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Boiling and Burnout Phenomena under Transient Heat Input*

(1st Report, Experiment)

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In order to simulate the thermo-hydrodynamic conditions at reactor power excursions, a test piece was placed in a forced convective channel and heated with exponential power inputs.

The boiling heat transfer and the burnout heat flux under the transient heat input were measured, and pressure and water temperature changes in the test section were recorded at the same time.

Following experimental results were obtained; (1) Transient boiling heat transfer characteristics at high heat flux stayed on the stationary nucleate boiling curve of each flow condition, or extrapolated line of the curves. (2) Transient burnout heat flux increased remarkably with decreasing heating-time-constant, when the flow rate was lower and the subcooling was higher. (3) Transient burnout phenomena were expressed with the relation of $(q_{\max} - q_{sB0})\tau = \text{constant}$ at several flow conditions. This relation was derived from the stationary burnout mechanism of pool boiling.

1. Introduction

Transient boiling and its burnout phenomena under the transient heat input are very important problems in a liquid cooled reactor safety analysis.

Rosenthal⁽¹⁾ and Johnson⁽²⁾ studied the time history of the heater temperature from nonboiling to boiling region when the exponential heat input was supplied to the heater ribbon in the pool. Cole⁽³⁾, Martenson⁽⁴⁾, Hall et al.⁽⁵⁾ and Tachibana et al.⁽⁶⁾ carried out the transient burnout experiments in pool boiling, and they concluded that the transient burnout heat flux was higher than the stationary one. Furthermore Sakurai et al.⁽⁷⁾ made the heat input wave more accurate, using the experimental equipment and analogue computer combined in a closed system. Sakurai et al. performed the transient boiling and burnout experiments, in which they took the water subcooling and time-constant at exponential heat input as experimental parameters. Then, they found the relation between the transient burnout heat flux, and the time-constant and life time. Kawamura et al.⁽⁸⁾ took high speed motion pictures during transient pool boiling, and tried a model analysis about the transient boiling heat transfer and burnout. The results appeared to agree with their experiment to some extent.

Most of traditional researches about the transient boiling have been performed under the pool boiling conditions, and the researches in forced convection (by Johnson⁽⁹⁾ and Kawamura et al.⁽¹⁰⁾) have been only the supplemental experiments of the pool boiling. At the transient boiling in forced convection, there are many thermo-hydraulic parameters affecting the transient burnout. As the flow conditions affect the transient boiling complicatedly, the transient boiling and burnout in forced convection have not been made clear at all. Since the mechanism of transient burnout is not known, many researchers have defined the transient burnout point differently, for example, as DNB and maximum heat flux point on boiling curve, and sudden rising point of the heater temperature. Though these points come to agree with each other in stationary boiling, there are some possibilities of much difference occurring due to the heat capacity of the heater and the heating rate.

In this study, in order to simulate the thermo-hydrodynamic conditions a test piece was placed in a forced convective channel and heated with exponential power inputs. The boiling heat transfer and the burnout heat flux under the conditions were measured, and the changes of the pressure and the water temperature in the test section were recorded at the same time.

Nomenclature

P_I	: inlet pressure of test section kg/m^2
P_O	: outlet pressure of test section kg/m^2
Q	: heat generation rate $\text{kcal/m}^2\text{h}$
q	: heat flux $\text{kcal/m}^2\text{h}$
$q_{\max}$	: maximum heat flux $\text{kcal/m}^2\text{h}$
q_0	: initial heat flux $\text{kcal/m}^2\text{h}$
q_{sB0}	: stationary burnout heat flux $\text{kcal/m}^2\text{h}$
T_c	: water temperature at center part of heated section $^{\circ}\text{C}$
T_{Ii}	: inlet water temperature of test section $^{\circ}\text{C}$

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- T_o : outlet water temperature of heated section °C
 T_{w1} : heater surface temperature of downstream °C
 T_{w2} : heater surface temperature of upstream °C
 ΔT_{sat} : degree of superheat deg.
 ΔT_{sub} : degree of subcooling at inlet of the test section deg.
 t : time ms
 t_{msx} : time for arriving at maximum heat flux ms
 t_s : time for arriving at stationary burnout heat flux ms
 τ : time-constant of heating ms
 U_i : inlet water flow rate of test section m/s

2. Experimental Apparatus

The experimental apparatus is shown in Fig. 1 schematically. Pure water was passed in the sequence of pump-orifice flow meter-preheater-test section-separator-subcooler. System pressure was atmospheric. Inlet flow rate and water temperature were set by means of a flow control valve and a power regulator of the preheater respectively. The errors in set values were 5 % for the flow rate and 1 % for the water temperature in each experiment.

The test section is shown in Fig. 2 in detail. The flow channel was annular, and the flow direction was vertical upward. The outer tube was made of Pyrex glass having 8 mm I.D., and the inner tube (5 mm O.D.) was a stainless steel heater. Both ends of the heater were joined with copper bus bars to provide entrance regions of the flow (see Fig. 2). Total length of the test section was 800 mm.

The heater was 5 mm O.D., 0.1 mm thickness and 100 mm length. Effective heated length was 92 mm excluding solder connecting parts. Measuring length of electric resistance to obtain a heater mean temperature was 80 mm excluding 8 mm for upstream and 4 mm for downstream from the heated length, considering heat losses to the bus bars and a burnout position on the downstream heater surface.

Stainless steel wires (0.1 mm dia.) to measure the heater resistances were spot-welded vertically on the heater to reduce a disturbance for the flow and the measuring error caused by variation of magnetic field due to the transient heating current. Each resistance of the heater which was divided two equal parts was measured to examine a burnout position and a temperature difference in axial direction of the heater. Therefore, four wires were welded on the heater shown in Fig. 2.

After the heater was soldered to copper bus bars, oil and contamination on its surface were washed out. Then, the heater was fixed on the center-line of the outer

tube of the test section. Pressure transducers were used to measure the static and differential pressure changes at inlet and outlet of the test section. A characteristic frequency of the pressure transducer was 40 kHz.

Sheathed thermocouples (0.25 mm O.D.) were used to measure the water temperature changes during transient boiling. These thermocouples were laid at the outlet and the center part of the heated section, and their apexes were located on the center part of the flow channel clearance. A time response of the thermocouple was about 5 ms in water.

Fig. 1 Experimental apparatus

Fig. 2 Test section

3. Heating procedure of the heater

The heater was heated up by means of D.C. Joule heating. The heat generation rate changed exponentially. A control signal of the heat generation rate having a certain time-constant was given from the analogue computer, and the signal was transmitted to the heating current amplifier (see Fig. 1). There was a difference between the change of the heat generation rate and the given exponential function due to an operation error of the analogue computer (0.4%), a linearity of the heating current amplifier (0.5%) and a change of the heater resistance. The error due to the resistance change was less than 3%, according to a calculation where a maximum change of heater temperature was assumed to the 100 °C and other circuit resistances were considered, too. In the experiments, the initial heat generation rate was $2 \times 10^4 \text{ kcal/m}^2\text{h}$ and the time-constants were changed from 50 ms to 1000 ms.

4. Measuring procedures

The measuring procedures of the heater surface temperature, the heat generation rate, the heat flux, and the pressure and the water temperature in the test section are shown in Fig. 1.

First, the heater resistances were measured using the double bridge method, and the heater mean temperature in a radial direction was calculated using a temperature coefficient of resistance for a stainless steel heater which had been measured previously. Then, using the equation of heat conduction, a correction for the heater temperature profile in a radial direction was performed. Thus, the heater surface temperature was calculated.

The heat generation rate was calculated with the heater resistance and the heating current which was derived from a voltage drop in the inductionless standard resistance.

When the heater temperature is changing, the heat flux is not equal to the heat generation rate due to the heat capacity of the heater. Therefore, the heat flux was obtained by subtracting the heat capacity from the heat generation rate.

These calculations were performed at the operation circuits in the analogue computer. Input signals for the operations were the derivation voltage of the double bridge and the voltage drop in the standard resistance.

Output signals of the pressure transducers and the thermocouples were transmitted to the analogue computer, and were processed in it. Thus the changes of pressure and water temperature were measured.

All physical values after processing in the analogue computer were recorded simultaneously on the multi-channel magnetic tape recorder. The frequency characteristics of its recorder were 20 kHz.

When analyses of data were performed, the recorded data were reproduced on the multi-pen recorder with the time scale extended between 20 and 400 times. Total error of the experiments due to these measuring instruments and the operation circuits was less than 4.5%.

5. Method of the burnout detection

The burnout was detected when the heater temperature exceeded a set value. At that time the control signal for the heat generation rate was turned off, and the breaking signal for the heating current was turned on. The heater temperatures were measured at two parts of the heater. Therefore, when the heater temperature of either the upstream part or the downstream, or at the same time both heater temperatures exceeded a set value, the heating current breaker acted. In increasing the set temperature at the interval of 5 °C from the heater temperature at the stationary burnout, there occurred a sudden rise in the curve of the heater temperature caused by the transient burnout. Then, the final set temperature was chosen as a detecting temperature of burnout. The difference between the set temperature and the real heater temperature was less than 0.5 °C, and the time required from burnout detection to current break was less than 20 micro-seconds.

To improve the reproducibility and precision of the experimental data about the boiling heat transfer, it is necessary to increase substantially the precision in all the measurements, but it is more important than that the same heater is used (to make uniform the heater surface condition). In this experiment, when the set temperature interval was 10 °C, a part of the heater surface became dark brown with the heater reaching a very high temperature locally, because the measured heater temperature was an axial mean temperature. On account of the above mentioned precision, break time and selecting method of the set temperature, all of the following data were obtained with the one heater, and there was seemingly no change in the heater surface condition.

6. Experimental results and considerations

6-1. Typical experimental results of transient boiling

Typical experimental results of transient boiling in a forced convection are shown in Fig. 3. The changes of heat flux and surface temperature were not different substantially from the results of transient pool boiling obtained by Rosenthal and other researchers. From the surface temperatures obtained in the two parts of the heater, and the pressures and the water temperatures in the test section, the following was revealed.

Comparing the upstream surface temperature (T_{w2}) with the downstream (T_{w1}),

T_{w2} was lower than T_{w1} , and T_{w2} attained a maximum overshoot temperature w_2 later than T_{w1} . Under transient boiling in a forced convection, there is recognized the effect of entrance region in an axial direction of the heater. Therefore, the boiling starts at the most downstream part in the first instance, and after that, the nucleation sites in upstream part are activated successively. Considering the temperature overshoot, it is necessary to consider seriously on the distribution of the nucleation sites in the axial direction. When the heat generation rate increased to a certain value, a pressure oscillation corresponding to boiling incipience occurred, and, after the heater temperature overshooted, the oscillation and the absolute value of the pressure showed a decreasing trend. When the heat generation rate increased much more, the pressure and the pressure drop in the heated section increased. From these pressure changes, the bubble behaviors were considered as follows;

Fig.3 Typical experimental results under the transient heat input

Due to the generation of initial bubbles, the water in the vicinity of the heater surface was disturbed very much, and the heater temperature was reduced consequently. Therefore, the nucleation was suppressed. Since the bubbles generated before had been condensed by the surrounding subcooled water, bubbles in the flow channel decreased temporarily or disappeared in some cases. And at that time the pressure decreased slightly. After that, the pressure drop caused by friction and acceleration in a two phase flow increased with an increasing heat generation rate. Here, as the zero points for P_0 and P_1 the absolute pressures in the single phase flow were selected.

Water temperature in the heated section increased with the heat generation rate. Especially the outlet water temperature drop-

ped temporarily, after the heater temperature overshooted. Comparing T_o with T_c , T_c rose later than T_o . From these water temperature changes, the following results were obtained; There was a time lag in the nucleation in the axial direction of the heater and the nucleation was suppressed for a time after the heater temperature overshooted.

6-2. Effects of inlet water subcooling

The time histories of various values measured in this experiment are illustrated in Fig. 4, where the flow rate is kept constant (1.0 m/s), and the time-constant and the inlet water subcooling are chosen as experimental parameters. The shorter the time-constant, the higher the maximum heat flux became. When the water subcooling increased, the maximum heat flux increased. Details are described later.

The time history of the surface temperature of heater is illustrated using the temperature difference between its temperature and the inlet water temperature. In this experiment, when the subcooling and the flow rate were low and the time-constant was short, the burnout occurred on all of the heater surface, but at other flow and heating conditions it occurred on the downstream heater surface (T_{w1} side). Therefore, the downstream heater surface temperature is shown in Fig. 4.

The surface temperature overshoot was nearly equal to the experimental results obtained in a pool boiling. The higher the subcooling and the shorter the time-constant, the wider the overshoot region and the higher the maximum temperature of overshoot superheat. When the subcooling was higher than 12.8 °C, the surface temperature stayed in the nucleate boiling region where the surface temperature changed slightly with the heat flux, after the surface temperature overshooted. When the subcooling was 2.8 °C, the temperature overshoot and the stagnation at the nucleate boiling temperature did not appear clearly. In this low subcooling, the flow pattern was annular after the boiling incipience. Under transient boiling in a forced convection, the time history of the surface temperature depended on two phase flow patterns. And it was not identical always in a pool boiling.

Under high subcooling, the pressure time histories included the high frequency oscillation caused by condensation. Therefore, the pressure time histories obtained by averaging the high frequency are shown in Fig. 4. And X in that figure denotes the onset of the pressure change corresponding to the boiling incipience. The shorter the time-constant, the higher the slope and the maximum value on the time history of inlet and outlet pressure. When the subcooling was 2.8 °C, the pressure for each time-constant increased with time monotonously. But under higher subcooling than 2.8 °C, there were two maximum values about the boiling incipience and the nucleate boiling region for the short time-constant, and for the long time-constant the pressure was lower than atmospheric.

Under low subcooling, there was a high void fraction flow after the boiling incipience, and the nucleation was continuous.

Fig.4 Time histories of the measuring values
(Effects of the subcooling)

Therefore, the pressure increased monotonously. And corresponding to an increasing rate of heat flux, the shorter the time-constant, the higher the slope of the pressure change.

When the subcooling became higher than 12.8 °C, a strong condensation effect was superposed on the vaporization increasing with the heat flux. Since the thermal energy stored in water in the vicinity of the heater surface increases with an increasing overshoot superheat, more bubbles are produced and the growth rate of bubbles becomes faster at the same time. In these cases, the bubbles come to be hemispheroidized on the heater surface caused by the water inertia. Therefore a force in a radial direction of the flow channel is produced, and consequently the choking of flow happens. The inlet and outlet pressures, and the pressure drop in the test section increased to join the dynamic pressure and the choking due to the bubble growth.

On the other hand, for the long time-constants, it seems that since many sharp condensation pulses were observed in the pressure changes, a strong condensation occurred in the vicinity of the heater surface. In these cases the bubbles do not leave the heater surface and form layers covering the heater surface. The subcooled water outside of this layer flowed out from the test section, while the water was affected by the attraction toward heater surface caused by the condensation effects. For these reasons, it seems that the pressure in the test section is reduced.

In Fig. 4, the time histories of the outlet water temperature are shown, too. Under low subcooling, the shorter the time-constant, the higher the maximum water temperature became. This was caused by an increasing saturation temperature due to the pressure increase in the test section. Since the water temperature reached nearly the saturation temperature in all experiments, it seems that there had been a number of bubbles near the heater surface at the burnout incipience.

6-3. Effects of water flow rate

The time histories of the heater surface temperature, the pressure and the water temperature in the test section are shown in Fig. 5 where the water subcooling is kept constant (12.8 °C) and the flow rate changes from 1.0 m/s to 4.0 m/s.

The maximum heater temperature and the inversed temperature at the overshoot increased with the flow rate. If the heating rates are identical, the magnitude of the overshoot depends on the thickness of a superheated layer produced at the boiling incipience in a forced convection. The effect of thinning the superheated layer at high flow rate is the same as under high subcooling.

At low flow rate (0.5 m/s), the shorter the time-constant, the larger the maximum value of the pressure became. At high flow rate (2.0 and 4.0 m/s), the difference of the maximum pressure at various time-constants was small. At every flow rate, the maximum

Fig.5 Time histories of the measuring values
(Effects of the flow rate)

pressures at the boiling incipience and nucleate boiling region appeared separately. Even when the flow rate was 4.0 m/s, there was a moment of the nucleation being suppressed after the boiling incipience.

In Fig. 5, the water temperature at the center part of the heated section (T_c) is shown, too. Comparing T_0 with T_c , at the temperature rise near the boiling incipience, the higher the flow rate, the shorter the time lag between T_0 and T_c became. And the higher the flow rate, the thinner the superheated layer became. However, this time lag

means that once the boiling occurs, all nucleation sites are activated on the heater surface at the same time.

6-4. Boiling under the transient heat input

The transient boiling heat transfer is considered referring to the boiling curve. In Fig. 6 and Fig. 7, the boiling curves for different time-constants are shown, where the subcooling and flow rate are experimental parameters respectively. Furthermore, in these figures the correlation line obtained by Jens & Lottes⁽¹⁰⁾ in a forced convective boiling at the steady state is given, too.

The boiling curve at 1000 ms time-constant was regarded as the boiling curve at steady state. Because it was considered that, since there was no difference between the heat generation rate and the heat flux throughout the experiment, the heat transfer in the single phase flow and in the boiling could always catch up with such a transient heat generation rate.

The transient boiling heat transfer rates near the temperature overshoot were less than that estimated from the correlation of Jens & Lottes. But both heat transfer rates became equal to each other according as the heat flux was higher. When the flow rate was high, the exponent of the wall superheat was a larger number than that by the correlation of Jens & Lottes in a wide range of the nucleate boiling. The boiling curve at the condition of 1.0 m/s flow rate, 42.8 °C subcooling and 1000 ms time-constant, changed singularly, because the pressure in the test section was reduced at higher heat generation rate than that in the middle of the nucleate boiling region.

At all flow conditions, according as the time-constant became short, the S curve of boiling due to the overshoot became large. And the higher the flow rate and the subcooling, the larger the S curve.

When the single phase heat transfer rate becomes high, and the superheated layer becomes thin (i.e. if the heat flux is same, the thermal conduction at the short time constant, the flow rate and the subcooling make the superheated layer thin.), the boiling incipience is suppressed. But this superheated layer is thicker than the one in the fully developed boiling region, and in the initial boiling region, the nucleation sites are sparsely distributed and the bubble frequency is low. Furthermore, under transient boiling the heat flux increases momentarily in such an initial boiling region. For the above mentioned reasons, the S curves of boiling were produced. As the water enthalpy increases in the flow direction, there is a time lag in the nucleation between downstream and upstream of the heater. This time lag affected the magnitude of the S curves.

When the boiling takes place in higher heat flux, the bubble frequency is higher, the nucleation sites are denser and the boiling develops fully in the flow direction. At high heat flux the transient boiling

curves obtained by this experiment turned out close not only to each other, but also to the stationary boiling curve in each flow condition. Therefore, for the difference

Fig.6 Boiling curves under the transient heat input
(Effects of the subcooling)

Fig.7 Boiling curves under the transient heat input
(Effects of the flow rate)

of the time-constants in this experiment, it seems that there is no difference about the heat transfer mechanism between transient and stationary in each flow condition. In general, under stationary boiling it is likely that the heat transfer of nucleate boiling at high heat flux is hardly affected by the flow rate and the subcooling. And in this experiment there was little difference in the boiling curves at high heat flux due to the flow conditions. In the nucleate boiling region at high heat flux, the temperature field determining the heat transfer rate is a very thin layer in the vicinity of the heater surface, and the bubble frequency is very high. Therefore, the heat transfer responds very rapidly to the change of the heat flux.

The shorter the time-constant, the higher the maximum heat flux became. At a higher heat flux than the stationary burnout, the transient boiling curves were situated on the extrapolated lines of the stationary boiling curves at each flow condition. These results have been obtained by Sakurai et al. (7) in a pool boiling, too. Then, these facts suggest that in analyses of the boiling mechanism in this high heat flux region, a common model can be assumed for the pool and for the forced convective boiling.

6-5. Burnout under the transient heat input

Since in the transient boiling experiment the heat transfer rate which changes every second is measured, there is not a discontinuous point of the heat flux such as the stationary burnout when the heat flux is controlled. Then, the transient burnout is hard to determine definitely. In the transient boiling experiment previously performed the burnout have been correlated from the following points; (1) a sudden rising point in the time history of the heater temperature, (2) a DNB point on the transient boiling curve, (3) a maximum point in the time history of the heat flux.

In the experimental results, the sudden rising points were hard to determine uniformly for the various data since the heating rate was different, and the existence of the DNB point was uncertain as a narrow region on the transient boiling curve was indicated with a linear relation of $q \propto \Delta T_{\text{sat}}^n$ (see Fig. 6 and Fig. 7). Therefore, considering that one heater was used in all experiments and there were maximum points in the time histories of the heat flux in any data since the rise in the heater temperatures due to the burnout was faster than any heating rates, the burnout point were correlated by means of the maximum points of the heat flux (3).

The relation between the maximum heat flux and the subcooling is shown in Fig. 8 for several time-constants and the relation between the maximum heat flux and the flow rate in Fig. 9. The flow conditions in which the maximum heat flux was apt to be affected by the time constants were the low flow rate and high subcooling regions. The increasing rate of the stationary burnout heat flux due

to the increase of the flow rate was higher than that of the maximum heat flux for shorter time-constants. Under transient boiling for any time-constants, the maximum heat flux was higher than under steady states.

Fig. 8 Maximum heat flux under the transient heat input (Effects of the subcooling)

Fig. 9 Maximum heat flux under the transient heat input (Effects of the flow rate)

Fig. 10 A model of the burnout under the transient heat input

Fig. 11 Relation between the average heat flux and the burnout time

From the time histories of the pressure and the water temperature in the test section, it seems that there were a number of bubbles over the heater surface at high heat flux near the burnout. Moreover, considering that the heat transfer characteristics at such heat flux were situated on the extrapolated lines of the stationary nucleate boiling curves, the transient burnout was grasped as follows (see Fig. 10).

When the heat flux becomes high near the stationary burnout, there develop many vapor masses on the heater surface as observed by Katto et al.⁽¹¹⁾. Until a dry-out state of the heater surface is reached due to the waste of the nucleate boiling layer beneath the vapor mass, the heat transfer characteristics over the stationary burnout move on the extrapolated line of the stationary nucleate boiling curve. When the dry-out heater surface is produced during the stagnation of the vapor mass over the heater surface, a transient burnout occurs. In other words, the heat transfer characteristics on the extrapolated line observed under transient boiling correspond to the nucleate boiling part under the transition boiling at steady state. When the heat flux exceeds the stationary burnout, then the transient burnout occurs. Therefore, the sudden rise in the heater temperature and the maximum point of the heat flux does not correspond to the burnout, but is no more than a phenomenon under transition boiling. But, under transient boiling this transition boiling is not stable. When the heat flux increases, the heater temperature goes on increasing. Therefore, the thermal margin and the time to pass from the stationary burnout to the incipience of the sudden rising of the heater temperature are very important for the nuclear engineering.

Assuming that the change of the heat flux is exponential for the same time-constant as the heat generation rate, as shown in Fig. 10, the average heat flux about q_{sbo} and q_{max} is as follows;

$$\frac{1}{t_{max} - t_s} \int_{t_s}^{t_{max}} q_0 e^{+t/\tau} dt = \frac{(q_{max} - q_{sbo})\tau}{t_{max} - t_s}$$

Investigating the energy to consume the nucleate boiling layer, the relation between the average heat flux and the time to pass from q_{sbo} to q_{max} is shown in Fig. 11. The relation between the heat flux and the consumption of the nucleate boiling layer measured by Katto et al.⁽¹¹⁾ under stationary pool boiling is shown together in it.

In Fig. 11, three different tendencies are identified in the experimental data. (1) At the low flow rate and the low subcooling, the shorter the time-constant, the larger both the average heat flux and $(t_{max} - t_s)$ become, i.e. when the time-constant becomes short, much energy is necessary for consumption of the nucleate boiling layer. (2) $(q_{max} - q_{sbo})\tau$ is a constant, i.e. a constant consumption energy. (3) At high flow rate, the average heat flux is almost a constant independent of $(t_{max} - t_s)$.

The fact that the data in tendencies of

(1), (2) are incoherent comes from the following reasons. The heat transfer margin depends on the nucleate boiling layer thickness (δ) at the time when the heat flux exceeds just q_{sBO} , in a model as shown in Fig. 10. The reproducibility of the data was not good at the flow conditions in the tendencies of (1) and (2), comparing with (3). Moreover, in a forced convective boiling, it seems that the flow patterns of the two phase flow play an important part in the crisis of the heat transfer.

In the case (1), the flow pattern was annular. Therefore, it is proper to interpret the burnout with such that the production of the dry-out surface depends rather on the consumption of the annular liquid film than on the nucleate boiling layer. In the annular flow, when the time constant becomes short, the outlet quality of fluid becomes poor and the annular liquid film becomes thicker than under stationary boiling, comparing for the same heat flux. In such a case, it is supposed that both of the time for the consumption of liquid film and the average heat flux increase.

In the case (2), when the time constant became short, the average heat flux increased extremely. The heat transfer characteristics at high heat flux in various flow and heating conditions, became close to each other and were represented by stationary boiling curves. Therefore, it seems that the vapor mass and the nucleate boiling layer when the heat flux passes over the stationary burnout are nearly equal at any experimental conditions. The correlation of $(q_{max} - q_{sBO})\tau = \text{constant}$, means that the thermal energy which is used to consume the nucleate boiling layer is a constant. If there is an identical relation between the departure period of the vapor mass from the heater surface and the passing time of the heat flux over q_{sBO} in every experiment, the data should converge along a line of inverse proportion in Fig. 11. In this experiment, for several flow conditions the data converged along the dashed line in the figure.

In the case (3), the shorter the time-constant, the shorter the time for the consumption of the nucleate boiling layer became, but the average heat flux increased slightly. Namely, total energy to consume the nucleate boiling layer decreased as the time constant became short. Since the removing effect of the vapor mass becomes large at the high flow rate, it becomes questionable whether the vapor mass is able to exist over the heater surface or not. Then, at the high flow rate, the transient burnout is not explained only by the consumption of the nucleate boiling layer. Whenever a burnout occurs, the heater surface has to be dried out. At high flow rate, the burnout may be caused by primary bubbles in the

nucleate boiling covering the whole heater surface. In general, since the nucleation site density and the primary bubble diameter depend on the heat flux and the bubble frequency at high heat flux is very high, it seems that the behaviors of the primary bubbles respond very quickly to the change of the heat flux. The burnout caused by this process is hardly affected by the time constant and is determined only by the heat flux. At higher flow rate than in this experiment, it is expected from Fig. 9 that the maximum heat flux will be less affected by the time constant.

7. Conclusions

An experiment in a forced convection was performed about the boiling heat transfer and the burnout under the transient heat input. The following results were obtained;

- (1) Transient boiling heat transfer characteristics at high heat flux stayed on the stationary nucleate boiling curve of each flow condition, or extrapolated line of the curve.
- (2) Transient burnout heat flux increased remarkably with decreasing heating-time-constant, when the flow rate was lower and the subcooling was higher.
- (3) Transient burnout phenomena were expressed with the relation of $(q_{max} - q_{sBO})\tau = \text{constant}$ at several flow conditions. This relation was derived from stationary burnout mechanism of poor boiling.

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