MECHANISM OF VAPOR BUBBLE CONDENSATION

IN A VAPOR–WATER MIXTURE UNDER IMPACT

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The mechanism and the cause of vapor bubble condensation in a vapor–water stream are analyzed. The causes (inertia of the liquid and heat transfer) actively contributing to condensation are examined. Experimental data are presented on the collapse of vapor bubbles in boiling water under impact.

The normal operation of heat exchangers in power plants deteriorates under impact.

The hydrodynamics of a vapor–water stream subjected to impacts of varying intensity was studied experimentally in a vessel with an 80 mm inside diameter and 750 mm high. Plain water was poured into the vessel and then heated to boiling under a given pressure with the aid of a Permalloy element. The thermal flux density was maintained constant at the element surface, $q = 0.5 \cdot 10^6$ W/m^2, in all tests.

In order to maintain a constant pressure in the vessel, a small condenser was placed in the vapor zone.

The behavior of the vapor–water mixture during and after an impact was observed through quartz glass windows and a model SKS-1M high-speed moving-picture camera was used for photographic recording at a rate of 1000-2000 frames/sec.

In additional to a visual inspection of the vapor bubbles, the pressure pulses in the liquid zone were measured at a certain marker height h = 30 cm from the free surface in the test cell. The liquid level was maintained the same in all tests: at the mid-height of the upper window.

Pressure pulses were measured with a low-inertia high-frequency small-size model TDD pressure strain gage hooked on to a model UTS-1VT-12 amplifier. The processes occurring during tests were recorded on an electromagnetic model N-102 oscillograph. At the same time, the temperature of the boiling water was measured with two Chromel–Alumel thermocouples in the lower and in the upper heater zone respectively.

An impact was effected on a special device where the test cell with the boiling water in it was struck against a base plate during a free fall. The magnitude of the resulting acceleration was measured with special transducers.

The velocity of the test cell changed suddenly during an impact and, as a result of high accelerations produced here, the dynamic effect on the mass of vapor–water mixture was strong. The impact strength was defined in terms of acceleration and pulse time, both depending on the free fall height of the test cell.

The pressure usually rose within 5-7 μsec and was picked up on the strain gage.

Such a pressure rise Δp amounted to 1.5-2.5 bar, depending on the imparted acceleration $a(t)$ (Fig. 1). The graph here indicates a slightly smaller Δp at higher static pressures p_0 in the system, because the pressure rise Δp depends on the weight of the water column and the specific gravity of water is lower at higher saturation pressures.

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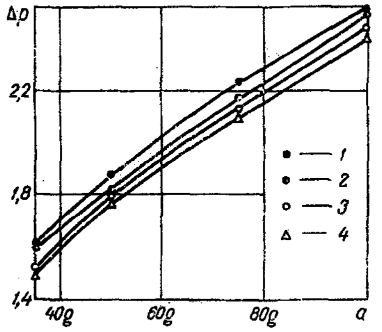

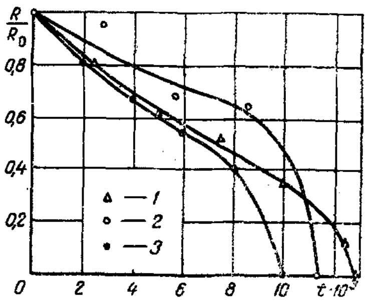

Fig. 1 Fig. 2

Fig. 1. Pressure rise Δp (bar) as a function of the imparted acceleration a (m/sec^2): p_0 = 1 bar (1), 10 bar (2), 20 bar (3), 30 bar (4).

Fig. 2. Relative radius of vapor bubbles as a function of the condensation time, at p_0 = 20 bar: a = 35 g (1), 50 g (2), 75 g (3).

The pressure level at the front of an impact wave can also be determined from the Second Law of mechanics. Thus, a pressure pulse recorded by a gage located at height h from the water level will be

$$\Delta p(t) = \frac{ma(t)}{F} = h\rho_{mix}a(t), \tag{1}$$

where $\rho_{mix} = \rho' - \bar{\varphi}(\rho' - \rho'')$.

The calculated values agree closely with the test data.

In our study $\Delta p(t)$ and $a(t)$ were determined experimentally, whereupon, when the liquid contained vapor bubbles, it was easy to determine by Eq. (1) the true vapor content in the test cell throughout the entire impact time:

$$\bar{\varphi} = \frac{\rho' - \dfrac{\dfrac{1}{\tau_1}\displaystyle\int_0^{\tau_1} p(t)\,dt}{h\dfrac{1}{\tau_2}\displaystyle\int_0^{\tau_2} a(t)\,dt}}{\rho' - \rho''}. \tag{2}$$

In the evaluation of oscillograms taken during the tests, the numerical values of integrals $\int_0^{\tau_1} p(t)\,dt$ and $\int_0^{\tau_2} a(t)dt$ were measured with a planimeter under the p(t) and a(t) curves.

The mean true vapor content during the tests varied within the $\bar{\varphi}$ = 0.2-0.3 range. With the aid of high-speed cinematography it was possible to establish that the vapor bubbles had assumed an irregular and hard to define shape during the free fall of the test cell. This was, evidently, due to an insufficiently far displacement of the generated vapor from the heating surfaces and a resulting merger of small bubbles into a bulkier vapor formation. For exactly this reason, the vapor bubbles still remaining at the heating surface had assumed a rather irregular shape. After separation from the heating surface, such bubbles became more distinct and symmetrical.

The initial bubble radii measured between 2 and 7 mm. The buoying velocity of the vapor bubbles before an impact was the same v_b = 0.434 m/sec, regardless of the difference in size. This agrees with the results of studies made by S. Usyskin and R. Siegel [1].

At the instant of impact there occurred a perturbation inside the bulk of liquid which traveled through the cavity volume filled with boiling water at saturation pressure and which acted on the vapor bubbles. As a consequence, all bubbles inside the test zone vanished within 10-15 μsec.

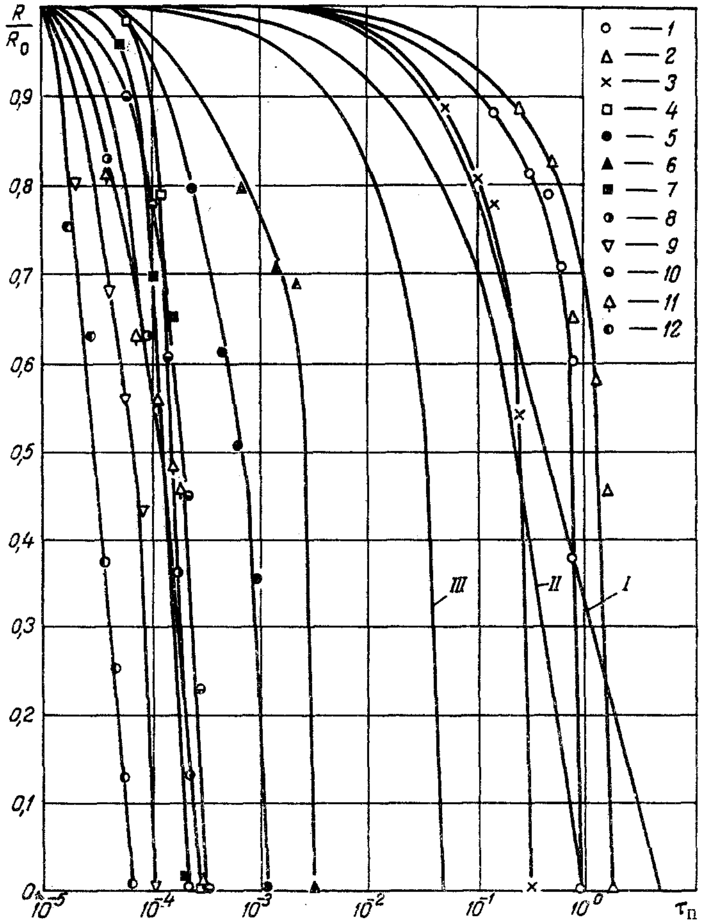

Fig. 3. Relative radius of vapor bubbles as a function of the dimensionless time parameter $\tau_N = (4/\pi)Ja^2Fo$: p = 1 bar and a = 35 g (1), p = 1 bar and a = 50 g (2), p = 1 bar and a = 75 g (3), p = 10 bar and a = 35 g (4), p = 10 bar and a = 50 g (5), p = 10 bar and a = 75 g (6), p = 20 bar and a = 35 g (7), p = 20 bar and a = 50 g (8), p = 20 bar and a = 75 g (9), p = 30 bar and a = 35 g (10), p = 30 bar and a = 50 g (11), p = 30 bar and a = 75 g (12).

According to the photographs, during an impact all bubbles separated from the heating surface and flowed into the main stream. At the same time, two other phenomena occurred here: condensation and buoyance of vapor bubbles. Moreover, an impact caused the velocity of bubble ejection from the test zone to become higher than the velocity of their free buoyance in a normal gravity field and caused it to vary from 1.16 to 3.5 m/sec, depending on the acceleration. This effect could be explained by the formation of a water stream during an impact which carried off the vapor bubbles. The condensation rate characterized by the rate of change of the bubble radius dR/dt, on the other hand, and dependent on the prevailing acceleration as well as on the static pressure and on the bubble size did vary here from 0.15 to 0.8 m/sec. The photographs showed that the cross section of a bubble had been oscillating periodically between a slightly prolate and a slightly oblate shape, while under compression such a bubble appeared to loose its symmetry and to become convex in the direction of the impact wave – as was also observed by V. K. Kedrinski and R. I. Soloukhin [2].

According to the empirical relation $R/R_0 = f(t)$, the process of bubble collapsing is oscillatory (Fig. 2). An analogous observation has been reported by Chzho and Seban in [3].

The condensation time of individual vapor bubbles could be determined on the basis of taken photographs. The shortest time was τ_{cond} = 5-6 μsec at low static pressures inside the vessel. A rise in pressure had resulted in a longer condensation time, up to τ_{cond} = 14 μsec. The same test data were also evaluated in terms of the general condensation problem, considering that the collapse of vapor bubbles in a boiling liquid would be determined by the heat transfer and by the inertia of the liquid [4].

The equation of motion for a bubble wall in an incompressible fluid is

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho'}[p''(T_{\text{mix}})-p_\infty(t)]. \tag{3}$$

Considering the vapor inside a bubble to be compressed adiabatically, we have for the radial displacement of the wall of a spherical cavity representing a vapor bubble:

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho'}\left[p_\infty-p''\left(\frac{R_0}{R}\right)^{3\gamma}\right]. \tag{4}$$

The pressure p_∞ at the front of an impact wave is adequately well described by the expression

$$p_\infty=p_0\exp\left(-\frac{t}{\tau}\right),$$

with τ denoting the pulse width (sec).

The heat emitted from a vapor bubble is taken into account by the equation of heat transmission:

$$\frac{\partial T}{\partial t}+\dot{R}\frac{R^2}{r^2}\frac{\partial T}{\partial r}=k\left(\frac{\partial^2 T}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial T}{\partial r}\right),\ r>R. \tag{5}$$

With viscosity and surface tension disregarded, and with the heat transfer from vapor bubbles to the surrounding liquid assumed to be conductive only, the solution of Eqs. (3) and (5) for the case of vapor bubble condensation will be as stated in [5] (Fig. 3, curves I, II, III). Curve I ($\tau_N = 1/3[2(R_0/R) + (R/R_0)^2 - 3]$) represents the condensation process governed by heat transfer according to the Plisset –Zwieck solution. Curve II ($R/R_0 = 1-\sqrt{\tau_N}$) represents the solution to this problem for the case of a flat interface between phases. Curve III ($\tau_N = t/R_0\sqrt{(2/3)(\Delta p/\rho)}$) represents condensation governed by the inertia of the liquid. Here $\tau_N = (4/\pi)Ja^2(at/R_0^2)$ is a dimensionless time parameter.

An analysis of data shows that the test curves are generally similar to the theoretical ones. The rate of bubble collapse is determined, essentially, by the inertia of the liquid as well as by the heat transfer process. Only under low static pressures (p_0 = 1 bar) does the effect of heat transfer predominate.

This can be explained by the large temperature deficiency ΔT = 30°C during a pressure rise. In all other cases the temperature deficiency is much smaller (ΔT = 5°C) at higher static pressures in the boiling cavity, because the relative pressure rise $\Delta p/p_0$ become insignificant at high p_0 levels.

Otherwise, the test curves indicate a condensation rate of vapor bubbles somewhat higher than in theory.

The higher rate of bubble collapse in the experiment can be explained, primarily, by the high velocity v_b which the bubbles attained during an impact between test cell and barrier.

According to an analysis of the processes recorded in this experiment, boiling ceased within the test zone within 0.01-0.015 sec after an impact and individual bubbles appeared at the heating surface only 0.03-0.07 sec after an impact. The cessation of boiling within the test zone can be explained by a partial condensation of vapor bubbles and an ejection of the rest. The formation of new vapor bubbles was delayed by a certain amount of subcooling due to the pressure rise and by a displacement of liquid (mass transfer) during an impact. Furthermore, during an impact all bubbles were thrown off the heating surface and the superheated layer was perhaps removed together with the vapor nucleation centers. Consequently, boiling seemed to resume fully about 0.40-0.50 sec after an impact.

NOTATION

- g is the acceleration of gravity, m/sec^2;
- F is the surface area, m^2;
- ρ', ρ'' is the density of water and vapor at saturation temperature;
- t is the time, sec;
- R is the bubble radius, m;
- R_0 is the initial radius of bubble, m;
- p'' is the vapor pressure inside a vapor bubble, N/m^2;
- p_∞ is the water pressure at a far distance from a bubble, N/m^2;

T	is the temperature, °C;
γ	is the exponent of the adiabatic law;
e	is the specific heat;
$Fo = at/R_0^2$	is the Fourier number;
$Ja = \rho' c_p \Delta T/\rho'' r$	is the Jacob number;
a	is the thermal diffusivity of water;
$\Delta T = T_s - T$	is the temperature deficiency below saturation temperature;
$a(t)$	is the acceleration imparted to the test cell.

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