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Critical Heat Flux under Forced and Natural Circulations of Water at Low-Pressure, Low-Flow Conditions

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Abstract

The CHF phenomenon has been investigated for water flow under forced and natural circulation modes with vertical round tubes at low pressure and low flow conditions. Experiments have been performed by using three different test sections for mass fluxes below 400 kg/m²s under near atmospheric pressure. The experimental data for forced and natural circulations are compared with each other. To predict the flow rate at the two-phase region our test condition has been analyzed by RELAP5/MOD3 because the local two-phase conditions inside the stainless steel tube cannot be directly measured. To predict the CHF with accuracy we have to consider the parameters at the single-phase region as well as the flow behavior at the two-phase region.

1. Introduction

The critical heat flux (CHF) is a major parameter which determines the cooling performance and therefore limits the power level of a nuclear reactor. Natural circulation is, especially, an important means for passive decay heat removal during transient and accident conditions of existing nuclear reactors. It becomes more important for advanced reactors with passive or inherent safety characteristics which are now actively investigated all over the world.

The CHF for natural-circulation flow has so far been investigated by several workers [1-3]. It has been generally recognized that natural-circulation flow is more susceptible to flow oscillations and therefore shows a lower CHF compared with forced-circulation flow of the same average local flow conditions. Several attempts have been made to identify the effects of the loop and flow parameters on the flow stability and on the CHF under natural-circulation conditions. Though many parametric effects have been identified, the existing works are mainly based on the average mass flux measured at the single-phase region so that the practical application in thermal-hydraulic (T/H) analysis is hard to be achieved for the two-phase region with a severe flow oscillation.

A survey of the previous work on the low-pressure and low-flow CHF for both natural and forced circulations reveals that:

(a) The circulation mode gives no effect for very low-flow conditions.
(b) Flow oscillations can considerably lower the CHF due to the occurrence of a premature CHF for both natural and forced circulations.
(c) Natural-circulation is much more susceptible to flow oscillations for certain loop and flow conditions; and
(d) Most of the correlations were developed using the inlet or single-phase conditions rather than the local two-phase conditions at the CHF location.

A series of low-pressure, low-flow CHF tests has been conducted at the KAIST to identify the effects of flow circulation modes and flow oscillations. To date the CHF experiments have been performed for flow rates less than 400 kg/m²s at near atmospheric pressure with three vertical round tube test sections made of stainless steel. This study aims to improve the qualitative understanding of the CHF phenomenon, to derive a practical approach to consistently deal with the effects of circulation modes (natural or forced) and flow oscillations on the CHF, focusing on low-pressure and low-flow conditions.

2. Background

The CHF condition is characterized by a sharp reduction of the local boiling heat transfer coefficient which results from the replacement of liquid by vapor adjacent to the heat transfer surface [4]. For uniformly heated tube, the CHF is mainly affected by the following five parameters: tube diameter (D), tube heated length (L_h), system pressure (P), mass flux (G), and inlet subcooling (Δh_i) or the exit quality of the heater (X_e). The CHF is a function of five independent variables, thus

$$\text{Critical Heat Flux } (q_{CHF}) = f(P, D, L_h, G, \Delta h_i) \text{ or } f(P, D, L_h, G, X_e) \qquad (1)$$

For the CHF under natural circulation flow, following workers have studied; Griffith *et al.* [3] investigated the dryout phenomena in a two phase natural circulation system where two phases were gravitationally separated in a heated rod bundles. They proposed that the dryout zone is the region between the calculated pool liquid level and the point where a rod or tube submerged in the pool dries out. Koizumi *et al.* [1] examined the dryout phenomena in two-phase natural circulation system of R-113. The dryout heat fluxes were much higher than those of the closed thermosiphons. The dryout was observed near the exit end of the heated section under an annular flow state. They proposed a correlation to predict the relationship between the dryout heat flux and the film flow rate at the dryout point. Mishima *et al.* [2] performed the CHF experiments for low flow (0~40 kg/m^{2}s) of water in a vertical annulus near atmospheric pressure. There was no difference in the CHF between natural and forced circulation. Ozawa & Umekawa *et al.* [5] performed the CHF experiments under oscillatory flow condition. They investigated effects of two factors, i.e. the period and the amplitude of the density wave oscillation which was induced by the forced flow oscillation using a pump and an oscillator. The mode of temperature fluctuation was classified into three types and the effects for the amplitude and the period of the flow oscillation on the CHF were discussed. The reduction of the CHF from the steady-state value increased with the increase in the amplitude and in the period of the flow oscillation.

3. Experiments

The experimental loop that can operate either in the natural-circulation or forced-circulation modes was constructed to perform various boiling experiments under low pressure. Its schematic diagram is shown in Fig. 1. The loop is filled with filtered and ion-exchanged water which was degassed prior to the start of experiment. The outlet pressure of the test section is maintained at about 120 kPa. Three Type-304 stainless steel tubes have been used as test section. Dimensions of the test sections are summarized in Table 1 and they are schematically shown in Fig. 2 for TS-1. A copper electrode was welded to each end of the test section. Eight chromel-alumel thermocouples (type-K) were spot-welded onto the outside wall of the stainless steel tube which was heated electrically by a direct current (DC) power supplier (40V, 5000A Rectifier). Test section inlet and outlet temperatures were measured by Type-T thermocouples. The inlet flow rate of the test section was measured by turbine flow meter according to the flow rate. The output voltage from the turbine flow meter, the voltage drop at both ends of test section and the temperatures of Type-K and -T were recorded and displayed on a Hewllet Packard Series 300 workstation with HP 3852A Data Acquisition/Control Units, and the signals were processed and analyzed by IBM PC-AT.

Experiments have been performed for upward flow of water under two circulation modes (forced and natural circulations) with changing inlet conditions such as inlet mass fluxes, inlet throttling. During the experiment, the inlet water temperature was kept near 20°C and the pressure at the test section outlet at near 120 kPa. After setting the inlet water temperature and the condition of inlet throttling, the increment of heat flux between power levels was kept sufficiently small and the measured parameters were stabilized before raising the power level again. At the CHF tests, the CHF condition was defined as the condition that the maximum wall temperature increased continuously and abruptly exceeded 250°C. The mass flux was calculated from the volumetric flow rate measured by the turbine flow meters. The average mass flux when CHF occurs was calculated as,

$$\text{Average Mass Flux}(G_{avg}) = \frac{1}{N}\sum_{i=1}^{N} G_i = \frac{1}{\tau}\int_0^{\tau} G\,dt\,. \tag{2}$$

The amplitude(ΔG) of flow oscillations is the peak-to-peak amplitude of mass flux which is the difference between the local maximum and minimum of the mass flux oscillation.

4. Experimental results and discussion

From the CHF data obtained in this work, in the forced-circulation flow condition for all the test sections, CHF monotonously increases with increasing mass flux. In the natural-circulation, however, the characteristic of the CHF can be divided into two regimes with the threshold mass flux. The threshold mass fluxes which may be a function of the loop geometry and operating conditions are about 100 kg/m^{2}s ($G_{th,}$ threshold mass flux that may be depended on the loop system) as shown in Table 2 for the test section. At very low flow below the threshold mass flux, the trend of CHF under natural circulation is similar to that under forced circulation. On the other hand, at the higher flow rates than the threshold mass flux, the CHF under natural circulation is much smaller than that under forced circulation.

4.1. Comparison with existing correlations

Figure 3 compare our test data with existing correlations. The correlations by Lowdermilk *et al.* [6], Weber-Johannsen [7] and KAIST [8] are useful to compare the data at the low pressure low flow conditions. It is found that prediction for the forced circulation and the natural circulation below about G_{th} agree relatively well with the experimental data except for the test section-3. However the prediction for the natural-circulation above about G_{th} did not agree with the test data. From the results we can know that the CHF under natural circulation above G_{th} conditions is affected by the measured average mass flux at single-phase region as well as the different parameters , such as the flow oscillations and the flow behaviors at the two-phase region.

4.2. Effect of flow oscillation on CHF

Figures 4 through 6 show the effect of the average and minimum single-phase mass fluxes, the amplitude of flow oscillations on the CHF under both circulation modes for each test section. The effect of flow oscillation on CHF can be divided into two regimes using G_{th}. The characteristic of CHF for each regime is as follows;

(a) For the lower mass flux region ($G_{avg} \leq G_{th}$), there is no significant difference in the CHF between forced and natural circulations as shown in figures 4 through 6 at the same inlet conditions. The reason is that the flow in this region is very stable for both circulation modes when the CHF occurs.

(b) For the high mass flux region ($G_{avg} > G_{th}$), however, a significant difference in CHF between natural and forced circulation modes was observed as shown in figures 4 through 6. The CHF under natural circulation was significantly lower than that under forced-circulation. Moreover, the CHF under natural circulation was maintained at almost the same values for mass fluxes above the threshold: ~350 kW/m^2 for T/S-1, ~690 kW/m^2 for T/S-2 and ~517 kW/m^2 for T/S-3 as shown in Table 2. In this region, significant flow oscillation appeared for natural-circulation tests, showing the general trend of growing $\Delta G/G_{avg}$ with the increase of the average mass flux. Flow oscillations also appeared for forced circulation tests, sometimes showing $\Delta G/G_{avg}$ larger than that for natural circulation. However, the CHF decrease due to flow oscillations for forced circulation was observed much smaller than that for natural circulation. The similar difference in the CHF between forced and natural circulation modes is observed even in the case that the minimum mass flux is considered instead of the average mass flux.

The present work has clearly identified that the circulation modes do not affect the CHF as far as the flow is maintained sufficiently stable. Also identified is that flow oscillations can decrease the CHF regardless of the circulation modes. However, what would be the main reason that the CHF reduction was much greater for natural circulation? This can be partly explained by the lower frequency of oscillations for the natural circulation mode. Then what would be the reason that the CHF stayed at almost constant value even with the increase of the mass flux for natural circulation? The answer should be sought by considering the two-phase flow conditions near the location of CHF occurrence.

5. Flow analysis for the two-phase region

RELAP5/MOD3 which is based on two-fluid has been widely applied to simulated the LOCA of light water reactors. In this study, RELAP5/MOD3 has been used to calculate and predict the two-phase flow parameters at the CHF location. First attempt was to simulate the whole test loop by the code; any meaningful results were obtained. Next we tried to simulate the test section only with boundary conditions for the inlet (single-phase) flow rate, inlet temperate, inlet pressure and wall heat fluxes. After several failures, we could get some results for further analysis. The nodalization scheme is shown in Fig. 7. As shown in the figure, the inlet boundary condition is set up by using both time dependent volume and time dependent junction and the outlet pressure condition is specified by using time dependent volume. The test section is divided into 6 nodes. Figures 8 and 9 illustrates some conditions calculated by RELAP5 near CHF conditions. From the analysis results, we could understand the behavior of the parameters such as mass flux and void fraction at the two-phase region where CHF is occurred at the inner test section. The behavior of the calculated mass flux at the top of test section is considerably different from that of the measured mass flux at the single-phase region. Though the average mass flux is same at the two-phase and at the single-phase, the minimum mass flux and the amplitude of the flow oscillation is different. To predict the CHF with accuracy we have to consider the parameters at the single-phase region as well as the flow behavior at the two-phase region.

6. Conclusions and recommendations

Experimental investigation on the critical heat flux was conducted under the forced-circulation and natural-circulation flow conditions. It is thought that the single-phase flow oscillation does not adequately represent the local two-phase flow oscillation at CHF locations. Based on the present and existing data, the following conclusions are drawn:

(a) At mass fluxes below a threshold (~100 kg/m^{2}s), the loop flow was maintained very stable for both circulation modes and there was no effect of the circulation mode on the CHF.

(b) At mass fluxes above the threshold, the natural-circulation CHF was much lower than the forced-circulation CHF for the same average single-phase mass flux. The natural-circulation CHF did not increase even with the significant increase of the inlet flow rate. This region corresponds to the region of significant oscillations of natural circulation flow.

(c) An increased flow oscillation also decreased the forced-circulation CHF; however, the effect was much smaller than the case of natural circulation. This could be partly related to the oscillation frequency.

(d) From the flow analysis at the two-phase region using RELAP5/MOD3, the local two-phase flow at the location of CHF occurrence is much more unstable(oscillation) than the single-phase flow for both circulation modes. So the effects of flow oscillations may be well explained by using the local two-phase flow conditions at the location of CHF occurrence.

(e) To predict the CHF with accuracy we have to consider the parameters at the single-phase region as well as the flow behavior at the two-phase region.

Further work will be concentrated on the analysis of the data using the local two-phase flow conditions and the development of CHF correlation considering flow oscillation.

References

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Table 1. Test sections and test conditions

Test Sections	L_h (m)	D (mm)	L_h/D (-)	Circulation Modes	
TS-1	0.6	5.0	120.0	Forced (FCHF-1)	Natural (NCHF-1)
TS-2	0.5	6.6	75.7	Forced (FCHF-2)	Natural (NCHF-2)
TS-3	0.6	9.8	61.2	Forced (FCHF-3)	Natural (NCHF-3)

Table 2. Summary of Test Results

Test Sections	G_{th} (kg/m^{2}s)	q_{th} (kW/m^2)
TS-1	100	350
TS-2	113	690
TS-3	95	517

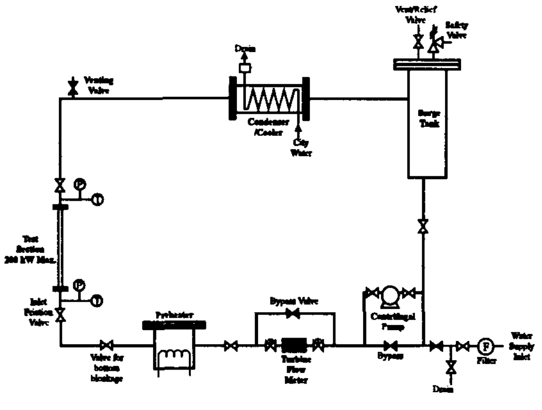


Fig. 1. Schematic diagram for experimental loop

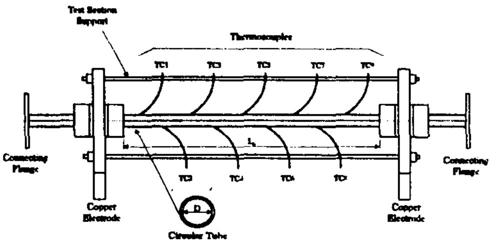
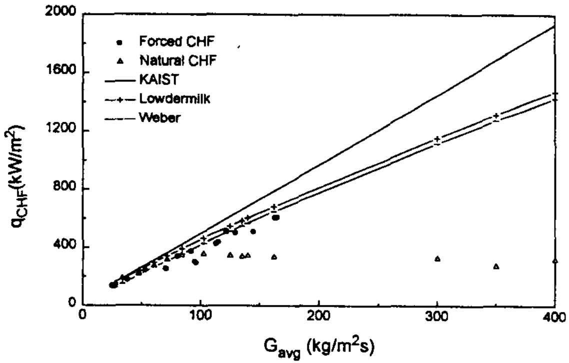
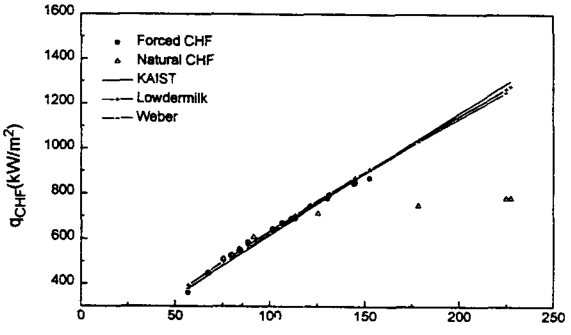


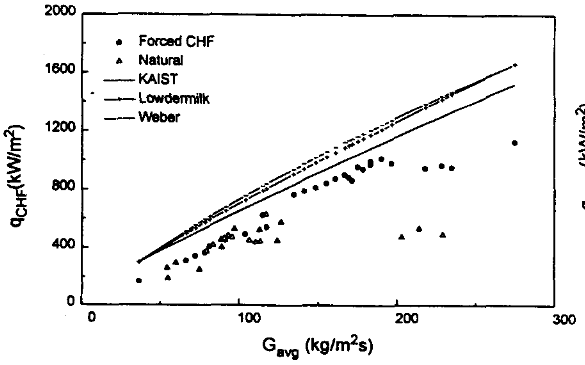
Fig. 2. Test section with thermocouple locations



(a) For test section-1 *(D=5.0mm, L_h=0.6m)*

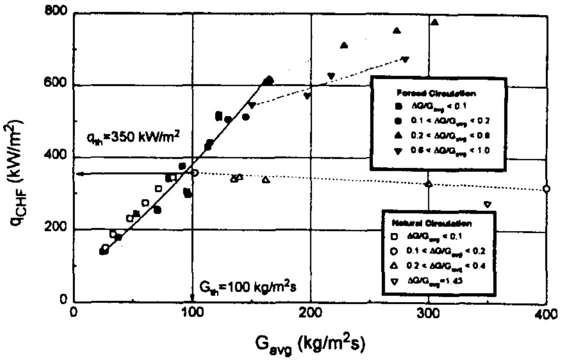


(b) For test section-2 *(D=6.6mm, L_h=0.5m)*

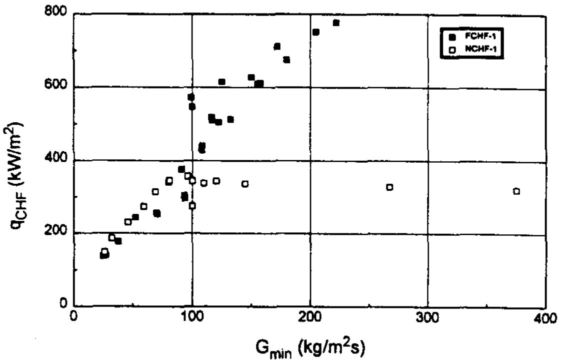


(c) For test section-3 *(D=9.8mm, L_h=0.6m)*

Fig. 3. Comparison of CHF data with correlations

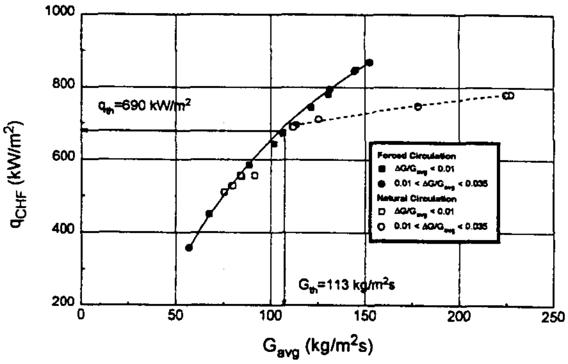


(a) based on the average mass flux

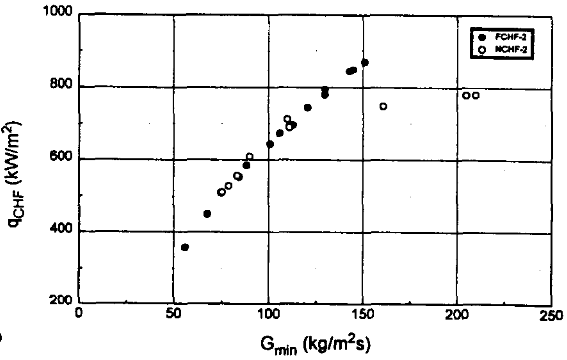


(b) based on the minimum mass flux

Fig. 4. CHF data for the Test Section-1
(D=5.0mm, L_h=0.6m)

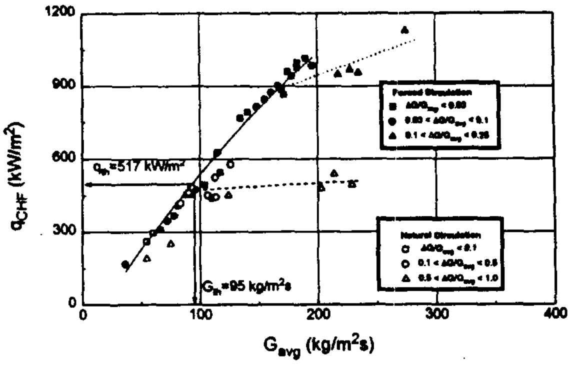


(a) based on the average mass flux

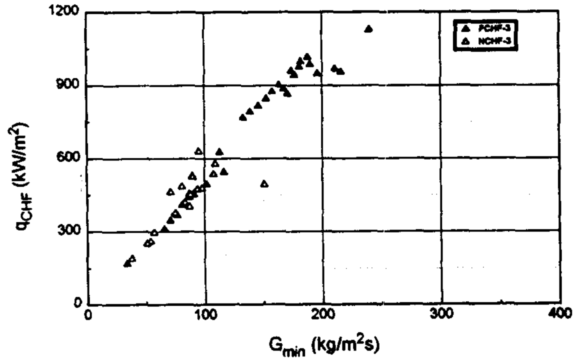


(b) based on the minimum mass flux

Fig. 5. CHF data for the Test Section-2
(D=6.6mm, L_h=0.5m)



(a) based on the average mass flux



(b) based on the minimum mass flux

Fig. 6. CHF data for the Test Section-3 *(D=9.8mm, L_h=0.6m)*

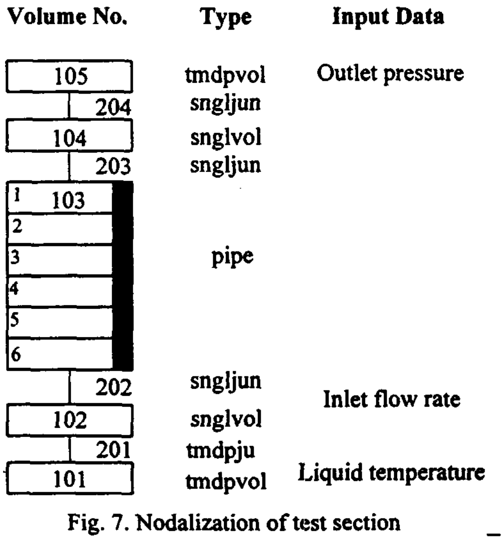
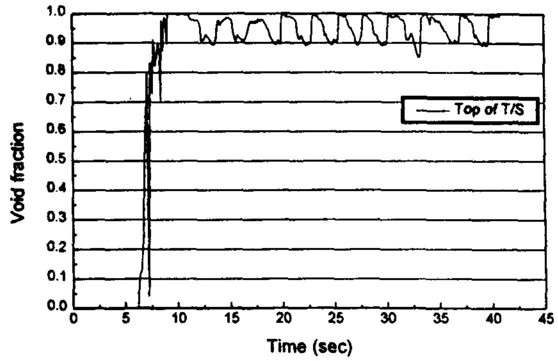
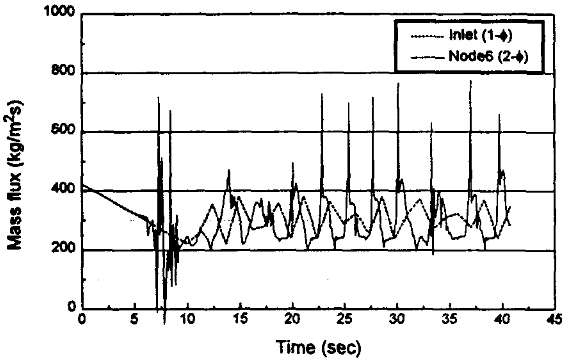


Fig. 7. Nodalization of test section

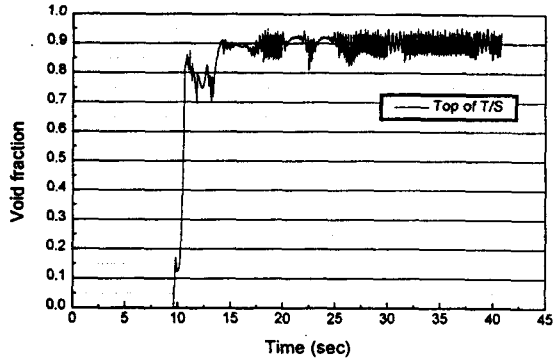


(a) Void fraction in the test section

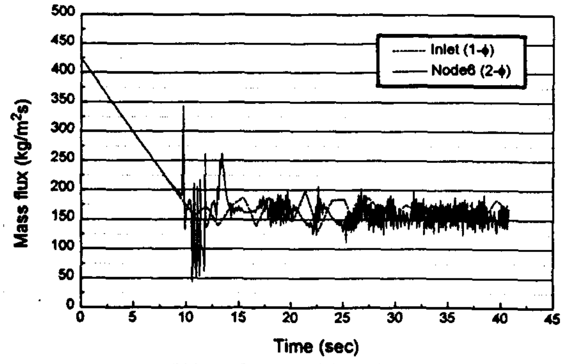


(b) Mass flux at the inlet and inner of T/S

Fig. 8. Results for flow analysis under forced circulation *(D=5.0mm, L_h=0.6m)*



(a) Void fraction in the test section



(b) Mass flux at the inlet and inner of T/S

Fig. 9. Results for flow analysis under natural circulation *(D=5.0mm, L_h=0.6m)*