Int. J. Heat Mass Transfer. Vol. 15, pp. 2419–2426. Pergamon Press 1972. Printed in Great Britain

TEMPERATURE VARIATION AND COLLAPSE TIME AT THE CONDENSATION OF VAPOUR BUBBLE

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(*Received* 28 *December* 1971)

Abstract—The collapse of vapour bubble in subcooled liquid is studied in view of the fact that the predicted duration is delayed in comparison with the recorded graphs of size reduction. Deduced from well-known physical laws, a hypothesis was elaborated by which the delay is attached to neglecting the vapour temperature variation during the process, on the one hand, and disregarding the effect of the interfacial surface energy, on the other hand. The temperature rise of vapour bubble during its collapse, tending to and ending in the critical state, is explained, as well as the interrelation of the interfacial surface tension and latent heat is yielded. The hypothesis seems to agree well with the character of experimental results, and to be justified by the studies on the mechanism of cavitation damage. Bošnjaković's heat balance equation and other functions are produced by means of dimensionless groups adequate for bubble.

NOMENCLATURE

a,	thermal diffusivity;
c,	specific heat;
E,	specific energy;
m,	mass;
p,	pressure;
q,	heat flux density;
R,	bubble radius;
r,	latent heat of vaporization;
s,	entropy;
T,	temperature;
t,	time;
W,	work;
$\mathrm{d}R/\mathrm{d}t$,	radial velocity of spherical interface;
$\mathrm{d}^2R/\mathrm{d}t^2$,	radial acceleration of spherical interface;
α,	heat transfer coefficient;
λ,	thermal conductivity;
ν,	kinematic viscosity;
ρ,	mass density;
σ,	interfacial surface tension;
Δp,	pressure drop;
ΔT,	temperature drop;
$'$,	refers to liquid phase;
$''$,	refers to bulky vapour;
$*$,	refers to bubbly vapour;
Eu^*,	= Euler number of bubble, $\dfrac{\Delta p}{\rho'(\mathrm{d}R/\mathrm{d}t)^2}$;
Ga^*,	Galilei number of bubble, $= \dfrac{(\mathrm{d}^2R/\mathrm{d}t^2)\,R^3}{(\nu')^2}$;
Ja,	Jakob number, $= \dfrac{\Delta T\, c'\rho'}{r\rho''}$;
Ja^*,	Jakob number of bubble, $= \dfrac{\Delta T\, c'\rho'}{r^*\rho''} = \dfrac{r}{r^*} Ja$;
Nu^*,	Nusselt number of bubble, $= \alpha R/\lambda'$;
Pr,	Prandtl number, $= \nu'/a'$;

Re^*, Reynolds number of bubble,

$$= \frac{R(\mathrm{d}R/\mathrm{d}t)}{\nu'};$$

St^*, Stanton number of bubble,

$$= \frac{Nu^*}{Re^*Pr};$$

We^*, Weber number of bubble,

$$= \frac{\sigma}{(\rho' - \rho'')(\mathrm{d}^2R/\mathrm{d}t^2)\,R^2}.$$

IN NUMEROUS industrial processes occurs direct contact between vapour bubbles and liquid, therefore the behaviour of bubbles has been repeatedly studied concerning both theoretical and experimental aspects.

At the analytical and numerical solutions there were made various simplifying physical assumptions. Nevertheless, the solutions, as a rule, are rather too complicated, they are in more or less satisfactory agreement with the experimental results.

A good agreement can be observed especially at the investigation of vapour bubble in superheated liquid, i.e. when the bubble growth is not followed by collapse [1–11].

The agreement between analytical and experimental results is by far not so close at the investigation of the collapse of vapour bubble what can occur only in subcooled liquid. Comparing the analytical and experimental results, a deviation consequently in the same direction can be found, namely *the bubbles disappear anterior to the predicted time* needed for the collapse [2, 12–16], with a single exception [17], the author of which himself remarks, nevertheless, that direct comparison of theory and experiment is a little inappropriate.

The observed delay of predicted duration will probably increase in the size interval beyond the lower limit of optical observation. Under the circumstances arises the question *what may cause the delay.* It seems reasonable to search for the cause in the simplifying assumptions, based on the criterion that the neglected effect decreases, maybe finally ceases, with the bubble growth, and on the contrary, increases during the collapse.

According to one of the simplifying assumptions applied rather often, the variation of the bubble size may be regarded as an isothermal process, i.e. the variation of the physical properties may be neglected. In case of small temperature variations yields this imagination, undoubtedly, an approximation of acceptable accuracy, as shown by the mentioned experimental results related to the bubble growth. But, on the contrary, to support the *assumption about the isothermal bubble collapse is impossible*, as will be seen in the sequel.

The basic equation of heat transfer per unit area in Newton's formulation

$$q = \alpha\,\Delta T \tag{1}$$

is a relation of universal validity.

Let us begin to study the problem e.g. with the well-known specific form of the basic equation (1), adequate for vapour bubbles in liquid, as it was transformed by Bošnjaković, based on the theory that the temperature drop which maintains the radical motion of the phase interface is localized in a thin thermal boundary layer surrounding the bubble [1, 7, 11]. For the bubble growth in superheated liquid the approximative heat balance at the phase interface

$$\alpha\,\Delta T = r\,\rho''\frac{\mathrm{d}R}{\mathrm{d}t} \tag{2}$$

was obtained. The size variation during the growth and collapse of vapour bubble may be described in the same way, since both the processes are of identical nature but of reverse direction. Therefore the equation (2) is valid not only for the growth of bubble in superheated liquid, but also for both its growth and collapse in subcooled liquid [7, 16].

It was established by Plesset and Zwick that the temperature and pressure in vapour bubble surrounded with superheated liquid is necessarily decreased when it is growing, because of the heat input and evaporation at the bubble boundary [4]. One has no reason to suppose that the analogue of this phenomenon does not proceed under adequate conditions when the bubble is collapsing. Thus it is to be expected that in case of bubble collapse in subcooled liquid, heat output and condensation taking place at the bubble boundary, the temperature and pressure within the bubble are thereby increased. This supposition is in keeping with the results yielded by Akiyama's theoretical and experimental investigation [17]. The heat output of condensation, however, depends on the rate of bubble collapse, so the heat transfer problem is coupled with dynamic problem.

The basic equation for the pressure drop between phases can be deduced from Laplace's theorem about the capillary superpressure, corrected by Thomson [11]. Under equilibrium conditions the pressure drop would be determined by

$$\Delta p = \frac{2\sigma}{R} \cdot \frac{\rho'}{\rho' - \rho''} \tag{3}$$

where, in case of bubbles, the pressure in vapour phase always exceeds the liquid pressure.

It should be noted that equilibrium between vapour bubble and surrounding subcooled liquid cannot exist what necessarily results in heat output followed by size reduction. In other words, the vapour bubble always has a radially moving boundary, in consequence of what dynamic and thermal effects are produced which are not shown by the equation (3). So this relation may be regarded as a qualitative estimation reflecting the primary effect of the interfacial surface energy.

Owing to the condensation at the interface, the bubble radius decreases and the pressure drop increases, even if the liquid pressure remains constant, as can be seen from the equation (3), however its increase is moderated by the variation of the surface tension which is decreased by the temperature rise. The growing pressure drop means a higher vapour pressure which may be regarded as a result of the compression work produced by the surface energy, on the one hand, and which induces a higher bubble temperature because of its saturated condition, consequently an increased temperature drop in the thin thermal boundary layer, on the other hand. These circumstances produce a more intensive heat output at the interface^{i} followed by further decrease in the bubble size.

Since the driving force of the size variation is the temperature drop [4, 7, 13], and the size reduction reacts upon the temperature drop in increasing sense, the process will be excited ever more thoroughly, so the variation does not tend to the immediate equalization of the phase temperatures, on the contrary, the process is of *positive feedback*. Arises the question *how high* can be increased the *temperature* in vapour phase. In answer to it one has nothing else to suppose but the phenomenon, as a rule, proceeds until it is affected by the maintaining cause. Under the circumstances it seems reasonable to assume that the increase of the temperature within vapour bubble is theoretically limited only by the critical point of saturation in the diagram of state. From all these it should be supposed that *the vapour bubble inside subcooled liquid bulk ceases to exist in the critical state*, in which the phase interface and surface tension necessarily disappear, the residual mass of the bubble dissolves in the liquid [22].

It should be mentioned that the bubble does not show necessarily uniform or monotonic size reduction, respectively, but the size variation may be of oscillatory character [17] in consequence of secondary effects superposed on the primary one. Moreover, experience shows that the surface tension becomes practically nil already by a few degrees below the critical temperature. In spite of these and other additional effects of secondary significance, the basic tendency of the adcritical temperature rise is not inhibited at most modified, since it can undoubtedly be established that the *driving force* of the process in question all the time is the *temperature drop* between phases [4, 7, 13], on the one hand, and the interdependence of the temperature drop and pressure drop is determined by the Clausius–Clapeyron equation [5, 12, 14], on the other hand.

Experience shows that vapour bubbles of large size cannot exist in subcooled liquid environment, they are of small size, by all means. The final size of the bubble ceasing in critical state depends on the external pressure, in case of slight liquid pressure the critical radius is of the order of 10^{-5} mm. The process of *temperature equalization* in subcooled liquid bulk with vapour bubbles is carried out *after* having reached the *critical state* in vapour phase, when their mass is already very slight.

The heat flux per unit area is determined not only by the temperature drop between phases but, as can be seen in the equation (2), it is affected also by other factors of the process, such as the vapour density and the latent heat of vaporization which are temperature functions, as well as the heat transfer coefficient which is a function of more variables.

By taking the equation (2) as a basis, the rate of bubble collapse may be written in the explicit form

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \frac{\alpha\,\Delta T}{r\,\rho''} \tag{4}$$

in which relation the term ΔT increases, the product $r\,\rho''$ in denominator decreases together with the rising vapour temperature, the relative variation of their ratio depends on the initial temperature drop. In addition, other things being equal, the heat transfer coefficient is usually increased if the pressure grows higher, but the degree of its increase could hardly be estimated. These circumstances result that the equation (2) yields the more accurate approximation the smaller initial temperature drop prevails between the phases, on the one hand, and the rising tendency of the vapour temperature is accompanied by increasing rate of bubble collapse, on the other hand.

The average temperature and pressure in the vapour phase during the collapse are, by all means, of essentially higher value than the initial ones, and the same is valid also for their drop between phases, as can be seen from the foregoing, accordingly the heat transfer proceeds more intensively, i.e. *shorter time* is needed for the collapse *than* heretofore *predicted*.

Furthermore, it is to be noted that the *latent heat* of vaporization depends not only on the temperature but it is *affected by the bubble size*, too, as will be seen in the sequel.

The work required for creating the bubble surface, after Volmer's explanation [2], is

$$W = 4\pi R^2\sigma - \tfrac{4}{3}\pi R^3\Delta p = \tfrac{4}{3}\pi R^2\sigma \tag{5a}$$

which does not include the density ratio, contrary to the equation (3). By correcting with them

$$W^* = 4\pi R^2\sigma\left(1 - \frac{2}{3}\cdot\frac{\rho'}{\rho' - \rho''}\right) \tag{5b}$$

is resulted.

Based on the equation (5a), it was established by Tong [8] that the entire energy needed for creating a bubble is

$$m''E = \tfrac{4}{3}\pi R^3\,\rho''\,r + \tfrac{4}{3}\pi R^2\sigma \tag{6a}$$

from which can be derived its specific value per unit mass. For this purpose using also the equation (5b) at the same time

$$E^* = r + \frac{\sigma}{R\rho''}\left(1 - \frac{2}{3}\cdot\frac{\rho'}{\rho' - \rho''}\right) \tag{6b}$$

is yielded as the specific energy required for bubble creating.

On the other hand, according to a theorem of the thermodynamics the entropy of two-phase media is larger than that of the separate phases without interface, in case of their total mass, temperature, and pressure are identical [9, 18–20].

As we know, the latent heat of vaporization in general

$$r = T(s'' - s') \tag{7a}$$

is valid for bulky vapour without phase interface. With regard to the mentioned thermodynamic principle, in case of bubble form the vapour entropy is

$$s^* = s'' - \frac{3}{R\rho''}\cdot\frac{\mathrm{d}\sigma}{\mathrm{d}T} \tag{8}$$

accordingly, the latent heat of bubbly vapour is defined by

$$r_* = r - \frac{3}{R\rho''}T\frac{\mathrm{d}\sigma}{\mathrm{d}T} \tag{7b}$$

which includes the additional effect caused by the entropy increment of bubbly state, beside the latent heat of bulky vapour.

As can be seen, the equations (5a)–(6b) do not contain the additional effect of the entropy increment, thus in case of bubble *collapse* the accuracy of the equations relating to the determination of the energy needed for bubble creating is not sufficient. To achieve an adequate accuracy is proposed in the following way.

The definition of the entire specific energy required for bubble creating can be obtained by substituting the corrected latent heat (7b) into the equation (6b) instead of the usual latent heat (7a). The resulted energy has the form

$$r^* = r + \frac{3}{R\rho''}\left[\sigma\left(1 - \frac{2}{3}\cdot\frac{\rho'}{\rho' - \rho''}\right) - T\frac{\mathrm{d}\sigma}{\mathrm{d}T}\right] \tag{9}$$

and so it may be regarded as a latent heat which is amplified in accordance with the additional effects of the interfacial surface energy and entropy increment, both of them inseparably belonging to the bubbly state.

From all these it can clearly be seen that *during* the process of reverse direction, the *condensation of vapour bubbles* not only the latent heat but *also the interfacial surface energy will be released*, as shown by the equation (9).

The equations (7b) and (9) show that at the same temperature, in the form of bubbles, the vapour phase has the larger latent heat the wider interface exists between the phases, i.e. the smaller radii belong to the bubbles. Thus the alteration of the latent heat is caused by the bubble sizes of capillary magnitude, therefore the notion defined by the equation (9) may be regarded as *capillary latent heat*, opposite to the usual one which is of macroscopic character.

Nevertheless, it is to be noted that the substitution of the capillary latent heat instead of the macroscopic one into the equation (4), in case of perceptible deviation between them, has a restraining influence on the size reduction against the effect of increasing vapour temperature. This fact is in full agreement with the experimental results, inasmuch as it is well observable that in the recorded bubble size vs. time graphs the initial section is of steep fall, the continuation is moderately inclined. In the background of this variation can be found the relative increase of the latent heat; at first the effect of the temperature rise dominates, practically being no difference between macroscopic latent heat and that of capillary character, then the restraining effect of capillary latent heat (9) relatively increasing becomes of perceptible and comparable magnitude, respectively. This tendency is perhaps most expressly shown in Prisnyakov's paper ([15], Fig. 2), and not much less by Florschuetz and Chao ([13], Figs. 9 and 10). According to them, in spite of the latter fact, the time needed for the total collapse is shorter than heretofore predicted.

The importance of the adcritical temperature rise and capillary latent heat, in case of *collapse*, is emphasized by the fact that the initial bubble sizes in subcooled liquid, as a rule, are already fairly small, so that their effect is by all means to be considered, especially if the vapour phase is dispersed in the liquid bulk.

In addition to the foregoing, it should be noted that the bubble collapse was studied not only inside the liquid bulk but also on solid surface. The experimental investigation of the mechanism of cavitation damage lead to interesting result. Searching for the cause, Plesset and Ellis found as the *single possibility* that essentially *higher temperatures* are encountered in the cavitation bubbles when they are collapsed, than the temperature of surrounding liquid. Their observations all point to the interpretation of cavitation damage as arising primarily from repeated application of *high stresses* of short duration which accompany the vapour bubble collapse [21]. For the sake of completeness, it should be noted that the temperature and pressure oscillation is of high frequency, in a number of cases, probably, of *ultrasonic frequency*, and in the moment of bubble disappearance it is *concentrated quasi punctually*. All these conditions represent a fatigue load for the solid surface and lead to failure.

As can be seen, the main results of the cavitation-damage studies support the above imagination about the mechanism of bubble collapse effectually, though the final state was not identified with the critical parameters, as well as the possible ultrasonic magnitude of frequency was not assumed.

Finally, it is interesting to note that the phenomena in question can be described also by means of *dimensionless groups*, as follows.

The rate of bubble collapse, in other words the radial velocity of bubble wall, can be expressed from the bubble Reynolds number proposed by Ellion and Zuber [6, 7], using the bubble radius as characteristic length and the radial velocity of spherical interface as significant velocity. On this analogy it will hereby be suggested *to introduce further dimensionless groups* modified adequately for bubble the usual ones.

It is possible to express the heat transfer coefficient and temperature drop from the Nusselt and Jakob numbers, respectively, using the mentioned significant physical quantities. Besides applying the capillary latent heat instead of the usual one, after substitution, reduction and ordination the heat balance equation (2) takes the shape

$$Nu^* \, Ja^* = Re^* \, Pr \tag{10}$$

what can be rewritten in the shorter form

$$St^* \, Ja^* = 1 \tag{11}$$

representing nothing else but Bošnjaković's conceptual model [1, 7, 11, 16] in dimensionless formulation.

Similarly to the heat balance, the basic equation for pressure drop (3) also can be transformed into dimensionless relation. Using the radial acceleration of spherical interface as significant acceleration instead of gravitation, the pressure drop and surface tension can be expressed from the Euler, Reynolds and Weber numbers, respectively. In consequence of this action appears the Galilei number, thus after substitution, reduction and ordination

$$\frac{(Re^*)^2 \, Eu^*}{Ga^* \, We^*} = 2 \tag{12}$$

is yielded as a dimensionless equation for the pressure drop between phases, based on the Laplace–Thomson theorem about the capillary superpressure.

The equations (10) and (12) contain the Reynolds number what urges to connect them by means of this link. Having performed this operation

$$Nu^* = \frac{Pr}{Ja^*} \sqrt{\left(\frac{2 \, Ga^* \, We^*}{Eu^*} \right)} \tag{13}$$

is produced for the determination of heat transfer coefficient.

In summary, it may be stated that the imagination about the conditions mainly causing the delay of predicted bubble collapse seems justified by the pragmatic method, inasmuch as the phenomena, neglected when investigating the heat transfer at bubble boundary, affect in the wanted direction: the adcritical temperature rise makes the heat transfer and, consequently, the size reduction more intensive, as well as the capillary increment of latent heat yields the restrained character of the later size reduction. The hypothesis is effectually supported by the main results of cavitation-damage studies. The introduction of dimensionless groups adequate for bubble may make the description of process easier. The treatment of the problem based on the anisothermal character of process and the presence of interfacial surface energy covers both the ranges of physical interest and practical importance, especially at the processes wanting phase interface of large extent.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Prof. Dr. S. Endrényi for the careful review of manuscript and the promotion of its publication, to Prof. Dr. I. Fényes for his helpful discussions prior to the publication, to Docent Dr. T. Jászay for the counsel often taken with him and a large number of his appreciable remarks relating to the manuscript, as well as to research engineer F. Horváth for the willing cooperation during the study.

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VARIATION DE TEMPERATURE ET TEMPS DE DISPARITION LORS DE LA CONDENSATION D'UNE BULLE DE VAPEUR

Résumé—L'évanouissement d'une bulle de vapeur dans un liquide sous-refroidi est étudié pour montrer que la durée estimée est prolongée en comparaison avec les enregistrements de diminution de taille. On déduit de lois physiques bien connues une hypothèse par laquelle le retard est lié d'une part au fait que l'on néglige la variation de température de la vapeur durant le processus et d'autre part à l'oubli de l'effet de l'énergie interfaciale. L'élévation de température de la bulle de vapeur durant sa réduction, tendant vers l'état critique, est expliquée ainsi qu'est proposée la relation entre la tension superficielle interfaciale et la chaleur latente. L'hypothèse semble s'accorder avec l'allure des résultats expérimentaux et être justifiée par les études sur le mécanisme destructeur de la cavitation. L'équation de bilan thermique de Bošnjaković et les fonctions sont exprimées au moyen de groupes adimensionnels bien adaptés pour la bulle.

TEMPERATURSCHWANKUNGEN UND KOLLAPSZEIT BEI DER KONDENSATION VON DAMPFBLASEN

Zusammenfassung—Die Kondensation von Dampfblasen in unterkühlter Flüssigkeit wird im Hinblick darauf untersucht, dass die berechnete Dauer verzögert ist gegenüber der aufgezeichneten Grössenabnahme. Abgeleitet von bekannten Gesetzmässigkeiten, wurde eine Hypothese ausgearbeitet, wonach die Verzögerung einmal mit der Vernachlässigung der Temperaturänderung während des Vorganges, zum anderen mit dem unbeachteten Einfluss der Oberflächenenergie zusammenhängt. Es wird der Temperaturanstieg in der Dampfblase während des Zusammenbrechens erklärt, der auf den kritischen Zustand hinzielt und darin endet. Die Beziehung zwischen Oberflächenspannung und Kondensationswärme wurde aufgestellt. Die Hypothese zeigt gute Ubereinstimmung mit der Tendenz der experimentellen Ergebnisse und wird anscheinend gerechtfertigt durch die Untersuchung über Kavitationsschäden. Bosnjakovic's Wärmeenergiegleichung und andere Funktionen werden dargestellt mittels dimensionsloser Ausdrücke für Blasen.

ИЗМЕНЕНИЕ ТЕМПЕРАТУРЫ И ВРЕМЯ РАЗРУШЕНИЯ ПРИ КОНДЕНСАЦИИ ПУЗЫРЬКА ПАРА

Аннотация—Разрушение прзырька пара в недогретой жидкости изучается в связи с тем, что расчетные значения времени разрушения ниже по сравнению со значениями, зарегистрированными на диаграммах. Исходя из хорошо известных физических законов, разработана гипотеза, в которой запаздывание объясняется, с одной стороны, пренебрежением изменением температуры пара в течение процесса и, с другой стороны, тем, что не учитывается влияние энергии ограничивающей поверхности. Объясняется повышение температуры пузырька пара во время разрушения, которая стремится к критическому состоянию и достигает его. Показана также взаимосвязь между напряжением на ограничивающей поверхности и скрытой теплотой. Гипотеза хорошо согласуется с экспериментальными результатами и подтверждается исследованиями механизма нарушения кавитации. Уравнение теплового баланса Бошняковича и другие функции получаются с помощью безразмерных групп для пузырька.