Abstract

Although the flow oscillation strongly affects the characteristic of the critical heat flux, the detailed feature of these phenomena had not been fully understood, so far. One of the reasons of the lack of the reports is owing to the characteristics of the flow oscillation, i.e. the flow oscillation is strongly influenced by the operating condition. This means the oscillatory condition changes by the heating condition, thus general discussion becomes difficult. In this series of investigations, the critical heat flux (CHF) was investigated under artificial flow oscillation generated by a mechanical flow oscillator. By using these means, the influence of the flow oscillation was systematically obtained, and several results and model were presented. In this investigation, the similar experimental investigation was conducted to estimate the dynamic movement of the void fraction. In the visualization procedure, 0.03 second exposure image which synchronized with the flow oscillator was taken, and by using the ensemble averaging of 34 images, the image which had enough dynamic range could be reconstructed.

Keywords: Neutron radiography; Oscillatory flow condition; Critical heat flux; Void fraction; Image processing

1. Introduction

One of the important design limitations of boiling systems is a critical heat flux (CHF) [1, 2]. Thus many investigations of the CHF have been widely conducted, but most of those investigations were
Nomenclature

- $G$: Gain
- $G_0$: Averaged mas flux
- $\Delta G$: Oscillation amplitude of mass flux
- $O$: Offset
- $\Delta p$: Differential pressure among the test section
- $u_{in}$: Inlet velocity
- $x$: Horizontal coordinate of the visualization plane
- $y$: Vertical coordinate of the visualization plane
- $z$: Longitudinal distance of the test section from the inlet of the heating section
- $q_{CHF}$: Critical heat flux
- $\alpha$: Void fraction
- $\delta$: Thickness along the projected direction
- $\mu$: Mass Attenuation coefficient
- $\rho$: Density
- $\tau$: Oscillation period

Conducted under the steady flow condition. Of course some information of the flow instability was also reported, and the fact that the decreasing of the CHF under unstable flow condition was known [3]. But the detail tendency of the influence of the flow oscillation on CHF had not been clearly understood, so far.

![Graph showing critical heat flux under oscillatory flow condition.](image)

**Fig. 1** Critical heat flux under oscillatory flow condition.
The flow instability is also important feature of actual boiling systems, thus the fundamental characteristics have been also widely investigated. Especially, the mechanism of the typical flow instability of boiling system, such as density wave oscillation, pressure drop oscillation, has been investigated analytically and experimentally [4]. Although these results can be considered as the common knowledge, the flow instability is difficult to avoid in actual plants. It is because these flow instabilities are generated by a whole of the system, not only by a boiling channel. This characteristic is also the reason of the difficulty of the investigation of the CHF under oscillatory flow condition. The parameter of the flow oscillation, such as oscillation period or oscillation amplitude, was changed by the operating condition, thus the discussion of the general tendency is difficult.

In this series of the investigation, the CHF experiment has been done under artificial oscillatory flow condition caused by a mechanical flow oscillator. By using this experimental apparatus, the CHF experiment under oscillatory flow condition can be conducted under arbitrary oscillatory flow condition. The general tendency of the CHF under oscillatory flow condition can be clearly observed in Fig.1. As shown in figure, the critical heat flux drastically decreases with the increasing of the oscillation period and oscillation amplitude, and these characteristics can be expressed by the simulation of the lumped-parameter model [5]. Although the influence of the heat capacity of the heating tube was also estimated with the proposal of the scaling parameter, the evaluation of the influence of the heat capacity has still not been enough [6].

The heat capacity of the tube can be considered as the heat storage. In the procedure of the former simulation, the flow field was firstly solved, and the heat conduction of the tube was solved on the basis of the results of the flow field calculation. This “one-way coupling” method is useful against the small capacity tubes, but the interaction between the tube and flow field “Two-way coupling” cannot be neglected in the case of the large heat capacity tube. But this treatment between the heating wall and fluid under transient condition has not been established. In this investigation, to obtain the fundamental information, the void fraction movement under the oscillatory flow condition was measured by using the thermal neutron radiography.

2. Experiment

1.1 Experimental apparatus

Figure 2 is the schematic diagram of the experimental apparatus. The experimental apparatus mainly consisted of a reserve tank, a pump, an orifice, a heating section, a separator and a mechanical flow oscillator. The working fluid was the ion-exchanged water degassed by boiling, and was fed into the test section by a pump. The valve at the outlet of the pump was regulated enough to prevent the influence of the mechanical flow oscillator. Flow oscillator was consisted of a cylinder, a piston and a linkage mechanism, and it was driven by a geared stepping motor. This oscillator superimposed the predetermined flow oscillation on the steady flow from the pump. In the experiment, the phase of the flow oscillation was monitored by the pressure drop at the orifice but the mass flux was estimated by using the following equation to avoid the uncertainty of the non-linearity of the orifice.

\[ G = G_0 + \Delta G \sin \left( \frac{2\pi t}{\tau} \right) \]  

(1)
The test section was SUS 304 tube with I.D.=5.0mm O.D.=7.0mm and L=1000mm in heated length, and it was heated by Joule heating of A.C. power.

In the experiment, outer wall temperature, pressure drop of the test section were also measured. The experimental condition was as follows; averaged mass flux $G_0=300\text{kg/m}^2\text{s}$, oscillation amplitude $\Delta G/G_0=1.0, 1.5$ and oscillation period $\tau =4\text{s}$.

1.2 Facility of Neutron radiography

For the visualization, B4 port of the Kyoto University Research Reactor (KUR) was used. KUR was operated at 5MW and the neutron flux at the port exit was $5\times10^7\text{n/cm}^2\text{s}$. This amount is relatively weak for the quantitative measurement of the void fraction as dynamic image. But owing to this low neutron flux, the strict radiation shield is not required (photo in Fig.2), then the open area can be used for the control system. Especially this room has a pit hole, thus it can be used for the visualization of the long object by using the lifting frame. Moreover, a low voltage, high current power supplier, a water recirculation and condensation equipment is located in the room. In this meaning, this B4 room can be considered as the specialized facility for the visualization of the convective flow boiling.

The dimension of the visualization area was a.30mm $\times$ a.100mm. The detail specification of B4 port, such as L/D, n/$\gamma$ ratio and Cd-ratio, has not been evaluated, so far. Consequently, the dimension of the beam exit (10mm$\times$75mm), the distances between the beam exit and object (4675mm), the object and the converter (25mm) were used for the evaluation of the spatial resolution.

3. Result and discussion

In this investigation, the phenomena can be considered as the periodical phenomena which synchronized with the mechanical flow oscillator. Thus, to obtain the high quantitative dynamic image, the procedure of the ensemble average was used.
Figure 3 (a) is the one shot image of the oscillatory flow condition. The exposure period of this image is 0.03s, and it was taken synchronized with the pulse of the geared stepping motor of mechanical flow oscillator. Figures 3(b) and (c) are the ensemble images of 32 frames which were taken at the same phase of the oscillatory. Figure 3(b) used the image which was used the median filter, and Fig.3(c) used the raw image. As shown in these figures, Fig.3(c) constructs the sharp image but it includes so many white spot caused by $\gamma$-ray. Although the more detailed evaluation about the procedure may be required, the Figure 3(b) is used for the image processing in this stage.

The gray level of the visualization image is expressed by the exponential decays of the wall and water,

$$S_{(x,y,t)} = G_{(x,y,t)} \exp \left[ - \rho_T \mu_T \delta_T(x,y) \right] + O(x,y)$$  \hspace{1cm} (2)

In the image processing, firstly offset image is subtracted from the original image

$$S_{O(x,y,t)} = S_{(x,y,t)} - O(x,y) = G_{(x,y,t)} \exp \left[ - \rho_T \mu_T \delta_T(x,y) \right]$$  \hspace{1cm} (3)

In Fig.4, the brightness is plotted against the time. As shown in figure, the intensity of neutron flux was shifted owing to the operating schedule of KUR. To compensate of this shift, next scaling procedure is used. Firstly, two indicators are set in the image, one of them is the image of the gadolinium plate which is shown as a triangle shape in Fig.3, and another is the center part image without test section. As the compensation procedure, the simple interpolation expressed by the next equation was used,

$$G'_{(x,y)} = \frac{G_{(x,y,t)} - G_{\text{gadolinium}}}{G_{\text{void}} - G_{\text{gadolinium}}}$$  \hspace{1cm} (4)

After compensation of the intensity, Eq(3) becomes

Fig.3 Visualization image (a) one shot image (b) ensemble average after median filter (c) ensemble average of raw image.
\[ S'_{(x,y,t)} = G'_{(x,y)} \exp\left(-\rho_T \mu_T \delta T_{(x,y)}\right) - \left\{ 1 - \alpha_{(x,y,t)} \right\} \rho_w \mu_w \delta w_{(x,y)} \]  

(5)

By using the Image filled with water \( S'_{L(x,y)} \) and Image without water \( S'_{G(x,y)} \),

\[ \alpha_{(x,y,t)} = \frac{\log S'_{(x,y,t)} - \log S'_{L(x,y)}}{\log S'_{G(x,y)} - \log S'_{L(x,y)}} \]  

(6)

In this investigation influence of scattering was estimated less than 5% on the basis of the estimation results of umbrella method [6]. This error can be negligible compared with the accuracy of the measurement at this stage.

The influence of the broadening of the neutron beam was estimated as 0.8mm in vertical direction and 0.11mm in horizontal direction on the basis of the geometrical estimation. To reduce this influence, the

![Graph showing the shift of the brightness over time.](image)

**Fig.4 Shift of the brightness.**

![Graph showing the accuracy on the basis of the Dynamic range.](image)

**Fig.5 Accuracy on the basis of the Dynamic range.**
By using this procedure, the dynamic range becomes more than 500 bits, and the estimation error of this value as the void fraction is shown in Fig.5. This accuracy is not enough for the quantitative measurement of void fraction at z=950mm (a) $\tau = 4s$ $\Delta G/G_0=1.0$ $q=124.8$kW/m$^2$ (x=0.01) (b) $\tau = 4s$ $\Delta G/G_0=1.0$ $q=227.4$kW/m$^2$ (x=0.17)

moving average of this size was adapted.

Fig.6 Visualization image of void fraction (a) $\tau = 4s$ $\Delta G/G_0=1.0$ $q=124.8$kW/m$^2$ (x=0.01) (b) $\tau = 4s$ $\Delta G/G_0=1.0$ $q=227.4$kW/m$^2$ (x=0.17)
measurement of the liquid film thickness, but it is enough to estimate the dynamic movement of the void movement.

The estimation results of the void fraction image are shown in Fig. 6 with the signal of the inlet mass flux movement. Also the estimation results of the void fraction at z=950mm are confirmed with the simulation results. As shown in the Fig. 6, the void fraction movement under oscillatory flow condition can be captured well, and it has enough quality to reconstruct the pseudo dynamic image of the void fraction. Moreover, Fig. 7 expresses the fact that the void fraction movement can be estimated well, even in the case of the high void fraction. These data are very meaning full data, not only in the analyzing of the dryout under oscillatory flow condition, but also to estimate the transient of the void fraction under transient flow condition.

5. Conclusion

The visualization and the quantitatively measurement of the void fraction of the boiling two-phase flow under oscillatory flow condition are key issue of this paper. As the results, the pseudo dynamic image of the void fraction, and comparing results of the void fraction with the calculation results were presented. The results expressed that the ensemble average can provide the acceptable data not only qualitatively but also quantitatively. The detail discussion include the heat transfer will be appeared in the future.

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References