Int. J. Heat Mass Transfer. Vol. 33, No. 10, pp. 2065–2071, 1990
Printed in Great Britain

0017–9310/90 $3.00+0.00

Transient boiling heat transfer characteristics of nitrogen (bubble behavior and heat transfer rate at stepwise heat generation)

KUNITO OKUYAMA and YOSHIHIRO IIDA

Department of Materials Science and Chemical Engineering, Yokohama National University, Yokohama, Japan

(*Received* 17 *July* 1989)

Abstract—Transient boiling heat transfer characteristics of liquid nitrogen at stepwise heat generation is investigated. A series of heat transfer experiments are carried out using a 0.10 mm diameter horizontal platinum wire as the test heater. Bubble behavior is observed by taking high-speed movie photographs. The history of heat transfer rate corresponds well with the bubble behavior during the transition stage to film boiling. In the case of a low heat generation rate, boiling transition occurs due to the coalescence of nucleate boiling bubbles. In the case of a high heat generation rate, a vapor sheath grows along the heater wire. Boiling transition occurs due to the settling of the vapor sheath around the wire and the heat transfer rate just after the boiling transition becomes much lower than that of stationary film boiling. In the case of an extremely high heat generation rate, a lot of fine bubbles grow rapidly and simultaneously when the heater temperature reaches the homogeneous nucleation temperature. Boiling transition occurs due to the filling of fine bubbles on the heater.

1. INTRODUCTION

IN A SUPERCONDUCTING magnet, disturbances such as flux jump or wire movement may cause local quenching of the wire. As many superconducting wires are used under high current density, a transient heat load much higher than the stationary boiling critical heat flux of liquid coolant may be produced during such an accident. If the boiling of coolant is initiated and the transition from nucleate boiling to film boiling occurs, the wire may burn out due to the deterioration of heat transfer. Therefore, transient boiling heat transfer of liquid helium under the condition of a rapid increase of heat generation rate has been investigated by many researchers and such characteristic data as the time history of heat transfer, wall superheat at boiling incipience and critical heat flux have been revealed [1–5].

On the other hand, the need for use of liquid nitrogen as the coolant has increased with the recent discovery of the high-temperature superconductors the critical temperatures of which are more than 77 K. Sinha *et al.* reported the experimental results of the transient boiling heat transfer of liquid nitrogen at stepwise heat generation in a platinum wire. They have shown that boiling transition to film boiling occurs even at a low heat load of about 40% of the critical heat flux [6], and at an extremely high heat generation rate, the nucleation occurs when the wall temperature reaches the homogeneous nucleation temperature [7]. The observation of bubble behavior which is indispensable for the understanding of the boiling and heat transfer mechanisms, however, was not performed in their study. Tsukamoto and Uyemura [8] observed the boiling bubble behavior of liquid nitrogen subjected to transient heating. The correspondence between the bubble behavior and heat transfer, however, is not discussed in detail. Previously many researches concerning the transient boiling including that of liquid nitrogen have been focused on the phenomena from boiling initiation to boiling transition to film boiling in the rapidly increasing process of the heat generation rate. The transient boiling heat transfer of both stages of before and after the boiling transition as well as that before the boiling transition are also important for the cooling of superconducting wire, since superconductor damage depends on not only the boiling transition but also the whole process of heat transfer. However, the transient boiling heat transfer characteristics in the wide range from the nucleate boiling regime to the film boiling regime have not been clarified yet, except those of liquid helium. The bubble behavior in such a wide transient boiling process, especially that in the case that the boiling is initiated when the wall temperature is rapidly raised up to the homogeneous nucleation temperature, is also unknown.

Thus, in this study, the transient boiling experiment of liquid nitrogen at stepwise heat generation is carried out. The history of the boiling heat transfer rate from boiling initiation to stationary film boiling is investigated. The bubble behavior during transient boiling

NOMENCLATURE

c_p specific heat [J kg^{-1} K^{-1}]
d diameter of platinum wire [m]
h heat transfer coefficient [kW m^{-2} K^{-1}]
L latent heat [J kg^{-1}]
P system pressure [MPa]
Q heat generation rate [MW m^{-2}]
Q_0 stepwise heat generation rate [MW m^{-2}]
q_1 net heat flux transferred to the fluid [MW m^{-2}]
$[q_1]$ stored energy in superheated liquid layer [J m^{-2}]
T heater temperature [K]
ΔT_{sat} wall superheat [K]
t time [s]
t_g growth time of vapor sheath [s]
V_G unbalance voltage of bridge [V]
V_I voltage drop across standard resistance [V].

Greek symbols
δ vapor film thickness [m]
ρ density of platinum [kg m^{-3}]
ρ_v density of vapor [kg m^{-3}].

Subscript
B.I. boiling incipience.

is observed by high-speed movie photographs. The correspondence between the bubble behavior and the heat transfer rate is discussed.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

The schematic diagram of the experimental apparatus is shown in Fig. 1. The test heater is a thin platinum wire the diameter and length of which are 0.1 and 50 mm, respectively, and is mounted horizontally in a transparent 70 mm i.d. glass dewar filled with liquid nitrogen. The test wire is electrically heated by a d.c. current. The temperature of the wire is obtained by measuring the variation of the electrical resistance between potential taps which are spot-welded 10 mm apart in the central part of the wire. The heat generation rate can be calculated by measuring the resistance and the current. The electrical resistance of the wire is measured precisely by using a double bridge. The unbalance voltage V_G of the bridge and the voltage drop V_I across the standard resistance inserted in series into the heating circuit are recorded in a wave memorizer. The net heat flux q_1 transferred from the heater to the fluid can be obtained by subtracting the heat capacity of the heater from the heat generation rate $Q(t)$, and is calculated from the following equation:

$$q_1(t) = Q(t) - \frac{d}{4} c_p \rho \frac{dT}{dt}. \quad (1)$$

Here the temperature–time response and the temperature drop across the radial direction of the heater can be regarded as less than 0.1 ms and 0.1°C, respectively, and are neglected in calculations.

Transient boiling is initiated by heating the test wire stepwise. The resistance of platinum wire increases by more than 10 times the initial value in accordance with the increase of the wire temperature from the start of heating to the attainment of stationary film boiling. Therefore, the heating current is obtained by amplifying the heating signal which is controlled by the negative feedback circuit prepared to keep a constant heat generation rate by analog computation of signals V_G and V_I. The bubble behavior during transient boiling is observed by taking 16 mm high-speed movie photographs. All data are taken at atmospheric pressure.

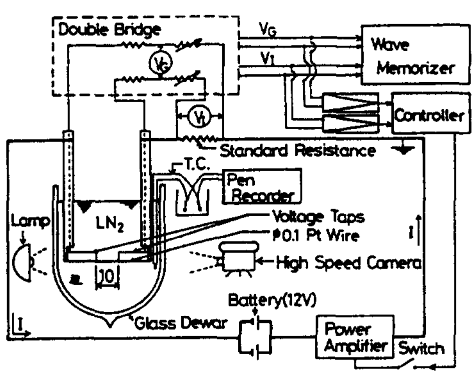

FIG. 1. Schematic diagram of the experimental apparatus.

3. EXPERIMENTAL RESULTS AND CONSIDERATIONS

Figure 2 shows the boiling curve obtained by a stationary boiling experiment. With the gradual increase of heat flux, nucleate boiling is initiated at the higher wall superheat than that of the developed nucleate boiling. In the developed nucleate boiling region, a hysteresis can be slightly recognized with the increase and decrease of the heat flux. In the film boiling region in which stable film boiling is realized in the whole length of the wire, experimental results are in fair agreement with Nishikawa–Ito's correlation [9].

Figure 3 shows the measured and calculated histories at stepwise heat generation, where Q, q_1 and ΔT_{sat} indicate the heat generation rate, the net heat flux transferred to the fluid and the wall superheat,

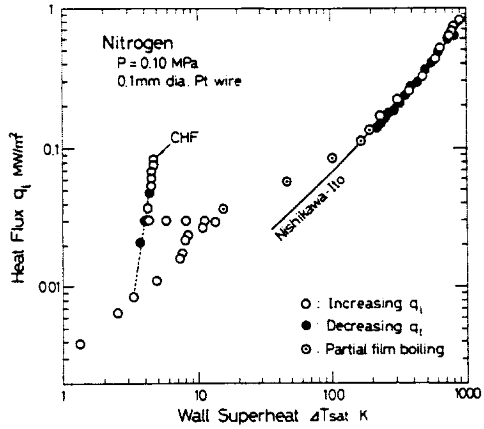

FIG. 2. Boiling curve obtained by the stationary boiling experiment.

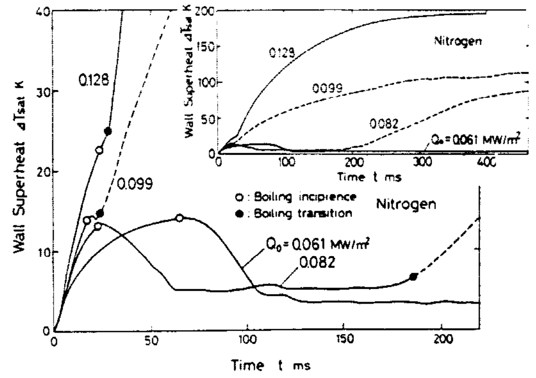

FIG. 4(a). Change of wall superheat history at relatively low heat generation rates.

respectively. The time of boiling incipience is determined from high-speed motion pictures. The time of boiling transition is judged from the rapid increase of ΔT_{sat} and the rapid decrease of q_l.

Figures 4(a) and (b) show the changes of the wall superheat history with the increase of the stepwise heat generation rate Q_0. Figure 4(a) shows the change at relatively low Q_0, Fig. 4(b) at higher Q_0. The upper right figure in both figures shows the whole history, the lower left the enlarged one of the initial stage. The circle on the lines indicates the condition of the boiling incipience and the black circle the boiling transition. The dotted line implies that the partial film boiling along the wire develops to stationary film boiling. In the case of lower Q_0, a marked overshoot of the wall superheat can be observed at the boiling incipience, and boiling transition occurs after the recovery of the wall superheat to that of stationary nucleate boiling. As Q_0 is increased, the recovery becomes hard to observe and the wall superheat goes on increasing from the boiling incipience to the boiling transition. The minimum value of Q_0 for the boiling transition to occur was 0.082 MW m^{-2}, which is nearly equal to the critical heat flux in stationary boiling obtained by our apparatus.

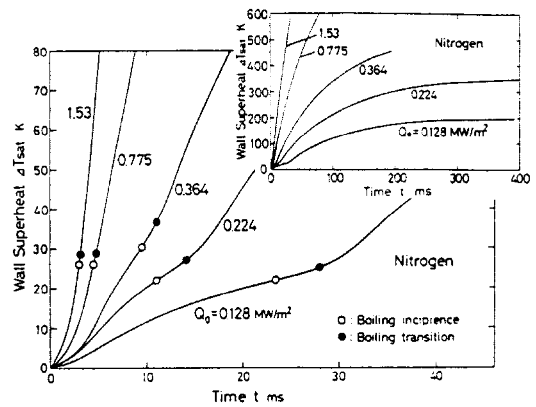

FIG. 4(b). Change of wall superheat history at relatively high heat generation rates.

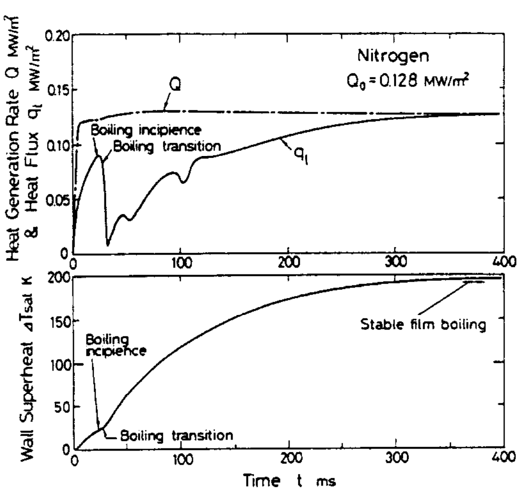

FIG. 3. Typical histories of transient boiling heat transfer at stepwise heat generation.

Figure 5 shows photographs of the high-speed motion filmings of the bubble behavior just after boiling incipience. The bubble behaviors are roughly classified into three patterns depending on the heat generation rate, and Figs. 5(a)–(c) are the typical examples of these three patterns, respectively. In the case of $Q_0 = 0.082$ MW m^{-2}, the nucleate boiling bubbles similar to those of stationary nucleate boiling appear along the heater wire. Boiling transition occurs due to the coalescence of the nucleate boiling bubbles. In the case of $Q_0 = 0.128$ MW m^{-2}, a vapor sheath which has a smooth interface rapidly grows along the wire. The sheath breaks into some vapor bubbles which uniformly depart from the wire. Boiling transition occurs while the sheath is settling on the heater surface. The sheath is considered to be the same as the one observed by Tsukamoto and Uyemura [8]. From a detailed observation, it is recognized that the active nucleate boiling occurs near the leading tip of

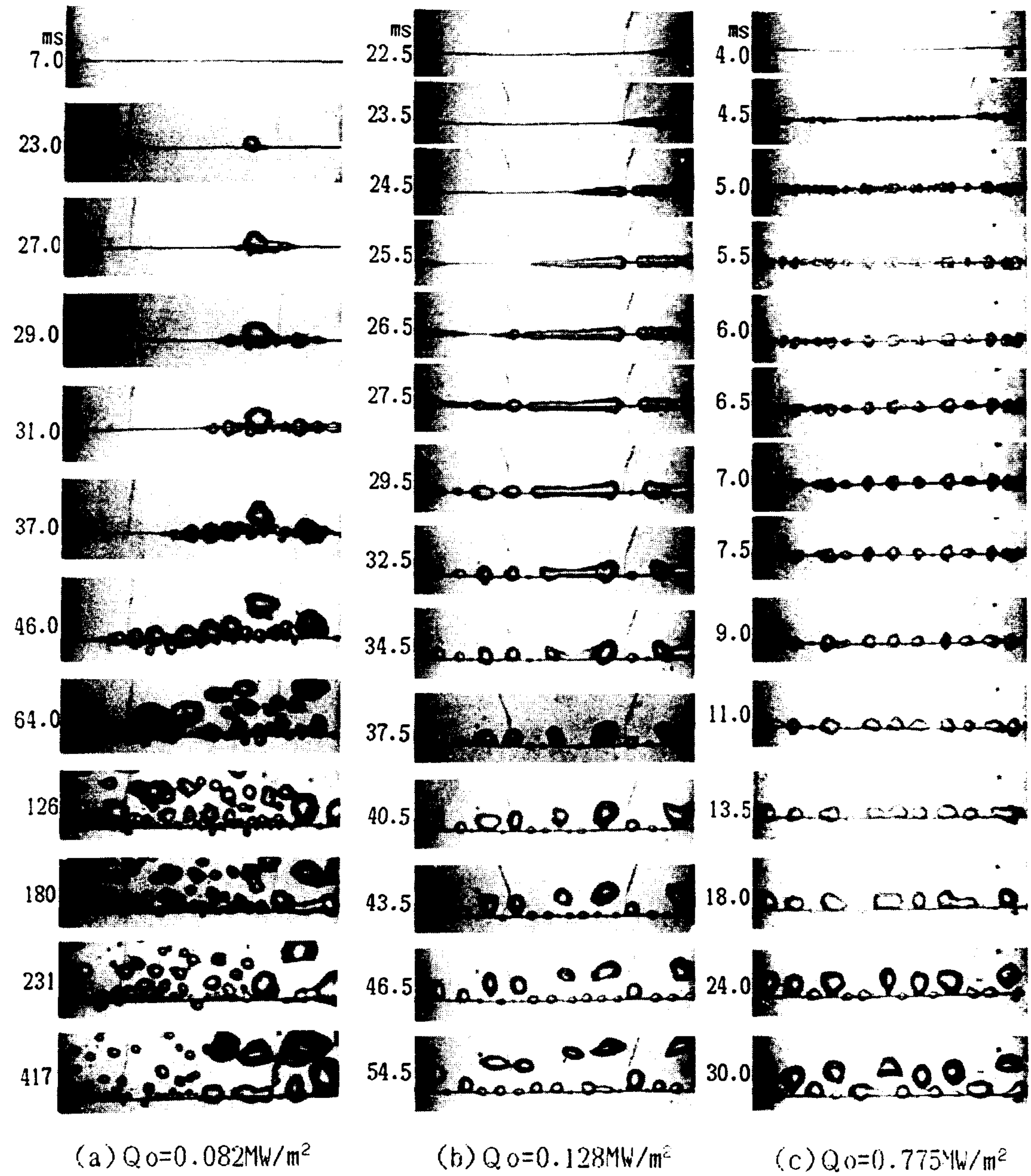

FIG. 5. Three typical patterns of bubble behavior observed just after boiling incipience.

the sheath, where the liquid–vapor interface fluctuates and tiny bubbles often break out of the sheath. In the case of $Q_0 = 0.775$ MW m^{-2}, many fine bubbles generate simultaneously and uniformly on the heated wire accompanying a sharp sound. The bubbles grow to coalesce into several vapor bubbles. Boiling transition occurs due to filling of the initial bubbles on the heater surface.

Figure 6 shows the transient boiling curves obtained under the three conditions of Q_0 in Fig. 5, where the numerals on the curves indicate the time passing the points. In the case of $Q_0 = 0.082$ MW m^{-2}, the transient boiling curve after the boiling transition asymptotically approaches the stationary film boiling curve (Nishikawa–Ito line) from the higher heat transfer side, since boiling transition occurs due to the coalescence of nucleate boiling bubbles similar to that at stationary boiling. Such a tendency of the boiling curve can be also recognized for the transient boiling of water [10] and/or liquid helium [3]. In the case of $Q_0 = 0.128$ MW m^{-2}, the transient heat transfer rate just after the boiling transition becomes much less than that at the stationary film boiling and fluctuates asymptotically as it approaches the stationary film boiling curve from the lower heat transfer side. In the case of $Q_0 = 0.775$ MW m^{-2}, the deterioration of heat transfer after boiling transition becomes still remarkable. Such a tendency of the boiling curve has not been recognized for the transient boiling of water and/or liquid helium.

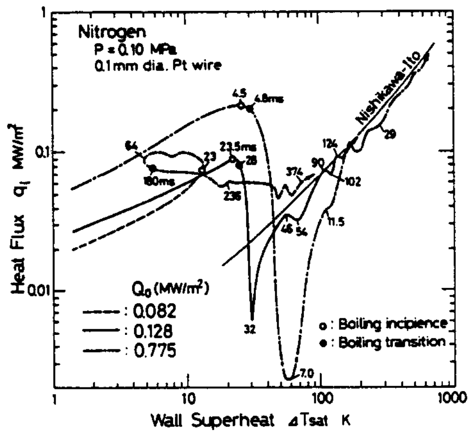

FIG. 6. Three typical boiling curves measured by transient boiling at stepwise heat generation.

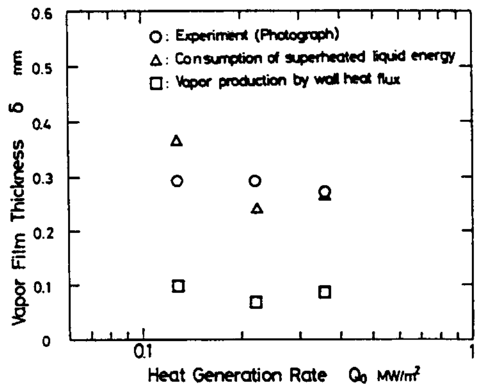

FIG. 8. Vapor film thickness of vapor sheath.

Figure 7 shows the histories of the heat transfer coefficient defined as $h = q_l/\Delta T_{sat}$ and the averaged vapor film thickness δ, of the lower end of the heated wire, which is obtained from the filming, in the case of $Q_0 = 0.128$ MW m^{-2}. The stationary film boiling heat transfer coefficient by Nishikawa and Ito's correlation [9] and the vapor film thickness which is obtained from their correlation by assuming a linear temperature distribution across the film are calculated with the same wall superheat as the transient condition and are also shown in the figure. It will be observed in the figure that the boiling transition corresponds to the generation of the thick vapor sheath and the thickness of the sheath is more than 20 times that of stationary film boiling, and the fluctuation of the heat transfer coefficient after boiling transition corresponds to the variation of the vapor film thickness due to the uniform growth and departure of vapor bubbles on the heater.

It is considered that the vapor sheath grows not only due to the wall heat flux $q_{l\,B.I.}$ at the boiling incipience but also due to the stored energy $[q_l]_{B.I.}$ in the superheated liquid layer at the boiling incipience which can be expressed as the integration of q_l with time from the start of heating to the boiling incipience. The thickness of the vapor film produced due to the evaporation rate corresponding to $q_{l\,B.I.}$, δ_1, and the thickness of the vapor film produced due to the whole consumption of $[q_l]_{B.I.}$, δ_2, can be expressed by considering the geometrical shape of the film, respectively, as follows:

$$\delta_1 = \frac{1}{2}\left\{\sqrt{\left(\left(\frac{4q_{l\,B.I.}\cdot t_g}{\rho_v L} + d\right)d\right)} - d\right\} \qquad (2)$$

$$\delta_2 = \frac{1}{2}\left\{\sqrt{\left(\left(\frac{4[q_l]_{B.I.}}{\rho_v L} + d\right)d\right)} - d\right\} \qquad (3)$$

where t_g is the growth time of the vapor sheath obtained from the photograph. These calculated film thicknesses are plotted in Fig. 8 and compared with the thickness of the vapor sheath obtained from the photograph. The vapor sheath is thicker than the vapor film which grows due to $q_{l\,B.I.}$ and is rather close to the vapor film which grows due to $[q_l]_{B.I.}$. The vapor sheath, therefore, can be regarded to grow due to the superheated liquid energy at boiling incipience rather than due to the wall heat flux.

Figure 9 shows the wall superheat at the boiling

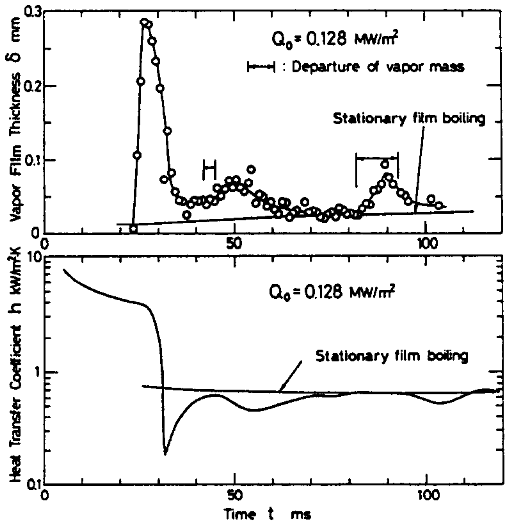

FIG. 7. Histories of the heat transfer coefficient and averaged vapor film thickness.

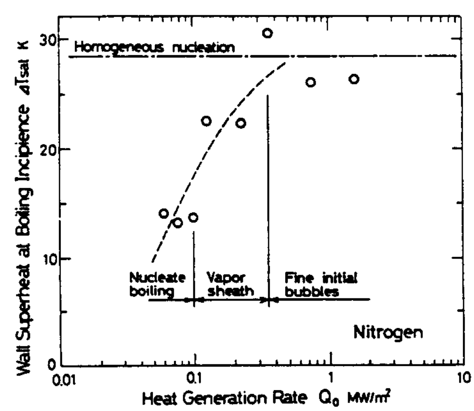

FIG. 9. Wall superheat at boiling incipience vs heat generation rate.

incipience. The range of heat generation rates of the three boiling patterns illustrated in Fig. 5 is also shown in the figure. The wall superheat of transient boiling is much higher than that of stationary boiling and is asymptotic to the homogeneous nucleation temperature with the increase of Q_0. It is considered that the thick vapor sheath is apt to grow at higher wall superheat since the excess superheated energy is stored in the liquid layer with the increase of the wall superheat. In the case of $Q_0 = 0.775$ MW m^{-2}, the wall superheat at boiling incipience almost reaches the homogeneous nucleation temperature, having some scatter. The fine initial bubbles generate simultaneously and rapidly over the whole wire surface with a shock sound and the boiling transition occurs just after filling of the initial bubbles on the wire surface. Such bubble behavior is quite different from those of usual nucleate boiling and/or the vapor sheath. On the other hand, Sinha *et al.* [7] have already confirmed experimentally using a 0.10 mm diameter platinum wire heater that the wall temperature at boiling incipience of liquid nitrogen is asymptotic to the upper limit value with the increase of the stepwise heat generation rate and the limit value agrees with the homogeneous nucleation temperature over a wide range of system pressures. Though the nucleation occurs on the heater surface, the nucleation temperature of the liquid nitrogen at the superheat limit is little affected by the platinum wall, since the difference in the nucleation temperature with and without the smooth solid surface can be estimated to be less than 0.1 K from the classical nucleation theory and the contact angle between liquid nitrogen and platinum, which is less than about 30° from the shape of the liquid surface adjacent to platinum. The homogeneous nucleation, therefore, may occur in the case of Fig. 5(c) in all likelihood. There will be no study based on the observation of bubble behavior for the homogeneous nucleation of liquid nitrogen subjected to transient heating. The results observed in our experiment may give further information to explicate the mechanism of the boiling initiated by homogeneous nucleation.

4. CONCLUSIONS

The history of transient boiling heat transfer rate of liquid nitrogen corresponds well with the bubble behavior during the transition stage to film boiling. The bubble behavior can be roughly classified into three patterns depending on the heat generation rate. In the case of a low heat generation rate, boiling transition occurs due to the coalescence of nucleate boiling bubbles. In the case of a high heat generation rate, a vapor sheath grows along the test wire, since the excess superheat energy is stored in the liquid layer at boiling incipience. Boiling transition occurs due to the settling of the vapor sheath and the heat transfer rate becomes much lower than that of stationary film boiling. In the case of an extremely high heat generation rate, a lot of fine initial bubbles grow rapidly and simultaneously. Boiling transition occurs due to the filling of the bubbles on the heater. Since the heater wall temperature at boiling incipience reaches the homogeneous nucleation temperature, transient boiling may be initiated by homogeneous nucleation in all likelihood.

REFERENCES

1. D. N. Sinha, J. S. Semura and L. C. Brodie, Homogeneous nucleation in ^{4}He: a corresponding-states analysis, *Phys. Rev.* **A26**, 1048–1061 (1982).
2. W. G. Steward, Transient helium heat transfer—I. Static coolant, *Int. J. Heat Mass Transfer* **21**, 863–874 (1978).
3. Y. Iwasa and B. A. Apgar, Transient heat transfer to liquid helium from bare copper surfaces in a vertical orientation—I: film boiling regime, *Cryogenics* **18**, 267–275 (1978).
4. O. Tsukamoto and S. Kobayashi, Transient heat transfer characteristics of liquid helium, *J. Appl. Phys.* **46**, 1359–1364 (1975).
5. A. Sakurai, M. Shiotsu, K. Hata and Y. Takeuchi, Transient critical heat flux in liquid helium, I. *Prepr. 25th Japan Natn. Heat Transfer Symp.* 238–240 (1988) (in Japanese).
6. D. N. Sinha, L. C. Brodie, J. S. Semura and F. M. Young, Premature transition to stable film boiling initiated by power transients in liquid nitrogen, *Cryogenics* **19**, 225–229 (1979).
7. D. N. Sinha, L. C. Brodie and J. S. Semura, Liquid-to-vapor homogeneous nucleation in liquid nitrogen, *Phys. Rev.* **B36**, 4082–4085 (1987).
8. O. Tsukamoto and T. Uyemura, Observation of bubble formation mechanism of liquid nitrogen subjected to transient heating, *Adv. Cryogen. Engng* **25**, 476–482 (1981).
9. K. Nishikawa, T. Ito, K. Matsumoto and T. Kuroki, Free convective film boiling heat transfer in saturated liquid from a horizontal cylinder, *Trans. J.S.M.E.* **38**, 858–864 (1972) (in Japanese).
10. F. Tachibana, M. Akiyama and H. Kawamura, Heat transfer and critical heat flux in transient boiling (I): an experimental study in saturated pool boiling, *J. Nucl. Sci. Technol.* **5**, 117–126 (1968).

CARACTERISTIQUES DU TRANSFERT VARIABLE DE CHALEUR PAR EBULLITION DE L'AZOTE (COMPORTEMENT DES BULLES ET TRANSFERT THERMIQUE POUR UNE GENERATION EN ECHELON)

Résumé—On étudie les caractéristiques du transfert variable de chaleur par ébullition de l'azote liquide soumis à une génération de chaleur en échelon. Une série d'expériences a été conduite en utilisant comme chauffoir un fil horizontal de platine, de diamètre 0,10 mm. Le comportement des bulles est observé en prenant des photos à grande vitesse. L'histoire du flux thermique correspond à la vie de la bulle pendant une étape transitoire vers l'ébullition en film. Dans le cas d'une génération faible de chaleur, la transition d'ébullition se produit à cause de la coalescence des bulles d'ébullition nucléée. Dans le cas d'une génération intense, une couche de vapeur croît le long du fil chaud. La transition d'ébullition se produit à cause de la formation de la vapeur autour du fil et le flux de chaleur juste après la transition d'ébullition devient plus faible que pour l'ébullition stationnaire en film. Dans le cas d'une génération thermique extrêmement élevée, beaucoup de fines bulles croissent rapidement et simultanément quand la température du chauffoir atteint la température de nucléation homogène. La transition d'ébullition se produit à cause du remplissage des fines bulles sur tout le chauffoir.

WÄRMEÜBERGANG BEIM NICHTSTATIONÄREN SIEDEN VON STICKSTOFF (BLASENVERHALTEN UND WÄRMEÜBERGANGSKOEFFIZIENT BEI STUFENFÖRMIG GESTEIGERTER WÄRMEZUFUHR)

Zusammenfassung—Es wird der Wärmeübergang beim nichtstationären Sieden von Stickstoff bei stufenförmiger Erhöhung der Wärmezufuhr untersucht. Eine Reihe von Wärmeübergangsmessungen wurde mit einem 0,1 mm dicken horizontalen Draht als Heizelement durchgefürt. Mit Hilfe von Hochgeschwindigkeits-Aufnahmen wurde das Blasenwachstum beobachtet. Der Verlauf des Wärmeübergangs hängt mit dem Blasenverhalten während der Übergangsphase zum Filmsieden zusammen. Im Bereich niedriger Wärmestromdichte erfolgt der Siedeübergang aufgrund der Koaleszenz von Dampfblasen. Im Bereich hoher Wärmestromdichte wächst ein Dampffilm entlang des Heizdrahtes. Der Siedeübergang ereignet sich aufgrund eines sich um den Draht einstellenden Dampffilms. Der Wärmeübergang direkt nach dem Siedeübergang wird viel geringer als beim stationären Filmsieden. Bei extrem hohen Wärmestromdichten wachsen sehr viele kleine Blasen schnell und gleichzeitig, wenn die Temperatur des Heizdrahtes die Temperatur der homogenen Verdampfung erreicht. Der Siedeübergang erfolgt durch Auffüllen der kleinen Blasen auf dem Heizdraht.

ПЕРЕХОДНЫЕ ХАРАКТЕРИСТИКИ ТЕПЛОПЕРЕНОСА ПРИ КИПЕНИИ АЗОТА (ПОВЕДЕНИЕ ПУЗЫРЬКОВ И СКОРОСТЬ ТЕПЛОПЕРЕНОСА ПРИ СКАЧКООБРАЗНОМ ТЕПЛОВЫДЕЛЕНИИ)

Аннотация—Исследуются переходные характеристики теплопереноса в процессе кипения жидкого азота при скачкообразном тепловыделении. Проведена серия опытов по теплопереносу с использованием горизонтальной платиновой проволоки диаметром 0,10 мм в качестве экспериментального нагревателя. Наблюдение за поведением пузырьков осуществлялось высокоскоростной киносъемкой. Изменение скорости теплопереноса хорошо согласуется с поведением пузырьков на стадии перехода к пленочному кипению. В случае низкой интенсивности тепловыделения вскипание происходит за счет слияния зарождающихся пузырьков. В случае же высокой интенсивности тепловыделения паровая оболочка образуется вдоль проволочного нагревателя. Вскипание обусловлено формированием паровой оболочки вокруг проволоки; скорость теплопереноса непосредственно носле вскипания становится намного ниже, чем при стационарном пленочном кипении. В случае крайне высокой интенсивности тепловыделения происходит быстрый одновременный рост большого количества малых пузырьков, когда температура нагревателя достигает температуры однородной нуклеации. Векипание происходит при попадании пузырьков на нареватель.