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Experimental research on dryout point of flow boiling in narrow annular channels

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Abstract An experimental research on the dryout point of flow boiling in narrow annular channels under low mass flux with 1.55 mm and 1.05 mm annular gap, respectively, is conducted. Distilled water is used as working fluid and the range of pressure is limited within 2.0~4.0 MPa and that of mass flux is 26.0~69.0 kg·m^{-2}·s^{-1}. The relation of critical heat flux (CHF) and critical qualities with mass flux and pressure are revealed. It is found that the critical qualities decrease with the increasing mass flux and increase with the increasing inlet qualities in externally heated annuli. Under the same conditions, critical qualities in the outer tube are always larger than those in the inner tube. The appearance of dryout point in bilaterally heated narrow annuli can be judged according to the ratio of q_o / q_i.

Key words Narrow annular channel, Flow boiling, Dryout point

CLC numbers TL33, O359

1 Introduction

There are basically two classes of critical heat flux (CHF) situations: departure from nucleate boiling (DNB) and dryout (DO) [1]. DO is also sometimes known as burnout or departure from forced convective boiling in vapor-continuous flow. From the point of view of engineering, the CHF caused by the DO mechanism is of particular importance since boiling annular flow is one of the most common flow patterns in gas–liquid two-phase flow and occurs in a wide range of vapor qualities of interest.

The prediction of DNB and DO point is most crucial in designing various transfer units including nuclear reactors fossil-fueled boilers, fusion devices, and so on. When DO occurs, the surface being cooled is no longer in intimate contact with the liquid film. As a result, the heat transfer ability decreases dramatically and the corresponding wall temperature rises rapidly that it can even melt the heat transfer surface [2]. The power generated is often limited by the CHF value. It is an important parameter to be predicted in safety analysis. Therefore, the research on DO point has been extensively carried out during the last four decades for various geometries. Among these geometrical CHF studies, less investigation has been carried out for annular geometries than for round tubes and bundles.

The experimental study on DO point in bilaterally heated narrow annuli under low mass flux condition has been carried out. Test section's gap is 1.55 mm and 1.05 mm. The range of pressure is limited within 2.0~4.0 MPa and that of mass flux is 26.0~69.0 kg·m^{-2}·s^{-1}. The objective of this article is to expose the thermal–hydraulic characteristics when DO occurs and to discuss the parametric trends for narrow annuli.

2 Experimental arrangements

Fig. 1 is a schematic diagram of the boiling upflow

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system apparatus used in the experiments. It consists of a pump, pressurizer, preheater, flow meter, condenser, test section, valves, and pipes. Distilled water is used as the working fluid. Subcooled water circulated by the pump flows through the system pipes, preheater, and flow meter, then it is fed to the test section, and finally into the cooler where the fluid is condensed, thereby completing the circulation. The pressurizer connected to a high-pressure nitrogen system via a regulating valve is used to maintain a predetermined pressure in the loop.

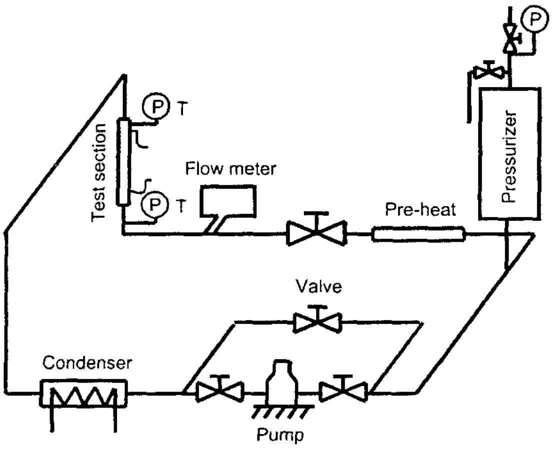

Fig. 1 Schematic of the experimental apparatus.

All the tubes in the system are made of stainless steel. The test section is made of specially processed straight stainless steel tubes with linearity error less than 0.001% to form narrow concentric annuli. Their geometrical parameters are shown in Table 1. The inner tube and the outer tube by itself are used to provide heat input through its electrical resistance. A direct voltage is applied to two brass flanges, each brazed to one end of the heater, making the electrical resistance of the terminals negligible compared to that of the heater tube. To reduce the heat losses to a minimum, a guard heater is built around the heater. This construction maintains the heat losses to a level less than 5%. The test section is insulated from the rest of the system through PTFE unions at both ends.

A copper block is placed near the inlet to enhance the enthalpy to a required level.

Table 1 Geometrical parameters of the test section / mm

ε	d_i	δ_i	d_o	δ_o	d_e
1.05	7.9	1.0	14.0	2.0	2.1
1.55	6.9	2.0	14.0	2.0	3.1

Note: ε is gap size; d_i is outer diameter of the inner tube; δ_i is wall thickness of the inner tube; d_o is outer diameter of the outer tube; δ_o is wall thickness of the outer tube; d_e is equivalent diameter.

Temperature measurements are made with standard copper–constantan thermocouples. Two flow-through thermocouples are present at the inlet side and a third flow-through thermocouple at the exit side of the test section are used for fluid temperature measurements. Fifteen thermocouples are fixed on the inner surface of the inner tube and the outer surface of the outer tube at 50 mm intervals for the wall temperature measurements. Loop mass flow rate is measured using a flow meter. The heat input is determined by measuring the current and the voltage drop across the test section.

3 Experimental results

In total, 211 experimental data have been collected with the annular test section. The range of parameters is shown in Table 2.

Table 2 Experimental parameters

ε/mm	N	P/MPa	G/kg·m^{-2}·s^{-1}	q_o/kW·m^{-2}	q_i/kW·m^{-2}
1.05	90	2 ~ 3	49.0 ~ 69.0	10 ~ 65	14 ~ 55
1.55	121	2 ~ 3	26.0 ~ 53.0	10 ~ 70	12 ~ 50

Note: N is number; P is pressure; G is mass flux; q_o is heat flux of the outer tube; q_i is heat flux of the inner tube.

3.1 Location of DO

When DO occurs, the corresponding wall temperature rises rapidly. The location of DO can then be detected according to the rapid change in temperature. Fig. 2 shows two typical conditions. From Fig. 2, it is easy to find the location of DO: in Condition 1, DO occurred only at the sixth section of the outer tube, while in Condition 2, DO occurred on the surface of both tubes. After obtaining the location of the DO point via the heat balance, the critical qualities can be calculated.

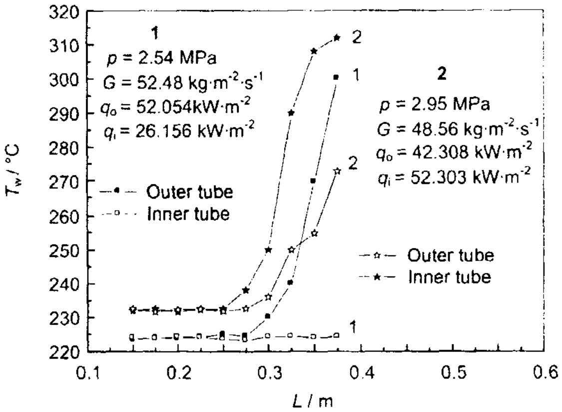

Fig. 2 Wall temperature vs axial length of the channel.

3.2 Parametric trends of CHF

An exact understanding of parametric trends is important to develop reliable prediction models in annular channel. In this study, parametric trends are analyzed with fixed inlet conditions.

3.2.1 Inner tube heating

For a fixed inlet superheat and pressure, in general, the CHF monotonously increases with the increasing mass flux only for inner-tube heating. The CHF data as a function of mass flux are shown in Fig. 3. However, the rate of CHF increases with increasing mass flux to a certain extent. The mass flux effect becomes larger when the mass flux is higher. In a normal mass flux, the CHF decreases with increasing inlet superheat.

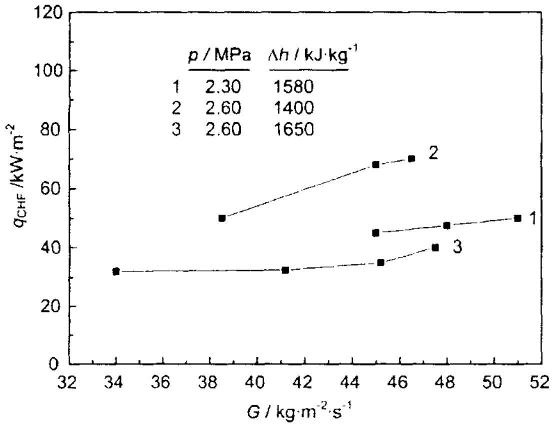

Fig. 3 Effect of mass flux on CHF for inner-tube heating.

The effect of mass flux on critical qualities is shown in Fig. 4. Although the effect is not large, it is clear that critical quality decreases with the increase in mass flux. The film thickness decreases, and entrainment increases with increasing mass flux, which results in an early occurrence of DO. It also leads to a decrease in critical quality. Critical qualities for higher inlet superheat are larger than those for lower inlet superheat with the same pressure and mass flux because of higher inlet quality.

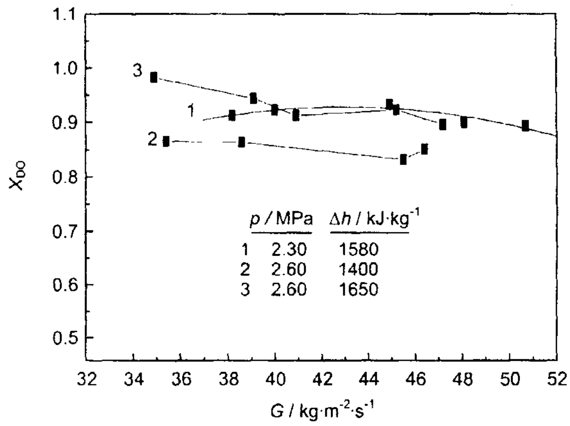

Fig. 4 Effect of mass flux on critical quality for inner-tube heating.

3.2.2 Outer tube heating

The CHF data as a function of mass flux for the outer-tube heating are shown in Fig. 5. The observed trends are not similar to those for only inner-tube heating. The CHF is not significantly affected by mass flux. But it is obvious that pressure has an effect on CHF. At $\Delta h = 1650\,\mathrm{kJ{\cdot}kg^{-1}}$, the CHF values for higher pressure are larger than those for lower pressure with the same mass flux.

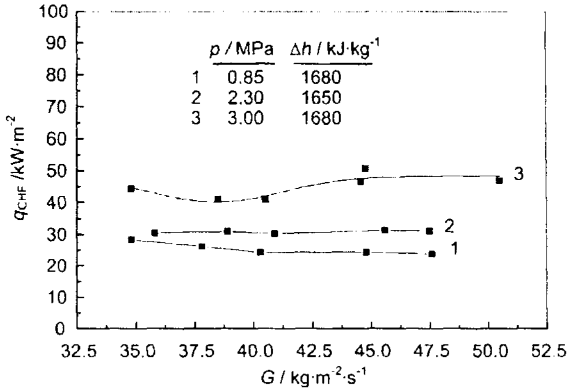

Fig. 5 Effect of mass flux on CHF for outer-tube heating.

The effect of mass flux on critical quality for outer-tube heating is shown in Fig. 6. The trends are very similar to those for inner-tube heating.

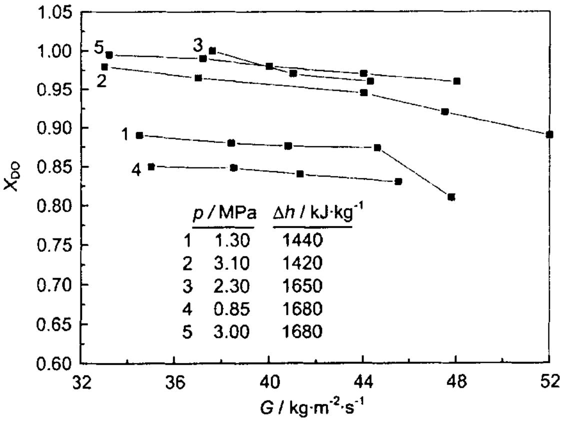

Fig. 6 Effect of mass flux on critical qualities for outer-tube heating.

It is generally known that CHF increases with the increase in pressure, reaches a maximum, and then decreases with pressure. This is also observed in annular channels [3] (Fig.7).

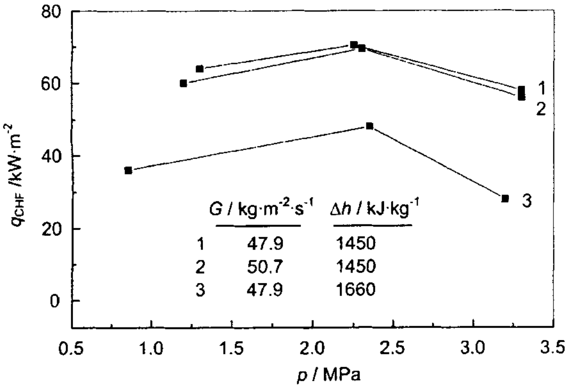

Fig. 7 Effect of pressure on CHF for outer-tube heating.

As pressure increases, surface tension, latent heat of vaporization and steam-to-water specific volume ratio decrease. In annular flow, generally CHF occurs when the liquid film dries by evaporation and entrainment. Evaporation increases as pressure increases because of low latent heat at a higher pressure. Entrainment is related to the disturbance waves at the interface of liquid film. If the slip ratio, which is the increasing function of specific volume ratio, is high, entrainment can take place easily. By these two mechanisms, the trend of increase or decrease in pressure can be explained. At a low pressure, the highly decreasing specific volume ratio would be the main reason for the increase of CHF because of the dominant effect of entrainment. Under high-pressure condition, the liquid film becomes thin mainly because of the lower latent heat of vaporization. Due to this phenomenon, the CHF decreases as pressure increases.

3.2.3 Comparison between inner-tube heating and outer-tube heating

Under the same inlet condition and heat flux, critical quality for outer-tube heating is always more than that for inner tube heating (Fig. 8). The reason is as follows: (1) The shearing force of outer tube acting on fluid τ_0 is lesser than that of inner tube τ_i in annular flow [4], so the film thickness on the outer tube is more than that on inner tube. Under the same heat flux and mass flux conditions, first DO takes place on the liquid film of the inner tube surface and correspondingly the critical quality is lesser than that of the outer tube; (2) Deposition of outer tube is bigger than that of inner tube because of more area. First, DO takes place on the liquid film of the inner tube with the same condition; (3) Entrainment rate of outer tube is less than that of inner tube because the shearing force and film thickness of the two surfaces are different.

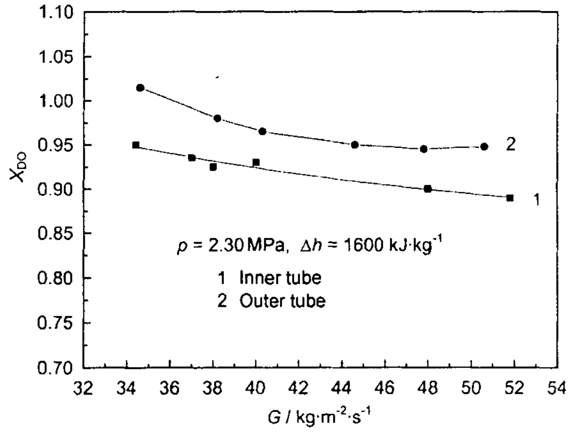

Fig. 8 Comparison between inner tube heating and outer tube heating.

3.2.4 Bilateral heating

It is clear that the CHF on one surface decreases as the heat flux of the other surface increases. It is shown in Fig. 9.

Two obvious conclusions can be drawn from Fig. 10: (1) Under the same pressure and mass flux conditions, DO takes place at an early stage with higher inlet superheat, and correspondingly the critical quality is less; (2) The CHF increases with the increase in mass flux for bilateral heating. This is very similar to the case for inner-tube heating.

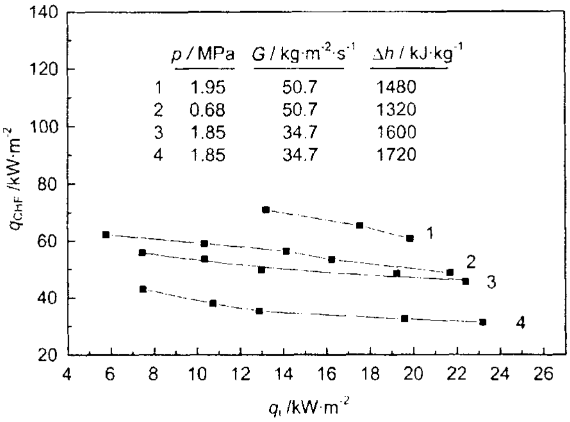

Fig. 9 Effect of inner tube's heat flux on CHF of outer tube.

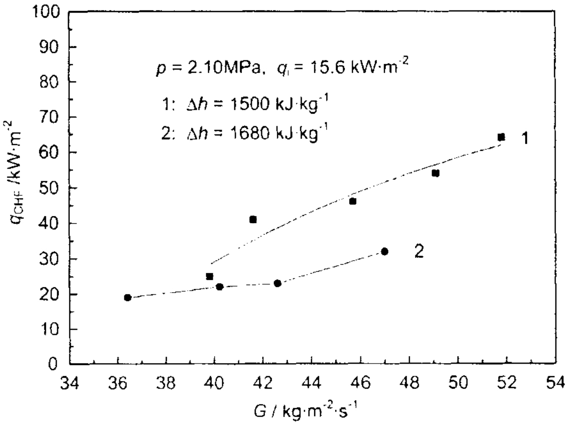

Fig. 10 Effect of mass flux on CHF for bilateral heating.

The CHF sometimes occurs either only on the inner tube or on the outer tube and sometimes occurs on both tubes, depending on the difference of heat flux between the two tubes. This difference results in the differences in film thickness, deposition, and entrainment on the two surfaces. Outer tube to inner tube heat flux ratio R is defined. The heat flux of the outer tube increases as R increases, which means that the evaporation capacity increases and deposition decreases and, correspondingly, the CHF occurs only on the outer tube. On the contrary, a smaller R means that the CHF occurs only on the inner tube. When R is of an intermediate value, CHF occurs on both surfaces. It can be concluded from Fig.11 that: (1) when $0<R<R_1$, CHF occurs on the inner tube; (2) when $R_1<R<R_2$, CHF occurs on both the tubes; (3) when $R>R_2$, CHF occurs on the outer tube.

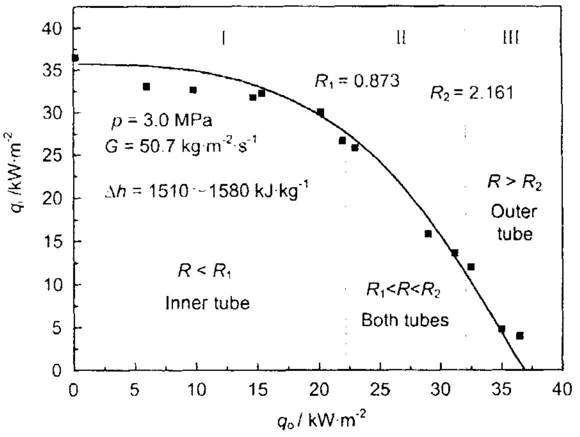

Fig. 11 Criterion of the appearance of DO point.

4 Conclusions

(1) An experimental study on DO in vertical narrow annuli has been carried out under the low mass-flux condition. A total of 211 data points were obtained for 1.05 mm and 1.55 mm annular gap size of the test section.

(2) The CHF monotonously increases and critical quality decreases with the increasing mass flux for the inner-tube heating.

(3) The CHF is not significantly affected by mass flux for outer-tube heating. Critical quality decreases as mass flux increases.

(4) Under the same inlet condition and heat flux, critical quality for outer-tube heating is always more than that for inner-tube heating.

(5) A criterion of the appearance of DO point for bilateral heating has been presented.

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