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Technical Note

Experimental Investigation on Critical Heat Flux in Bilaterally Heated Annulus with equal heat flux on both sides

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A B S T R A C T

A phenomenological study on CHF in a bilaterally heated annulus with equal heat flux on both sides was experimentally performed. The working fluid of the present test was R-134a. Variation characteristics of CHF and transition of CHF occurrence location were investigated under different pressure, mass flux and quality conditions. With the increase of critical thermodynamic quality, it was found that CHF first occurred on the outer surface of the annulus, then simultaneously occurred on both sides, and finally occurred on the inner surface at relatively high critical quality. After the CHF location transitioned to the inner rod, the sharp fall of CHF in the limiting critical quality region was observed. The critical quality corresponding to the CHF location transition decreased with the increase of mass flux and pressure. Besides, CHF in tube, internally heated, externally heated and bilaterally heated annuli were compared under the same hydraulic diameter conditions. The present study is conducive to improving the understanding of complicated CHF mechanism in bilaterally heated annulus, enriching the experimental database, and providing evidence for developing accurate CHF mechanism model for annuli.

1. Introduction

Critical Heat Flux (CHF) is one of the most important safety criteria in the thermal-hydraulic design of pressurized water reactors (PWRs). Once CHF occurred, the heat transfer between the fuel cladding and the coolant would be deteriorated, which leads to a rapid rise in the cladding temperature and even the failure of the fuel cladding. Since CHF usually limits the core power of nuclear reactor, it is quite necessary to accurately predict CHF of fuel assemblies, which contributes to optimizing the reactor power and improve the operation safety of nuclear reactor [1].

Since the 50's of last century, CHF characteristics and prediction method in tube, i.e. the simplest geometry of flow channel, was widely studied [2–4]. However, The CHF predicting method built based on tube didn't take into account the geometry features of reactor fuel bundle, such as the gap size between rods and the existence of adjacent heated surfaces. Compared to the tube, the annulus can better reflect the geometry features of rod bundle, which have been extensively studied in the field of nuclear engineering. [5] compared the CHF in tubes with that in internally heated annuli. The results showed that the CHF value in tubes was higher than in internally heated annuli at positive critical qualities, because the shear stress near the heated surface in tubes was much lower than that in annuli at the same hydraulic diameter. In addition, the actual qualities near the heated surface in tubes were also different to that in internally heated annuli owing to the cold-wall effect. For the bilaterally heated annuli, [6] observed that CHF always occurred on the internal rod surface in the case of equal heat fluxes on both walls of the annulus, and CHF of the outer surface was 30%–70% higher than that of inner surface in the case of dual nonuniform heating. [7,8] studied the effect of bilateral heating on CHF of inner surface under high pressure condition. It was found that CHF at the inner surface was always higher than that at the outer surface, and CHF at the inner surface was independent of the heat flux at the outer surface. [9] experimentally investigated the CHF characteristics in a bilaterally heated annulus. They concluded that the CHF value at outer surface was higher than that at inner surface when simultaneous CHF occurrence at both annulus surfaces and the CHF occurrence location in the bilaterally heated annulus was determined by the ratio of external and internal heat fluxes. Similar phenomenon was observed by Ref. [10] that CHF occurred at both sides when the heat flux ratio between external and internal surfaces was from 0.68 to 1.44.

According to the previous studies, it is generally known that

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Nomenclature

CHF	critical heat flux
D	diameter [m]
DNB	departure from nucleate boiling
G	mass flux [$\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$]
L	distance [m]
M	mass flow rate [$\mathrm{kg \cdot s^{-1}}$]
P	inlet pressure [MPa]
q	heat flux [$\mathrm{kW \cdot m^{-2}}$]
T	temperature [°C]
x	thermodynamic quality [−]
Greek Letters	
δ	wall thickness/film thickness [mm]
τ	shear stress [$\mathrm{N \cdot m^{-2}}$]
Subscripts	
cr	critical
equi	equivalent
h	hydraulic
i	inner
o	outer

literatures on CHF in bilaterally heated annuli is very scarce compared to that in unilaterally heated annuli. The conclusions of some previous studies were inconsistent probably because the range of critical qualities of previous studies was different. In addition, the transition mechanism of CHF occurrence location in the bilaterally heated annuli was still not fully understood. More experimental researches should be carried out to figure out the CHF characteristics in the bilaterally heated annuli, which contributes to accurately predicting CHF and understanding on CHF mechanism.

In this paper, CHF experiments were carried out in a vertical annulus which is bilaterally heated with equal heat fluxes. The working fluid of the present experiments was R-134a. The test condition was determined by Katto's fluid-to-fluid modeling method with reference to the operation condition of Pressurized Water Reactors (PWRs). Variations of CHF and CHF occurrence location were examined and analyzed under different pressure and mass flux conditions. The differences in CHF among tube, internally heated, externally heated and bilaterally heated annuli were also compared. The present study was conducive to improving the understanding of complicated CHF behavior in bilaterally heated annulus, enriching the experimental database, and providing evidence for developing accurate CHF prediction methods for annuli.

2. Experimental facility and methodology

2.1. Experimental loop

The present experiments were conducted at the R-134a forced convection boiling CHF facility at Xi'an Jiaotong University (XJTU), which was built to study the CHF and heat transfer characteristics in tubes, annuli and rod bundles. The experimental loop was schematically shown in Fig. 1. The experimental loop can operate under the conditions of pressure from 0.5 to 4 MPa, mass flow rate from 0.1 to 12 $\mathrm{t \cdot h^{-1}}$, heating power from 0 to 180 kW. The details of the experimental loop are introduced in authors' previous work [1,11].

2.2. Test section

For modeling a local region of fuel bundle of reactor core in PWR, two vertical bilaterally heated annuli with different gap sizes was tested in the present study. The schematic of the test section is shown in Fig. 2. The test section was mainly composed by a inner rod, an outer tube, three spacer grids and four electrodes. The inner rod was made by Inconel 690 with the diameter and thickness of 9.5 mm and 1 mm respectively. The diameter of inner rod was the same as the actual reactor fuel of PWR. The outer tube was made by the same material as the inner rod, of which the inner diameters were 15.5 mm. Copper electrodes were welded at the bottom and top of the rod and tube and both the inner rod and the outer tube can be electrified and heated. Two separated high-precision DC powers were respectively connected to inner rod and outer tube by the copper electrodes to make both sides of annuli could be heated simultaneously and separately. A heating power control system was developed based on LabVIEW to synchronously control the variation of heating power on both sides. Since the internal surface area of the outer tube and the external surface area of the central rod were fixed but proportional ($A_o/A_i = 1.632$), to achieve equal heat flux on both surfaces, the heating power was provided to the both sides in the same proportion as the ratio of the surface areas. Since the power shape was uniform, CHF would occur at the top end of inner rod or outer tube. To monitoring CHF, six thermocouples was installed on both the inner rod and the outer tube near the outlet of test section. Three axial locations, from 10 mm, 20 mm and 30 mm to the top of heated region, were selected to install these thermocouples. To ensure the concentricity of the inner rod and the outer tube along the axial, three self-designed spacer grids were placed between tube and rod. The picture of spacer grid was given in Fig. 3. The distances between installation locations of spacer grids and the bottom of heated region were 300 mm, 822 mm and 1083 mm. In addition, an insulating layer made by PEEK plastic was placed at the outside surface of spacer grid to ensure insulation between inner rod and outer tube. The detailed geometric parameters of test sections were given in Table 1.

2.3. Instrumentations

The key parameters measured in the present study was heating power of both sides, mass flow rate, pressure, fluid and wall temperature. The heating power of inner rod and outer tube was provided by two independently programmable DC powers. Both the DC powers had the maximum power of 25 kW and the accuracy of 0.2%. The mass flow rate was obtained by a Coriolis mass flow meter with a measurement range of 0–1200 $\mathrm{kg \cdot h^{-1}}$ and the accuracy of 0.5%. Two Rosemount 3051 pressure transducers were employed to determine the inlet and outlet pressure, which had the measuring range of 0–4 MPa and the accuracy of 0.075%. Additionally, Two T-type sheathed thermocouples were used to measure the fluid temperature at the inlet and outlet of test section. The wall temperatures were obtained by the K-type thermocouples welded on the surfaces of heated rod and tube for the purpose of monitoring CHF.

During each test, the inlet parameters i.e. pressure, mass flux and inlet subcooling were kept unchanged, and the heating powers of both sides were simultaneously gradually increased until CHF occurred. The occurrence of CHF was determined once the wall temperature was detected to suddenly and dramatically increase from a value slightly higher than the saturated temperature.

2.4. Test matrix and uncertainties

In the present study, CHF characteristics in the bilaterally heated

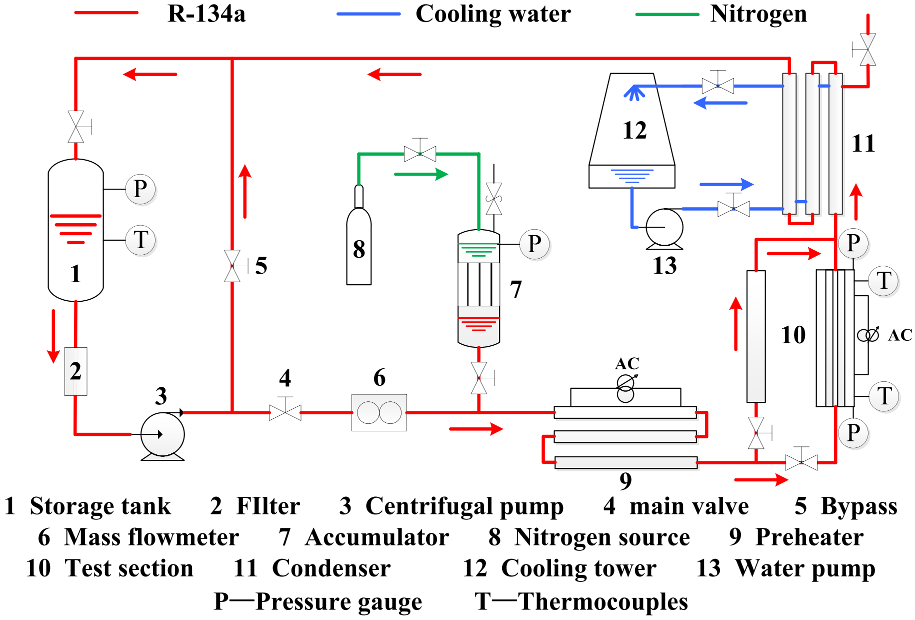


Fig. 1. The schematic diagram of the experimental loop in the present study.

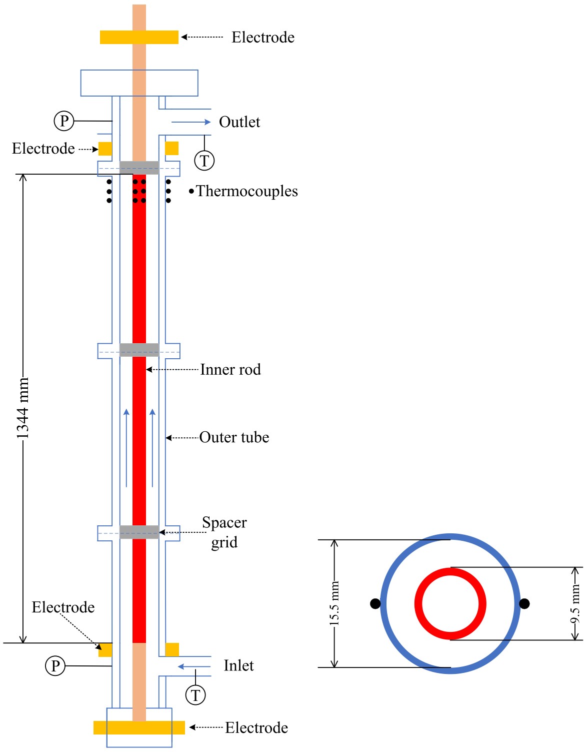


Fig. 2. The schematic diagram of test section.

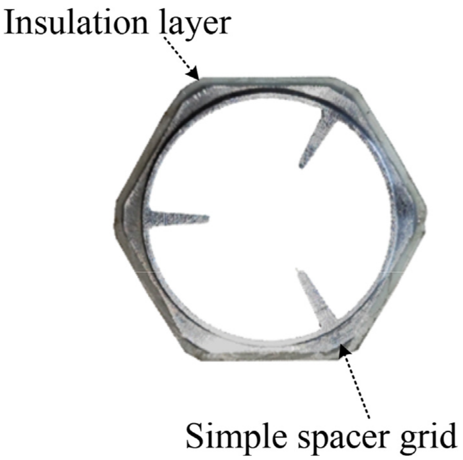


Fig. 3. The picture of spacer grid used in the present study.

Table 1
The details of geometric dimensions of test sections (mm).

	Test section
Inner diameter of outer tube D_o	15.5
diameter of inner rod D_i	9.5
Gap width δ	3.0
Heating length L	1344
hydraulic diameter d_h	6.0

annuli were studied in the case of equal heat fluxes on both sides. The test matrix was determined based on Katto's fluid-to-fluid (FTF) scaling method to cover the typical PWR operation condition [12]. The detailed scaling method had been introduced in the previous work [11]. The test matrix of the present study was listed in Table 2.

In this study, the uncertainties of key parameters were evaluated carefully. For the directly measured variables including pressure, mass flow rate and temperature, the uncertainties were determined by the accuracy and the measurement range of instruments. For the derived variables, such as mass flux, heating power, and heat flux, the uncertainties are calculated by the uncertainties of relevant measured variables according to the error transfer function [13]. The uncertainties of main measured and derived variables in the present study were summarized in Table 3.

Table 2
Test matrix of the present study.

Parameters	R134a	Water
Pressure (MPa)	1.8–2.7	10.9–15.7
Mass flux ($kg\cdot m^{-2}\ s^{-1}$)	600–2100	800–3000
Inlet subcooling (°C)	20–60	173–290

3. Results and discussion

3.1. The transition mechanism of CHF location in bilaterally heated annulus

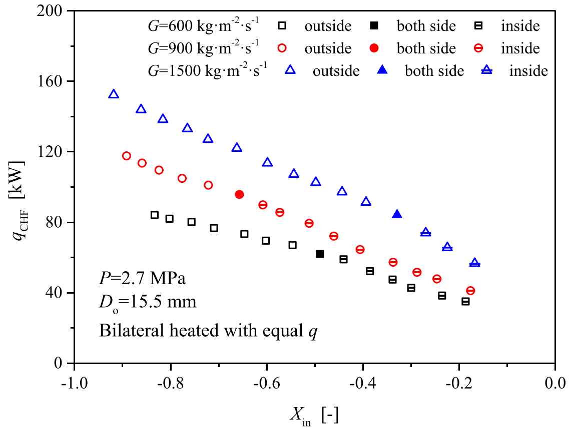
In this paper, CHF variation characteristics in the cases where both the external and internal surfaces of the annulus was heated by equal heat flux was experimentally studied under different parameters conditions. Fig. 4(a) and Fig. 5(a) showed the variations of CHF and CHF occurrence location in the bilaterally heated annulus against inlet quality at the constant pressure (2.7 MPa and 2.4 MPa) and three different mass fluxes (600 $kg\ m^{-2}\ s^{-1}$, 900 $kg\ m^{-2}\ s^{-1}$ and 1500 $kg\ m^{-2}\ s^{-1}$). It was found that CHF occurred initially on the surface of outer tube at the relatively low inlet quality. With the further increasing inlet quality, CHF simultaneously occurred on both sides of the annulus, and finally occurred only on the inner rod surface at relatively high inlet quality. Meanwhile, CHF almost linearly decreased with the increase of inlet quality, smoothly going through all the CHF location transitions.

Figs. 4(b) and Fig. 5(b) presented the variations of CHF and CHF occurrence location in the bilaterally heated annulus against critical thermodynamic quality at the constant pressure and different mass fluxes. Different trends were observed. With the increase of critical thermodynamic quality, CHF first occurred on the surface of outer tube, and then simultaneously occurred on both sides of annulus, and finally occurred on the inner rod surface at relatively high critical quality. Before the CHF location turning to the inner rod surface, CHF decreased with the increase of critical thermodynamic quality. Once the CHF location transitioned to the inner rod, CHF declined drastically. The CHF curve no longer followed the decreasing trend with the increasing critical thermodynamic quality and the slope of CHF curve even turned from negative value to positive value at low mass fluxes. The reason for the slope changing was considered to correspond to the so-called limiting critical quality under certain conditions, which represented the CHF mechanism transitioned from entrainment-controlled dryout to deposition-controlled dryout in the annular flow regime [14].

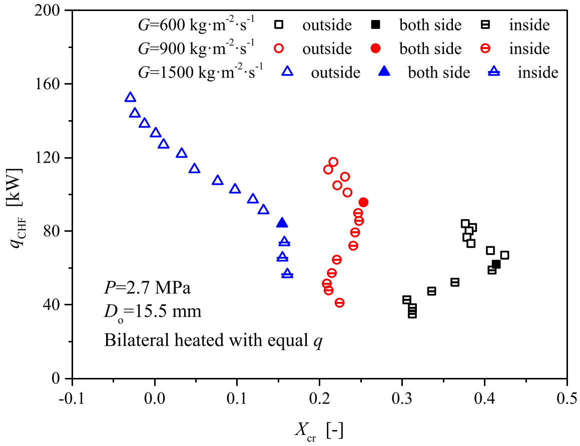
In the previous study, the CHF occurrence location in bilaterally heated annulus was considered to depend on the heat flux ratio between the inner and outer surfaces, which decided the entrainment rate and deposition rate in annular flow [9,15]. However, only the dryout-type CHF was discussed in the previous study. The transition mechanism was not explained in greater depth. In this paper, the transition mechanism of CHF occurrence location in bilaterally equally-heated annuli was discussed at different critical quality regions and different CHF types. “The competition” in the CHF value between the outer and inner surface determined the CHF occurrence location in annulus with equal heat flux on both sides. The CHF location transition was essentially the change in CHF mechanism.

Table 3
Summary of uncertainties.

Parameter	Uncertainty
Pressure [MPa]	±0.21%
Mass flow rate [$kg\cdot s^{-1}$]	0.54%
Wall temperature [°C]	±0.4°C
Heating power [kW]	±0.71%
Heating length [mm]	±1 mm
Diameter of inner rod [mm]	±0.5 mm
Inner diameter of outer tube [mm]	±0.5 mm



(a) Under inlet condition

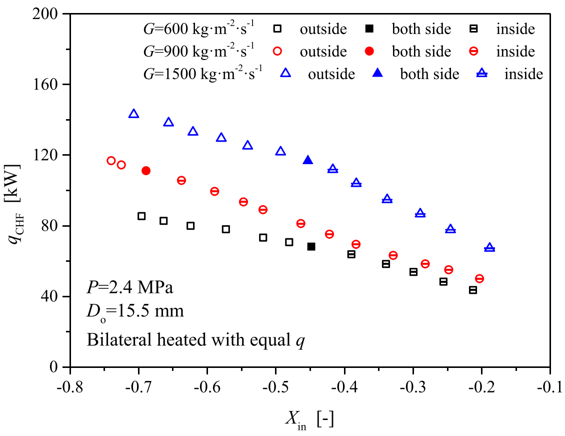


(b) Under local condition

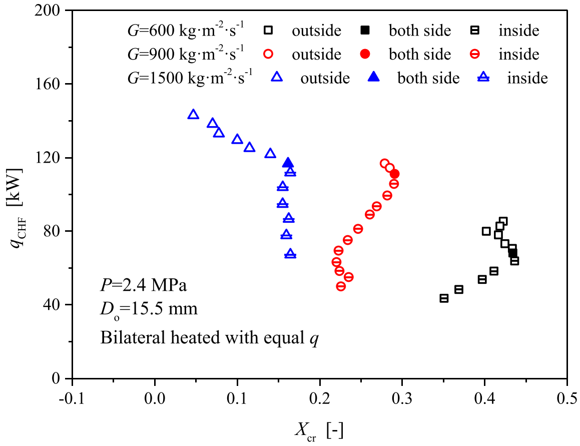
Fig. 4. Effect of mass flux on CHF in bilaterally heated annulus at pressure of 2.7 MPa.

At relatively low critical quality, the DNB-type CHF occurred in the bilaterally heated annulus, which was dependent on the local bubble behavior near the heated surfaces. Researches indicated that the peak value of velocity distribution along the radial was closer to the inner surface of the annulus [6,9]. In this case, the shear stress near the inner surface (τ_i) was greater than that near the outer surface (τ_o), which caused easier departing of bubble and more effective cooling on inner surface and prevented bubble crowding near the inner surface. Therefore, CHF on the inner surface was higher than that on the outer surface under the condition of equal heat flux on both sides of the annulus. That was the reason for CHF firstly occurred on the outer surface at relatively low critical quality.

In relatively high critical quality region, CHF mechanism turned from DNB to dryout with the flow regime gradually transitioning from bubbly flow to annular flow. The dryout-type CHF in the bilaterally heated annulus was controlled by three key factors, i.e. initial liquid film thickness, entrainment rate and deposition rate. Each of factors would be discussed separately. With the equal heat



(a) Under inlet condition



(b) Under local condition

Fig. 5. Effect of mass flux on CHF in bilaterally heated annulus at pressure of 2.4 MPa.

flux on both sides of annulus, the initial liquid film thickness on the outer surface (δ_o) was thicker than that on the inner surface (δ_i) because the shear stress near the outer surface (τ_o) was lower than that near the inner surface (τ_i) [9]. This factor was conducive to making CHF more easily occurred on the inner surface since the fewer heat flux was needed to vaporize out the thinner liquid film. The entrainment rate depended on the liquid film thickness and the shear stress. On the one hand, the thicker liquid film on the outer surface resulted in a greater entrainment rate. On the other hand, the lower shear stress near the outer surface might decrease the entrainment rate. It was difficult to quantify at which surface the entrainment rate was larger. In addition, the deposition rate on the surface of outer tube was higher than that on the inner rod since the droplets entrained in the vapor core had a larger chance to deposit on the outer surface which had the larger view factor. That was to say, CHF would occurred on the inner rod at very high critical quality in the deposition-controlled dryout region.

The present experimental results indicated that CHF dropped sharply and turned into the limiting critical quality region once the CHF location transitioned to the inner rod surface. Hence, we could guess that CHF still occurred on the outer tube in the entrainment-controlled dryout region. With the further increase of critical thermodynamic quality, CHF on the inner surface firstly turned from the entrainment-controlled dryout to the deposition-controlled dryout and the limiting critical quality was appeared, because the both the liquid flim thickness and the deposition rate on the surface were smaller. The dramatic decrease of CHF on the inner surface resulted in the CHF location transition. That was to say, the transition of CHF location was essentially the change in CHF occurrence mechanism, which lead to the difference in CHF on the two surfaces of the bilaterally heated annulus.

3.2. *Effect of mass flux*

The effect of mass flux on CHF in the bilaterally heated annulus with equal heat flux on both sides was also shown in Figs. 4 and 5. At the constant inlet conditions, it was observed that CHF increased with increasing mass flux at any constant inlet quality. For the local conditions, it was found that the transition of CHF occurrence location, i.e. the limiting critical quality, appeared at lower critical thermodynamic quality with the increase of mass flux. This general trend agreed with the observations in the previous studies [16]. The reason for this phenomenon was the flow regime transition could be affected by mass flux changing. For the same critical thermodynamic quality, the bubbly flow was easier to turn into the annular flow at higher mass flux. As the flow regime transformed at lower quality, the CHF mechanism turned into deposition-controlled dryout, more easily, resulting in the transition of CHF occurrence location. Besides, it was difficult to directly compare the value of CHF among different mass flux since the critical quality ranges at each mass flux were different. CHF experiment with broader test matrix should be conducted in the future.

3.3. *Effect of pressure*

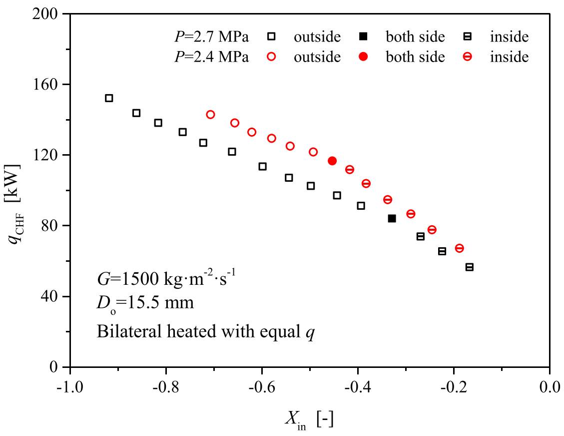
The variations of CHF against inlet quality and critical thermodynamic quality under different pressure conditions were illustrated in Fig. 6 ($G = 1500$ kg m^{-2} s^{-1}) and Fig. 7 ($G = 600$ kg m^{-2} s^{-1}). As shown in Figs. 6(a) and Fig. 7(a), it was found that CHF decreased with the increase of pressure at the constant inlet quality no matter which side CHF occurred. In Figs. 6(b) and Fig. 7(b), it could be seen that CHF increased with the decrease of pressure when CHF occurred on the outer surface of the bilaterally heated annulus. This variation trend was consistent with that in tube [1]. In addition, it should be noted that the limiting critical quality corresponding to the transition of CHF occurrence location seemed to decrease with the increase of pressure, which was also observed in Pioro's study [16]. That was, both the mass flux and pressure had an effect on the limiting critical quality as well as the transition of CHF occurrence location under the local conditions. However, the effect of mass flux was more significant than pressure. The effect mechanism of flow parameters on CHF location transition needed to verify by the more visualization experimental studies in the future.

3.4. *Comparison of CHF in tube, internally heated, externally heated and bilaterally heated annuli*

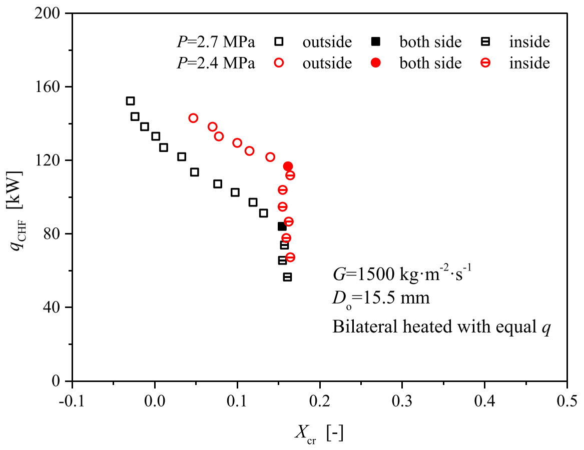
A comparison of CHF in tube, internally heated, externally heated and bilaterally heated annuli was made at the same pressure and mass flux, as shown in Fig. 8. The CHF data in tube was tested in a vertical tube with the inner diameter of 8 mm. To consider the effect of difference in hydraulic diameter, another set of CHF data was corrected to that with the equivalent diameter of 6 mm by the following method [17]:

$$\mathrm{CHF}_{D_{\mathrm{equi}}} = \mathrm{CHF}_{D=8\mathrm{mm}} \left(\frac{D_{equi}}{8} \right)^{-0.5} \tag{1}$$

It was found that CHF in tube was higher than that in annuli,

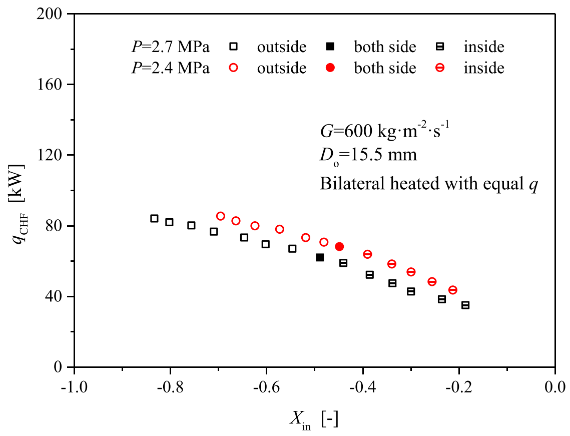


(a) Under inlet condition

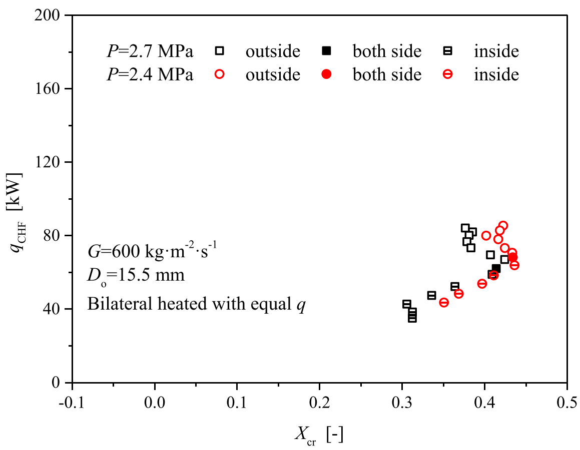


(b) Under local condition

Fig. 6. Effect of pressure on CHF in bilaterally heated annulus at mass flux of 1500 kg m^{-2} s^{-1}.



(a) Under inlet condition



(b) Under local condition

Fig. 7. Effect of pressure on CHF in bilaterally heated annulus at mass flux of 600 kg m^{-2} s^{-1}.

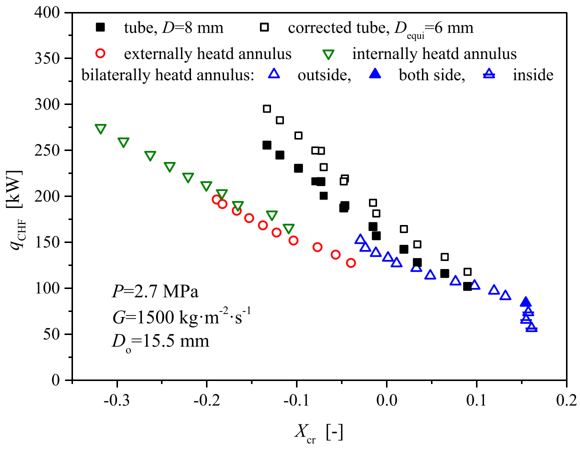


Fig. 8. Comparison of CHF in tube, internally heated annulus and bilateral heated annulus with equal heat flux.

regardless of the heating mode to the surfaces, which was also observed in the previous study [9]. For CHF in annuli, the comparable parts were at the relatively low critical quality region. It could be observed that CHF in the internally heated annulus was higher than that in the externally heated annulus when DNB-type CHF occurred at relatively low critical quality. This phenomenon also indicated that CHF should occurred on the outer surface of the annulus bilaterally heated with the same heat flux at relatively low critical quality, as a result of competition in CHF value between the outer and inner surfaces. In addition, CHF in the bilaterally heated annulus was likely to be greater than that in the externally heated annulus, because the cold wall effect of the unheated inner surface in the externally heated annulus could result in the increase of local quality and the decrease of CHF on the outer surface.

4. Conclusions

In this paper, a phenomenological study on CHF in a bilaterally heated annulus with equal heat flux on both sides was experimentally performed. Variation characteristics of CHF and transition of CHF occurrence location were investigated under different pressure and mass flux conditions. CHF in tube, internally heated, externally heated and bilaterally heated annuli were also compared. The main conclusions were summarized as follows:

With the increase of critical thermodynamic quality, CHF first occurred on the outer surface of the annulus, then simultaneously occurred on both sides, and finally occurred on the inner surface at relatively high critical quality. "The competition" in the CHF value between the outer and inner surface determined the CHF occurrence location in annulus with equal heat flux on both sides. After the CHF location transitioned to the inner rod, the sharp fall of CHF in the limiting critical quality region was observed, which represented that the CHF mechanism transitioned from entrainment-controlled dryout to deposition-controlled dryout on the surface of inner rod. Additionally, the critical quality corresponding to the CHF location transition decreased with the increase of mass flux and pressure.

The CHF location transition was essentially the change in CHF mechanism, which was affected by the difference in shear stress between the inner and outer surfaces of the annulus. At the relatively low critical quality region, the CHF mechanism was DNB or entrainment-controlled dryout, and CHF occurred on the outer surface because the higher shear stress near the inner surface or the higher entrainment rate from the outer surface. With the increase in critical quality, CHF turned to occur on the inner rod in the deposition-controlled dryout region since the deposition rate on the surface of outer tube was higher than that on the inner rod.

With the same hydraulic diameter, CHF in tube was higher than that in annuli, regardless of the heating mode to the surfaces. CHF in the internally heated annulus was higher than that in the externally heated annulus when DNB-type CHF occurred at relatively low critical quality. In addition, CHF in the bilaterally heated annulus was likely to be greater than that in in the externally heated annulus owing to the cold wall effect.

Declaration of competing interest

We wish to confirm that there are **no known conflicts of interest** associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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