Effects of mechanical vibration on Critical Heat Flux in vertical annulus

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ABSTRACT

This study presents the investigation of the vibration effect on CHF. The experiments condition was under atmospheric pressure at vertical heated annulus channel. The experiments for dynamic response of the heater section without vibration excitation were carried out at mass flux of 50 kg/m^2/s and 400 kg/m^2/s. Vibration amplitude was increased at the ONB point during boiling process and the reason of the vibration increase is expected as the results of the flow regime change from subcooled region to bubbly region. CHF experiments with and without mechanical vibration were performed at mass flux of 115 kg/m^2/s and 215 kg/m^2/s. Totally 162 data of CHF with vibration were gained and CHF was increased by mechanical vibration maximum 13.4 % at the mass flux of 115 kg/m^2/s and 16.4 % at the mass flux of 215 kg/m^2/s. The maximum CHF enhancement condition was at 30 Hz vibration frequency and 0.5 mm vibration amplitude. The dominant parameter of vibration which was effective on CHF enhancement was vibration amplitude and the reason of the CHF increase is expected as the increase of the liquid film thickness by increase of deposition of liquid droplet on the film.

Vibration was effective not only heat transfer enhancement but also CHF enhancement. Therefore, FIV could be important parameter in CHF enhancement and must be investigated further more.

1. Introduction

Above a certain heat flux, the liquid can no longer permanently wet the heater surface. This situation leads to an inordinate decrease in the surface heat transfer. This heat flux is commonly referred to as the critical heat flux (CHF). The CHF in nuclear reactors is one of the important thermal hydraulic parameters limiting the available power.

Flow induced vibration (FIV) is the vibration caused by a fluid flowing around a body. In the fluid flowing system, FIV occurred by structures and flow condition. Many structures in nuclear power plant system are designed to prevent from structure failure due to FIV.

Recently, Hibiki and Ishii (1998) carried out an experimental investigation on the effect of flow-induced vibration (FIV) on two-phase flow structure in vertical tube and reported that the FIV drastically changed the void fraction profiles. The void fraction profiles is one of the important parameter for determining CHF. Therefore, the investigation on the effect of FIV on CHF are needed.

The research on enhancement of CHF by mechanical vibration has been carried out for tube test section in KAIST. The results of the experiments showed that increase of the mechanical vibration amplitude increase also increased the CHF about 10%. But, more data for other geometry are required because CHF is a function of geometry. Especially a significant amount of work for annular channels is required because they are essentially deemed to simulate more closely the rod bundle geometry than round tubes.

This study presents the investigation of the vibration effect on CHF. The experiments condition was under atmospheric pressure at vertical heated annulus channel. CHF experiments with and without mechanical vibration were performed and the experiments for dynamic response of the heater section without vibration excitation were carried out. Also, natural frequency test of heater section and amplitude detection tests were performed at the CHF occurring position.

2. Background

2.1 The dynamic response of structure with heat transfer or CHF

When either the local liquid temperature is increased above the corresponding saturation temperature or the local pressure is below the vapour pressure, bubble generation/growth could be occurred at the nucleation site of heated surface. Moreover, if high degrees of subcooling are involved, collapse/condensation of the vapour bubbles are activated. These processes are sometimes accompanied by the noise and vibration of the heating surface.

In order to simulate the subcooled boiling thermal hydraulics of a divertor tube mock-up, Celata et al.(1995), made use of accelerometer equipment, used in the field of cavitation and boiling detection, and high heat flux test facility, used in hypervapotron experiments. In their experiments, measurement of noise or vibration originated form the bubble growth and collapse is method for the detection of the subcooled boiling phenomenon covering the whole heat transfer regime, on externally heated cylindrical channels from the single-phase up to the CHF. Their basic understandings are as follows:

a) At the onset of nucleate boiling, bubble cavities increase with the related noise emissions and then, with increasing heat flux, the accelerometer signal reaches a maximum.

b) The signal can be quite stable during fully developed boiling (FDB), when the bubble dimensions and frequencies increase.

c) At the higher heat flux, the vibrations reduce gradually because of the appearance of another phenomenon. In fact, due to the damping of the greater bubbles that begin to implode in the bulk of the fluid rather than on the heated surfaces, this padding effect procures a noticeable reduction of the vibrations.

d) Approaching to the CHF, a sudden drop of the signal was recorded due to the vapour film formation on the inner tube surface.

These are considered as very comprehensive explanations about vibration characteristics at heating condition. Nevertheless, there are some limitations in application because of the data of short test section (e.g., L/D = 10, 15) and somewhat different geometry. Another information on the intensive subcooled boiling-induced vibration in annular flow channel, presented by Nematollahi et al. (1999), gives the influence of subcooling temperature, linear power density and flow rate on vibration.

2.2 The effect of vibration on convective heat transfer or CHF

Because vibration is regarded as an alternating method of heat transfer enhancement, a great deal of experimental investigations have been performed to demonstrate the influence of vibrations/sound upon the rate of convective heat transfer from heated surfaces to fluid. For examples, Martinelli and Boelter (1938) investigated the effect of vertical vibrations upon heat transfer rate from a horizontal tube immersed in a tank of water. They reported that the coefficient of heat transfer was not affected at low Reynolds numbers, but the coefficient was observed to increase by as much as 400 percent of its value without vibrations for sufficiently intense vibrations. And they empirically correlated the data by means of several dimensionless values such as the Nusselts with Grashof, Prandtl and vibration Reynolds numbers. Another experimental work, carried out by Bergles (1964) in single-phase heat transfer region, gives that low frequency (f) flow vibration can improve heat transfer capability but there is a threshold temperature below which no influence of vibration on heat transfer is observed. He concluded that the improvement in heat transfer could be due to the flow separation account for the increased turbulence. The same explanation was given by Takahashi and Endoh (1990). Vibration

creates an oscillating relative velocity vector between a heated surface and a fluid. Therefore, the vibration of the heat transfer surfaces gives rise to turbulence in the case of laminar boundary layers. Since it is well known that the heat transfer rate is greater in turbulent flow than in a laminar flow, their conclusions are very reasonable.

The effect of vibration amplitude on heat transfer had been examined by Klaczak (1997). He showed that the heat transfer enhancement ratio depends on amplitude, much less on frequency of vibrations. But, the deteriorate effect of vibration also appeared in his data, compared with a system which is not exposed to vibrations.

There is no information about the effect of vibration on CHF besides Bergles' experiment. Judging from only a couple of burnout data, Bergles concluded that there is no significant change in the burnout heat flux with vibration. Due to the deficient data, however, more systematic investigations are needed to find out the effect on CHF

3. Experiments and Results

CHF experiments for mechanical vibration excitation effect were carried out under the condition of atmospheric pressure at vertical heated annulus channel as shown in Table.1. The experimental test section is shown in Fig.1. Totally, 8 experimental CHF data have been collected without vibration excitation and 162 experimental CHF data with mechanical vibration excitation.

The experiments for dynamic response of the heater section without vibration excitation were carried out at mass fluxes of 50 kg/m^2/s and 400 kg/m^2/s to detect dynamic vibration characteristics of annulus tube during boiling process and to detect vibration parameters which occurring at various flow pattern. Vibration amplitude increased at the ONB point as shown Fig.2 and Fig.3.

Natural frequency test of heater section were carried out to check the dynamic properties of the heater section. The first natural frequency was 14.5 Hz and the second natural frequency was 29.25 Hz. The similar excitation frequency which are possible to occur resonance phenomena are 15 Hz and 30 Hz.

Amplitude detection tests were performed at the CHF occurring position. These experiments were carried out to analyse the effect of vibration on CHF with actual displacement excited at CHF occurring position. At vibration frequency of 30 Hz, vibration amplitude at CHF occurring position were higher than other frequency. This phenomena is expected as vibration resonance matching natural frequency of the heater section.

CHF experiments with mechanical vibration excitation were carried out at two mass fluxes of 115 kg/m^2/s and 215 kg/m^2/s. For parametric analysis these CHF data were rearranged by

amplitude (displacement) and frequency and vibration intensity. The vibration displacement in these experimental results is based on the excitation position connecting vibration exciter and the CHF occurring position.

- Vibration amplitude effect on CHF

The exciting displacement was given by vibration exciter and their amplitude were from 0.1 mm to 0.5 mm by increment of 0.05 mm. At the constant frequency CHF increased as vibration amplitude increases. At excitation vibration frequency of 30 Hz, CHF data is higher than the others at the same vibration excitation position displacement.

After CHF occurring position displacement detection test, these CHF data were rearranged about actual vibration amplitude as shown in Fig.4 and Fig.6. After this test the actual vibrating displacements at CHF occurring position at excitation vibration frequency of 30 Hz were detected higher than other frequency excitation. So, the dominant parameter of vibration which is effective on CHF is proven as not vibration frequency but vibration amplitude. This special increase of amplitude at vibration frequency of 30 Hz is expected as the results of vibration resonance.

- Vibration frequency effect on CHF

The vibration frequency is determined by function generator and frequency range is from 10 Hz to 50 Hz by increment of 5 Hz. At the constant vibration amplitude at excitation position CHF was increased as vibration frequency increases till 30 Hz, but CHF was decreased as frequency increased more as shown in Fig.5 and Fig.7. But this amplitude trend is same as the results of the detection test of the vibration displacement at the CHF occurring position. So, if the CHF data rearranged as the actual vibration amplitude at CHF occurring position, no effect trend is shown.

- Vibration intensity effect on CHF

Vibration intensity is the value defined by multiplication vibration amplitude and frequency.

As vibration intensity increased, CHF was increased. The CHF data were scattered at high vibration intensity arranging with the vibration amplitude of excitation position. Most data points are gathered at low vibration intensity and scattered but lower than high vibration intensity condition data arranging with the vibration amplitude of CHF occurring position as shown in Fig.8 and Fig.9. This phenomena is explained by the effect of the vibration amplitude on CHF

As vibration amplitude increased, CHF was increased. But, the effect of the vibration frequency on CHF is not clear so assumed that vibration frequency has no effect on CHF. As results, the CHF trend about vibration intensity is not linear but has inclination slope decreasing. At the mass flux of 115 $kg/m^2/s$ the maximum CHF enhancement ratio was 13.4 %. At the mass flux of 215 $kg/m^2/s$ the maximum CHF enhancement ratio was 16.4 %. The maximum CHF was at the condition of 30 Hz vibration frequency and 0.5 mm vibration amplitude

5. Conclusions

In this study, the effect of vibration on CHF was investigated. The experiments condition was under atmospheric pressure at vertical heated annulus channel. CHF experiments with and without mechanical vibration were performed and the experiments for dynamic response of the heater section without vibration excitation were carried out. Also, natural frequency test of heater section and amplitude detection tests were performed at the CHF occurring position. Important findings of this study are summarized as follows:

a) Vibration detecting test were carried out during boiling process without mechanical vibration excitation at mass flux of 50 kg/m^2/s and 400 kg/m^2/s. Vibration amplitude was increased at the ONB point during boiling process due to flow pattern change from subcooled region to bubbly region.

b) CHF was increased by vibration excitation of the heater section at atmospheric pressure condition. The maximum CHF enhancement ratio was 16.4 % at mass flux of 215 kg/m^2/s and 13.4 % at mass flux of 115 kg/m^2/s.

c) The maximum CHF enhancement condition was at 30 Hz vibration frequency and 0.5 mm vibration amplitude. At vibration frequency of 30 Hz, vibration amplitude at CHF occurring position were higher than other frequency. This phenomena comes from vibration resonance matching natural frequency of the heater section

d) The dominant parameter of vibration which is effective on CHF enhancement was not vibration frequency but vibration amplitude.

e) The reason of the CHF increase in LFD condition is expected as the increase of the liquid film thickness. As heater vibrates, increase of deposition of liquid droplet on to the film may be expected to increase liquid film thickness.

The mechanical vibration was effective not only heat transfer enhancement but also CHF enhancement. The investigation on CHF enhancement method and application is very important connecting the nuclear power plant design, and FIV could be important parameter in CHF enhancement. Therefore, CHF experiment connecting to FIV must be investigated further more.

Nomenclature

A	ampere	A
Avg.	average	-
D	diameter	m
D_e	equivalent diameter	m
D_h	hydraulic diameter	m
D_i	inner diameter	m
D_o	outer diameter	m
G	mass flux	$kg/m^2 s$
Dh_i	inlet subcooling	kJ/kg
L	length	m
L/D	length-to-diameter ratio	-
N	number of data	-
P	system pressure	kPa
q_c	critical heat flux	kW/m^2
f	frequency	-
V	voltage	volt
z	heated length	m

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Table. 1 Experimental conditions of this study

Condition	Parameter	
Geometry	Vertical annulus	
	Heater material	SUS 304
	Heater outer diameter (mm)	6.35
	Outer tube material	Quartz
	Quartz inner diameter (mm)	17
	Quartz thickness (mm)	2
	Heater length (m)	0.7
Flow	Vertical upward flow	
	Pressure (kPa)	101
	Mass flux (kg/m^{2}s)	50 ~ 600
	Inlet subcooling (kJ/kg)	309.4 ~ 342.3 kJ/kg
Vibration	Transverse to flow direction, sinusoid input	
	Frequency (Hz)	5 ~ 50 (step size : 5)
	Amplitude (mm)	0.05 ~ 0.5 (stemp size : 0.05)
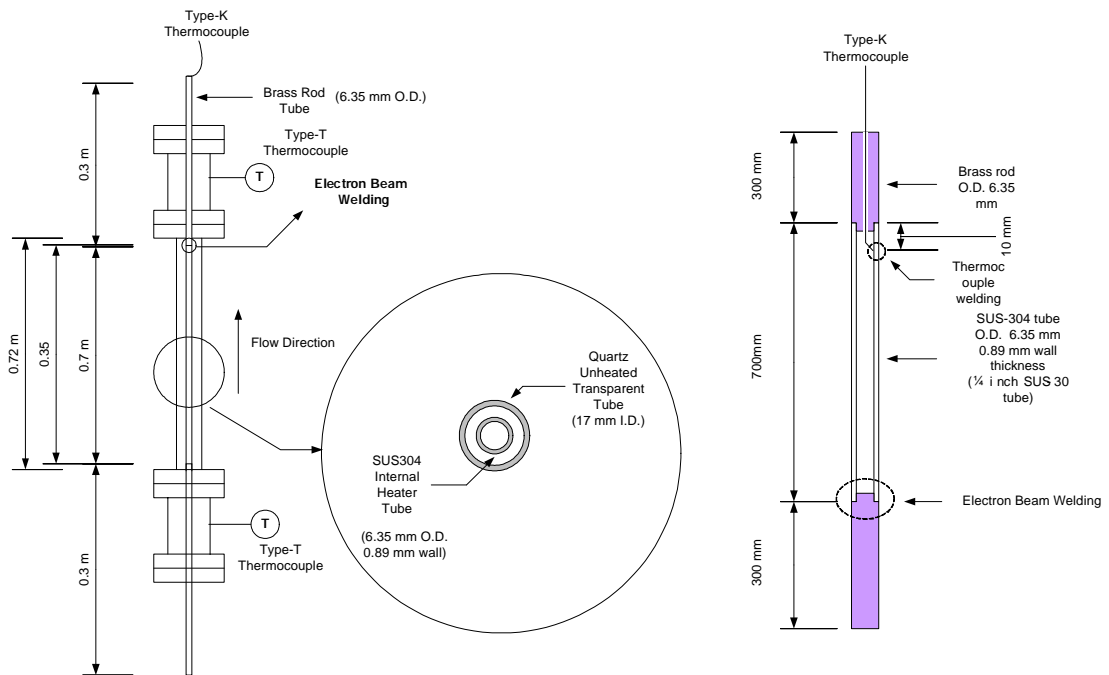
. Fig. 1 Schematic diagram of the experimental test section
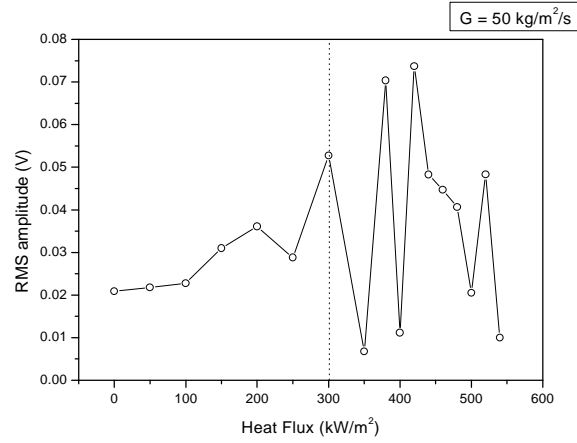
Fig. 2 Vibration amplitude in boiling process at G = 50 kg/m^2/s

(KAIST)
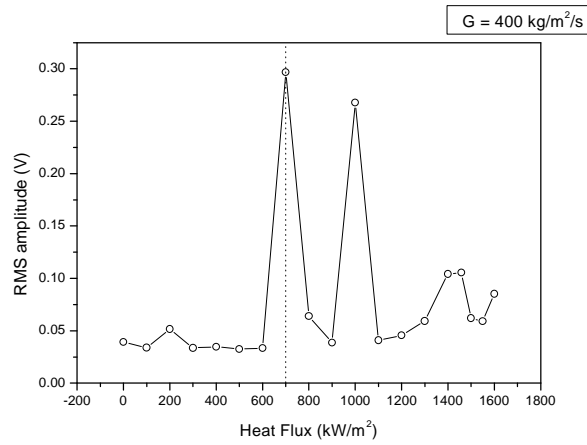
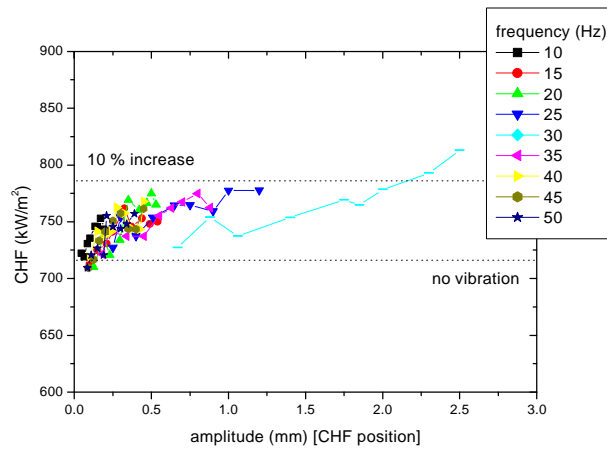Fig. 3 Vibration amplitude in boiling process at G = 400kg/m^2/s

(KAIST)

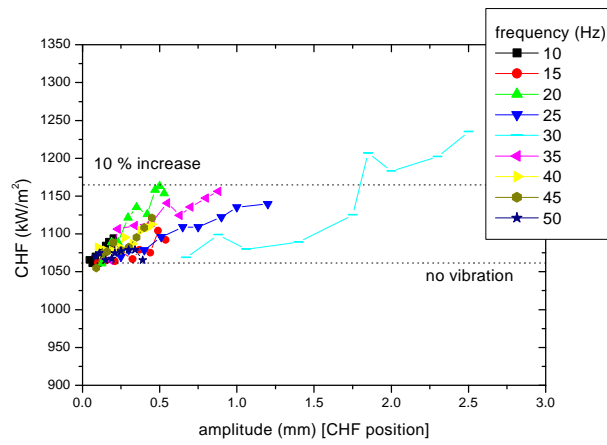Fig. 4 CHF change in various amplitude with constant frequency at G = 115 kg/m2/s
(KAIST)

Fig. 5 CHF change in various amplitude with constant frequency at G = 215 kg/m2/s
(KAIST)

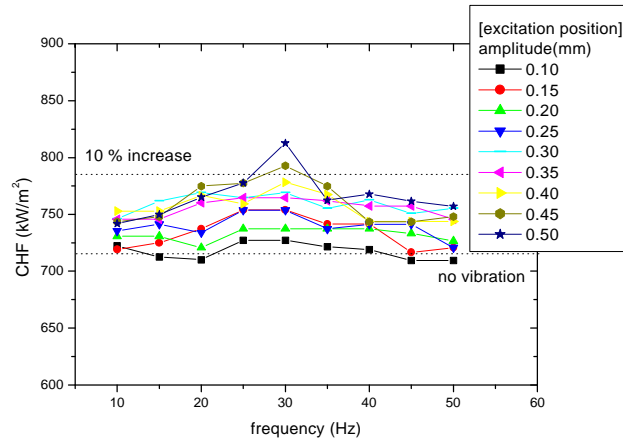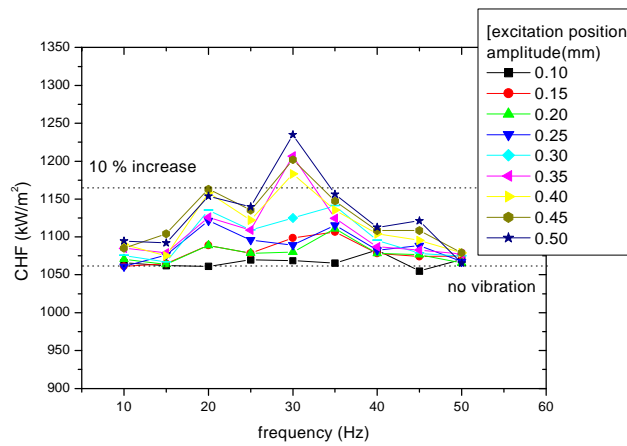Fig. 6 CHF change in various frequency with constant amplitude at G =115 kg/m^2/s (KAIST)

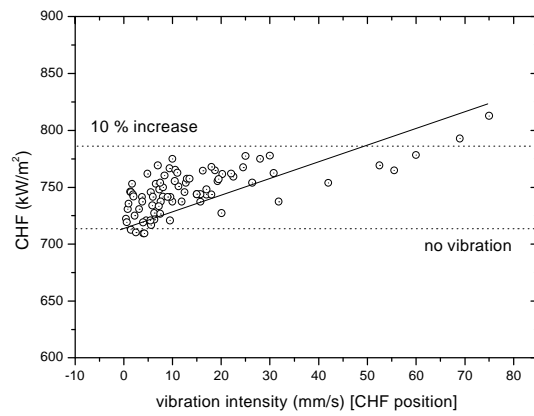Fig. 7 CHF change in various frequency with constant amplitude at G =215 kg/m^2/s (KAIST)

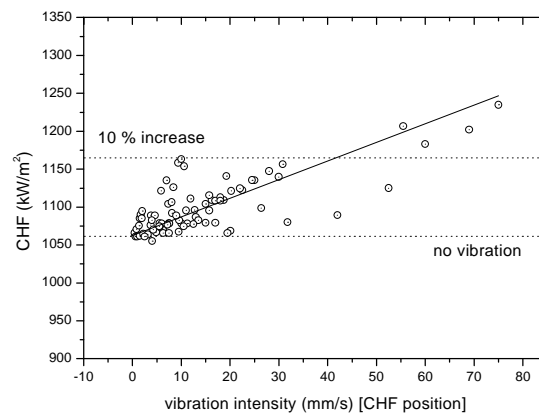Fig. 8 CHF change in various vibration intensity at G =115 kg/m^2/s

(KAIST)

Fig. 9 CHF change in various vibration intensity at G =215 kg/m^2/s

(KAIST)