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Azimuthal Critical Heat Flux in Narrow Rectangular Channels

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Abstract

Tests were conducted to examine the critical heat flux (CHF) on the one-dimensional downward heating rectangular channel having a narrow gap by changing the orientation of the copper test heater assembly in a pool of saturated water under the atmospheric pressure. The test parameters include both the gap sizes of 1, 2, 5 and 10mm, and the surface orientation angles from the downward-facing position (180^{o}) to the vertical position (90^{o}), respectively. Also, the CHF experiments were performed for pool boiling with varying heater surface orientations in the unconfined space at the atmospheric pressure using the rectangular test section. It was observed that the CHF generally decreases as the surface inclination angle increases and as the gap size decreases. In consistency with several studies reported in the literature, it was found that there exists a transition angle above which the CHF changes with a rapid slope. An engineering correlation is developed for the CHF during natural convective boiling in the inclined, confined rectangular channels with the aid of dimensional analysis.

1. Introduction

In recent years, the effect of surface orientation and gap size on the pool boiling heat transfer and the critical heat flux (CHF) have received increased attention because of the potential benefits pool boiling brings to many applications including cooling of the electronic and power devices, heat treatment of the metallic parts, and cooling of the superconductor coils. In view of severe accident management for a high power nuclear reactor, it is essential to accurately predict quantitative magnitude of the CHF. In the TMI-2 accident, lower part of the reactor vessel was overheated but then rather rapidly cooled down [1,2]. This accounted for the possibility of cooling in the narrow gap on the order of millimeters and centimeters that may have been formed between the consolidated core debris and the reactor vessel lower head. For this reason, it is recommended to investigate the CHF from the standpoint of in-vessel retention (IVR). The CHF test sections need to address key features of the engineering device to simulate the IVR environment. In particular, major issues are centered about such geometric parameters affecting the CHF as the surface orientation and the gap size. Hence, research on the CHF during pool boiling in confined channels is important as a fundamental study of the CHF phenomenon as well as for its application to industrial problems. In this case, owing to the complexity of flow mode, many investigators have suffered from difficulties in interpreting the heat transfer phenomena in highly confined channels. Additionally, the CHF triggering mechanism still defies full understanding owing mostly to the effect of surface orientation. Thus, a series of fundamental studies were conducted to develop engineering correlations taking account of the combined effect of heated surface orientation and gap size using the GAMMA 1D (Gap Apparatus against Molten Material Attack One Dimensional) apparatus at the Seoul National University.

2. Background

Previous studies regarding the surface orientation and gap size effect on the pool boiling CHF have been primarily quantitative in nature. A few investigators have attempted to correlate the orientation effect on the CHF or to provide physical insight into the problem. On the other hand, some predominant researchers gave contribution in understanding of the CHF phenomena by performing their experiments in the narrow gap structured channel, and at the same time, correlating their CHF data. At present, quite a few authors have derived generalized correlations that are applicable to the CHF data for many kinds of fluids. Some critical studies available in the literature are now presented concerning the surface orientation and gap size effect on the CHF.

2.1. Surface orientation effect

Ishigai et al. [3] and Githinji and Sabersky [4], among the first investigators to explore the effect of orientation on the pool boiling CHF, noted that the CHF decreases drastically when the heated surface is oriented in the horizontal, downward-facing position (180^{o}) because the vapor accumulates and prevents liquid access to the heated surface. Numerous other pool boiling CHF studies examined the orientation effect, and in general these investigations found that the CHF decreases as orientation changes from upward-facing horizontal (0^{o}) to vertical (90^{o}) to downward-facing horizontal (180^{o}).

Vishnev [5] was the first to correlate the effect of orientation on the pool boiling CHF, and his correlation is still the most widely utilized as

$$\frac{q_{CHF}}{q_{CHF,0}} = (190-\theta)^{0.5} / 190^{0.5} \qquad (1)$$

Nishikawa et al. [6] performed nucleate boiling experiments with a copper plate with the inclination angles varying from 0°(upward) to 175°(inclined downward). They carried out the experiments for the saturated pool boiling of water at the atmospheric pressure to clarify the effect of the surface configuration on nucleate boiling heat transfer. They reported that the effect of the surface configuration is remarkable at low heat fluxes and the heat transfer coefficient increases as the inclination angle is increased in this case, while no marked effect is observed at high heat fluxes. In particular, they considered two mechanisms concerning heat transfer from the inclined surface facing downwards. One is the sensible heat transport due to compulsory removal of the thermal layer by the elongated bubble rising along the surface. The other is the latent heat transport due to evaporation of the thin liquid film beneath the elongated bubble. Their analytical model of these mechanisms indicated that the heat transfer from the inclined surface facing downwards is controlled mainly by the latent heat transport.

El-Genk and Guo [7] experimentally studied the effect of surface inclination on heat transfer in differing boiling regimes with a 12.8mm copper disk having a diameter of 50.8mm in a pool of saturated water near the atmospheric pressure. They reported on the following experimental results. First, the CHF and minimum film boiling heat flux, as well as the corresponding wall superheat, increase with increasing angle of inclination. Second, in the nucleate boiling region, increasing the surface inclination angle results in a decrease in heat transfer rate at lower wall superheats. At higher wall superheats, the nucleate boiling heat transfer coefficient decreases slightly with the inclination angle. Third, the CHF and minimum film boiling heat flux for the downward-facing position are significantly lower than those for other inclination angles. The quenching time depends strongly on the angle of inclination. The quenching time for the downward-facing surface is about six times that for 5° inclination and 23 times that for 90° inclination. El-Genk and Guo [8] later developed the CHF correlations for water taking account of orientation as

$$q_{CHF} = \left(0.034 + 0.0037(180-\theta)^{0.656}\right)\rho_g h_{fg}\left[\sigma(\rho_f - \rho_g)g/\rho_g^2\right]^{0.25} \quad (2)$$

Chang and You [9] also carried out the experiments to understand the effect of surface orientation on the saturated FC-72 pool boiling performance of flush-mounted square heaters. They presented interesting results that higher inclination angles provided better heat transfer in the nucleate boiling regime, as the plain surface was rotated from $\theta=0^o$ (downward) to 90^o (vertical). They suggested, however, that as the orientation angle was further increased from $\theta=90^o$ (vertical) to 180^o (upward), nucleate boiling heat transfer noticeably decreased at higher heat fluxes. They claimed that this reduction in boiling heat transfer contrasts with previous researchers' observations at the partially developed nucleate boiling region. Finally, they correlated the normalized CHF data at different inclination angles as

$$q_{CHF} = 1 - 0.00120\cdot\theta\cdot\tan(0.414\theta) - 0.122\cdot\sin(0.318\theta) \quad (3)$$

Recently, Brusstar and Merte [10], and Brusstar et al. [11] developed an empirical CHF model for pool and flow boiling. They used a copper plate to investigate the surface orientation effect in the R-113 pool.

El-Genk and Guo [8] avoided the use of a single universal correlation for all fluids. Instead, they derived separate correlations for three fluids based on data from the literature:

$$\frac{q_{CHF}}{q_{CHF,0}} = \begin{cases} 1.0 & 0^o < \theta \le 90^o \\ (\sin\theta)^{0.5} & 90^o \le \theta \le 180^o \end{cases} \quad (4)$$

Howard and Mudawar [12] performed the saturated pool boiling experiments and flow visualization studies at various heater surface orientations to ascertain the CHF triggering mechanism associated with each orientation. Based on the vapor behavior observed just prior to the CHF, they analyzed that surface orientations can be divided into three regions: upward-facing ($0^o \le \theta \le 60^o$), near-vertical ($60^o \le \theta \le 165^o$) and downward-facing ($\theta > 165^o$). In the upward-facing region, the buoyancy forces remove the vapor vertically off the heater surface. The near-vertical region is characterized by a wavy liquid-vapor interface that sweeps along the heater surface. In the downward-facing region, the vapor repeatedly stratifies on the surface, greatly decreasing the CHF. They concluded that the vast differences between the observed vapor behavior within the three regions indicate that a single overall pool boiling CHF model cannot possibly account for all the observed orientation effect, but instead three different models should be developed for the three regions.

2.2. Gap size effect

As presented earlier, bubble behavior has various modes in the confined channel geometry. From the viewpoint of micro-layer heat transfer, a number of investigations suggest that the heat transfer rate decreases when a bubble is confined by the channel geometry. Hence, for the past decades, different authors have reported on the experiments for the geometrical effect on the heat transfer. At the same time, they performed the experiments for natural convection boiling, pool boiling and convective boiling. Some researchers have made the empirical correlations considering the geometrical effect derived from the experimental data.

Katto and Kosho [13] conducted the CHF experiments in boiling at the atmospheric pressure for disk diameters of d=10 and 20 mm, the distance between the parallel disks s in a range of d/s=0~120, and four different fluids: water, R-113, ethyl alcohol and benzene. They correlated a generalized form with an uncertainty of about ±15% from the experiment data as

$$\frac{q_{CHF}/\rho_g h_{fg}}{\sqrt[4]{\sigma g(\rho_f-\rho_g)/\rho_g^2}}=\frac{0.18}{1+0.00918\left(\rho_g/\rho_f\right)^{0.14}\left(g(\rho_f-\rho_g)d^2/\sigma\right)^{0.5}\left(d/s\right)} \tag{5}$$

Monde et al. [14] performed the CHF experiments with a copper plate forming the vertical rectangular channel with gap sizes varying from 0.45 to 7.0mm with corresponding l/s being less than 120 in four test liquids: water, ethanol, R-113 and benzene. They developed a generalized correlation of the CHF data which agreed with the experimental data within ±20% as

$$\frac{q_{CHF}/\rho_g h_{fg}}{\sqrt[4]{\sigma g(\rho_f-\rho_g)/\rho_g^2}}=\frac{0.16}{1+6.7\times10^{-4}\left(\rho_f/\rho_g\right)^{0.6}\left(l/s\right)} \tag{6}$$

Chang and Yao [15] performed the CHF experiments with the annular vertical tube with closed bottoms in R-113 pool. They used the annular tube having gap sizes of 0.32, 0.8 and 2.58mm. Their results suggested that the CHF in the narrow gap was much smaller than in the pool boiling. With the help of experimental data, they correlated the CHF prediction model pursuant to the counter-current flow limitation (CCFL).

Chyu [16] proposed a one-dimensional two-phase flow model in a narrow vertical channel assuming that saturated liquid enters the horizontal annulus channel at the bottom, and is vaporized by the heated wall while ascending due to buoyancy. Considering the inclination angle, Kim et al. [17] derived the CHF correlation as

$$q_{CHF}=\rho_g h_{fg}\left(s/l\right)\left[\frac{gl\sin\theta\left(\rho_f/\rho_g-2\right)}{1+f\cdot l/2s}\right]^{0.5} \tag{7}$$

Chyu [16] obtained the friction factor from his experimental data as

$$f = 0.13\left(\frac{\rho_f - \rho_g}{\rho_g}\right)^{0.5} Bo^{1.3} \qquad (8)$$

where

$$Bo = s\left(g(\rho_f - \rho_g)/\sigma\right)^{0.5}$$

Kim et al. [17] modified Chyu's correlation by adopting the new friction factor correlation considering the vertical and inclined channels. They suggested the new friction factor with the root-mean-square error of 5.87% as

$$f = 0.0041 \times s^{(3.66 \log s - 0.94)} \qquad (9)$$

Fujita et al. [18] investigated the pool boiling heat transfer in a confined narrow space for saturated water at the atmospheric pressure between heated and unheated parallel rectangular plates. Experiments were conducted at heat flux from boiling inception to the CHF on heating surfaces with a width of 30mm, lengths of 30 and 120mm, and gap sizes of 0.15, 0.6, 2 and 5mm under three surface peripheral conditions with all-open edges, closed side edges, and closed side and bottom edges. The inclination angles of the heating surface included 90^{o} (vertical surface), 150^{o} and 175^{o} (inclined surfaces facing downwards). Their experimental results indicated that the heat transfer increases up to a certain maximum value as the gap size decreases at a moderate heat flux, while degradation occurs for a further decrease of the gap size over the whole heat flux range. For the enhanced boiling heat transfer, a predictive method was proposed based on the consideration of heat transfer mechanisms.

Bonjour and Lallemand [19] experimentally studied the CHF during natural convective boiling of R113 in vertical channels. They used a vertical channel having gap sizes ranging from 0.3 to 2.5mm with a fixed height. They confirmed that, at any pressure, reducing the gap size reduces the CHF and that increasing the pressure increase the CHF. Especially, they developed the correlation by modifying the Monde et al. [14] correlation to account for the influence of pressure. Finally, they reported that a more fundamental study of the triggering mechanisms of the CHF in confined boiling is necessary in order to fully understand the phenomena observed during their study.

3. Experiment

3.1. Experimental apparatus and conditions

For the heat generation portion of the GAMMA 1D experimental apparatus, a heat source was acquired by the DC power supply of 6kW with the DC output voltage of 300V and the current of 20A. The quantitative information about the output voltage, ampere and watt generated on the test heater material was exported by RS-232C to IBM PC communication. A quasi-direct heating method was adopted to generate sufficient heat flux in this experiment. The power lead contact area on the test heater can drastically be reduced by silver-soldering the high resistance thin film resistor underneath the test heater.

The heater assembly was fabricated utilizing the copper block test heater and the film resistor. For the heater configuration, two different copper blocks heated by a thin film resistor were utilized in this study. A copper block having the wetted surface of $15 \times 35 mm^2$

was introduced. Thin film resistors having resistance of 20ohm were affixed into the copper block heater to measure the CHF and to visualize the vapor behavior in the confined space. This also facilitated to gain the required heat flux by applying the current less than 10A. A schematic diagram of the copper block heater is illustrated in Fig.1, in which a chromel-alumel (K-type) thermocouple for measuring the temperature behavior on the wetted surface was inserted into the hole off the wetted surface by 0.6mm. For the test heater used in this study, three K-type thermocouples were inserted into depths of 5, 17.5 and 30mm, respectively. The test heater was slightly coated with nickel to prevent the test heater from getting oxidized.

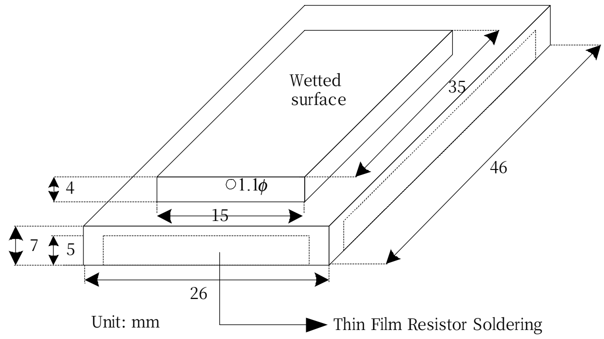


Fig. 1. Schematic diagram of test heater block

Regarding the device holding the heater assembly, stainless steel housing was designed to ensure most efficacious insulation on the heated section, as illustrated in Fig. 2. As aforementioned, a thin film resistor was embedded underneath the copper block heater. To efficiently insulate the heated section, the interior of the housing can be evacuated if the inner surface of the housing is polished smoothly. The insulation efficiency is surprisingly high in the state of vacuum. Hence, as part of forming vacuum, an O-ring frame was grooved in the upper part of the housing, and a link of O-ring was sealed on the housing with vacuum grease. After sticking the copper block heater into the housing, a vacuum pump loaded about 10^{-4} torr, which can considerably reduce the heat loss from the bottom of the copper block heater. Pyrex glass was imbedded into the edge of the housing and designed to precisely maintain the gap sizes of 1, 2, 5 and 10mm, and to visualize the test apparatus having a narrow rectangular channel, as demonstrated in Fig. 2.

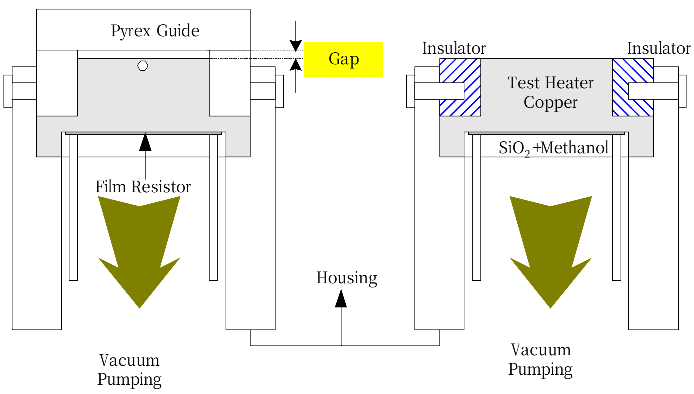


Fig. 2. Frontal view of test heater with vacuum housing

In the same way as the housing, the water pool shown in Figs. 3 and 4 was vacuumed for the purpose of insulation. Additionally, this functions to sustain a steady thermodynamic state of water at the atmospheric pressure. Eight immersion type heaters with the electric capacity of 2kW were homogeneously inserted into the test pool to pre-heat the demineralized water in the test pool up to the saturated state. A reflux condenser was equipped in the test pool itself to maintain the pressure in water pool. After installation was completed for the GAMMA 1D apparatus, the CHF was measured in the narrow channel of the crevice type copper heater block at predetermined inclination angles under the atmospheric pressure in the demineralized water pool. The temperature data were read from the six K-type thermocouples for the bulk fluid utilizing the computer based data acquisition system mainframe of HP VXI-E8406A functioned with the module of HP-1413C. A delicate control of the saturated water in the vacuum pool was performed with two temperature controllers. Temperatures were read 10 times a second, whose information was filed in a text file by the HP-VEE 5.0 measurement software.

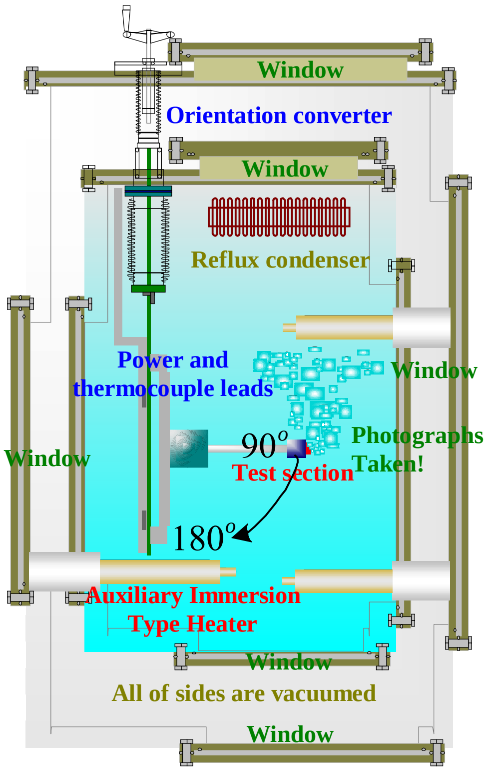


Fig. 3. Front view of vacuum water pool

3.2. Measurement uncertainty

The heater surface was lightly nickel-coated to prevent from becoming oxidized. Additionally, the heater surface was cleaned with acetone prior to each test. Water in the pool was deaerated by running the immersion heaters at the atmospheric saturated boiling conditions for at least an hour prior to reading data. Although this study is focused on the quantitative investigation of the CHF, data in the nucleate boiling regime prior to reaching the CHF were also obtained.

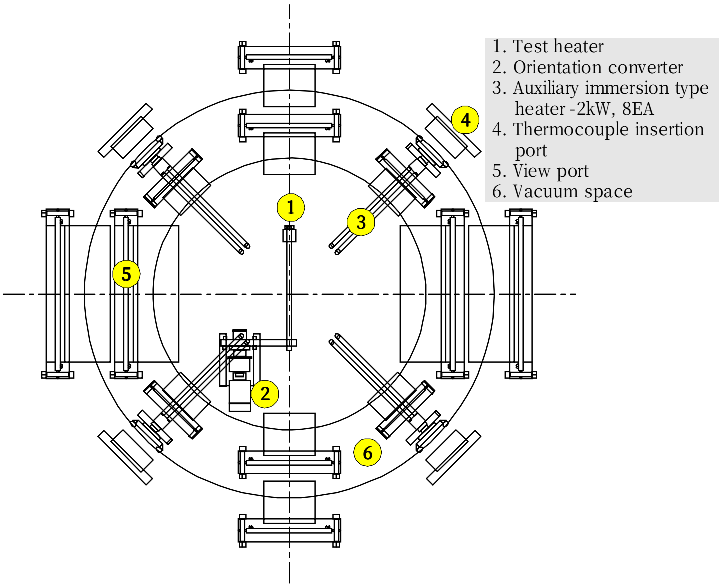


Fig. 4. Top view of vacuum water pool

Maintaining the thermodynamic state of saturation condition at the atmospheric pressure, the heat flux was gradually increased through direct power supply. The surface temperature behavior was monitored by HP VEE5.0 and stored in data file format. While monitoring the temperature, the CHF was judged to have taken place when the surface temperature soared. The CHF was determined as the highest average heat flux that gave a stable temperature reading plus one half of the last average power increment (~3% of the CHF). In order to protect the thin film resistor from burnout, the electric power was turned off immediately after the surface temperature had reached 190°C. After appropriate analysis of the heat flux and temperature data, the CHF values were obtained for all the surface orientation angles within ±5%. In calculating the uncertainties associated with the experimental data readings, propagation of error was utilized. The K-type thermocouples were calibrated for a maximum uncertainty of ±0.1°C. The uncertainty in the heat flux due to instrumentation limitations was estimated to be 1%. This study adopted the vacuum pumping method to prevent the generated heat from getting lost from the sides other than from the side adjacent to the working fluid. Hence, the heat loss was considered to be negligible enough to ascertain full energy transfer from the heated surface to the working fluid.

3.3. Results and discussion

3.3.1 Effect of gap size and surface orientation angle

This study is concerned with investigation of the CHF accounting for the gap size and surface orientation effect. Hence, in order to understand the fundamental CHF and related thermal hydraulic phenomena, one-dimensional test heater assembly was utilized in the experiment to obtain results and to explain the combined effect of gap size and the gravity force in the rectangular channel. Fig. 5 shows the CHF data plotted against the gap size and surface inclination angle. The CHF data for pool boiling with open periphery is shown in Fig.

6. Visual inspection of the fluid motion in the rectangular channel revealed that the Helmholtz instability motion was not detected in the gap sizes of 1 and 2mm. However, such instability manifested itself in the gap size of 5mm at certain inclination angles. In particular, a wavelength of about 21mm was observed at the vertical position (90^o) in the gap size of 10mm.

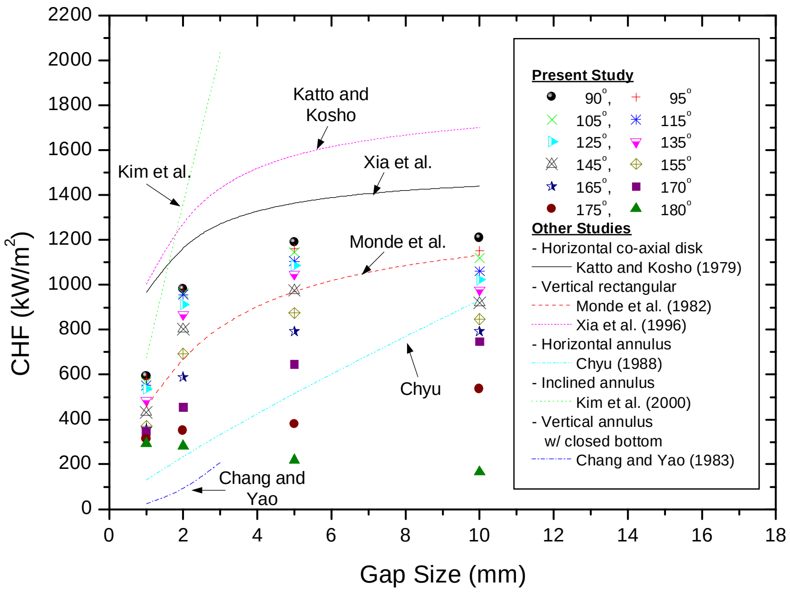
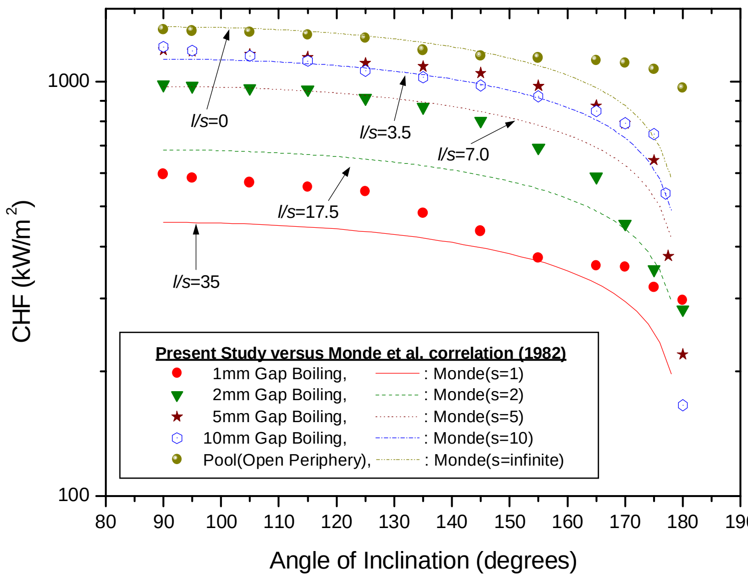


Fig. 5. Effect of gap size on the CHF

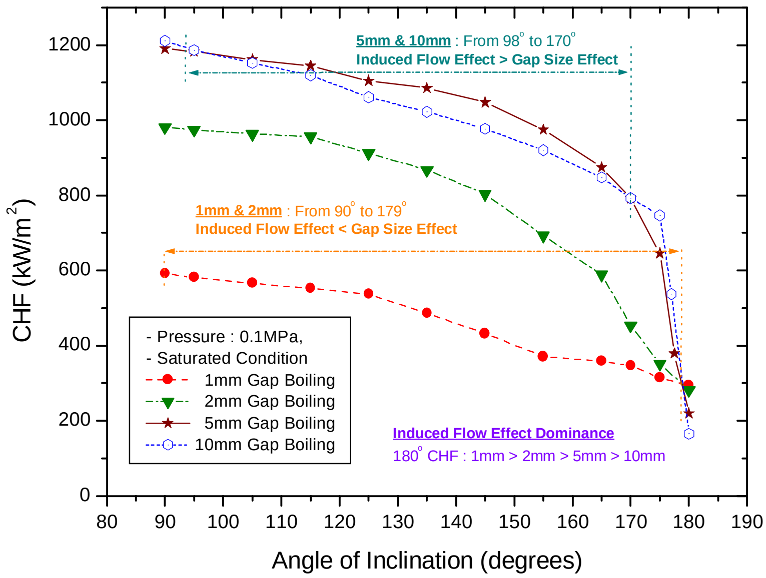
Generally, the vapor behavior in the narrow gap plays an important role in triggering the CHF. It has generally been claimed that the CHF decreases as the gap size decreases. Contrary to this general belief, however, the present study has found opposing results at certain surface inclination angles. At the vertical location (90^o), in consistency with the general belief, the CHF decreases as the gap size decreases. Especially, the CHF for the gap size of 10mm is smaller than that for any other gap sizes at the fully downward-facing location (180^o) as shown in Figs. 5 and 6.

The CHF generally increases as the gap size increases, but the increasing rate decreases with an exception at the fully downward-facing angle as shown in Fig. 5 where the experimental data in this study are compared with other results reported in the literature. In the vertical rectangular geometry of Monde et al. [14] and Xia et al. [20], the increasing trend of the CHF with the gap size is compared against the present experimental data. It is found that the CHF changing trend differs with geometry. Though the overall behavior of the CHF in the horizontal co-axial disk is comparable, the CHF is grossly overpredicted. The Monde et al. [14] correlation is observed to reasonably represent the current experimental data. Accounting for the gravity effect in Eq. (6), the Monde et al. correlation is compared against the CHF in the gap and pool boiling as shown in Fig. 6(a). The Monde et al. correlation underestimates the CHF for the 1, 2 and 5mm gaps. On the other hand, the correlation satisfactorily predicts the CHF for the 10mm gap and pool boiling for most of the angles below, say, 150^o.

Figs. 6(a) and 6(b) demonstrate that the CHF for 1 and 2mm gap decreases as the inclination angle increases and as the gap size decreases except at the fully downward-facing location (180°). At the downward-facing angle, the bubble formed in the gap smaller than its own thickness is affected by the induced flow effect due to the gap structure. To paraphrase, bubbles in the narrow gap can more easily escape the restricted channel than those in the gap whose size exceeds the bubble thickness. Though the bubble in the 1, 2 and 5mm gaps tends to be ejected due to the induced flow effect, the bubble in the 10mm gap is stagnated. That is, the induced flow effect increases as the gap size decreases at the fully downward-facing angle. Hence, at the fully downward-facing angle, the CHF decreases as the gap size increases contrary to the trend at other inclination angles. However, the CHF in the pool boiling with open periphery is greater than the CHF in the gap cooling because the bubble in the pool boiling with open periphery is free to escape in the azimuthal direction.



(a) Comparison against the Monde et al. correlation for the gap and pool boiling



(b) Effect of induced flow and gap size on the CHF in gap boiling

Fig. 6. Effect of surface inclination angle on the CHF

Though the CHF values for the 5 and 10mm gaps both decrease as the inclination angle increases, the CHF for the 10mm gap is less than that for the 5mm gap over a wide range of angles due to absence of the induced flow effect in the 10mm gap as shown in Fig. 6(b). The flow rate depends on the balance between the driving force and the pressure drop. The driving force for the 5mm gap is larger than that for the 10mm gap size due to high void fraction within the confined channel space. Given the flow rate, the pressure drop for the 5mm gap is greater than that for the 10mm gap. Then, the mass flux for the 5mm gap can exceed that for the 10mm gap due to the smaller flow area over a span of the inclination angles. Consequently, there can be a range of inclination angles over which the CHF increases as the gap size decreases. Interestingly enough, this newly theorized thermal hydraulic phenomenon appears to unmistakably take place at the fully downward-facing angle for all the gap sizes examined in this work, and occasionally over some range of angles for the 5 and 10mm gaps. Therefore, the CHF in the gap boiling is affected by the gap size as well as by the induced flow within the gap.

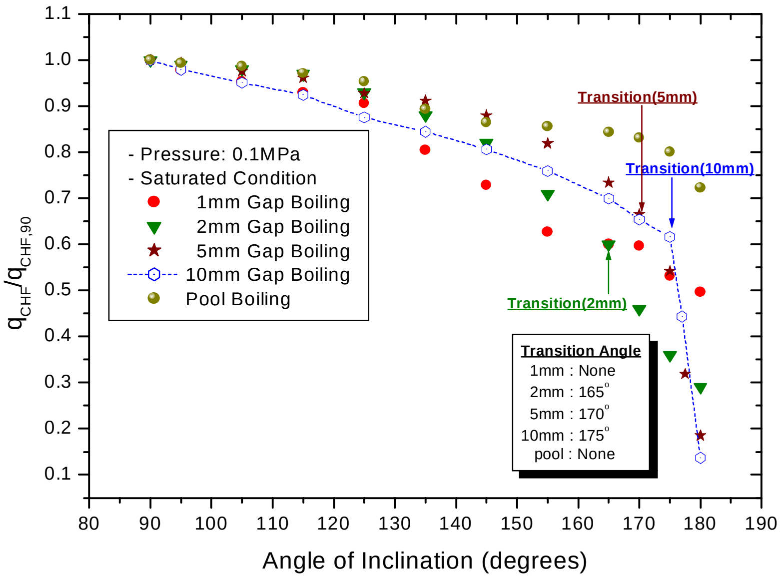
3.3.2 Transition angle

In recent years, some researchers have mentioned the existence of a transition angle at which the CHF changes with a rapid slope. Howard and Mudawar [12] suggested that based on the vapor behavior observed just prior to the CHF, the surface orientations can be divided into three regions: upward-facing ($0^o \sim 60^o$), near-vertical ($60^o \sim 165^o$) and downward-facing ($>165^o$). Yang et al. [21] noticed that a transition angle exists in the boiling behavior from vertical-like to downward-facing between 150^o and 174^o. The boundary between the near-vertical and downward-facing regions is generally defined as the transition angle.

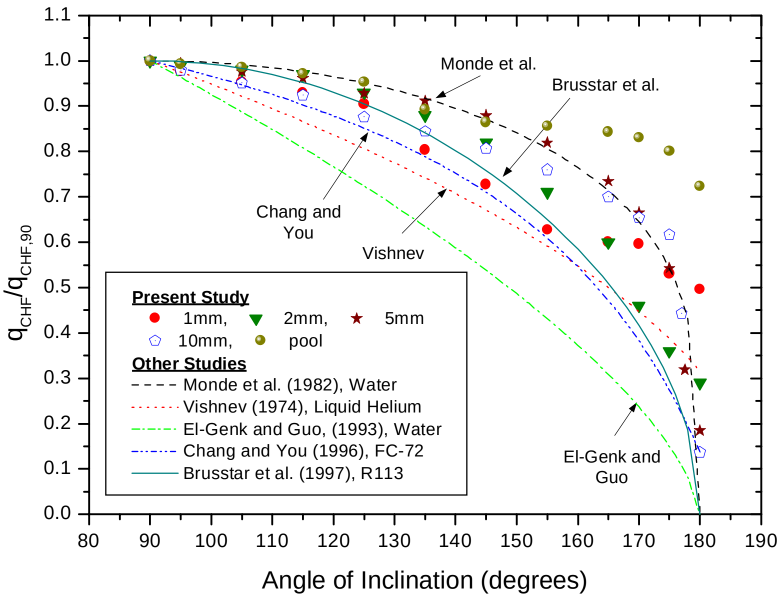
In the present study, certain transition angles were also identified for different gap sizes. For the gap size of 1mm and pool boiling with open periphery, the existence of the transition angle was not discernable as shown in Figs. 7(a) and 7(b). However, in the experiments for the gap sizes of 2, 5 and 10mm, rather distinct transition angles were observed as shown in Fig. 7(a). For the gap sizes of 2, 5 and 10mm, the transition angles were found to be 165^o, 170^o and175^o, respectively. At heat fluxes approaching the CHF, the boiling process can be divided into two regions with categorically different slopes in terms of the non-dimensionalized CHF. In this study, the near-vertical region is defined as the angular range from vertical (90^o) to transition and the downward-facing region is defined as angular span from transition to completely downward-facing (180^o). Albeit Howard and Mudawar [12] and Yang et al. [21] claimed a transition angle for the pool boiling CHF with open periphery, the current investigation could not necessarily confirm their claims. The reason may well be that the aspect ratio of the heater width to length in this study is considerably smaller than that in their experiments. Specifically, the heater aspect ratio is 2.3 in this study versus 10.9 and about 10 in Howard and Mudawar [12], and Yang et al. [21], respectively. It was also found that the values of $q_{CHF}/q_{CHF,90}$ for differing gap sizes broaden as the surface inclination angle increases as shown in Figs. 7(a) and 7(b).

The non-dimensionalized CHF data in this work are compared with predictions by the literature correlations developed from tests utilizing such varying fluids as FC-72, water, R113 and liquid-helium in Fig. 7(b). The non-dimensionalized form of the correlations in the cited literature is seen to shift for differing fluids, which appears to support El-Genk and

Guo's [8] assertion that different correlations be used for different fluids in describing the effect of orientation on the CHF. Howard and Mudawar [12] confirmed different transition angles for different fluids, viz. 150° for liquid helium, and 160° to 165° for water and FC-72. Fig. 7(b) suggests that one non-dimensionalized equation cannot possibly correlate the experimental data at various inclination angles, because the non-dimensionalized CHF values tend to spread with increasing angles beyond the acceptable error range. That is, the non-dimensionalized correlation will be affected not only by different fluid properties but also by the surface orientation effect. It is also noted that the Monde et al. [14] and Chang and You [9] correlations provide respectively with the upper and lower bounds for the data taken from the present study.



(a) Transition angles for different gaps



(b) Comparison of present study with other studies for the angle effect

Fig. 7. Effect of surface inclination angle on the non-dimensionalized CHF values

4. Conclusions

In this study, the CHF experiments for gap boiling were performed with various gap sizes of 1, 2, 5 and 10mm, and the heater surface orientations from 90^o to 180^o in confined narrow space at atmospheric pressure utilizing the rectangular test section. Also, the CHF experiments for pool boiling were performed with the same heater surface orientations in unconfined space at atmospheric pressure using the rectangular test section. Key conclusions from the study may be summarized as follows:

1. The CHF generally increases as the gap size increases, but the increasing rate decreases as the gap increases. In particular, the CHF in the gap size of 10mm is smaller than the value at any other gap sizes at the fully downward-facing location (180^o). At the vertical location (90^o), as is generally believed, the CHF increases as the gap size increases. The CHF in gap boiling is affected by the gap size as well as by the induced flow within the channel.

2. There is a transition angle for each gap size. The transition angle increase as the gap size increases. The transition angles for the 2, 5 and 10mm gap sizes were distinctly found to be 165^o, 170^o and 175^o, respectively. However, existence of a transition angle was not discernable for the gap size of 1mm and the pool boiling in unconfined space. The ratio of $q_{CHF}/q_{CHF,90}$ for each gap at the same angle broadens as the surface inclination angle increases.

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Nomenclature

q_{CHF}	critical heat flux (CHF)	[W/m^2]
$q_{CHF,0}$	CHF in ordinary pool boiling on upward-facing position (0^o)	[W/m^2]
$q_{CHF,90}$	CHF in ordinary pool boiling on vertical position (90^o)	[W/m^2]
g	gravitational acceleration	[m/sec^2]
h_{fg}	latent heat of vaporization	[J/kg]
d	disk diameter	[m]
s	channel gap	[m]
l	heater length	[m]
w	channel width	[m]
D_h	equivalent heated surface diameter	[m]
f	friction factor	

Greek Letters

θ	surface orientation angle (90^o: vertical position, 180^o: downward-facing position)	[Degree]
σ	surface tension	[N/m]
ρ	density	[kg/m^3]

Subscripts

f	saturated liquid
g	saturated vapor

References

[1] Suh, K. Y., Henry, R. E., 1996, Debris interactions in reactor vessel lower plena during a severe accident - I. Predictive model, Nucl. Eng. Des. 166, 147-163.

[2] Suh, K. Y., Henry, R. E., 1996, Debris interactions in reactor vessel lower plena during a severe accident - II. Integral analysis, Nucl. Eng. Des. 166, 165-178.

[3] Ishigai, S., Inoue, K., Kiwaki, Z., Inai, T., 1961, Boiling heat transfer from a flat surface facing downward, Proc. the International Heat Transfer Conference, Boulder, CO, USA, 224-229.

[4] Githinji, P. M., Sabersky, R. H., 1963, Some effects of the orientation of the heating surface in nucleate boiling, Trans. ASME, J. Heat Transf. 85, 379.

[5] Vishnev, I. P., 1974, Effect of orientating the hot surface with respect to the gravitational field on the critical nucleate boiling of a liquid, J. Eng. Physics. 24, 43-48.

[6] Nishikawa, K., Fujita, Y., Uchida, S., Ohta, H., 1984, Effect of surface configuration on nucleate boiling heat transfer, Int. J. Heat Mass Transf. 27, 1559-1571.

[7] El-Genk, M. S., Guo, Z., 1992, An experimental study of saturated pool boiling from downward facing and inclined surfaces, Int. J. Heat Mass Transf. 35, 2109-2117.

[8] El-Genk, M. S., Guo, Z., 1993, Transient boiling from inclined and downward-facing surfaces in a saturated pool, Int. J. Refrigeration 6, 424-432.

[9] Chang, J. Y., You, S. M., 1996, Heater orientation effects on pool boiling of micro-porous-enhanced surfaces in saturated FC-72, Trans. ASME, J. Heat Transf. 118, 937-943.

[10] Brusstar, M. J., Merte, H., Keller, R. B., Kirby, B. J., 1997, Effects of heater surface orientation on the critical heat flux - I. An experimental evaluation of models for subcooled pool boiling, Int. J. Heat Mass Transf. 40, 4007-4019.

[11] Brusstar, M. J., Merte, H., 1994, Effects of buoyancy on the critical heat flux in forced convection, J. Thermophysics and Heat Transf. 8, 322-328.

[12] Howard, A. H., Mudawar, I., 1999, Orientation Effects on Pool Boiling Critical Heat Flux (CHF) and Modeling of CHF for Near-Vertical Surfaces, Int. J. Heat Mass Transf. 42, 1665-1688.

[13] Katto, Y., Kosho, Y., 1979, Critical heat flux of saturated natural convection boiling in a space bounded by two horizontal co-axial disks and heated from below, Int. J. Multiphase Flow 5, 219-224.

[14] Monde, M., Kusuda, H., Uehara, H., 1982, Critical heat flux during natural convective boiling in vertical rectangular channels submerged in saturated liquid, Trans. ASME, J. Heat Transf. 104, 300-303.
[15] Chang, Y., Yao, S., 1983, Critical heat flux of narrow vertical annuli with closed bottoms, ASME J. of Heat Transf. 105, 192-195.
[16] Chyu, M. C., 1988, Prediction of boiling dryout flux for restricted annular crevice, Int. J. Heat Mass Transf. 31, 1993-1998.
[17] Kim, S. H., Baek, W. P., Chang, S. H., 2000, Measurements of critical heat flux for narrow annuli submerged in saturated water, Nucl. Eng. Des. 199, 41-48.
[18] Fujita, Y., Ohta, H., Uchida, S., Nishikawa, K., 1988, Nucleate boiling heat transfer and critical heat flux in narrow space between rectangular surfaces, Int. J. Heat Mass Transf. 31, 229-239.
[19] Bonjour, J., Lallemand, M., 1997, Effects of confinement and pressure on critical heat flux during natural convective boiling in vertical channels, Int. Comm. Heat Mass Transf. 24, 191-200
[20] Xia, C., Hu, W., Guo, Z., 1996, Natural convective boiling in vertical rectangular narrow channels, Experimental Thermal and Fluid Science 12, 313-324.
[21] Yang, S. H., Baek, W. P., Chang, S. H., 1997, Pool-boiling critical heat flux of water on small plates: Effects of surface orientation and size, Int. Comm. Heat Mass Transf. 24, 1093-1102.