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Dry patch formed boiling and burnout in potassium pool boiling

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Abstract—Experimental results are presented on dry patch formed boiling and burnout in saturated potassium pool boiling on a horizontal plane heater for system pressures from 30 to 760 torr and liquid levels from 5 to 50 mm. The dry patch formed boiling is a peculiar boiling state where the dry patch formation and the rewetting are alternately repeated in intermittent boiling at a heat flux smaller than burnout heat flux of continuous nucleate boiling and is considered to be a local phenomenon in transient transition boiling from the observations of the wall and liquid temperature fluctuations. The dry patch formation occurs in the intermittent boiling which is often encountered when liquid alkali metals are used under relatively low pressure conditions. Burnout is caused from both continuous nucleate and dry patch formed boiling. The burnout heat flux together with nucleate boiling heat transfer coefficients are empirically correlated with system pressures. A model is also proposed to predict the minimum heat flux to form the dry patch.

INTRODUCTION

BOILING crises of liquid metals have been studied for the safety considerations of liquid-metal-cooled fast breeder reactors (LMFBR). Many experimental studies have been carried out on nucleate boiling heat transfer and burnout heat flux of pool boiling and of forced convection boiling. These studies are summarized, for example, by Dwyer [1] and Subbotin *et al.* [2]. The results show that the burnout heat flux in pool boiling of liquid alkali metals is generally higher than the heat flux predicted by the correlations of Zuber or Kutateladze, and some other correlations have been proposed.

In some conceptual designs on cooling of nuclear fusion reactors, liquid alkali metals are used under subatmospheric pressure or evacuated systems, while the pressure in LMFBR system is superatmospheric. Since the boiling state under relatively low pressure conditions is possibly intermittent, it is important—for safety reasons—to study the intermittent boiling heat transfer. Although the burnout heat flux in the intermittent boiling is often lower than that in the stable boiling, only a few studies [2–4] have dealt with the effect of boiling stability on burnout heat flux.

Subbotin *et al.* [2] carried out pool boiling heat transfer experiments with various liquid metals on a horizontal, stainless-steel heating surface (38 mm in diameter) up to the critical heat flux. They examined the effect of argon cover gas on sodium pool boiling. They reported that the boiling was developed in the presence of the cover gas but it was unsteady in its absence, and that the critical heat flux in the unsteady boiling state was about 60% lower than that in the developed boiling. The effect of the boiling stability on the critical heat flux was also observed in the boiling of cesium and potassium. They carried out four series of boiling experiments with cesium. The boiling was only developed in the first series but was unsteady in the other series. The critical heat flux in the first series was higher than those in the other series. They concluded that the low critical heat flux during the unsteady boiling was due to the considerable superheating of the liquid over a fairly large surface as the burnout in unsteady boiling occurred at higher wall temperature even at lower heat flux than that in developed boiling. The considerable superheating resulted in the formation of large quantities of vapor, which increased the probability of stable vapor film on the heating surface, that is, the probability of the transition to film boiling.

Critical heat flux caused from either unstable boiling or natural convection state for cesium, potassium, benzene and ethanol was also dealt with by Kutateladze *et al.* [3] and Avksentyuk and Mamontova [4]. They tested two types of cylindrical heating surface, with and without re-entrant artificial cavities for cesium boiling. These cavities ensured stable boiling, but the critical heat flux of unstable boiling without the cavities was lower than that of stable boiling with them. A direct transition from natural convection to film boiling was also observed at lower heat flux than the critical heat flux of stable boiling. The same type of transition in benzene and ethanol boiling was also studied, and vapor film growing over a cylindrical heater was formed from the natural convection state. They illustrated the transition as a rapid expansion of the vapor nucleus at nucleation center which initiated the expansion of the neighboring vapor nuclei in the superheated layer of the fluid. They divided boiling heat transfer crises into some cases, which may be classified into three cases: (1) transition

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NOMENCLATURE

LL	liquid level [mm]
q	heat flux [W m^{-2}]
q_{DFmin}	minimum heat flux to form dry patch [W m^{-2}]
q_{max}	maximum heat flux [W m^{-2}]
SP	system pressure [torr]
T_l	liquid temperature [°C]
T_{sat}	saturation temperature [°C]
T_v	vapor temperature [°C]
T_w	wall temperature [°C]
T_{w_2H}, T_{w_2L}	wall temperature defined in Fig. 3(b) [°C]
y	vertical distance normal to wall surface [mm].

Greek symbols

α	heat transfer coefficient, $q/(T_{w_2}-T_v)$ [W m^{-2} K^{-1}].

from stable nucleate boiling (ordinary boiling crisis); (2) transition from natural convection to film boiling without nucleate boiling stage; and (3) transition from unstable boiling to film boiling. Magnitude of the critical heat flux in case (2) was similar to that in case (3) and both were smaller than that in case (1). They also concluded, as Subbotin *et al.* had, that those transitions occur due to the high superheating of the liquid.

As the magnitude of the critical heat flux depends on the boiling stability, the stability criterion must be examined. The results in refs. [2–4] indicate that nucleate boiling is more stable with either cover gas or artificial re-entrant cavities. The criterion for stable boiling is that the cavity must retain some residual vapor or inert gas at the waiting time of the ebullition cycle. Marto and Rohsenow [5] were the first to report the mathematical model on the criterion for boiling stability and Shai and Rohsenow [6] improved it; their model indicates that the artificial cavity ensures stable boiling. However, the effect of cover gas involves complicated problems on the diffusion of inert gas in the cavity, which was not considered in this model. According to the analysis by Singer and Holtz [7], a quantity of trapped inert gas in a cavity may increase or decrease by diffusion with time depending on the temperature distribution near the heating wall. This is because the solubility of inert gas in liquid metal is larger at higher temperatures and dissolved inert gas can be concentrated near the heating surface. This time-dependent effect of the diffusion causes poor reproducibility of the boiling stability in practical pool boiling experiments.

The authors have already reported [8, 9] that a peculiar boiling state named dry patch formed boiling in which the dry patch formation and the rewetting are alternately repeated is observed in the intermittent boiling of potassium. The dry patch formation is considered to be a similar phenomenon to the transitions (2) and (3) to film boiling as already mentioned except that rewetting follows. Two types of burnout are also observed; the burnout caused from stable boiling—the transition (1)—and the burnout from the dry patch formed boiling—the transitions (2) and (3).

This paper presents the details of the dry patch formed boiling and discusses the condition of the dry patch formation and the burnout in potassium pool boiling on a flat plate for various system pressures and liquid levels.

EXPERIMENTAL APPARATUS AND PROCEDURES

A schematic diagram of the experimental apparatus is shown in Fig. 1. The main components which come in contact with potassium are installed in a glove box of $1 \times 1 \times 2$ m^3 in which a dry atmosphere is maintained for considerations of safety. Before experiments, potassium heated up to 400°C in an upper tank (2) is circulated through a test vessel (1) and a cold trap (3) by helium gas pressure differences, thereafter it is stored in the cold trap, which can be cooled by a fan (8), at a temperature around 80°C for one day to remove oxide contamination in the potassium. Thus purified potassium fills the test vessel. Potassium vapor generated in the test section condenses in an air-cooled condenser (5) and it returns to the test section. A mist trap (6) is provided to prevent potassium mist from escaping to the vacuum pumps. The rotary pump (16) and the diffusion pump (17) are used to evacuate the tanks. A surge tank (13), the volume of which is about 30 times as large as that of the test vessel, is placed between the test vessel and the vacuum pumps to prevent pressure surges. Helium gas is injected from gas bombs (18) and (19). Pressures are measured by Burdon pressure gauges (12) and (20), a pirani gauge (9), a strain gauge (14) and a mercury manometer (15). To cool the atmosphere in glove box, copper fin tubes (10) provided outside of the box are connected with blower (7) contained in the box. A rupture disk (11) is equipped for a safety consideration.

The test section and the details of the heating wall are shown in Figs. 2(a), (b). The vessel is a type 600 Inconnel cylinder of 80 mm I.D. and 218 mm high. A horizontal heating wall of a nickel disk (1) of 40 mm in effective heating diameter and 6 mm thick is situated near the center of the cylinder. Potassium is charged in the upper part of the cylinder, and a heating element and

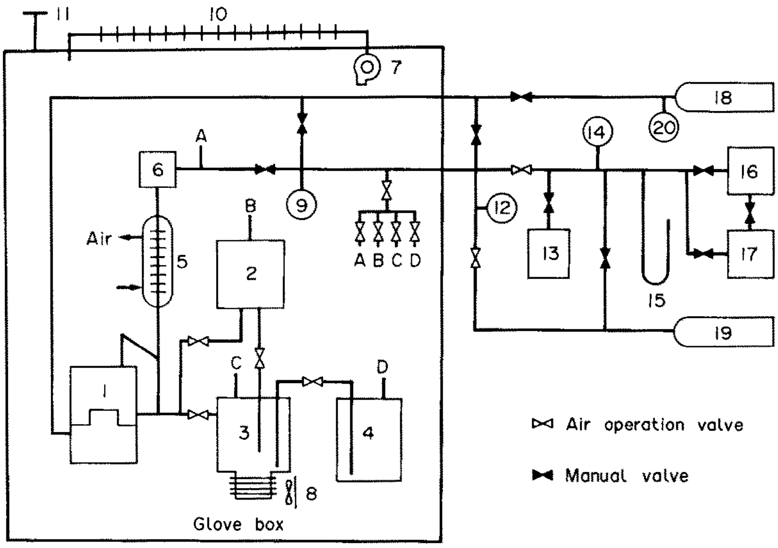

FIG. 1. Schematic diagram of experimental instrument. (1) Test section; (2) upper tank; (3) cold trap; (4) tank; (5) condenser; (6) mist trap; (7) blower; (8) fan; (9) pirani gauge; (10) copper fin tubes; (11) rupture disk; (12) pressure gauge; (13) surge tank; (14) strain gauge; (15) manometer; (16) rotary pump; (17) diffusion pump; (18) He bomb; (19) He bomb; (20) pressure gauge.

insulators are placed in the lower part, where helium gas is charged to prevent the heating element from oxidation. Before experiment the vessel is vacuum-dried at about 500°C for about half a day. The heating wall is heated by a 0.5-mm-thick tantalum element (2) manufactured as shown in Fig. 2(b), to which direct current is supplied through nickel electrodes (4). During the evacuation, the element is heated up to 800°C for about an hour to be baked out. A 1-mm-thick boron nitride plate (3) and its powder are inserted

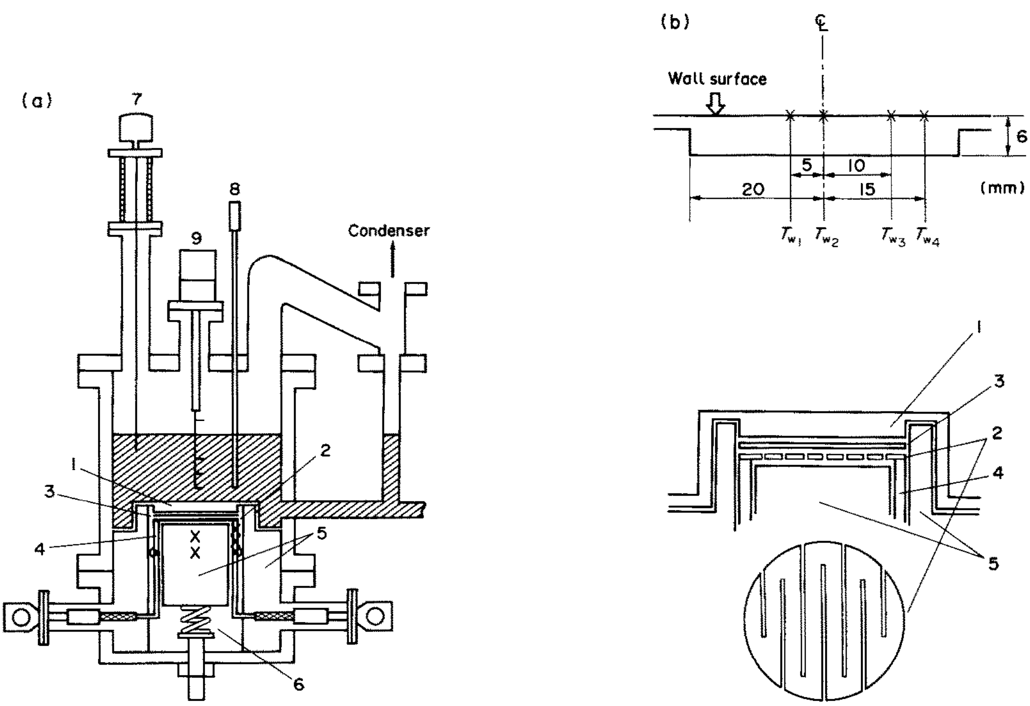

FIG. 2. (a) Test section; (b) details of heating section. (1) Nickel heating wall; (2) tantalum heating element; (3) boron nitride insulator; (4) nickel electrode; (5) ceramic insulator; (6) spring; (7) liquid level sensor; (8) piezo microphone; (9) thermocouple slider.

between the tantalum element and the wall as electrical insulators, and ceramic blocks (5) are set below them as thermal insulators. The heating element and the insulators are pressed against the wall with a spring (6) to obtain good contact. In this heating method, the thermal conductance between the wall and the heating element is more than 3×10^3 W m^{-2} K^{-1} and thus heat flux high enough for potassium boiling experiments can be obtained.

Four 0.5-mm-O.D. ungrounded type sheathed chromel–alumel thermocouples are inserted in the thermal insulator and the electrode to measure the downward heat leakages through them. These leakages are less than 10% of the total heat input. By subtracting these heat leakages from the total heat input, the heat flux at the heating surface is calculated with an assumption of uniform heat flux by virtue of a thick nickel heating wall.

The liquid and the vapor temperatures are respectively measured by 0.3 mm and 0.5 mm sheathed chromel–alumel thermocouples which can be traversed vertically. Boiling sounds are detected by a wave guide method. For this purpose one end of a 5-mm-O.D. stainless-steel rod is immersed in potassium and the other end, outside the vessel, is connected to a piezo microphone. Four 0.3-mm-O.D. sheathed chromel–alumel thermocouples are embedded in the heating wall at the center and at 5, 10 and 15 mm from the center, as shown in Fig. 2(b). The heating surface temperatures are determined by a simple correction with the one-dimensional heat conduction equation. By drilling holes carefully and filling a silver paste, which has high thermal conductivity, in gaps between the holes and the thermocouples, successful measurements are made. The surface temperature estimated by an extrapolation of liquid temperature distributions measured during natural convection is almost equal to that corrected above.

Signals of the thermocouples are amplified differentially and measured by a multi-pen recorder and a multi-channel digital voltmeter. The boiling sound is amplified and its root mean square (r.m.s.) value is measured by the multi-pen recorder. The temperature fluctuations and the boiling sound are carefully observed on the recorder chart traces and oscilloscopes to understand the boiling state.

The heating surface is polished with 6–12 μm grade diamond paste.

The range of variables covered are as follows: system pressure is from 30 to 760 torr; liquid level is from 5 to 50 mm; maximum heat flux is 2×10^6 W m^{-2}.

RESULTS AND DISCUSSION

The boiling state under present experimental conditions is classified into four regions: (1) non-boiling region; (2) intermittent boiling region; (3) stable boiling region and (4) dry patch formed boiling region where dry patch formation and rewetting are alternately repeated.

Typical pen recorder chart traces of the temperatures of the heating surface, liquid and vapor are shown in Figs. 3 (a)–(j), in which the experimental conditions of heat flux q, liquid level LL, system pressure SP and saturation temperature T_{sat} corresponding to the system pressure are also indicated.

Figures 3(a) and (b) show typical pen-recorder chart traces of those temperatures in (1) non-boiling, (2) intermittent boiling and (3) stable boiling regions, respectively. The heating surface temperature T_{w_2} is measured at the center of the wall, the liquid temperature T_l at $y = 0.5$ and 20 mm above the center and the vapor temperature T_v at about $y = 70$ mm above the wall. The averaged heating surface temperature during nucleate boiling is defined as the arithmetical average of T_{w_2H} and T_{w_2L} shown in Fig. 3(b). This definition is also used in the nucleate boiling stages in the regions (2) and (4) to discuss the nucleate boiling heat transfer.

Figure 3(c) shows traces of wall temperature T_{w_2} when burnout occurs from the stable boiling. Two typical traces in the region (4) are shown in Figs. 3(d) and (e). Figure 3(d) shows the dry patch formation and rewetting during the intermittent boiling and (e) shows those caused directly from natural convection. In Fig. 3(d) the dry patch formation occurs at the point marked by an arrow after the cessation of nucleate boiling, where the wall temperature begins to increase after a quick, small drop (the enlarged trace of the wall temperature is shown in the figure) and at the same time the liquid temperatures suddenly drop to and are kept at near the vapor temperature for several seconds. As the liquid temperature at 0.5 mm is almost equal to the vapor temperature, the heating surface near its center is considered to be dried. The quick, small drop of T_{w_2} at the dry patch formation seems to be caused by latent heat transport when the liquid evaporates quickly. The wall temperature rises to a certain value, and begins to drop and then nucleate boiling occurs again after the wall surface is rewetted. At higher heat flux the wall surface continues to rise without the rewetting and the burnout occurs as shown in Fig. 3(f). Figure 3(g) shows an example of the temperature traces for lower liquid level of 8 mm. The wall temperatures at which the dry patch is formed are not always the same value at fixed heat flux. The dry patch formation occurs more frequently for lower liquid level. Figure 3(h) shows the recorder chart traces of four wall surface temperatures, at the center (T_{w_2}), at 5 mm (T_{w_1}), at 10 mm (T_{w_3}) and at 15 mm (T_{w_4}) from the center when the dry patch is formed. The locations of the temperature measurement are shown in the figure. The r.m.s. value of boiling sound is also shown in the chart. The time constant of r.m.s. is 20 ms. The dry patch formation occurs at the point marked by an arrow after unsteady natural convection stage where boiling sound is not detected. These traces indicate that the wall surface at the center and the point 5 mm from the center is dried but that it is not dried at points 10 and 15 mm where the two wall temperatures decrease gradually to the temperatures observed during nucleate boiling. In this stage, boiling sound is detected. Traces of two liquid temperatures near the wall surface are shown in Fig. 3(i). The experimental conditions are the same as those of Fig. 3(h). The locations of temperature measurement are also in the figure. The wall surface temperature at the center (T_{w_2}), the liquid temperature (T_{l_1}) 0.5 mm above the T_{w_2} point, the wall surface temperature 10 mm from the center (T_{w_3}) and the liquid temperature (T_{l_2}) 3 mm above the T_{w_3} point are shown. The traces of T_{w_2} and T_{w_3} also indicate that the wall surface is dried only near the center and the liquid temperature T_{l_2} fluctuates in a similar manner to the nucleate boiling state shown in Figs. 3(a) and (d). The period of these fluctuations is almost equal to that measured at the center. Recorder chart traces in Figs. 3(h) and (i) indicate that the dry patch is formed near the center, the diameter of which is considered to be more than 5 mm under the condition in Figs. 3(h) and (i), while the nucleate boiling is still sustained around the dry patch. It is inferred that the dry patch formation occurs at the limited area on the heating surface. The dried area near the wall center can be cooled by radial heat conduction through the nickel wall to the surface where the nucleate boiling still occurs and hence the heat transfer rate from the wall to the liquid is high. Therefore the wall surface temperature begins to decrease after the dry patch formation and the rewetting is completed at a certain temperature. When the heat flux is high enough, however, the dried wall cannot be cooled by the radial heat conduction and burnout is caused as shown in Fig. 3(f). Since rewetting is inferred to occur due to the radial heat conduction through the heating wall, it is required for the rewetting that the heating wall is thick and is made of high heat conduction materials. The present heating wall, which is made of a 6-mm-thick nickel plate, seems to be thick enough and have a large enough thermal conductivity. Thermal conductivity of nickel is more than three times that of stainless steel which was used for the heating wall materials in the experiments of refs. [2–4]. A wall made of molybdenum, the thermal conductivity of which is larger than nickel, was used in some runs of refs. [3, 4] but its thickness was 1 mm. It is noteworthy that the dry patch formation was also observed in potassium pool boiling from a horizontal cylinder sheathed with 1-mm-thick stainless steel, but no rewetting was observed [9].

It might be said that this boiling crisis is extinguished since this phenomenon is not due to the hydrodynamic instability on the whole heating surface but due to the local dryout of the heating surface. As both nucleate boiling and film boiling occur locally at the same time on a wall surface, the dry patch formed boiling may be considered to be a transient transition boiling if we pay attention to the whole heating surface. Thus the dry patch formation is a local phenomenon during the transient transition boiling, which may go to burnout of the wall or may be extinguished depending on the shape and the thermal properties of the wall. However, it should be noted that the thermal fatigue of a heating wall will be attributed to the repetition of dry patch

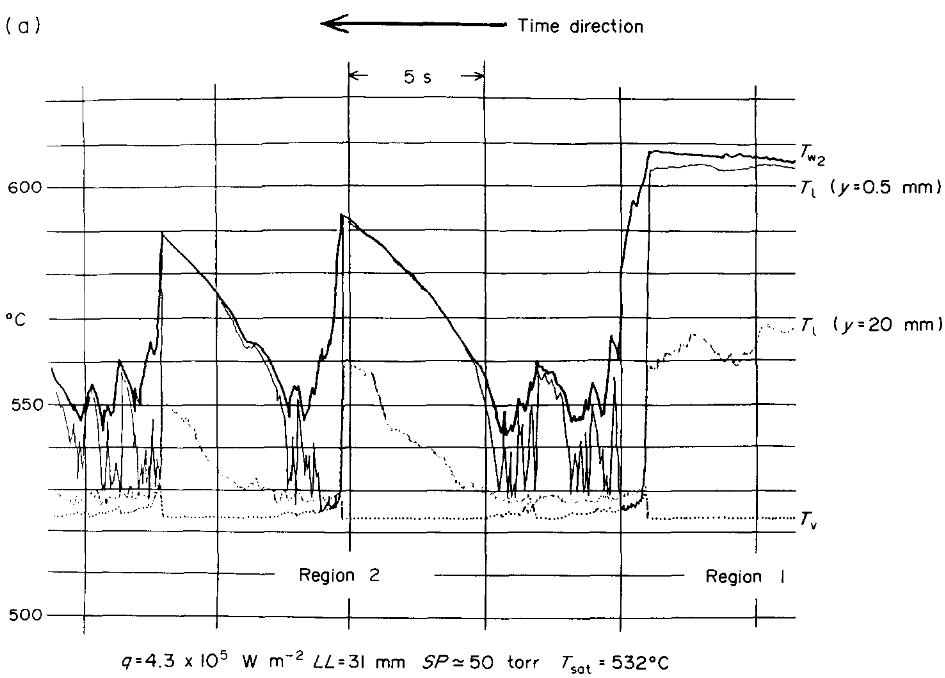

FIG. 3. Temperature traces. (a) Non-boiling (1) and intermittent boiling (2); (b) stable boiling; (c) burnout from stable boiling; (d) dry patch formation from intermittent boiling; (e) dry patch formation from natural convection; (f) burnout from dry patch formed boiling; (g) dry patch formed boiling for liquid level 8 mm; (h) dry patch formed boiling; (i) dry patch formed boiling.

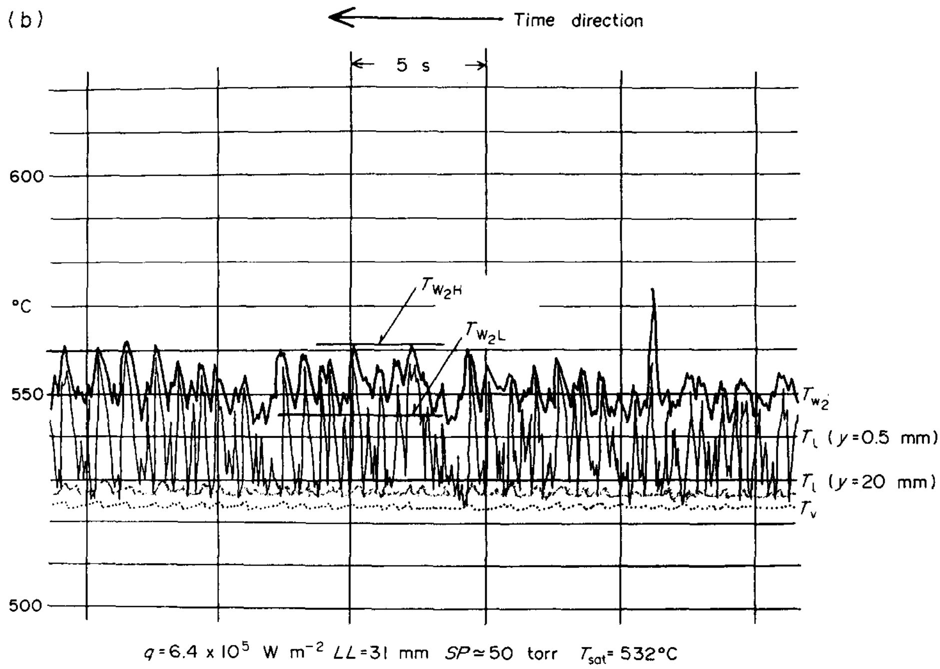
(b)
Time direction
5 s
600
°C
550
500
T_{w_2H}
T_{w_2L}
T_{w_2}
T_l (y=0.5 mm)
T_l (y=20 mm)
T_v
q=6.4 x 10^5 W m^{-2} LL=31 mm SP≃50 torr T_{sat}= 532°C

FIG. 3(b).

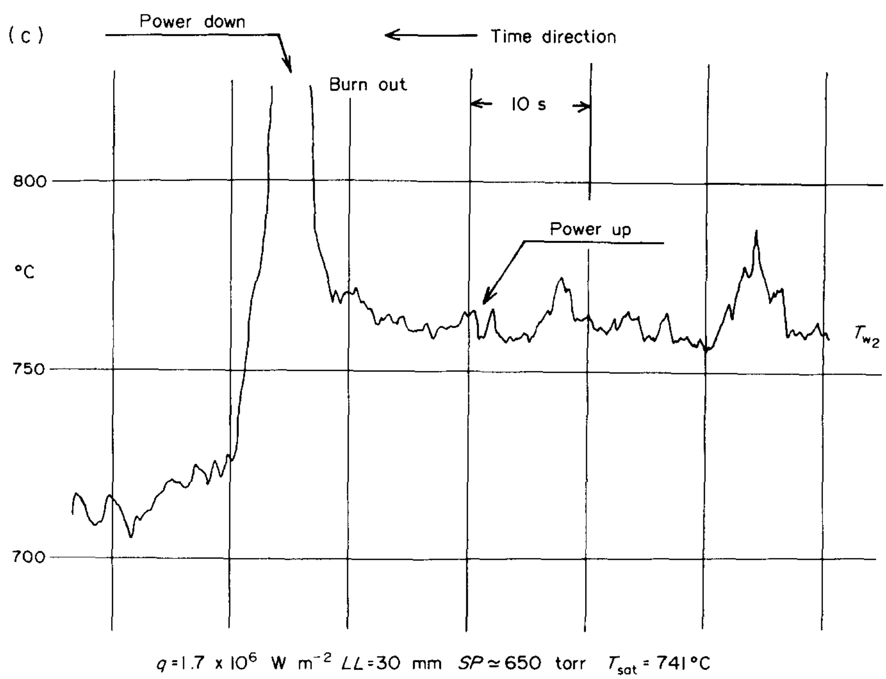
(c)
Power down
Time direction
Burn out
10 s
800
°C
750
700
Power up
T_{w_2}
q=1.7 x 10^6 W m^{-2} LL=30 mm SP≃650 torr T_{sat} = 741°C

FIG. 3(c).

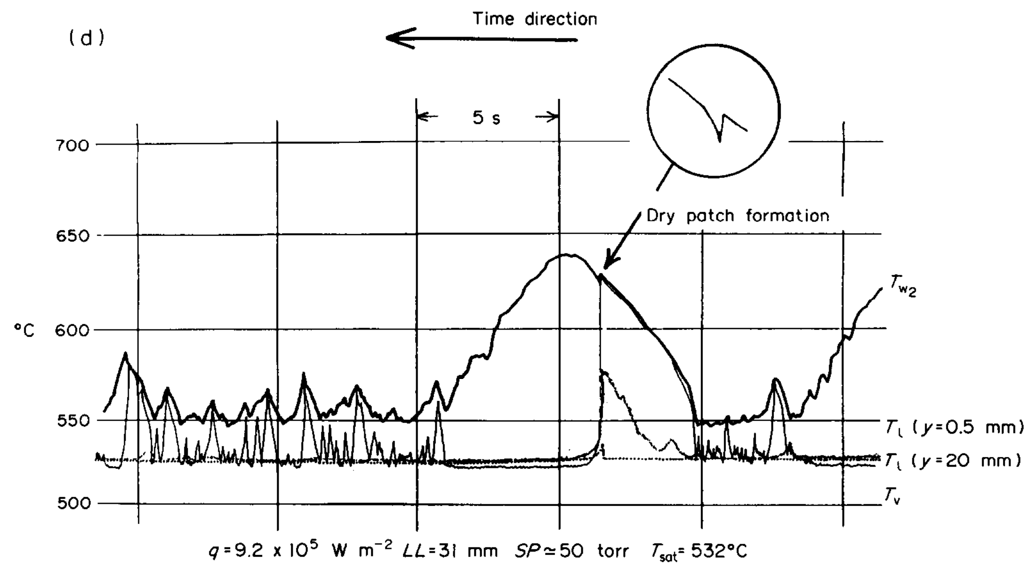
(d)
Time direction
5 s
700
650
600
550
500
°C
Dry patch formation
T_{w2}
T_l (y=0.5 mm)
T_l (y=20 mm)
T_v
q=9.2 x 10^5 W m^{-2} LL=31 mm $SP \simeq$50 torr T_{sat}= 532°C

FIG. 3(d).

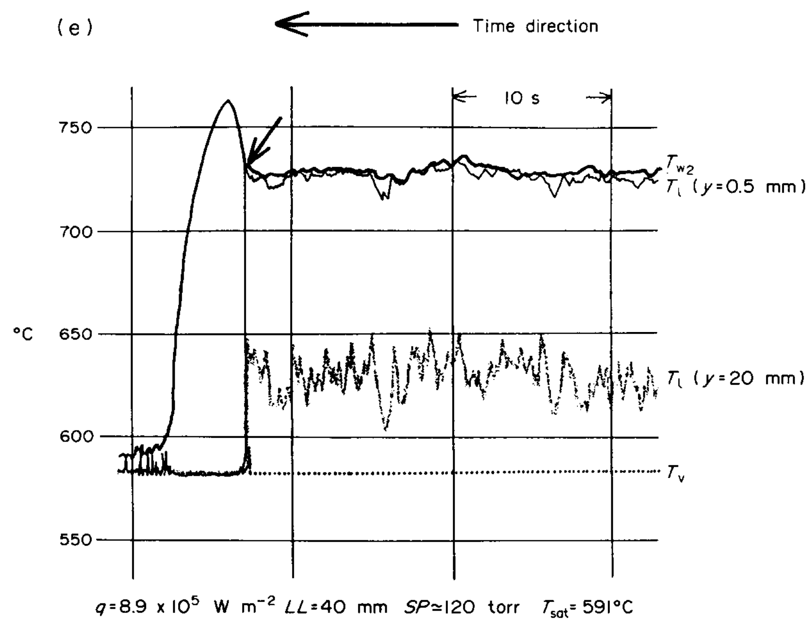
(e)
Time direction
10 s
750
700
650
600
550
°C
T_{w2}
T_l (y=0.5 mm)
T_l (y=20 mm)
T_v
q=8.9 x 10^5 W m^{-2} LL=40 mm $SP \simeq$120 torr T_{sat}= 591°C

FIG. 3(e).

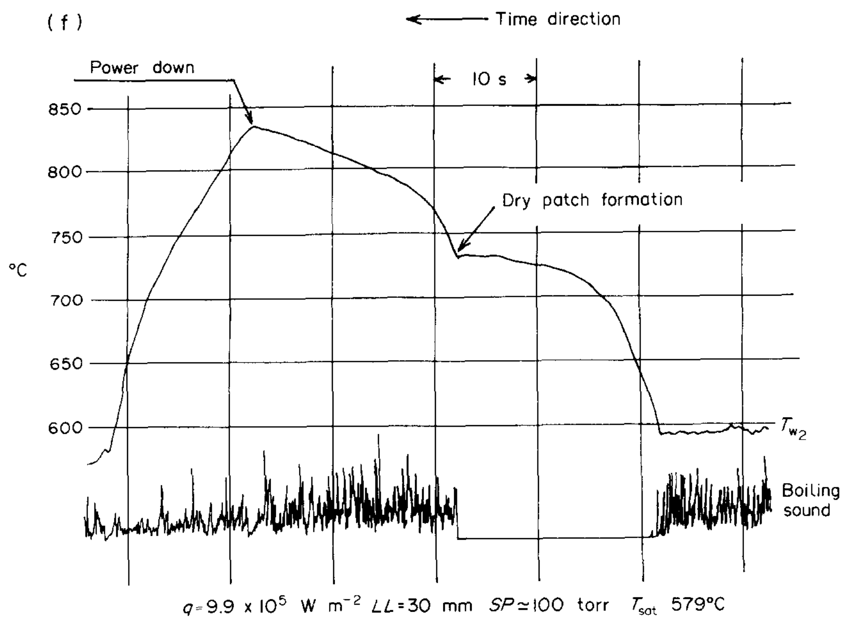
(f)
Time direction
Power down
10 s
850
800
750
700
650
600
°C
Dry patch formation
T_{w_2}
Boiling sound
$q = 9.9 \times 10^5$ W m^{-2} $LL = 30$ mm $SP \simeq 100$ torr T_{sat} 579°C

FIG. 3(f).

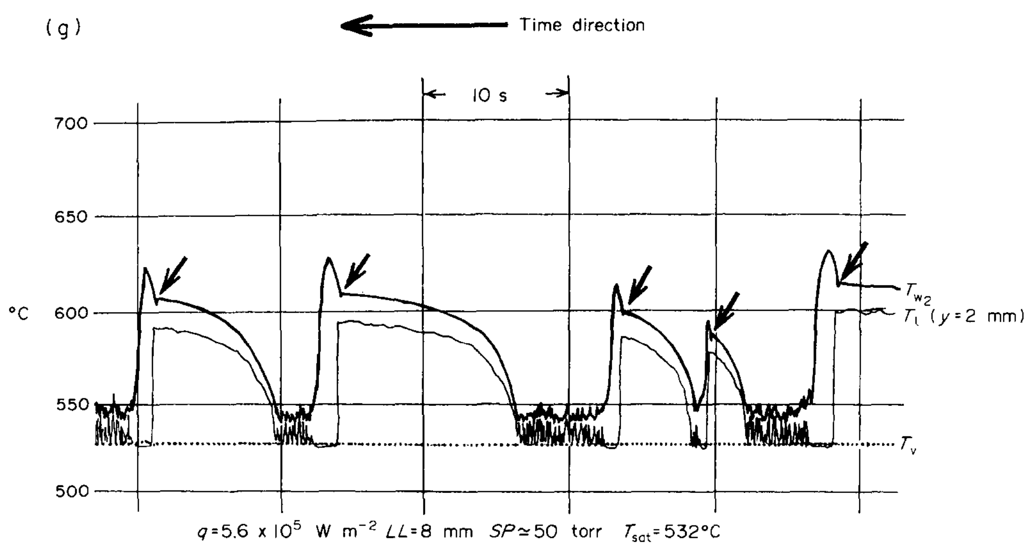
(g)
Time direction
10 s
700
650
600
550
500
°C
T_{w_2}
T_l ($y = 2$ mm)
T_v
$q = 5.6 \times 10^5$ W m^{-2} $LL = 8$ mm $SP \simeq 50$ torr $T_{sat} = 532$°C

FIG. 3(g).

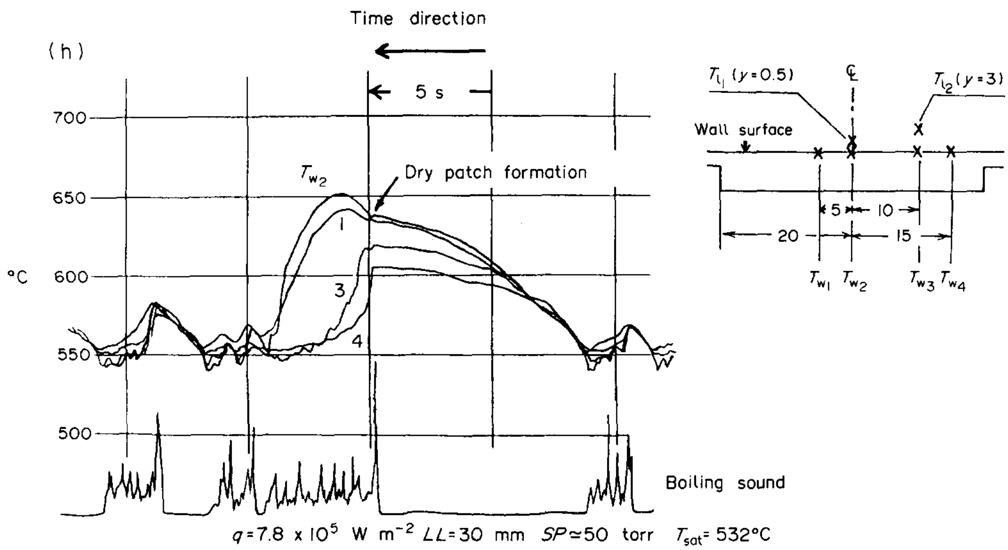
Time direction
(h)
5 s
700
650
600
550
500
°C
T_{w_2}
Dry patch formation
1
3
4
Boiling sound
T_{l_1} (y=0.5)
T_{l_2} (y=3)
Wall surface
5
10
20
15
T_{w_1} T_{w_2} T_{w_3} T_{w_4}
q=7.8 x 10^5 W m^{-2} LL=30 mm SP≃50 torr T_{sat}= 532°C

FIG. 3(h).

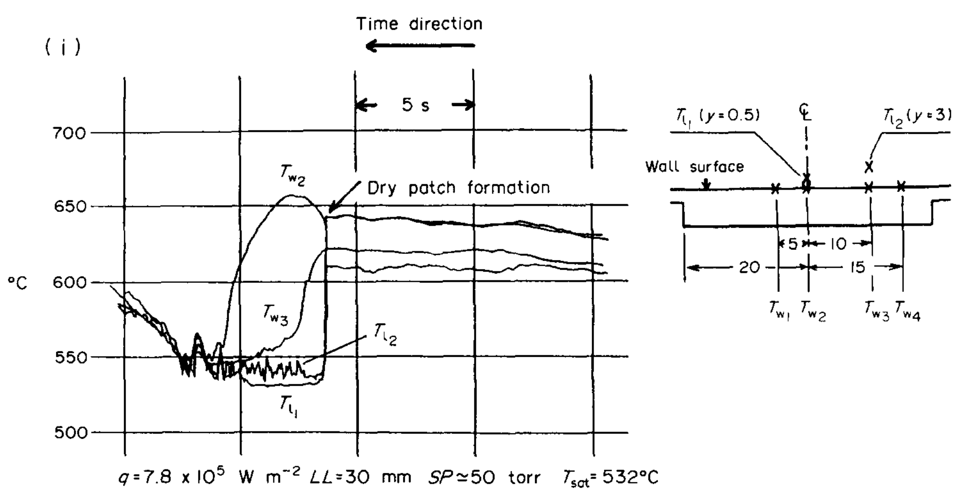
Time direction
(i)
5 s
700
650
600
550
500
°C
T_{w_2}
Dry patch formation
T_{w_3}
T_{l_2}
T_{l_1}
T_{l_1} (y=0.5)
T_{l_2} (y=3)
Wall surface
5
10
20
15
T_{w_1} T_{w_2} T_{w_3} T_{w_4}
q=7.8 x 10^5 W m^{-2} LL=30 mm SP≃50 torr T_{sat}= 532°C

FIG. 3(i).

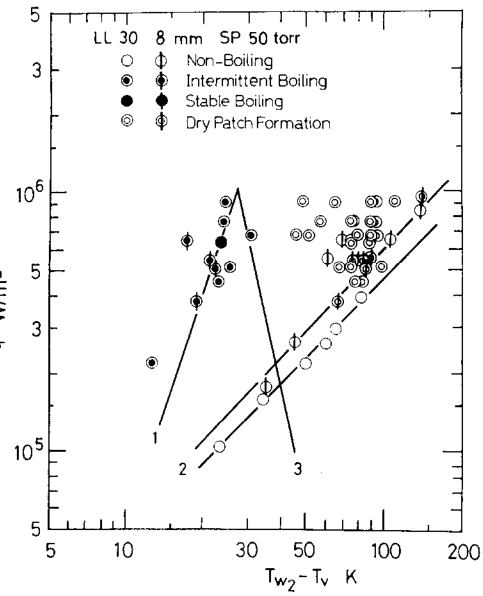

FIG. 4. Boiling curves, SP = 50 torr, LL = 8, 31 mm.

formation and rewetting because of the large amplitude of temperature fluctuation at high wall temperature. For safety considerations the minimum heat flux to form a dry patch must be examined.

Boiling curves for system pressure of 50 torr and liquid levels of 31 and 8 mm are shown in Fig. 4. All experimental results of temperature difference $T_{w_2}-T_v$ at which the dry patch is formed are plotted against heat flux. These data involve the data shown in Figs. 3(d) and (g). Line 1 shows the present correlation for nucleate boiling and line 3 the predicted steady transition boiling curve, the details of which will be discussed later; line 2 shows that for natural convection. It is very interesting to examine the relationship between the dry patch formation and the steady transition boiling curve, because the dry patch formed boiling seems to be the transient transition boiling. The figure shows that the dry patch is formed when both heat flux and temperature difference are higher than those of the steady transition boiling curve. Assuming from this result that the minimum heat flux to form the dry patch is given at the intersection point of the transition boiling curve and the natural convection curve, it is derived that the minimum heat flux to form the dry patch is higher for lower liquid level as shown in Fig. 4.

Since the steady transition boiling curve of potassium has never been obtained, an assumption is made to estimate the minimum heat flux to form the dry patch as follows: the transition boiling curve is linear in the log–log plot of q vs ΔT from the maximum point, the transition from stable nucleate boiling to film boiling, to the minimum point, the transition from film boiling to nucleate boiling, according to Berenson [10]. To obtain these points, the superheat or the heat transfer coefficient as well as the heat flux are needed.

First to estimate the maximum point, the present results of nucleate boiling curves for the liquid level of 30 mm and various system pressures up to 760 torr are shown in Figs. 5(a) and (b). Nucleate boiling heat

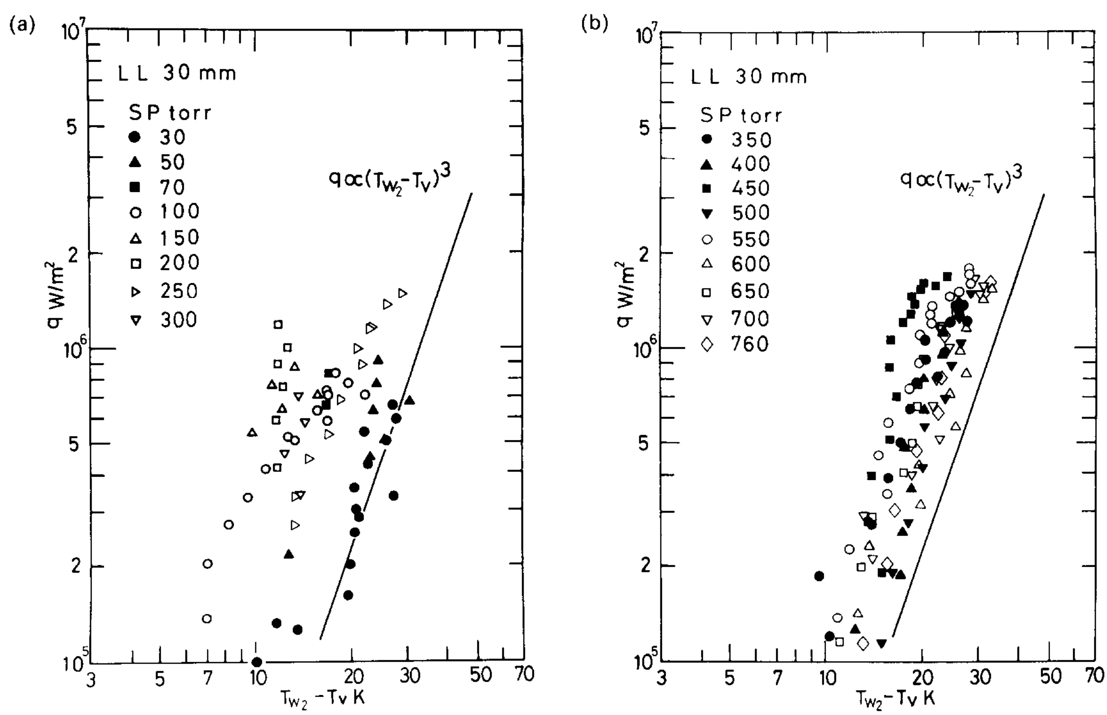

FIG. 5. Nucleate boiling curves. (a) SP = 30–300 torr, LL = 30 mm; (b) SP = 350–760 torr, LL = 30 mm.

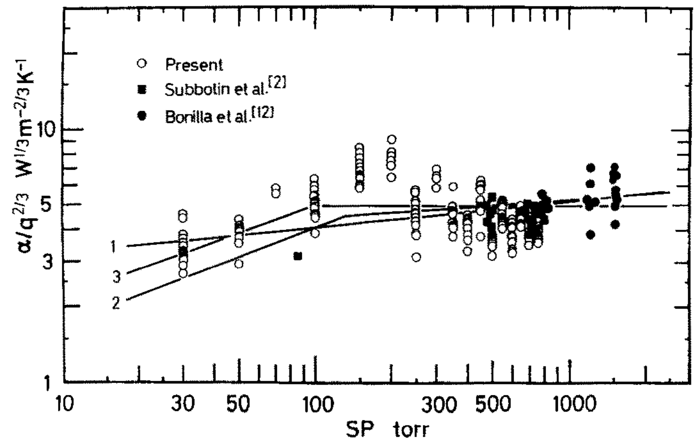

FIG. 6. Dependency of nucleate boiling heat transfer coefficient on system pressure.

transfer is discussed on the stable boiling region (3) together with the nucleate boiling stages in the regions (2) and (4). Since the heat flux shows a tendency to be proportional to about the third power of the temperature difference, $\alpha/q^{2/3}$ is plotted against system pressure, where the heat transfer coefficient α is defined as $q/(T_{w_2}-T_v)$. Figure 6 shows dependency of nucleate boiling heat transfer coefficient on the system pressure for 30 mm liquid level. The effect of liquid level on the boiling heat transfer has been already studied by the authors [8, 9, 11] and no apparent effect has been observed for liquid levels in the range of 5–50 mm. In this figure, experimental data of pool boiling heat transfer from a horizontal plate to potassium by Bonilla *et al.* [12] and Subbotin *et al.* [2] are also plotted, which are the only data available for potassium pool boiling on a horizontal plate, to the authors' knowledge. Line 1 is an empirical equation of Subbotin *et al.* [2] for potassium pool boiling based on their own [2] and Bonilla *et al.*'s [12] data. Line 2 is calculated by an empirical correlation proposed by Subbotin *et al.* [2] for pool boiling heat transfer from a horizontal plane heater to sodium, cesium and potassium. Line 3 is a correlation for the present experimental data together with the data of Bonilla *et al.* [12] and Subbotin *et al.* [2].

For $30 < SP < 100$ torr,

$$\alpha = 0.8\, SP^{0.4} q^{2/3} \tag{1a}$$

and for $100 < SP < 1500$ torr,

$$\alpha = 5\, q^{2/3}. \tag{1b}$$

Each correlation gives similar values for system pressures from 200 to 1500 torr.

Figure 7 shows the burnout heat flux and the dry patch formation for a 30 mm liquid level and various system pressures up to 760 torr. All heat fluxes where the dry patch formations occur are plotted. No dry patch formed boiling is observed for system pressures higher than 300 torr where the boiling is stable at high

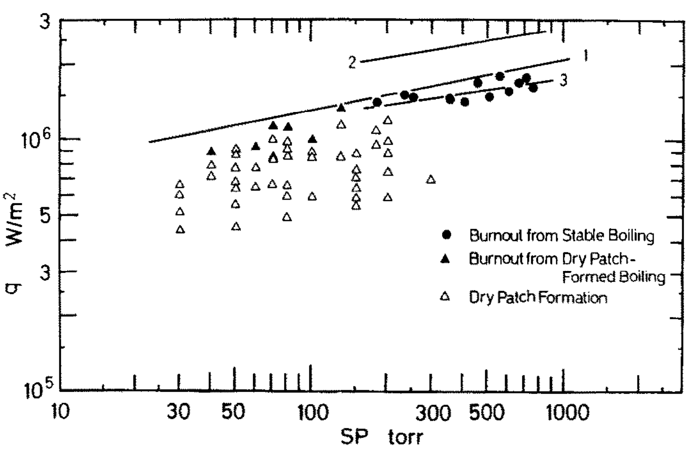

FIG. 7. Burnout heat flux and dry patch formation.

heat flux. Two types of the burnout heat flux which are caused from stable boiling and dry patch formed boiling as shown in Figs. 3(c) and (f), respectively, are also plotted. The maximum critical heat flux in potassium was studied by Subbotin *et al.* [2] for a horizontal plate and by Colver and Balzhiser [13] for a horizontal cylinder. Their results show almost the same heat flux. Line 1 is the equation proposed by Dwyer [1] based on all the data of Subbotin *et al.* [2] which included burnout data of both stable and unstable boiling. This equation shows similar values to the present results. Line 2 in the figure shows an empirical correlation of Subbotin *et al.* [2] for burnout heat flux of stable boiling in liquid alkali metals which was reported to be a satisfactory agreement with their own results for sodium, cesium, potassium and rubidium. This equation shows larger values than the present results but shows similar dependency on system pressure. Line 3 is an empirical correlation of the present results for burnout heat flux of stable boiling.

$$q_{\max} = 5.5 \times 10^5\, SP^{0.17}. \tag{2}$$

Thus the maximum point is obtainable by equations (1) and (2).

Next to estimate the minimum point, the following correlations on film boiling are selected: the film boiling heat transfer coefficient was derived by Berenson [14] and only the experimental data of Padilla and Balzhiser [15] showed some degree of agreement with it. The minimum heat flux was derived by Berenson [14]; Henry [16] modified Berenson's equation for superheating at the minimum point considering the heat removal by transient wetting of a heating wall and microlayer evaporation. His empirical equation was formulated by experimental data of film boiling with cryogens, water, organic liquids and alkali metals. Data of film boiling with a droplet, the so-called Leidenfrost phenomenon, were not used for his correlation. Data with alkali metals consisted of those of steady potassium boiling by Padilla and Balzhier [15] and of transient sodium boiling by Farahat *et al.* [17]. Henry seems to have used the physical poperties of potassium vapor predicted theoretically by Lee and Bonilla [18] to make the correlation of the minimum superheat. These theoretical values disagreed considerably with experimental values measured by Stefanov *et al.* [19]. In the present analysis, the physical properties of vapor by Lee and Bonilla [19] and those of liquid collected by Foust [20] are used. Thus the minimum point is obtainable with these equations.

Assuming the minimum heat flux to form the dry patch is given at the intersection point of the transition boiling curve and the natural convection curve, the predicted minimum heat flux is shown in Fig. 8 for 8 and 30 mm liquid levels. The experimental data of the minimum heat flux increases slightly with increasing the system pressure. The calculated results show the same tendency though their values are smaller than the experimental data and they indicate that the minimum heat flux is higher for lower liquid level because the natural convection heat transfer is better for lower liquid level, as was apparent in Fig. 4, though the present experimental results do not clearly show this tendency. Further studies on film boiling heat transfer and physical properties of vapor of alkali metals are required.

CONCLUSIONS

Experimental results are presented on dry patch formed boiling and burnout in potassium pool boiling from a flat nickel plate for various system pressures and liquid levels.

(1) Dry patch formed boiling where dry patch formation and rewetting are alternately repeated

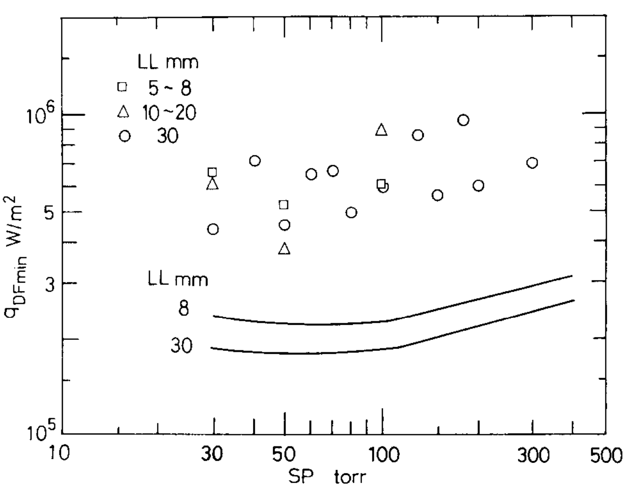

FIG. 8. Minimum heat flux to form dry patch.

is observed under system pressures lower than 300 torr and its boiling state is considered to be transient transition boiling, paying attention to the boiling state on the whole heating surface.

(2) The minimum heat flux to form the dry patch takes a similar value to the burnout heat flux of unstable boiling reported by Soviet researchers [2–4]. It is slightly higher at higher system pressure. The dry patch formation occurs more frequently for lower liquid level.

(3) Empirical correlations are presented on nucleate boiling heat transfer coefficient and burnout heat flux by equations (1) and (2), respectively.

(4) A model to predict the minimum heat flux to form the dry patch is proposed. It predicts a similar tendency to the experimental data but it predicts smaller values than those. Further studies on film boiling heat transfer and physical properties of vapor of alkali metals are required.

(5) The repetition of dry patch formation and rewetting will cause the thermal fatigue of a heating wall because of large temperature amplitudes at high wall temperature. From safety considerations, attention should be paid to the dry patch formed boiling as well as burnout, especially for low pressure boiling of alkali liquid metals.

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EBULLITION AVEC AIRE SECHE ET ASSECHEMENT DANS L'EBULLITION EN RESERVOIR DU POTASSIUM

Résumé—On présente des résultats expérimentaux sur l'aire sèche pendant l'ébullition en réservoir du potassium saturé sur une surface plane horizontale chauffée pour des pressions variant de 30 à 760 torr et des hauteurs de liquide allant de 5 à 10 mm. L'ébullition avec aire sèche est un état d'ébullition pour lequel se repètent alternativement assèchement et remouillage avec un flux de chaleur plus petit que le flux critique de l'ébullition nucléé permanente; on considère cela comme un phénomène local de transition à partir des observations à la paroi et des fluctuations de température. La formation d'aires sèches apparait souvent quand les métaux alcalins sont utilisés dans les conditions de pression relativement basse. Les flux thermiques de brûlage et les coefficients de transfert par ébullition nucléé sont empiriquement corrélés avec les conditions de pression. On propose aussi un modèle pour prévoir le flux thermique minimal qui forme l'aire sèche.

VORGÄNGE BEIM SIEDEN UND "BURN-OUT" AN AUSGETROCKNETEN FLÄCHENTEILEN BEIM BEHÄLTERSIEDEN VON KALIUM

Zusammenfassung—Die Vorgänge beim Sieden und beim "burn-out" an ausgetrockneten Flächenteilen beim Behältersieden von Kalium an einer waagerechten ebenen Heizfläche werden experimentell untersucht. Der Systemdruck beträgt 30 bis 760 Torr, die Füllmenge 5 bis 50 mm. Das Sieden an ausgetrockneten Flächenteilen ist ein spezieller Siedezustand, wobei abwechselnd eine Bildung von Trockenstellen und eine Wiederbenetzung stattfindet. Dabei ist die Wärmestromdichte kleiner als beim "burn-out" unter stetigen Siedebedingungen. Die beobachteten Schwankungen von Wand- und Flüssigkeitstemperatur deuten darauf hin, daß es sich um ein lokales Phänomen des instationären Übergangssiedens handelt. Die Bildung von Trockenstellen tritt beim intermittierenden Sieden auf, was oft bei der Verwendung von flüssigen Alkali-Metallen bei relativ kleinen Drücken vorkommt. "Burn-out" wird sowohl vom kontinuierlichen Blasensieden als auch vom Sieden an Trockenstellen verursacht. Die Wärmestromdichte beim "burnt-out" und die Wärmeübergangs-Koeffizienten werden mit dem Systemdruck korreliert. Darüber hinaus wird ein Modell zur Berechnung der minimalen Wärmestromdichte für die Ausbildung von Trockenstellen entwickelt.

КИПЕНИЕ С ВЫСЫХАНИЕМ И КРИТИЧЕСКИЙ ТЕПЛОВОЙ ПОТОК ПРИ КИПЕНИИ КАЛИЯ В БОЛЬШОМ ОБЪЕМЕ

Аннотация—Представлены экспериментальные результаты по кипению с высыханием и критическому тепловому потоку при кипении калия в большом объеме на горизонтальном плоском нагревателе в диапазоне давления от 30 до 760 тор и высоты жидкости от 5 до 50 мм. Кипение с высыханием—это особый случай кипения, когда образование сухого участка и повторное смачивание чередуются при периодическом кипении, когда значение теплового потока меньше критического при непрерывном пузырьковом кипении. Из наблюдений флуктуаций температуры стенки и жидкости можно сделать вывод, что в случае переходного процесса этот вид кипения носит локальный характер. Сухой участок образуется при периодическом режиме кипения, часто встречающемся при использовании жидкий щелочных металлов при относительно низких давлениях. Критический тепловой поток обусловлен как непрерывным пузырьковым кипением, так и кипением с образованием сухого участка. Получены эмпирические соотношения для критического теплового потока и коэффициентов теплопереноса при пузырьковом кипении в зависимости от давления. Предложена модель для расчета минимального теплового потока, необходимого для образования сухого участка.