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Experimental Study of Transition Boiling on a Vertical Wall in Open Vessel*

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Water in an open vessel was brought to the transition boiling from the outer surface of a vertical copper tube heated from inside with saturated steam. By analyzing the oscillograph record of the surface temperature and the steam film detecting probe, it was concluded that the transition boiling is a particular phenomenon in which the boiling surface gets alternately wet and dry. It was found that the boiling characteristic curve is smooth and continuous throughout the nucleate and the transition boiling, and a particular type of boining was observed in the vicinity of the maximum heat flux and was termed the burnout boiling.

1. Introduction

In transition boiling, the heat flux decreases when the film temperature drop increases. This type of boiling rarely takes place actually in practical heat exchangers because of its inherent instability. It is worth studying, however, because the study may be expected to contribute to the understanding of the neighboring important domains, namely, the nucleate and the film boiling.

The transition boiling has been the subject of a comparatively few papers. It may partly be due to the experimental difficulty of bringing about the transition boiling. In this experiment, saturated steam was injected against a thin copper wall to effect boiling on the other side of the thin wall. When the heating steam pressure was low, nucleate boiling was observed. When the steam pressure was raised gradually, the burnout point was reached and then transition boiling started. The surface temperature was observed and its fluctuation was analyzed. The mode of fluctuation was explained by considering the mechanism of transition boiling.

2. Apparatus

2·1 Points of consideration

In the experimental studies(1)(2) published hitherto on transition boiling, saturated steam was generally used for heating the boiling surface so that the surface temperature might easily be kept at any desired temperature above the bulk liquid temperature irrespective of the mode of boiling. This principle was also followed in our experiment with some modifications. The heating steam was generated by a sufficiently large boiler so that the steam pressure variation during a run of the experiment was prevented. The heating steam was injected against the heating surface to insure good heat transfer to minimize the temperature difference between the heating steam and the boiling surface. The boiling surface was made of a thin copper plate and thus the wall temperature drop was also minimized.

2·2 General arrangements

In our experiment, demineralized water was boiled under atmospheric pressure in an open vessel from a vertical boiling surface as illustrated in Fig. 1. In the diagram, ① is the vessel, 800×

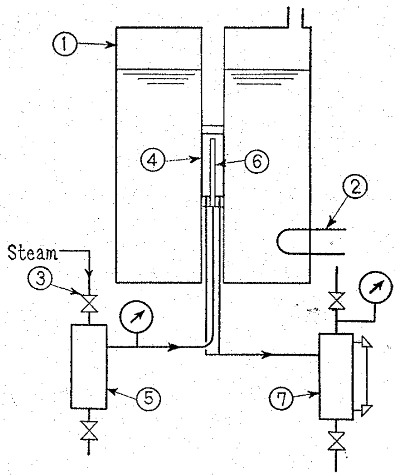

Fig. 1 Arrangement of boiling equipment

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600×600 mm^3, which is filled with water demineralized to several million Ω cm. Two electric heaters, 2 kW each, are indicated by ②. They bring the bulk water to boiling at the start of the experiment and also prevent it from cooling during the test run. Heating steam from a boiler in our laboratory flows through the stop valve ③, the drain trap ⑤ to the internal pipe ⑥ with 80 holes, 0.8 mm in diameter, and flows through the holes at high speed up to 40 m/sec to hit the heating surface. The condensate flows down the pipe and gathers in the drain meter ⑦.

2·3 Vessel and the boiling surface

Fig. 2 is a sectional view of the heater for effecting transition boiling. Transition boiling is observed on 1 made of a copper tube, 40 mm in outer diameter and 1 or 4 mm in nominal thickness. The roughness of the boiling surface was controlled at several levels. Both upper and lower ends of the copper tube are connected to stainless tubes to form one continuous cylinder to alleviate any disturbance in the water flow along the boiling surface. As mentioned before, the heating steam flows out through the small holes on the internal tube ③. The turbulence caused by the steam jet impinging against the heating surface further improves the heat transmission of the condensing steam which is an excellent heating medium even without such turbulence.

The boiling vessel is made of steel plate. Its inner surface is coated with boiler paint. Observation windows are privided on three sides of the vessel.

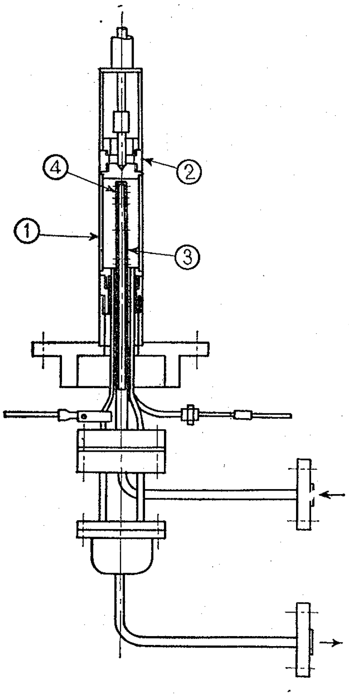
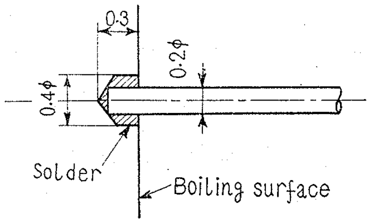


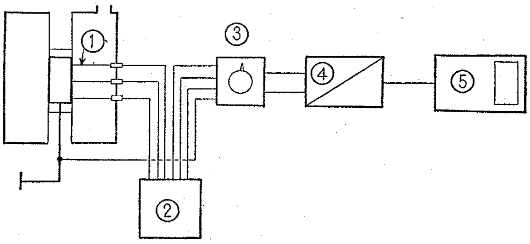
Fig. 2 Details of boiling surface construction

2·4 Temperature measurement

The wall was so thin that it was impossible to place two thermocouples along the direction of heat flow for the purpose of finding the surface temperature from the measured temperature gradient. Thermocouples placed directly on the surface would give erroneous temperature because of the cooling effect of the lead wires submerged in the liquid. It was expected, however, that, if the mechanism of bubble formation in nucleate boiling or in film boiling is different from the mechanism in transition boiling, the mode of the surface temperature variation would have a particular pattern for each of the three types of boiling. Therefore three thermocouples as illustrated in



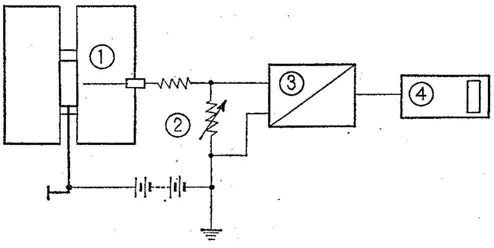
(a) Constantan wire mounted on the boiling surface



① Constantan wire ⑤ D.C. amplifier
② Cold junction ④ Pen writing oscillograph
③ Selecting switch

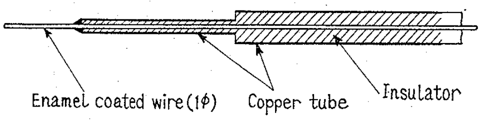
(b) Thermocouple circuit for measuring surface temperature fluctuation

Fig. 3 Measuring devices for surface temperature fluctuation



① Electrode ③ D.C. amplifire
② Variable resistance ④ Pen writing oscillograph

(a) Electric circuit for detecting steam film



(b) Cross section of electrode

Fig. 4 Measuring equipment for detecting the formation of steam film

Fig. 3 were mounted on the boiling surface at different heights. In Fig. 3, a constantan wire was soldered in a small, shallow cavity cut by drilling, and the wire and the copper wall formed a thermocouple. The temperature variation was recorded by an oscillograph.

2·5 Heat flux measurement

The heat flux was measured by observing the amount of condensate flowing out of the test tube. Heat losses from the upper and the lower ends of the test tube were negligibly small because both ends were heat-insulated with phenol resin.

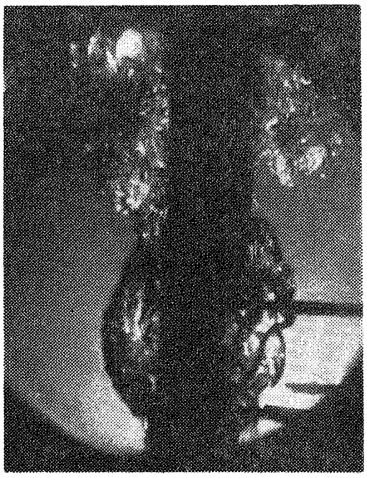
2·6 Steam film detection

In Fig. 4 is illustrated the device for detecting steam film on the boiling surface. As indicated in the drawing, a fine electrode was placed 0.2 mm apart from the boiling surface. The electrode was made of enamel-coated copper wire, whose end surface was not coated to insure good electric conductivity. The electrode was placed in the immediate vicinity of the constantan wire for measuring the temperature variation. If there is water between the electrode and the boiling surface, the electric circuit is closed. If steam film separates the electrode from the surface, the electric current is cut off. The signal from the electrode and the thermocouple was recorded simultaneously by an oscillograph.

3. Experimental results

3·1 Visual observations

In the low heat flux region in nucleate boiling, bubbles are generated at particular spots on the boiling surface. Under the light of a stroboscope at proper period, the bubbles can be seen stationary. When the temperature of the boiling surface is raised gradually, the number of the bubble generating spots increases, and bubbles begin to join with each other. Under these conditions, the boiling surface can be seen directly. As the surface temperature rises further, the boiling surface begins to be covered with a few large bubbles which are formed by gathering a large number of small bubbles. These large bubbles have various shapes, and the period is rather random. Under these conditions, heat flux can be further increased. Therefore it is logical to estimate that the boiling surface under the bubbles is still wet; in other words, a sufficient quantity of water to prevent it from drying up is left before the large bubble leaves the surface. As the surface temperature rises still more, the size and thickness of the combined bubbles increase further, and, in the vicinity of the burn-out point, the entire circumference at a height is covered by one continuous bubble which rises along the test tube. Water is still remaining on the boiling surface under these spherical bubbles and new bubbles are formed on the surface. Fig. 5 is a photograph of these bubbles taken with a light source behind the bubbles. New bubbles being formed can be seen under the large bubble. As heat flux rises very close to the maximum, pulse fluctuations appear in the record of the surface temperature as shown in **Fig. 13 (ii)**, and the bubble becomes large enough to cover the entire boiling surface thoroughly (Fig. 6). After the large bubble rises upward and leaves the surface, there occurs an instance when there are no bubbles at all on the boiling surface, and at the next moment, a large bubble begins to be formed and grows to cover the surface completely. In the beginning of this region in which the temperature record has pulse components, the period of the formation of the large bubble is about one second. The period gets shorter when the surface temperature rises. The heat flux reaches its maximum in this region, and when the surface temperature is raised further, the heat



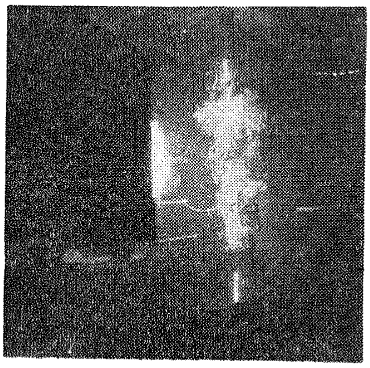
$q/A = 9.5\times10^5$ kcal/m^{2}hr
$\theta^* = 30$°C
Fig. 5 Nucleate boiling

$q/A = 10.6\times10^5$ kcal/m^{2}hr
$\theta^* = 37$°C
Fig. 6 Burnout

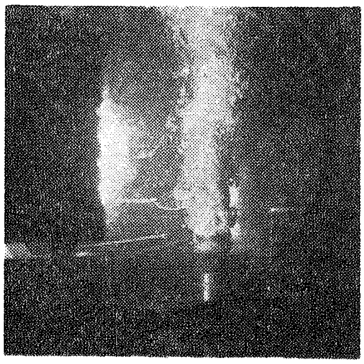
flux begins to decrease; in other words, the boiling goes into the domain of transition boiling. The bubble size becomes smaller by further going into the domain. At the time when heat flux is at its maximum, the boiling surface can be seen clearly under the large bubbles without any small new bubbles. In other words, there is no water left on the surface to be boiled under the large bubbles in the maximum heat flux region. It is logical to estimate that, in this region, the water film ordinarily left on the surface evaporates completely into a large bubble.

If the surface is heated by fire or by electricity in a usual manner, the surface temperature will rise rapidly as soon as the surface is dried up. On the contrary, if the surface is heated by saturated steam under constant temperature as in our experiment, the surface temperature can not rise largely even if the surface is dried up. When the surface is dried up, the rate of steam generation decreases, and the steam film once formed can not be maintained. Therefore, after the bubble floats up by buoyancy, water touches the surface, and this process is repeated. Further rise in the surface temperature results in less and less violent bubble formation hereafter.

Thus, the steam-heating method makes it possible to examine in detail the mode of bubble formation in the highest heat flux domain. It was found that, when the heat flux was gradually raised in the nucleate boiling region to a point at which the surface temperature was nearly 5°C less than that which corresponded to the maximum heat flux, some changes in the mode of bubble formation were observed. For example, pulses appear in oscillograms of the surface temperature, and also there appear visual evidences that indicate an intermittent drying up of the boiling surface. This type of boiling will be referred to in this paper as burn-out boiling. This domain is similar to the domain of nucleate boiling in that the heat flux increases with the surface temperature. As the surface temperature rises in this domain, the period of giant bubble generation gets shorter, and finally the heat flux reaches its maximum. Further surface temperature rise results in a decrease in the heat flux, and thus the mode of boiling steps into the domain of transition boiling. When the transition boiling starts, low explosive sounds are heard from the boiling surface and the bubbles are generated less and less violently, see Figs. 7 and 8.



$q/A=8.7\times10^5$ kcal/m^{2}hr
$\theta^*=53$°C
Fig. 7 Transition boiling



$q/A=4.5\times10^5$ kcal/m^{2}hr
$\theta^*=63$°C
Fig. 8 Transition boiling

The differences between nucleate and transition boiling are as follows. First is the explosive sound mentioned above. Next is that the boiling surface can be seen from between the bubbles at low heat flux ($2\sim3\times10^5$ kcal/m^2 hr) in nucleate boiling, while in transition boiling the boiling surface can never be seen. This is because light is totally reflected from the surface of the bubbles which closely cover the boiling surface. The third difference is that, when the water contains impurities, the boiling surface is more contaminated in transition boiling than in nucleate boiling.

3·2 Characteristic curves

3·2·1 Representative variables In this experiment, the boiling surface temperature was not measured because of the experimental difficulties explained before. The following θ^* was adopted in place of the generally used film temperature drop for constructing the characteristic boiling curve, i. e.,

$$\theta^*=(\theta_s-\theta_0)-\Delta\theta,$$

where

θ_s = saturated heating steam temperature,
θ_0 = bulk temperature,
$\Delta\theta$ = temperature drop in the copper tube wall,
$=\frac{q}{A}\frac{1}{2\pi\lambda}\log r_2/r_1,$
q/A = heat flux,
r_1 and r_2 = inner and outer dia. of copper tube,
λ = thermal conductivity of coppear tube.

It is to be expected that θ^* is affected by the heat transfer rate on the other side of the boiling surface. The data, however, indicated sufficiently good reproducibility unless the inner surface of the copper tube was excessively contaminated.

3・2・2 Characteristic curves In Figs. 9 through 12 is plotted the heat flux against θ^* explained above. The curves in the drawings will be referred to as the characteristic curves. The symbols in the diagrams represent experimental conditions. For example, C 1-86-Cr-1 indicates that the data were obtained by using a copper tube 1 mm thick, 86 mm long, and having a hard chrome plated surface. The last numbers in Fig. 9 designate the experimental run. Similarly, C 4-106-E 60 designates an experimental run with a copper tube 4 mm thick, 106 mm long, having a surface polished with emery paper ♯60. Fig. 9 is presented as an example of the reproducibility of data for 3 different runs of experiment under the same conditions.

These drawings indicate the following. (i) The burnout heat flux was nearly 10^6 kcal/m^2 hr for all experimental runs irrespective of surface roughness and wall thickness. Burnout presented itself not as a sharp point indicating a jump, but as a rather flat and continuous curve connecting the curves for nucleate and transition boiling. The burnout boiling region mentioned before extended over 5°C in temperature. (ii) Surface roughness has a significant effect on transition boiling as well as on nucleate boiling. The characteristic curve shifts to the left when roughness increases. On the other hand, since the minimum heat flux in film boiling is independent of surface roughness, the effect of roughness is less significant in the higher temperature part of the transition boiling domain. In other words, surface roughness makes

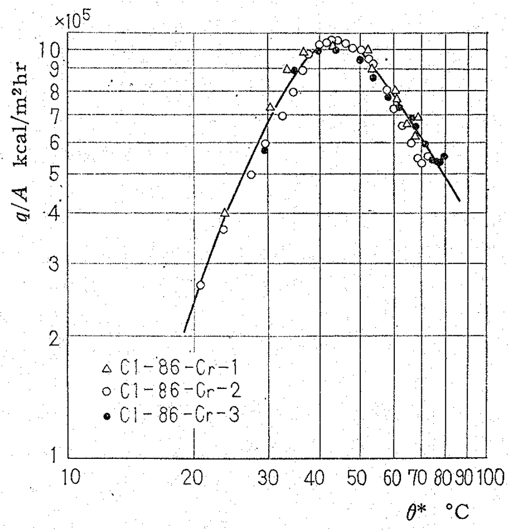


Fig. 9 Boiling curve (copper tube, wall thickness 1 mm, chrome plated)

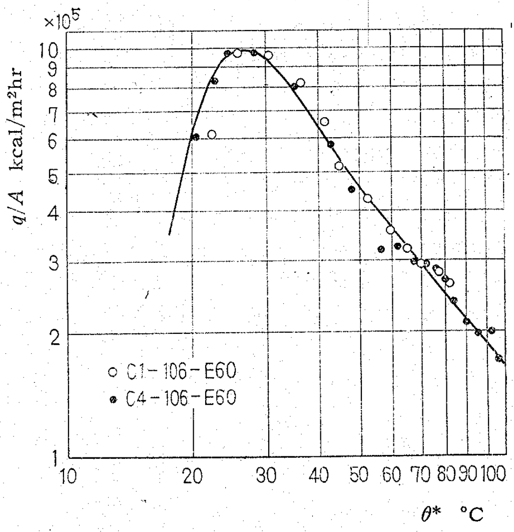


Fig. 10 Boiling curve (copper tube, wall thickness 1 mm, and 4 mm, surface roughness E 60)

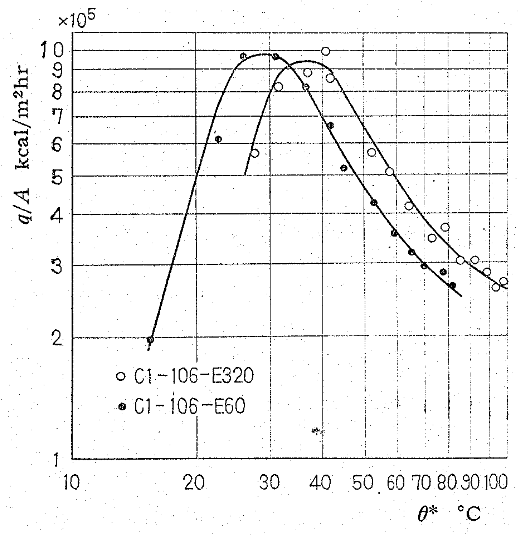


Fig. 11 Boiling curve (copper tube, wall thickness 1 mm, surface roughness E 320, E 60)

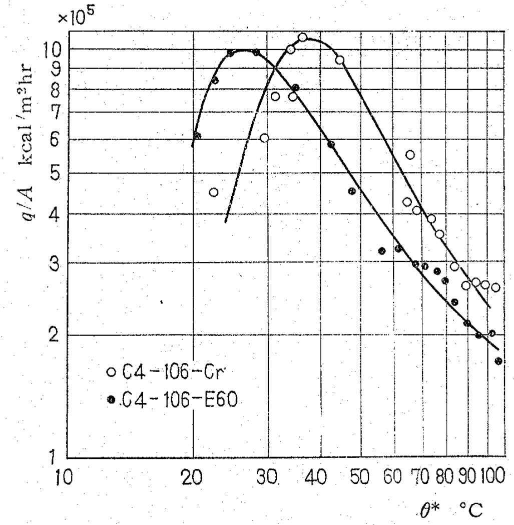


Fig. 12 Boiling curve (copper tube, wall thickness 4 mm, surface roughness E 60 and chrome plated)

a steep nucleate boiling curve and a gently sloped transition boiling curve. This result agrees with the tendencies pointed out by Berenson(2).

3·3 Temperature variation

Fig. 13 gives examples of recorded temperature variation together with the signal from the steam-film detecting probe. The curves over (i) were obtained in the nucleate boiling domain. It is to be noted that the temperature curve stayed stable whereas the probe signal violently fluctuated indicating bubble generation on the boiling surface. When the heating steam pressure was raised to an appropriate amount, pulses appeared in the temperature record as shown in the curves above (ii) in Fig. 13. This means that the burnout boiling as mentioned before started. By comparing the two curves over (ii), it will be noted that the temperature pulse appears when the film-detecting probe indicates the existance of steam film on the boiling surface. In other words, the temperature at a point near the thermocouple junction rises when water film dries up and steam film insulates heat flow from the surface.

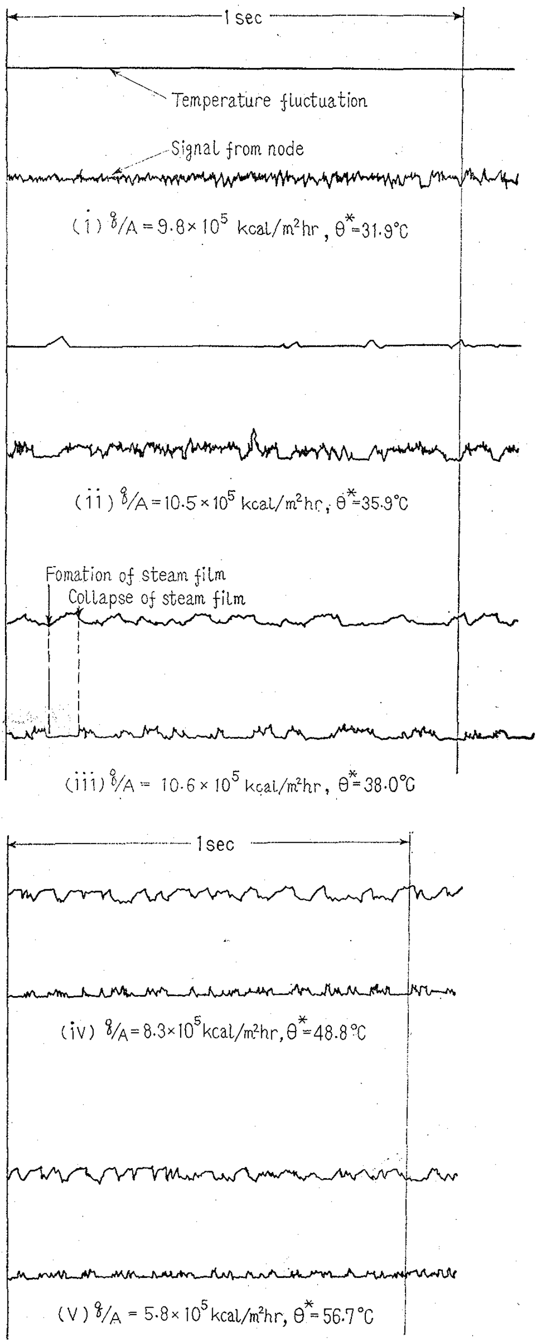


Fig. 13 Correspondence of temperature to signal of electrode

Although the amplitude of temperature fluctuation at the thermocouple junction itself may be larger than that at other parts of the surface because of the fin effect of thermocouple wire, the period of fluctuation must be the same. Therefore, the period, and not the amplitude, was further analyzed as described later.

The curves over (iii) represent conditions at the maximum heat flux point. The variations in the two curves correspond to each other, and the process of bubble growth may be traced on these curves. The surface temperature rise may be expected when water film vanishes by drying up. At the maximum heat flux point, the number of temperature pulses is less when compared with the transition boiling domain, and the film detecting probe indicates the existence of small bubbles which characterize the nucleate boiling domain.

The curves over (iv) correspond to the higher heat flux domain of transition boiling. By comparing the two curves, it will be noted that the temperature rises or drops when steam film appears or vanishes.

The curves over (v) are for the higher surface temperature region in transition boiling.

3·4 Analysis of temperature fluctuation

In analizing the temperature fluctuation, the time t_H in which the surface was covered with steam film and the time t_L in which water wetted the surface were defined as illustrated in Fig. 14, and their time averages, designated by $\bar{t}_H$ and $\bar{t}_L$, were measured on the oscillogram. In the averaging process, small temperature pulses less than 4°C such as indicated by small arrows in Fig. 14 were omitted for the purpose of saving time. This simplification leads to a considerable error in the well-developed transition boiling region where

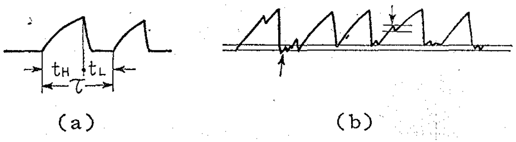


Fig. 14 Model of temperature fluctuation

many small fluctuations appear. This will be discussed later again.

The quantity $T_L=\bar{t}_L/(\bar{t}_L+\bar{t}_H)$ was termed the wet-surface time-ratio, and was plotted against the heat flux as in Fig. 15. The diagram indicates that the relation between these quantities is not linear. When the heat flux is high, the average tendency of the plotted points is nearly vertical, i.e., the heat flux does not decrease even when T_L decreases considerably. When transition boiling is well developed and consequently the heat flux is low, T_L is nearly constant over a rather wide range of heat flux.

The tendency in the high heat flux region may be explained by the surface temperature rise during the drying-up period, the heat thus accumulated being discharged in the wet period. In other words, the decrease in T_L is compensated by the increase in q/A during the wet period. The tendency in the low heat flux region may be accounted for by the error in evaluating t_L. As mentioned before, smaller pulses were neglected in the evaluating process. But, in the low heat-flux region, small pulses are so numerous that this simplification may lead to a considerable error. The thick full line in Fig. 15 is an estimate of the true curve which would be obtained if t_H were measured without such simplifications.

An example of the histogram of frequency distribution of t_H is illustrated in Fig. 16. The total duration was 4 seconds, and the time interval was 5/600 second. It is seen that the frequency is higher for smaller t_H. It must therefore be expected that the frequency of unaccountably small t_H may be very large. Moreover, the time-average $\bar{t}_H$ decreases with q/A as indicated in Fig. 17. It may therefore be safely assumed that the importance of smaller pulses increases in the well-developed transition boiling.

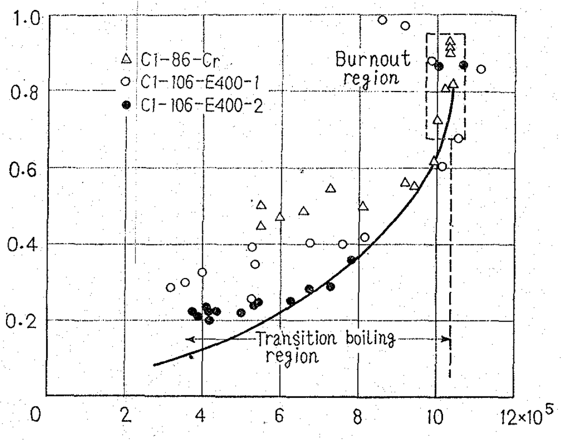
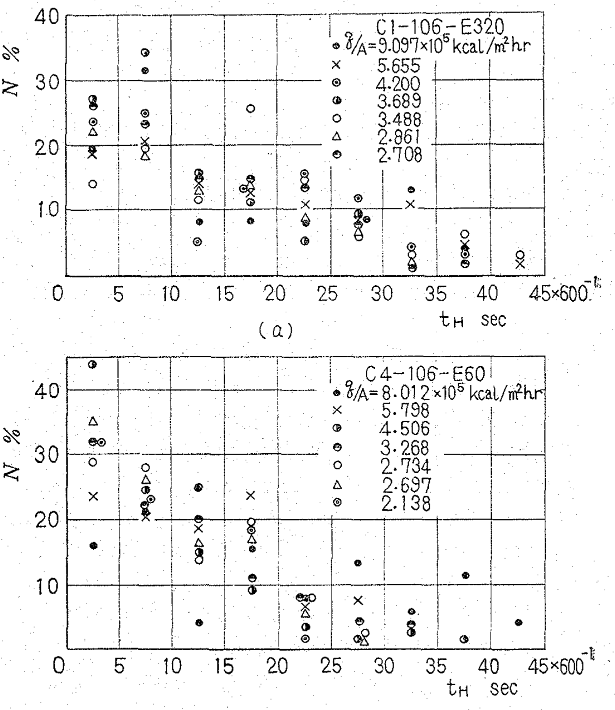


Fig. 15 Wet-surface time-ratio

It was at first expected that the boiling wall thickness might affect the mode of surface temperature variation because the amount of the thermal energy stored in the wall is dependent on the thickness. Actually this was not the case. Experimental result as shown in Fig. 16 (a) for a 1 mm wall is very similar to that in Fig. 16 (b) for a 4 mm wall. This is the reason why the characteristic curve is the same for two different thickness tubes as indicated in Fig. 10.

4. Mechanism of transition boiling

The observations explained above disclose the mechanism of transition boiling. In the high heat flux region of nucleate boiling, water film always stays on the boiling surface even when the surface



(a)

(b)

Fig. 16 Frequency distribution of t_H

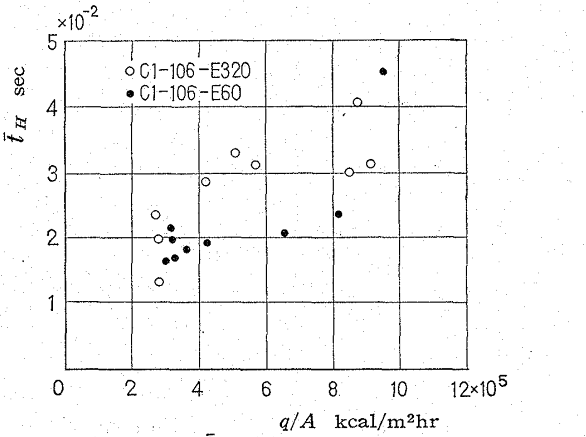


Fig. 17 Average $\bar{t}_H$ in relation to heat flux q/A.

is seemingly covered entirely with bubbles. When heat flux is increased and the before-mentioned burnout boiling starts, water film occasionally evaporates completely. At the beginning of burnout boiling this complete drying happens infrequently. As the surface temperature rises higher, the probability of complete drying-up increases gradually. This fact accounts for the shape of the boiling characteristic curve which is smooth and continuous through out the three domains, i. e., nucleate, burnout and transition boiling.

As the surface temperature rises after stepping into the burnout boiling domain, water film dries up more frequently, and the wet-surface time-ratio decreases. On the other hand, when water touches the surface after the drying-up period, heat flux is higher than usual because the surface temperature is higher. The average heat flux is therefore nearly constant in the burnout boiling domain.

When the surface temperature is raised further, the wet-surface time-ratio decreases to a point beyond which the decrease can not be compensated for by any increased evaporation in the wet period. This is the beginning of transition boiling in which heat flux decreases when the surface temperature is raised.

There is another evidence to the theory that the boiling surface gets alternately wet and dry in transition boiling. When water contains impurities, the boiling surface is contaminated more quickly in transition boiling than in nucleate boiling. One more evidence is that particular explosive sounds are heard continuously in the domain of transition boiling.

The rather remarkable effect of surface roughness on the boiling characteristic curves in the transition boiling domain as apparent in Figs. 9 through 12 can also be explained by the wet-and-dry mechanism. In brief, the rougher surface has more nucleating spots and therefore more readily gets into transition boiling at lower surface temperature. These differences gradually diminish when the heat flow through steam film, which is naturally not affected by surface roughness, has more share. This is the reason for the diminishing roughness effect in the highly developed transition boiling near film boiling.

5. Conclusion

By analyzing the oscillogram of surface temperature and the steam film detecting probe, it was concluded that transition boiling is a particular phenomenon in which the boiling surface gets alternately wet and dry. It was found that the boiling characteristic curve is smooth and continuous through out nucleate and transition boiling, and a particular type of boiling was observed in the vicinity of the maximum heat flux and was termed burnout boiling.

6. Acknowledgment

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