-5 were used in the second method only, specimens 6-8 were used in the first method.

Results of Experiments

First Method with Saturated Water. The water temperature at which the smallest visible air bubbles begin to form at the outside surface of a specimen depends on the conditions of the experiment. When the water temperature rises continuously above 20°C, then visible bubbles appear at 38-45°C. As the water temperature rises further, the number of bubble formation centers, as well as the size of bubbles and their rate of growth, all increase. At mass flow rates of water below 5 $\text{kg/m}^2\cdot\text{sec}$ the bubbles gradually grow to a diameter of nearly 1 mm, whereupon they separate and are carried away by the stream. An abundant release and accumulation of bubbles at a vertical outside surface of a specimen under a film of liquid descending along it during flow of warm saturated water is shown in Fig. 1. The diameter of the wire at the surface serving as a scale is 0.45 mm. At mass flow rates above 5 $\text{kg/m}^2\cdot\text{sec}$, the minute bubbles do not remain at the surface but are immediately carried away by the stream.

TABLE 1. Characteristics of Test Specimens (1-7 bronze, 8 stainless steel)

Species no.	Raw powder fraction, μm	Porosity	Thickness, mm	Diameter, mm	Mean pore size, μm
1	50—63	0,295	8,70	21	15,5
2	63—100	0,308	8,60	21	23,5
3	100—160	0,285	8,40	21	34,0
4	160—200	0,358	9,07	21	65
5	200—315	0,408	9,90	21	110
6	50—63	0,215	14,8	28	10,2
7	63—100	0,335	20,10	28	26,5
8	63—100	0,424	9,50	28	14,2

When the water temperature drops after a lengthy flow with release of bubbles, the release of bubbles ceases at a much lower temperature (28-29°C), identically for all specimens in this study. It is important to note that now visible bubbles cease to appear whether this temperature has been approached from above or from below. The equilibrium concentration of dissolved air in water under total atmospheric pressure of air and water vapor increases insignificantly as the temperature rises from 20 to 28°C, remaining at 87% of the equilibrium level of the original state.

This hysteretic change of the temperature at which visible bubbles appear from approximately 40 to 28°C can be explained by an appearance of the first air nuclei inside the porous structure due to an appreciable oversaturation. Then, after a gradual formation and accumulation of numerous air bubbles, the conditions of release of dissolved air during flow of water through porous metal begin to approach the equilibrium conditions. This results in a lower temperature at which the smallest air bubbles will appear at the outside surface of a metal specimen.

It is also noteworthy that in many experiments with saturated water within the 20-50°C temperature range, with interchanging of specimens without a hot water rinse, the temperature at which visible bubbles begin to appear drops to 26-28°C and the concentration of released bubbles increases: indications of "aging" of specimens.

First Method with Deaerated Water. The temperature of stable appearance and collapse of visible bubbles is rather high, viz. 92-93°C, for all specimens in this study. It has not been possible to establish a noticeable dependence of the temperature at which bubbles begin to appear on the conditions of the experiment. The equilibrium concentration of dissolved air in water under atmospheric total pressure at 92°C is 16% of its equilibrium level at 20°C.

Second Method with Saturated Water. The pressure at the outlet surface of specimens at which the smallest visible air bubbles begin to appear in the stream behind that specimen depends on the conditions of the experiment.

Saturated water is passed through after deaerated water has flown through, and the change of water is effected in such a manner that no air leaks into the specimen. Now, during flow of saturated water bubbles begin to appear at a pressure of 0.02 MPa behind the specimens, almost the same pressure for all five specimens. The bubbles do not dwell on the surface of a specimen, moreover, but are carried away from the specimen by the stream. When the pressure behind a specimen is maintained constant after bubbles have appeared, then the number and the size of bubbles in the stream will gradually increase. When the discharge flow pattern with few bubbles appearing is to be maintained unchangeable after these bubbles have appeared, this requires a continuous raising of the pressure behind the metal specimen. Within approximately 2 min this pressure reaches its critical level of 0.089 MPa. After this state has been reached, this pressure of 0.089 MPa will correspond to a vanishing of bubbles upon a further rise of the pressure as well as to appearance of bubbles upon a drop of the pressure from levels higher than that. This pressure level is, moreover, almost the same for all five specimens.

When the pressure behind a metal specimen is gradually lowered, after the stable state has been reached, then the number and the size of bubbles in the stream increase so that the stream becomes a distinctly two-phase one (Fig. 2). The specimens have in this case been hermetically mounted at the inlets to glass tubes and the latter numbered consecutively from the left to the right. The stream is upward in each.

It is interesting to note that the oscillatory decrease of pressure with an amplitude larger than 0.002 MPa, a phenomenon qualitatively observable during discharge flow of a two-phase stream from a metal specimen, is

Fig. 2. Two-phase stream with air bubbles behind specimens 1-5.

accompanied by an emission of a bubble "cloud" from the specimen. The intensity of such an emitted bubble cloud increases with increasing amplitude of pressure oscillations and with decreasing pressure behind the specimen; it also depends on the characteristics of the specimen.

Saturated water is passed through a dry specimen or after the latter has been scavenged with air. Now, large air bubbles first appear in the stream and then vanish. Then, as the pressure is lowered, the smallest bubbles appear in the stream at a pressure of 0.075 MPa, identically for all specimens. The pattern repeats itself completely and the pressure at which bubbles appear increases to the same as before critical level of 0.089 MPa. Therefore, scavenging of metal specimens with air raises the minimum initial pressure at which bubbles appear from 0.02 to 0.075 MPa.

All these phenomena attending the flow of saturated water according to the second method can be explained as follows. After passage of deaerated water through a metal specimen there are no air bubbles found in the latter. As saturated water is then fed to that specimen, there initially occurs a massive nucleation of first air bubbles due to appreciable oversaturation. Then, as bubbles form and accumulate in the porous structure, the conditions of release of dissolved air approach the equilibrium conditions. This in turn causes either a continuous increase of the number of bubbles in the stream under a constant pressure behind the metal specimen, or a gradual increase of the pressure at which the smallest bubbles will be carried away by the stream.

The oscillatory decrease of pressure behind a metal specimen causes an oscillatory increase of the flow rate, which in turn results in an expulsion of some bubbles from the porous structure in the form of a cloud.

As saturated water flows through a metal specimen, after the latter has been scavenged with air, the main part of air is expelled from the tunnel pores by the stream in the form of large bubbles. The air bubbles which remain in semiclosed pores facilitate a fast establishment of conditions under which equilibrium release of dissolved air occurs, which then causes visible bubbles to appear in the stream at the rather high pressure of 0.075 MPa.

The equilibrium concentration of dissolved air in water at the critical pressure at which bubbles appear in the stable mode is, according to Hertz's law, 89% of its equilibrium level in the original state. This figure is very close to the 87% obtained by the first method.

Second Method with Deaerated Water. Flow of deaerated water has been set up only through metal specimens with a high initial air content inside the porous structure, through dry specimens or after passage of water saturated with air. In either case, air is initially expelled from tunnel pores in the form of large bubbles, and then the remaining air is dissolved in the water. This process is attended by a gradual lowering of the pressure and is completed when the pressure is still rather high. As the pressure drops further, visible bubbles appear in the stream at a pressure of 0.006 MPa. The pressure then rises to a stable critical level of 0.01 MPa, the same for all specimens, which corresponds to appearance and vanishing of bubbles. The same phenomena are observed here as during flow of saturated water, but here they occur at a much lower concentration of dissolved air. The equilibrium concentration of air under that pressure of 0.01 MPa is 10% of its level in saturated water under atmospheric pressure. This figure is close to the 16% obtained for deaerated water in the experiment according to the first method.

It is noteworthy that the pressure at which air bubbles nucleate in a stream inside a porous metal specimen exceeds the pressure at the outlet surface, inasmuch as bubbles nucleate and first grow inside the specimen to a size comparable with the mean diameter of pores before being carried by the stream to the outside surface.

Keeping this in mind and considering the closeness of results obtained by both methods, one can conclude

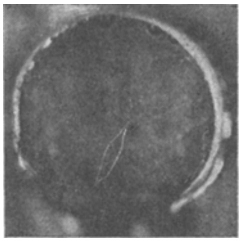

Fig. 3. Structure of two-phase vapor-water stream at the outside surface of a metal specimen during flow of deaerated water at 120°C.

that nucleation of gas bubbles in the stable mode, and subsequent release of dissolved air during flow of water in given specimens of porous metals, occur under conditions near those of equilibrium saturation.

The conditions of appearance of vapor bubbles were studied by the first method with gradual raising of the water temperature before the inlet surface of a specimen to 120°C. It has not been possible to determine the temperature at which vapor bubbles appear at the outside surface under atmospheric pressure because, after preliminary deaeration of the water under conditions of the experiment, there already appear vapor–air bubbles at temperatures of the water at the inlet surface as low as 92°C. As the temperature reaches 100°C, therefore, there always occurs an intense release of bubbles. At an initial water temperature of 100°C or higher there occurs a gradual transition from release of vapor–air bubbles to release of vapor bubbles. As the temperature of the water at the inlet surface rises from 100 to 102°C, both the number of bubble formation centers and the frequency of bubble separations from the surface increase so much that bubbles overshoot in chains and burst at the surface of the liquid film, forming here a ripple and a mist of microdroplets. The size of bubbles decreases in the process to a diameter of 0.1 mm. As the temperature rises further, continuous vapor microjets are discharged from almost every pore. The beginning of the zone of vapor bubble nucleation moves deeper then, from the outside surface of a metal specimen into its bulk where the higher pressure corresponds to the saturation state at the initial water temperature. The temperature of the outside surface remains constant and equal to the saturation temperature under atmospheric pressure. The liquid film on the surface of the metal specimen is made friable by the countless vapor microjets penetrating it and becomes white (Fig. 3). Noise is also generated and gradually intensified in the process.

Accordingly, formation of vapor bubbles inside porous metals studied here occurs under conditions of thermodynamic equilibrium. This is largely facilitated by preliminary formation of air and vapor–air bubbles.

The conclusion about prevalence of thermodynamic equilibrium during nucleation of vapor bubbles inside a porous metal has also been confirmed by the results of experiments with boiling of various liquids at heater surfaces with porous coatings: boiling of water [3-5], acetone and ethyl alcohol [5], and Freons [6]. It has been established in those experiments that the superheat of the heater surface to the temperature at which bubbles begin to appear at the surface of a porous coating is very small and amounts to 0.8-1.5°K. It is to be noted, moreover, that here the temperature of a continuous heater surface is measured. Consequently, the superheat of a porous material at the site of bubble nucleation is further decreased by the heat transfer from the continuous surface through conduction.

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VAPOR CONDENSATION ON PLATE DURING HORIZONTAL MOTION OF COOLANT

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An analytical study is made of heat transfer during vapor condensation on a vertical plate. An engineering method of verifying the heat transfer calculations is also shown.

We consider the problem of heat transfer during condensation of saturated vapor on a vertical plate while a coolant moves transversely relative to the descending condensate film. The same assumptions will be made here as those on which the derivation of the widely known Nusselt equation [1] is based. We will also assume that no stirring of the coolant occurs on the cooled side and that its temperature varies only in the direction of its flow. The latter condition is possible only in the case of laminar flow with a small vertical temperature gradient or with the stream subdivided into a large number of parallel channels.

The problem will be formulated as follows: it is required to determine the magnitude of heat transfer, the thickness of the condensate film, and the temperature of the coolant when on one side of the vertical plate there is vapor under pressure p_s (saturation temperature t_s) and on the other side the plate is wetted by a horizontal stream of coolant moving through a channel of width z at velocity w. The physical characteristics of the coolant are known and the temperature t_0 of the coolant at the entrance to this heat exchanger is given. This formulation of the problem is illustrated in Fig. 1.

The elementary quantity of heat expended on heating the coolant is

$$dQ = w\rho c_p z \frac{\partial t}{\partial y} dxdyd\tau = W \frac{\partial t}{dy} dxdyd\tau. \tag{1}$$

The same quantity of heat can be determined from the equation of heat transfer

$$dQ = K(t_s - t)\,dxdyd\tau = \frac{\lambda}{a+\delta}(t_s - t)\,dxdyd\tau, \tag{2}$$

where

$$K = \frac{1}{\frac{1}{\alpha} + \left(\frac{\delta}{\lambda}\right)_{\mathrm{w}} + \left(\frac{\delta}{\lambda}\right)_{\mathrm{f}}} = \frac{\lambda}{a+\delta}; \tag{3}$$

$$a = \left[\frac{1}{\alpha} + \left(\frac{\delta}{\lambda}\right)_{\mathrm{w}}\right]\lambda. \tag{4}$$

The parameter a characterizes both the thermal impedance and the heat transfer from wall to coolant.

Finally, according to the method used for deriving the Nusselt equation [1], the change in the rate of condensate flow in the film is

$$dm = \frac{g(\rho' - \rho'')}{3\nu} \frac{\partial \delta^3}{\partial x}. \tag{5}$$

The quantity of transferred heat will then be

$$dQ = r\frac{g(\rho' - \rho'')}{3\nu} \frac{\partial \delta^3}{\partial x}. \tag{6}$$

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*Deceased.

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