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EXPERIMENTAL STUDY ON THE BOILING PHENOMENA WITHIN A NARROW GAP

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Abstract—The experiments were carried out with annular narrow gaps having the gap widths 0.2, 0.3, 0.4, 0.5, 1.0 and 1.5 mm for the following two cases: (a) for the "open bottom" case, the heat transfer coefficient was improved as the gap width decreases, but it was not affected by gap lengths in the range $40 \leq L \leq 100$ mm. (b) for the "closed bottom" case, the heat transfer coefficient was not affected by gap width or length. The transition heat flux could be correlated by the equivalent gap length defined in terms of the cross-sectional area of the open end.

NOMENCLATURE

S, gap width;
L, gap length;
$\mathbf{q}''$, heat flux;
L_S, equivalent length $= LF_{0.2}/NF_S$;
$F_{0.2}$, cross-sectional area of open end for gap width $S = 0.2$ mm [m^2];
F_S, cross-sectional area for the gap width S mm [m^2];
L, gap length [mm].

1. INTRODUCTION

The steam generator for pressurised water reactor (PWR) is composed of several thousands of U tubes constituting heat transfer surface between primary and secondary fluids, which are supported by strap-plate or baffle-plates, and both whose ends are attached to tube-sheets. In recent years, tube thinning failures caused by corrosion have taken place in the crevices between tubes and straps or baffle-plates and between tubes and tube-sheets, which have resulted in the leakage troubles of primary coolant through pin holes and cracks in the tube walls.

These phenomena seem to be induced by the concentration of water treatment chemicals caused by boiling of water in the crevices [1]. The authors have studied the process of concentration of solutes in the secondary coolant inside a narrow gap using photography, which shows that some corrosion products in water have deposited rapidly on the heat transfer surface if alternate drying and wetting occurs within a narrow gap, as has been described by Nishikawa *et al.* [2]. These facts suggest that a close relation exists between the concentration process of chemicals and the drying and wetting phenomena. In order to study the fundamental process of the concentration of water treatment chemicals in secondary coolant an experimental study of the heat transfer within a narrow gap and transition heat flux to drying and wetting phenomena have been carried out using an apparatus which simulates the crevices between tube and baffle-plates and also between tube and tube-sheet.

2. BACKGROUND FOR THE NARROW GAP BOILING EXPERIMENTS

The first steam generator tube failure in Japan occurred at Mihama-1 on 13 June 1972, only one and a half years after the initiation of commercial operation on 28 November 1970. Since that time additional tube failures have taken place in Japan at Mihama-2 and Takahama-1 up to 1978.

Summarizing the operational experiences of PWR in Japan, the causes of failures seem to be related to the modes of heat transfer. In the case of Mihama-1, drying and wetting phenomena on the tube surface occurred and the concentration of chemicals took place because bubbles accumulated under the lower surfaces of tubes supported between two tube strap-plates. The concentrated solutes chemically attacked Inconel tube and wastage of tube-wall occurred. In the case of Takahama-1, it is believed that the stress corrosion cracking of Inconel 600 was caused by the concentration of free hydroxide due to alternate drying and wetting phenomena within the crevices between tubes and tube-sheet. (In Japan, stress corrosion cracking and wastage have been detected while denting has never taken place.)

Based on the new Japanese policy, the Phosphate Treatment (PO_4) has been converted to All Volatile Treatment (AVT) for the secondary coolant at Mihama-1, Mihama-2 and Takahama-1 after a short period of operation with PO_4 treatment. Since that time, however, tube failures at these plants have still taken place, which seem to be attacked by the residuals chemicals. The other six PWR plants are now operating well with AVT since start-up and have experienced no difficulty resulting from the water treatment.

3. EXPERIMENTAL APPARATUS AND METHODS

3.1. *Apparatus*

The experimental apparatus was mounted in a pool of water under atmospheric pressure. The test section consisted of a vertical annular channel, the inner tube of which was made of stainless steel and heated electrically with a cartridge heater inserted within the tube as shown in Fig. 1. For the outer tube, forming a

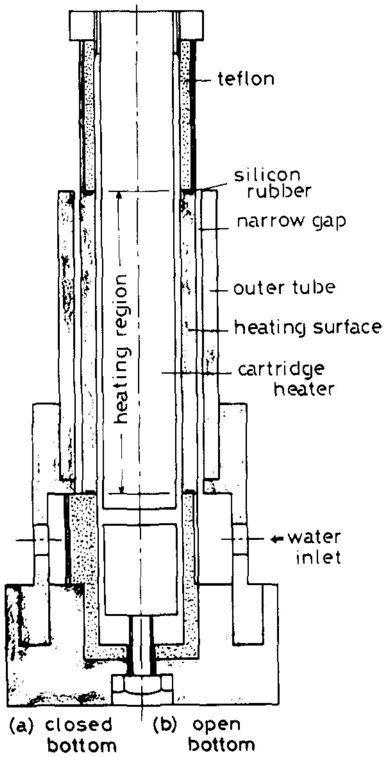

Fig. 1. Experimental apparatus.

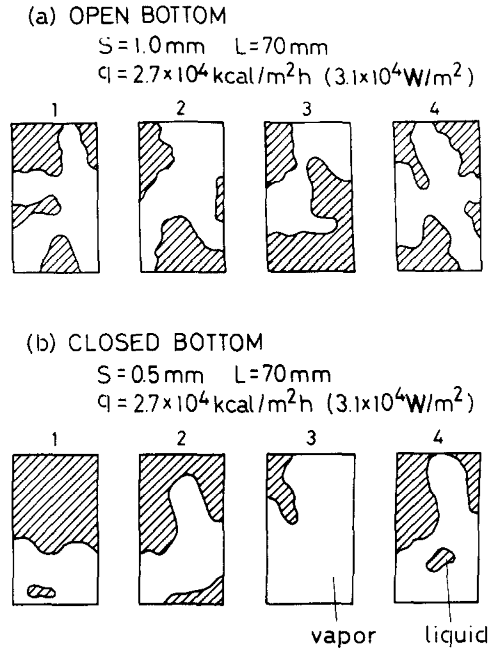

Fig. 2. Liquid–vapor behavior in the narrow gap.

uniform narrow annulus, a Pyrex tube was used in order to observe the drying and wetting process. Despite an accuracy of ± 0.01 mm for the inner tube diameter, the eccentricity of both tubes was as much as 0.02 mm. To reduce the heat loss, the surface was covered by cylindrical Teflon sheaths (except for the heating section) and, in order to prevent the deformation of the Teflon due to expansion, the outside of the Teflon was covered with a stainless tube. The inner diameter of the Pyrex tube was kept constant at 42 mm, and its length was the same as the heating section. The gap width between two tubes was varied between 0.2 and 1.5 mm by changing the outer diameter of the inner tube. Experiments were conducted also without the outer tube to determine the effect of the outer tube. Three heating lengths of $L = 40, 70$ and 100 mm were used.

The water temperature was always maintained at saturation. In order to measure the fluctuation of surface temperature, Chromel–Almel thermocouples of 0.1 mm dia., insulated by enamel, were welded axially and azimuthally at five points of the inner surfaces. The temperatures were recorded and processed by a real time correlator.

The experiments were carried out for the two cases as shown in Fig. 1. One of them was the "open bottom" case in which water could flow through the gap from the bottom to the top, simulating the crevices between tube and tube baffle-plates. The other was the "closed bottom" case in which water could penetrate into the gap only from the top, simulating the crevices between tube and tube-sheet plate.

3.2. *Experimental conditions*

Liquid—degassed and demineralized water at the saturation temperature.

Pressure—atmospheric.

Boiling state—saturated pool boiling (natural circulation).

Parameters—gap width $S = 0.2, 0.3, 0.4, 0.5, 1.0$ and 1.5 mm and without an outer tube,

gap length $L = 40$, 70 and 100 mm.

heat flux $\mathbf{q}'' = 0.34 \times 10^4 \sim 4.11 \times 10^4$ kcal m^{-2} h^{-1}

The test section was mounted in a stainless steel vessel ($100 \times 200 \times 400$ mm) and pure water was filled up to a height of 70 mm above the top of the test section and then heated up to the saturation temperature at atmospheric pressure by auxiliary heaters.

4. EXPERIMENTAL RESULTS

4.1. *Visual observation results by motion photography*

Typical examples of liquid–vapor behaviors in the narrow gap are schematically illustrated in Figs. 2(a)–(b), based on observations from 16 mm movie film. Fig. 2(a) shows the case of "open bottom" for the gap width $S = 1.0$ mm, in which the bubbles generated on the heating surface are pressed by the outer tube and grow in flattened shapes covering the heating surface, and then flow out from the top end, forcing the liquid upwards. With an increase in heat flux, the density of bubble generation increases and the bubbles coalesce together and grow, changing shape randomly. Even with the gap width of 0.2 mm at the low heat flux, liquid can enter easily from the bottom by natural circulation. With vapor bubbles on the heating surface, a thin water film appears to exist, which promotes the heat transfer. As the heat flux becomes higher, the gap is occupied by a great number of bubbles and liquid penetrates into the gap as scattering droplets, with repeated local drying and wetting being repeated. For the case of the gap width of 0.2 mm and low heat flux, comparatively small bubbles are generated and rise as if by crawling within the gap. With an increase in the heat flux, the alternately drying and wetting areas grow in extent and finally the heating surface becomes completely dry except for the top and bottom ends. Water can penetrate only a short distance from the bottom end as by droplets spreading, which cannot rewet the heating surface.

On the other hand, in the cases of "closed bottom" at the low heat flux and for the gap width $S = 0.5$ mm, as illustrated in Fig. 2(b), although liquid can penetrate in an amoeba-like flow from the open top end, vapor remains in the bottom part of the gap and grows upward, expelling the liquid. When the heat flux increases, liquid can enter as if by scattering, similar to the "open bottom", and the amount of liquid decreases. Even with the gap width of 0.2 mm and the length of 100 mm, thin liquid film can exist under the vapor on the surface. As the heat flux increases, further drying and wetting phenomena are repeated from the bottom end. When the gap is larger than 0.4 mm, dry part grows repeating drying and wetting phenomena alternately and finally the surface becomes almost dry in the lower region of the gap. If the gap is less than 0.4 mm, the dry state or the steady vapor blanketed state is maintained on almost the entire surface, and the intermittent penetration of liquid occurs only in the vicinity of the opened top end.

4.2. *Temperature fluctuation of heating surface*

4.2.1. *Nucleate boiling region.* The temperature fluctuations are obtained from the pen-recorder. The results are given in Fig. 3 for the gap length of 100 mm. The following are noteworthy:

(1) If the gap width is small compared to the case "without the outer tube ($S = \infty$)", the temperature fluctuations become violent.

(2) There is not clear difference between the case of "open bottom" and of "closed bottom".

(3) The period of temperature fluctuation is not constant (from the measurements by autocorrelation).

4.2.2. *Drying and wetting region.* In the drying and wetting region, the surface temperature fluctuates when the dried surface is rewetted by the liquid which penetrates intermittently into the gap. This region exists only when the gap width $S = 0.2$ mm. When the surface is kept at a high temperature (about 210°C), liquid penetrating the gap evaporates in a short time, and vapor flows out from the gap. At this time, the temperature fluctuation becomes several tens of degrees. The drying and wetting region is unsteady and finally becomes vapor blanketed.

4.2.2. *Vapor blanketed region.* In this region the surface is dry and blanketed by vapor completely. As liquid is not present, temperature fluctuation cannot be detected.

Figure 4 gives the probability density for heated surface superheat for the process from the nucleate boiling region to the vapor blanketed region.

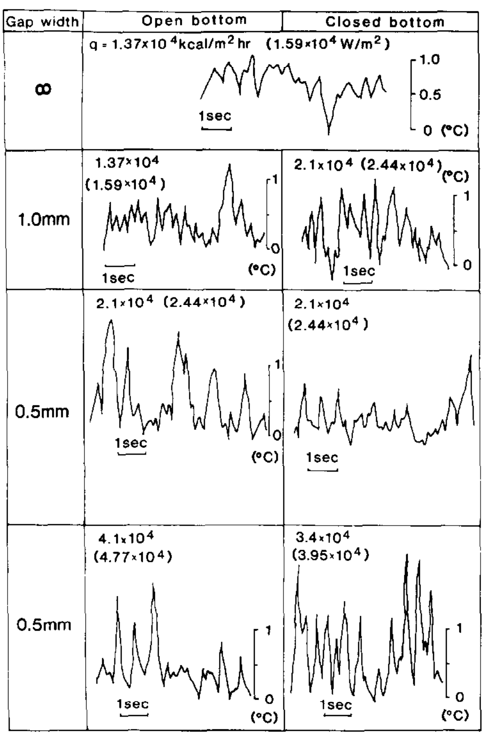

FIG. 3. Typical examples of temperature fluctuation.

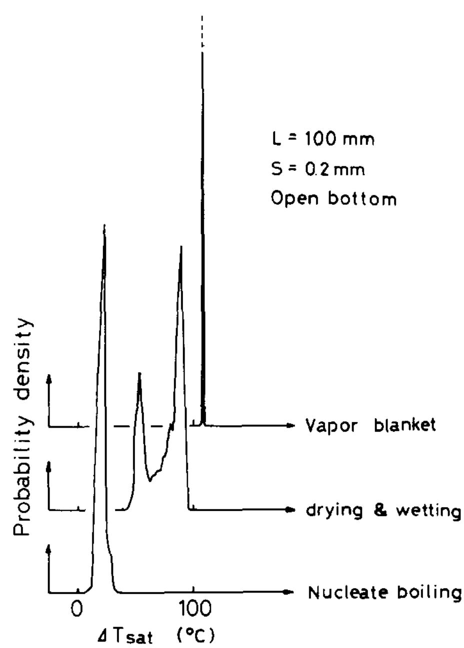

FIG. 4. Probability density distribution vs ΔT_{sat} in the "open bottom" case.

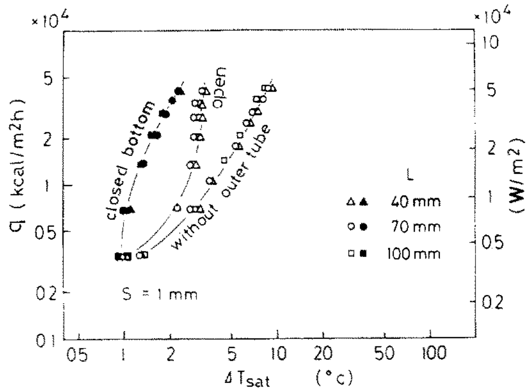

FIG. 5. Boiling curve for S = 1 mm.

5. DISCUSSION

5.1. *Nucleate boiling region*

The probability density profile of the temperature fluctuations in the nucleate boiling region is symmetrical. Its peak agrees with the mean value of fluctuations on the recorder and has been adopted as the representative temperature of the heating surface. Concerning the longitudinal temperature profile in the case of "open bottom", the surface temperatures are nearly uniform when experimental error is taken into consideration. The surface temperature in the case of "closed bottom" also appears uniform, except that the point 10 mm from the bottom is 1°C higher than elsewhere.

Figure 5 shows the typical boiling curves which indicate the effect of the gap length on the heat transfer. As is clear from the figure, the gap length does not influence the heat transfer in both cases of "open bottom" and "closed bottom".

The effect of the gap width S on the boiling heat transfer is considered next. Figure 6 illustrates the typical results for the gap length of 100 mm with the "open bottom" case. As the gap width increases, the boiling curve shifts to the left and the heat transfer coefficient increases, which are the same as the results obtained by Ishibashi and Nishikawa and Katto and coworkers [4, 5]. Figure 5 shows the same tendency also for L = 40 and 70 mm. The point differing from the results in ref. [3] however, is that the temperature fluctuation is random and has no periodicity. From this, the reason that the heat transfer improves with decreasing gap width seems to be that the bubbles are pressed against the outer wall, and the liquid film under the bubbles becomes thinner as the gap width becomes smaller with an associated increase in the evaporation rate.

Figure 7 shows the typical results for the "closed bottom" case. Being different from the "open bottom" case, the data for the gap width of 0.2–1.5 mm in the nucleate boiling region can be plotted on a curve including the experimental errors, and it is clear that the gap width does not affect the heat transfer. Figure 5 suggests a similar result for the gap lengths of 40–100 mm. In addition, it becomes clear from Figs. 5–7, that, in the nucleate boiling region, the boiling curve is located on the left side for the "closed bottom" case when compared with the "open bottom" case and that the heat transfer coefficient is improved. In the case of "open bottom", the heat transfer behavior is dominated by bubble generation and the liquid film under the bubble, with new saturated liquid being fed continuously from the lower, open end. In the "closed bottom" case, however, the gap is always filled with vapor and liquid is expelled by the growth of the massive bubbles which remain in the lower part of gap, as described above, except that the liquid is supplied to the thin film on the heating surface from the upper end. In this case, the heat transfer is dominated by the evaporation of the thin liquid film on the heating surface under the vapor. Therefore, the wall temperature rise required for the bubble formation is not necessary and the wall temperature remains low in comparison with the "open bottom" case. From this fact, gap widths of 0.2–1.5 mm do not affect the boiling heat transfer, and the heat transfer coefficient is improved in the "closed bottom" case.

Figure 8 shows the comparison of the results for the "open bottom" case with the data of ref. [3] for the gap width of 0.9–3 mm, in which both agree qualitatively. For the "closed bottom" case, however, since the data

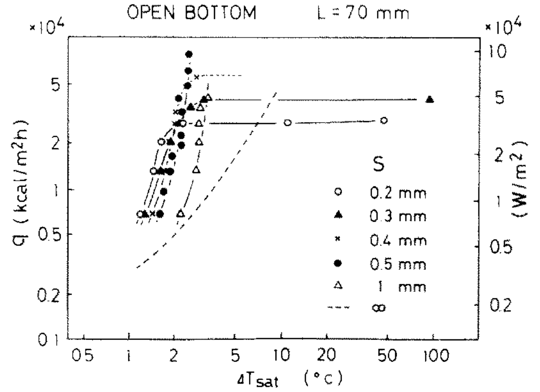

FIG. 6. Boiling curve for the "open bottom" case.

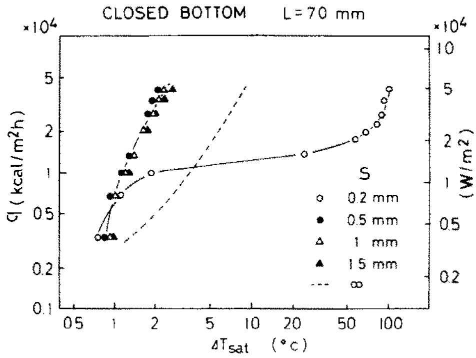

FIG. 7. Boiling curve for the "closed bottom" case.

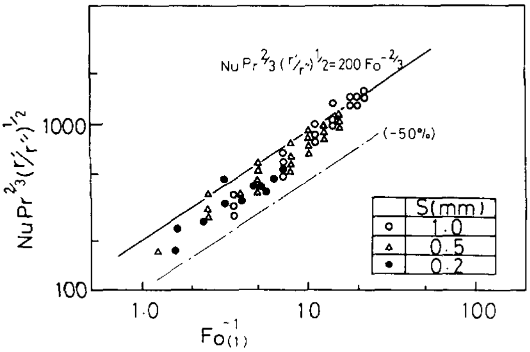

FIG. 8. Comparison of the experimental result for the "open bottom" case.

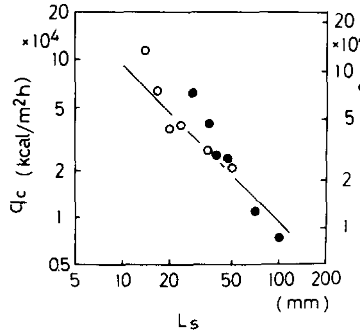

FIG. 10. Relation between drying and wetting, heat flux and gap length.

are not affected by the gap width it is impossible to compare the data with the correlation in ref. [3], in which the heat transfer coefficient varies inversely as two-third power of the gap width.

5.2. *Transition heat flux to drying and wetting region*

The transition from nucleate boiling to drying and wetting region is related to the concentration process of water treatment chemicals. When the boiling phenomenon shows drying and wetting behavior, wall temperature superheat increases remarkably on the boiling characteristic curve, and the amplitude of the temperature fluctuation increases abruptly from a few degrees to several tens of degrees, which is undesirable from the point of thermal fatigue. Figure 9(a) gives the relation between the heat transfer and the gap length whilst Fig. 9(b) shows the effect of gap width. When the "closed bottom" case is compared with the "open bottom" case, the transition heat flux is considerably smaller, although the heat transfer coefficient for the former is larger than that for the latter. For both cases the transition heat flux increases remarkably as the gap width increases and is affected also by the gap length, being different from the heat transfer coefficient in the nucleate boiling region. As the gap length increases, the transition heat flux reduces in both cases, but the effect of the gap length in the "closed bottom" case is rather significant.

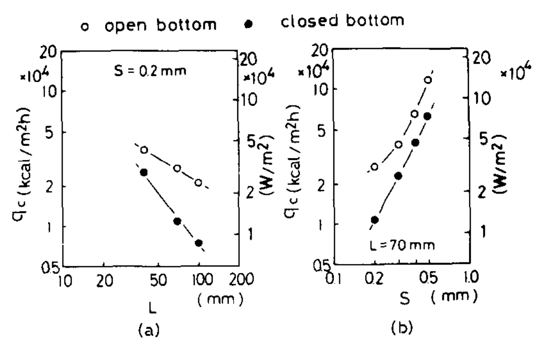

FIG. 9. Relation between the heat transfer and (a) gap length and (b) cap width.

Now, introducing the equivalent length L_S, the following correlation may be given:

$$L_S = LF_{0.2}/NF_S$$

where

$N = 1$ for "closed bottom", $= 2$ for "open bottom",

$F_{0.2}$ = cross-sectional area of open end for the gap width $S = 0.2$ mm,

F_S = cross-sectional area for the gap width S mm,

L = gap length, mm.

If the gap width of 2 mm is selected as the standard, the relation between the transition heat flux and the gap length is given by Fig. 10. In this figure the straight line describes the case in which the vapor generated in the gap flows out at a velocity of 4 m s^{-1} through the open end. Except for two data points at the gap width of 0.5 mm, almost all data are located in the vicinity of the line for the exit velocity of 4 m s^{-1}. This fact suggests that, if the gap width is between 0.2 and 0.4 mm in this experimental system sufficient liquid cannot be supplied to the gap and the liquid deficient phenomenon occurs when the exit vapor velocity through the open end reaches about 4 m s^{-1}.

6. CONCLUSION

(1) In the "open bottom" case, the heat transfer coefficient is improved as the gap width decreases, but it is not affected by the gap length, in the nucleate boiling region for the gap length of $40 \leq L \leq 100$ mm.

(2) In the "closed bottom" case, the heat transfer coefficient is not affected by the gap width or length.

(3) The transition heat-flux to the drying and wetting region can be correlated by the equivalent gap length defined in terms of the cross-sectional area of the open end, and it decreases as the gap length increases.

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ETUDE EXPERIMENTALE DE L'EBULLITION DANS UN ESPACE ETROIT

Résumé—Les expériences sont conduites avec les espaces annulaires de largeur 0.2, 0.3, 0.4, 0.5, 1.0 et 1.5 mm pour les deux cas suivants : (a) pour le cas à "base ouverte", le coefficient de transfert de chaleur est augmenté lorsque la largeur de l'espace décroît, mais il n'est pas affecté par la longueur $40 \leqslant L \leqslant 100$ mm ; (b) pour le cas de la "base fermée", le coefficient de transfert thermique n'est pas modifié par la largeur de l'espace ni la longueur. Le flux thermique de transition peut être exprimé à l'aide de la longueur équivalente définie en fonction de l'aire de la section droite de l'extrémité ouverte.

EXPERIMENTELLE UNTERSUCHUNG VON SIEDEVORGÄNGEN IN EINEM ENGEN SPALT

Zusammenfassung—Die Experimente wurden an engen Ringspalten mit Spaltweiten von 0,2; 0,3; 0,4; 0,5; 1,0 und 1,5 mm durchgeführt. Untersucht wurden zwei Fälle: a) die "offene" Anordnung und b) die "geschlossene" Anordnung. Bei der "offenen" Anordnung wurde der Wärmeübergangskoeffizient mit abnehmender Spaltweite größer, war aber unabhängig von der Spaltlänge von $40 \leqslant L \leqslant 100$ mm. Bei der "geschlossenen" Anordnung war der Wärmeübergangskoeffizient sowohl von Spaltweite wie -länge unabhängig. Die Übergangs-Wärmestromdichte konnte mit der gleichwertigen Spaltlänge korreliert werden, wobei letztere mittels der Querschnittsfläche des offenen Endes ausgedrückt wurde.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ЯВЛЕНИЙ КИПЕНИЯ В УЗКОМ ЗАЗОРЕ

Аннотация — Проведено экспериментальное исследование кипения в узких кольцевых зазорах шириной 0,2; 0,3; 0,4; 0,5; 1,0 и 1,5 мм. Рассматривались (а) зазор с «открытым дном», когда коэффициент теплообмена увеличивался с уменьшением ширины, но не зависел от его длины в диапазоне $40 \leq L \leq 100$ мм, и (б) зазор с «закрытым дном», когда зависимости коэффициента теплообмена от ширины и длины зазора не обнаружено. Тепловой поток в переходном режиме можно описать с помощью эквивалентной длины зазора, выраженной через площадь поперечного сечения открытого торца.