HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

EXPERIMENTAL STUDY ON CRITICAL HEAT FLUX UNDER ROLLING CONDITION

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ABSTRACT

This paper presents defining characteristics of the critical heat flux (CHF) for the boiling of R-134a in vertical tube operation under rolling motion in marine reactor. It is important to predict CHF of marine reactor having the rolling motion in order to increase the safety of the reactor. MArine Reactor Moving Simulator (MARMS) tests are conducted to measure the critical heat flux using R-134a flowing upward in a uniformly heated vertical tube under rolling motion. MARMS was rotated by motor and mechanical power transmission gear. The CHF tests were performed in a 9.5 mm I.D. test section with heated length of 1m. Mass fluxs range from 285 to 1300 kg/m^2s, inlet subcoolings from 3 to 38^oC and outlet pressures from 1.3 to 2.4 bar. Amplitudes of rolling range from 15 to 45 degrees and periods from 6 to 12 sec. To convert the test conditions of CHF test using R-134a in water, Katto's fluid-to-fluid modeling was used in present investigation. A CHF correlation is presented which accounts for the effects of pressure, mass flux, inlet subcooling and rolling angle over all conditions tested. Unlike existing transient CHF experiments, CHF ratio of certain mass flux and pressure are different in rolling motion. For the mass fluxes below 500 kg/m^2s at 13, 16 (region of relative low mass flux), CHF ratio was decreased but was increased above that mass flux (region of relative high mass flux) bar. Moreover, CHF tend to enhance in entire mass flux at 24 bar.

INTRODUCTION

The most prominent characteristic of marine reactor is that it should be operated during voyage over the ocean. Furthermore the ocean has the most dynamic motion such as heaving, rolling and pitching. In particular, the rolling is one of the most important factors to the variation of CHF. Thus, a prediction of CHF characteristic is an important matter of marine reactor safety and design has been considered over the past long period.

A considerable number of studies on thermal hydraulic behavior for marine reactor have been performed but much less for CHF at ship motion. Most of existing investigation for marine reactor has conducted for heaving motion. The CHF experiments with gravity acceleration changes have been performed by researchers such as Chang [1], Isshiki [2], and Otsuji [3]. They suggest that CHF ratio (ratio of the CHF under ship oscillating condition to the steady CHF) decrease almost linearly with acceleration increase. Fundamentally, suggestions of them are that CHF proportional to the 1/4th power of gravity acceleration in pool boiling by Zuber [4]. Several studies have investigated for rolling motion with experiment and system code. However, no one approached for CHF under rolling condition.

Presently, no method exists that is able to predict the CHF under rolling motion or even in single vertical tubes. This is due to the extreme complexity of the heat and mass transfer processes responsible for the occurrence of CHF and to the incomplete knowledge of the mechanisms involved. The CHF characteristics are closely related to the two-phase flow pattern. Thus, it is important to determine the dependence of CHF on the flow pattern regimes to understand mechanism. The CHF phenomena can generally be classified into two broad categories, depending on the vapor quality. The first, departure from nucleate boiling (DNB), usually at a low vapor quality typical of that encountered at high pressure and/or high coolant mass flow rates. This type of CHF phenomenon is associated with a transition from nucleate boiling to film boiling and leads to an abrupt increase in the heater surface temperature. Generally, CHF mechanism in DNB for bubbly, churn and slug flow regime. Second category of the CHF phenomena is dryout. This type of CHF usually occurs at high vapor quality or void fraction, typical of those occurring in constrained geometries and at saturated or near saturated flow conditions. In this case, CHF mechanism is associated with the disappearance of liquid film on heater wall in annular dispersed flow where by the thermal hydraulic conditions no longer support the continuous liquid film on the wall. The magnitude of the surface temperature rise at CHF during DNB is higher than that of dryout.

The main purpose of the study is the understanding on CHF characteristics under rolling motion was to investigate the CHF mechanism with flow regime in experiment condition.

NOMENCLATURE

χ_c	[-]	Critical Quality
C_p	[m^{3}K/W]	Specific Heat of the Liquid
G	[%]	Mass Flux
h_{fg}	[W/mK]	Latent Heat of Evaporation
q_c	[W/m^3]	Critical Heat Flux
ΔT_{in}	[m^{2}K/W]	Inlet Subcooling
Δh_{in}	[K]	Inlet Subcooling

EXPERIMENTAL APPARATUS AND PROCEDURE

The three-dimensional MArine Reactor Moving Simulator (MARMS) is shown in Figure 1. It is composed of a Freon circulation loop and rolling device system. The Freon (R-134a) circulation loop consists of the following components: a test section for CHF, a non-sealed canned motor pump for stable mass flow supply, a mass flow meter, a preheater for inlet temperature (inlet subcooling) control, a pressurizer (accumulator type) for pressure control of loop system, a cooler for condensing and heat exchange of outlet Freon, and a chilling system with water. A control valve is used to precisely control flow rate to the test section. The loop is filled with R-134a by vacuum system. The test loop is designed for pressure of 40 bar and 200^{o}C. The loop flow is measured by mass flow meter calibrated to be 2% of RMS error by manufacturer. Temperatures and pressures are measured at various locations as indicated by T and P, respectively.

The test section is schematically shown in Figure 2. It is stainless steel (SUS316) tube with upward flow. The tube is electrically heated directly with a direct current (DC) power supply, which controls the power by a power transformed with silicon controlled rectifiers (SCRs) with the maximum power capacity of 40V and 1200A. The heated length of test section is 1000 mm and the inside diameter and thickness are 9.5 mm and 1.65 mm, respectively. These geometric dimensions are selected to reflect the hydraulic diameter of marine reactor core. The temperatures of the liquid at the inlet and outlet of the test section are measured with the T-type sheathed thermocouples. The temperatures of the outside wall are measured at 14 locations along channel wall and K-type thermocouples are installed at each location. The first 4 couples are installed 5 mm space below from the end of upper power electrode. Outlet pressure and inlet pressure are measured with pressure transducer which is calibrated to be 0.5% of RMS error for a full range. Pressure difference of test section is measured by differential pressure transducer and both pressure transducers.

A pair of clamp-type copper electrodes grabs both ends of test tube. Test section is connected to the flange, which is insulated from other part of the test loop with Teflon. The supplied current and the voltage difference between both ends of the test section are measured and collected by a data acquisition system.

The rolling device consists of the loop stand, support, gear and motor for controlling the rolling. The loop stand is a 1m×1m square plane. Location of the rolling axis is top of device and height is 1.5m between axis and stand. The rolling device is driven by motor and gear from controller. The rolling amplitude and period can be controlled through the relationship with number of gear tooth and revolution and speed of electromotor to simulate a ship motion. The rolling angle was measured in clockwise direction from the perpendicular. Angular acceleration at each rolling amplitude and period were detected by two acceleration transducers; one thing for x-direction and the other thing for z-direction.

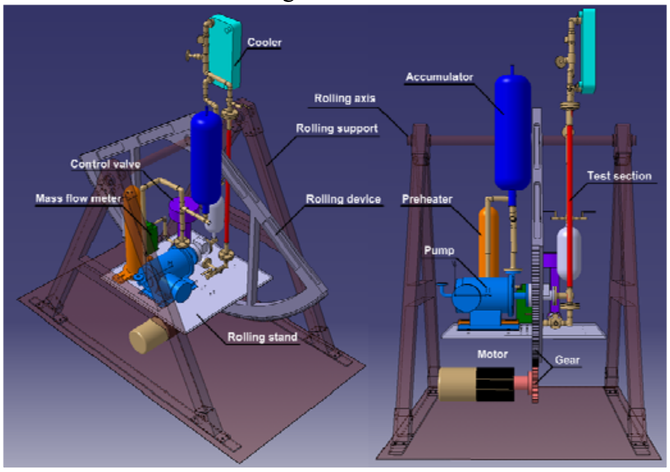


Figure 1 Isometric and lateral view of MARMS

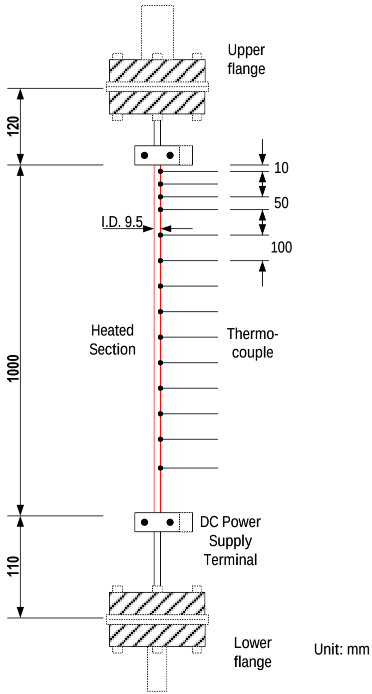


Figure 2 Schematic of test section

TEST PROCEDURE AND TEST MATRIX

Experiments have been performed for upward flow of R-134a with changing inlet conditions such as pressure, mass flux, and inlet subcooling in loop and rolling amplitude and period in rolling device. The procedures of stationary experiment were conducted as follows. Before each case of experiments, a heat balance test was performed and showed that the heat losses were within 2.5%. First, the pump starts and the mass flow rate is controlled by the speed control with the inverter and the control valve at a certain level. The system pressure in the Freon loop is increased by turning on the pre-heater and is controlled by venting and inflation the nitrogen gas in accumulator. After the pressure in the loop reached a desired level, the inlet temperature is controlled by pre-heater with SCR and cooler with chiller. Power is then applied to the test section and increased gradually in small step while the inlet conditions of test section are maintained at constant values. CHF is considered as a sharp and continuous rise of the wall temperatures of just below the upper power terminal. In case of measurement of CHF under rolling condition, rolling device is operated before power is applied to the test section.

Change in CHF due to rolling motion relative to stationary CHF is not larger than ±20%. This small change may be buried in scatter of measured value of stationary CHF, which is caused by an insufficient accuracy of measurement of test conditions, device variation of the heater surface and probabilistic phenomenon of CHF mechanism. In order to avoid these, the ratio of CHF under rolling condition to steady CHF rather than CHF itself was measured through measuring successively both values.

Table I summarizes the test matrix and the equivalent water-based conditions. The pressure at the outlet of the test section is specified as the system pressure. The water equivalent pressures are determined from the density ratio of the liquid to the vapor. The critical quality is the thermodynamic quality at a CHF location calculated from the heat balance of the test section. The main parameters measured in the present experiments are the fluid temperatures at the inlet and outlet of the test section, the wall temperatures of heated section, the pressure at the inlet and outlet of the test section, the flow rate and the power applied to the heated section.

TABLE I

Test matrix of loop condition in R-134a and their water-equivalent conditions

Pressure [bar]		Mass flux (R-134a) [kg/m^{2}s]				
		285	500	712	1000	1300
R-134a	Water	Mass flux (water) [kg/m^{2}s]				
13	70	402	705	1004	1410	1834
16	100	400	702	1000	1404	1826
24	140	396	695	990	1390	1807

TABLE II

Test matrix of rolling condition

Loop condition	+	Rolling amplitude	+	Rolling period
		15		6
		30		8
		40		12

EXPERIMENTAL RESULTS

Stationary CHF

In order to verify the CHF experiment under rolling condition, CHF was measured at every stationary condition. In the experiments, boiling occurred near the exit of the tube as it had the highest temperature along the tube.

Stationary CHF was measured as functions of mass flux, inlet subcooling and critical quality. Critical quality is defined by Eq. (1).

$$x_c = \frac{q_c^{"}}{Gh_{fg}} - \frac{C_p \Delta T_{in}}{h_{fg}} \qquad (1)$$

Figure 3 shows the effect of inlet subcooling enthalpy on stationary CHF at different mass flow conditions. The results are obtained at the pressures of 13, 16, 24 bar and the mass fluxed of 285, 500, 712, 1000 and 1300 kg/m^{2}s. The CHF increases almost linearly with inlet subcooling enthalpy, but the effect decreases with decreasing. Figure 4 shows the effect of pressure on CHF, indicating that CHF decreases with increasing the pressure. The observed linear variations of CHF with inlet subcooling and mass flux agree with many existing data.

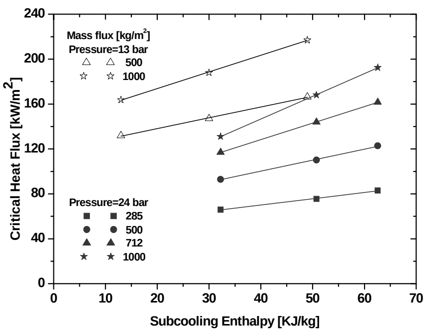


Figure 3 Effect of inlet subcooling enthalpy (pressure: 13 and 24 bar)

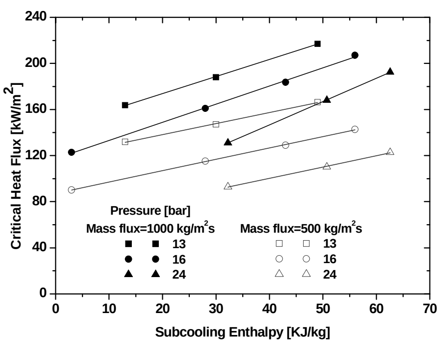


Figure 4 Effect of pressure (mass flux: 500 and 1000 kg/m2s)

Variation of CHF under the Rolling Condition

The cases of present experiment is divided into loop condition and rolling conditions. Loop condition is pressure, mass flux and inlet subcooling and rolling condition is amplitude and period of rolling device. Every test is performed by combination with loop and rolling conditions are summarized in Table II. The CHF ratio is defined the CHF under rolling condition to the stationary.

Determination of CHF under rolling motion

An occurrence of CHF condition in stationary state is obviously observed with a rapidly increase of the heater wall temperature after a small increment of power. In contrast, in every case under the rolling motion, the wall temperature begins to oscillate with the rolling condition synchronously. A further increase in heat flux leads the output of the wall temperature to oscillate more largely and finally to increase continuously without returning to the balanced value. Thus, it becomes difficult to recognize CHF under oscillating condition. In the present work, we define CHF as a heat flux at which the wall temperature increases irreversibly.

Effect of Rolling Amplitude on CHF

Figures 5 and 6 show the effect of the rolling amplitude on CHF ratio at different pressure conditions. There are clear differences between intermediate and high pressure region.

At intermediate pressure, the CHF ratio decrease as increasing the rolling amplitude. There are few changes in certain mass flux. In the cases of higher mass flux CHF under rolling condition tends to become higher than the stationary value. In higher quality (i.e. low subcooling), reduction rate decreases with increasing the rolling amplitude. As mass flux increase, CHF ratio is not depend on effect of rolling amplitude. Furthermore, variations of CHF ratio almost never more than certain mass flux.

However, every CHF is enhanced compare with the stationary CHF in the high pressure (24 bar) as shown in Figure 6. Almost CHF ratios in high pressure region increase as rolling amplitude increase.

Effect of Mass flux on CHF

Ranges of mass flux are 285 through 1300 kg/m^{2}s at 13, 16, 24 bar of pressure. At intermediate pressure (13, 16 bar), trend of CHF ratio changes according to certain range of mass flux is observed. CHF is similar to stationary CHF or rise slightly. However, when the mass flux is smaller than certain value it gradually decreases by the mass flux. Also, it depends on the effect of mass flux in lower subcooling. This tendency is significant for 16 bar of pressure.

The CHF is not dependent on mass flux strongly in higher pressure region (24 bar), as shown in Fig 8(c). Higher mass flux, change of CHF ratio is not significant than lower mass flux region. CHF ratio is increased as inlet subcooling increase in low mass flux. In other words, CHF ratio is affected by inlet subcooling in region of low mass flux.

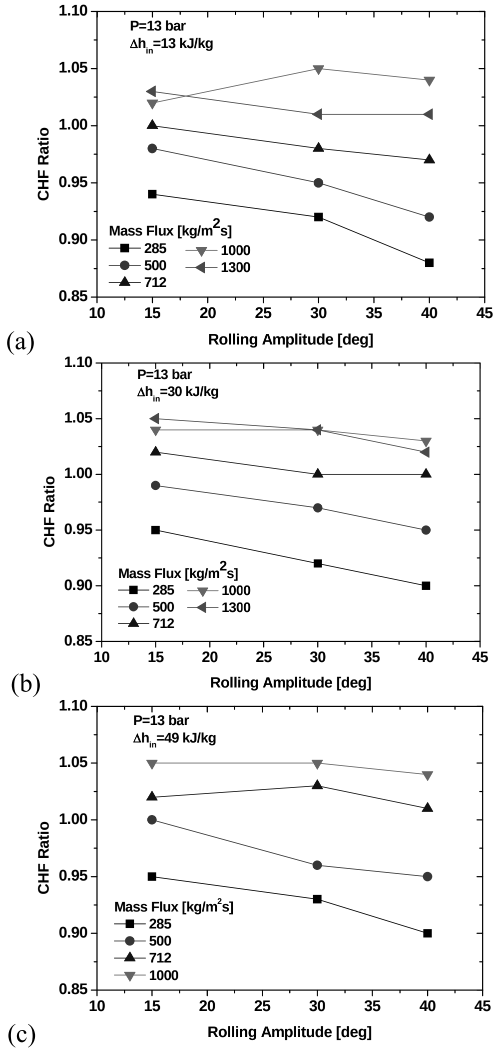


Figure 5 Effect of rolling amplitude on CHF ratio as inlet subcooling and mass flux. Outlet pressure: 13 bar

Variation of the inlet flow rate

The observed amplitude of flow oscillation is show in Figure 7 as a function of rolling amplitude. Over the range investigated, the amplitude of flow oscillation was proportional to rolling amplitude. As was expected the amount of flow oscillation strongly depended on the inlet subcooling, decreasing with increase in inlet subcooling. No variation of flow rate was detected in the cases where the inlet quality was high subcooling. The fluctuation of the inlet flow was inherent in flow and was observed in the stationary case also.

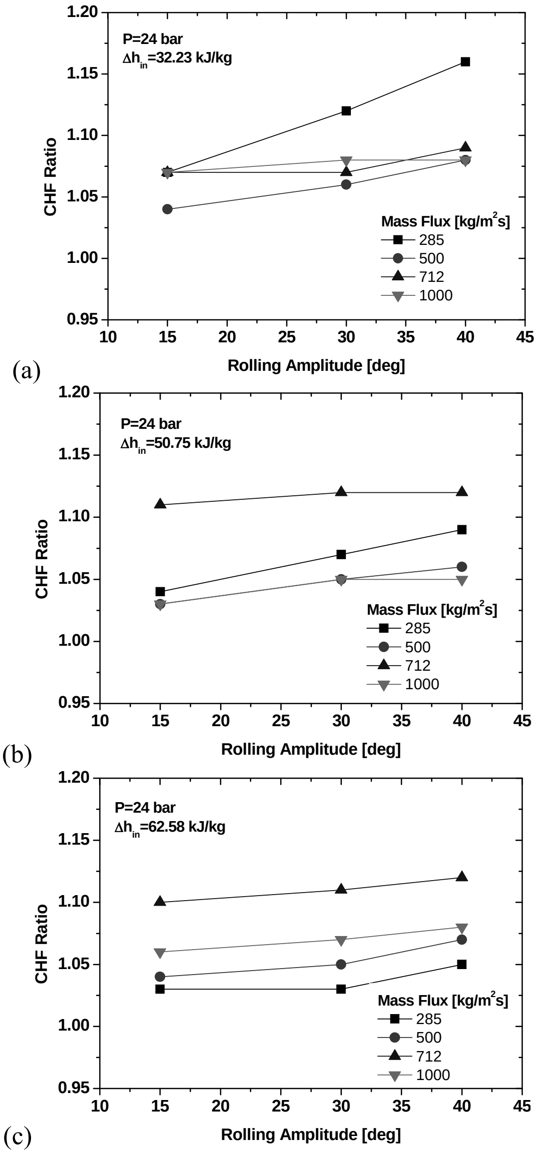


Figure 6 Effects of rolling amplitude on CHF ratio as inlet subcooling and mass flux. Outlet pressure: 24 bar

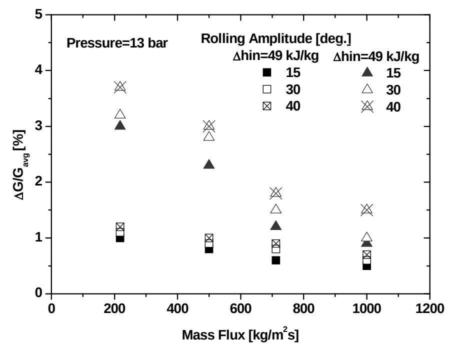


Figure 7 Amplitude of flow oscillation under rolling condition at 13 bar.

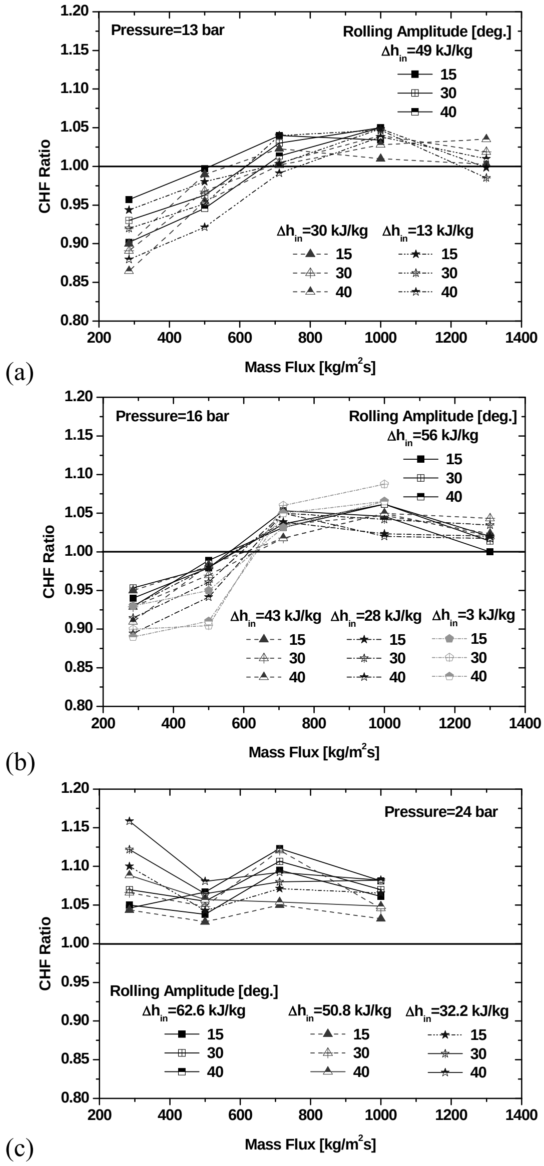
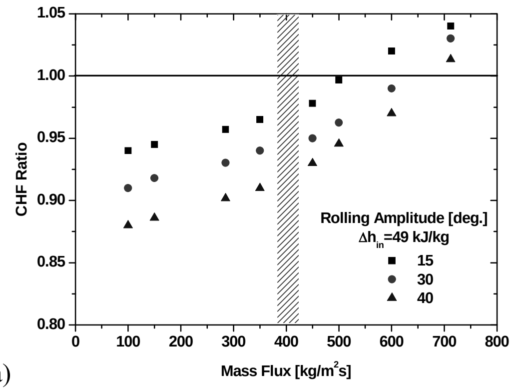
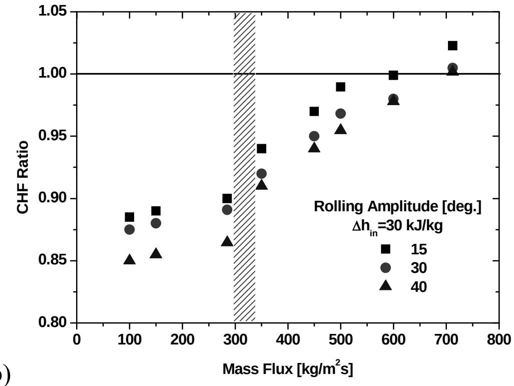


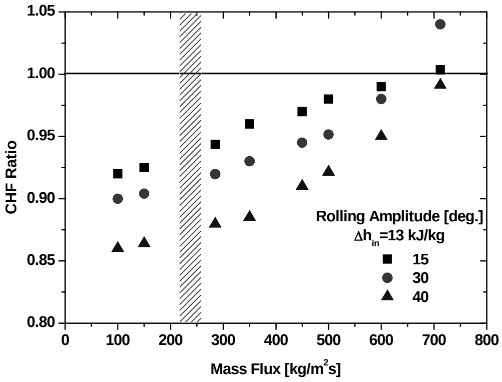
Figure 8 Effects of mass flux on CHF ratio as inlet subcooling and rolling amplitude.



(a)



(b)



(c)

Figure 9 Trend of CHF ratio in lower mass flux at13 bar

DISCUSSION

Experiment results show variation of CHF ratio changes depending on pressure, mass flux, inlet subcooling and rolling amplitude. General trend of CHF mechanism is adopted to understand the variation of CHF ratio under the rolling condition. Due to complex phenomenon of CHF under rolling motion, flow region have to divide at experiment conditions. Flow regime plays an important role in determining the CHF mechanism.

At intermediate pressure say at 13, 16 bar the CHF occur in annular flow region for lower values of the mass flux (for example, 100 through 600 kg/m^{2}s) as depicted in Figure 8. CHF mechanism can be explained by three types in these regions. If CHF occur in annular flow, minimum flow rate is generated by variation of inlet mass flow. This would contribute to promote the reduction of film thickness locally. The CHF occurs in region of minimum thickness film thickness after that. Another mechanism can be considered that rolling motion may be noticeably enhanced droplet entrainment rate in liquid film to vapor core. According to reduced the film thickness, CHF occur earlier than the stationary CHF. In order to support the above two mechanisms, additional data was collected for lower mass fluxes at pressure of 13 bar as shown in Figure 9. As you can see in Figure 9 the CHF ratio decreases as the mass flux decreases. However, its reduction rate relatively decreases below a certain mass flux, which indicates that a limiting entrainment rate exists. Finally, if CHF mechanism assumes the bubbly to slug transition, bubble crowding or heavy concentration of slug at side of heater wall can be considered by tangential force perpendicular to flow stream.

At high pressure and high mass flux in intermediate pressure CHF occur in bubbly and slug/churn flow (for example, 24 bar and more than 600 kg/m^{2}s in 13 and 16 bar). Two CHF mechanisms under rolling motion can be considered CHF enhancement in these regions. Basically, flow regime is bubbly flow. In order to enhance the CHF in bubbly flow under rolling motion, one of the ways is that in liquid layer agitation increases with increasing the tangential force perpendicular to flow stream during rolling amplitude. Other way is generated bubbly away from the boiling surface to liquid core easily because of tangential force by rolling motion and higher mass flux.

CONCLUSION

The CHF behavior under rolling motion has been experimentally investigated and the following conclusion can be achieved.

(1) The parametric trends of CHF of R-134a in vertical tube are similar with existing CHF data.
(2) Based on the characteristic regimes of CHF data belong to the dryout type CHF, the rest CHF data belong to DNB type.
(3) The CHF characteristics under rolling motion can be summarized as follow:
    - The CHF enhancement depends on the mass flux, pressure and rolling amplitude.
    - The CHF ratio decrease with decreasing the mass flux (below certain mass flux) and at intermediate pressure (13, 16 bar).
    - At intermediate pressure, with increasing the mass flux (over certain mass flux), the CHF ratio is enhancement or almost same.
    - At high pressure (24 bar), the CHF enhance at all mass flux and inlet subcooling.
(4) The characteristic of the CHF ratio variation under rolling condition was explained by CHF mechanism with inlet mass flow oscillation and tangential force.
    - In DNB region, over certain mass flux at intermediate pressure (13, 16 bar) and high pressure (24 bar), combination of tangential force and high mass flux contributed to CHF enhancement than stationary CHF due to increasing the liquid layer agitation and bubble departure rate.
    - In dryout region, below certain mass flux at intermediate pressure, rolling motion promote the reduction of film thickness due to minimum inlet mass flow and droplet entrainment rate in liquid film to vapor core.
    - In bubble to slug transition region, lower mass flux at high pressure, tangential force contribute to bubble crowding or heavy concentration of slug.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2009-0080599)

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