Analysis of a CHF Disappearing Phenomenon and the Prediction Correlations for the Threshold Pressures

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1. Introduction

The Critical Heat Flux (CHF) phenomenon is defined as an abrupt rise of a wall temperature due to a departure from a nucleate boiling occurring on a heated wall by a heat input. For the influence of a system pressure on water CHF, a sharp decrease of the CHF is observed near the critical pressure (pr > 0.94). This sharp decrease is closely related to the latent heat of a fluid; when the pressure reaches near to the critical point, the latent heat reduces sharply and becomes zero at the critical pressure. At a pressure which is higher than a critical pressure, a coolant becomes a supercritical state and it is heated without a phase transition; the wall temperature of a heater is increased monotonically with the power and no CHF phenomenon occurs. It is known that a CHF always exists whenever a system pressure is below a critical pressure. But, It is discovered a phenomenon where a CHF disappears before it reaches the critical pressure of a coolant in their 5x5 bundle CHF experiments [1]. They did not observe a CHF phenomenon above the channel outlet pressure of 4030kPa when the mass flux was held at 150kg/m²s. When they increased the mass flux, the pressure was reduced as shown in Fig. 1. There exists a "Threshold Pressure line" at a maximum pressure where a CHF can occur at a certain condition. Over the threshold pressure, the behavior of the wall temperature of the heater rod resembles the behavior in the supercritical pressure condition. This phenomenon of a threshold pressure has not been identified clearly yet.

2. Analysis of a threshold pressure

The CHF disappearing phenomenon can be identified by a study of the thermal hydraulic parameters near a critical pressure included the following subjects; "flow pattern", "Leidenfrost temperature with pressure", "boiling curve with pressure and flowrate", "stable liquid film thickness with heat flux, pressure, flowrate and inlet subcooling", "bubble departure diameter with pressure", "heat transfer in vapor film with specific heat and vapor density". The important stating point for the mechanism of a CHF disappearing is to obtain the flow pattern of a CHF near the critical pressure. Inverted annular flow (IAF) pattern is presumed for this case owing to the fact that it's critical quality is always negative at CHF-TP (CHF-Threshold Pressure); the CHF mechanism at a threshold pressure is a departure from a nucleate boiling (DNB).

2.1 Boiling Crisis and IAF near the Critical Pressure

At pressures near the critical pressure, it is not possible, to keep the inside surfaces of the tube walls in the evaporation zone wetted at all times. This is connected to the problem of a surface wetting that generally arises at pressures just below a critical pressure. In smooth tubes, the location of the boiling crisis can be seen to shift towards areas of low steam qualities as the pressure approaches the critical pressure. This is caused by a drop in the so-called Leidenfrost temperature to the value of a saturation temperature when the critical pressure is reached. In this case, the flow pattern established a stable IAF pattern. The Leidenfrost phenomenon refers to the film boiling of small liquid masses on a hot surface. Heat is transferred from the hot surface to the droplet by a conduction through the vapor film and by radiation. In the limit of the droplet radius approaching infinity, the Leidenfrost phenomenon becomes equivalent to a "stable film boiling," Because of this link, for large or small liquid masses, the minimum temperature supports a stable film boiling.

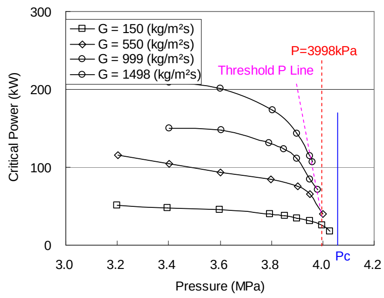
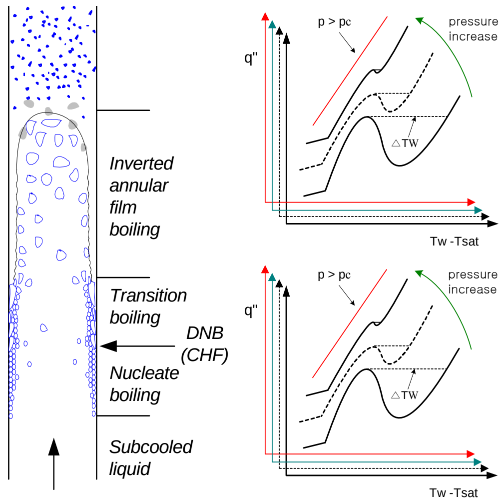


Fig. 1. Experimental evidence of the TP



(a) IAF (b) Boiling curves

Fig. 2. IAF and conceptual boiling curves representing a trend of the T_w jump on the flowrate and the pressure

2.2 Wall temperature jump behavior

Consequently, above a pressure of approximately pr=0.95 of water, only a small increase in the wall temperature is sufficient to result in a transition from a boiling with a wetted tube surface to so-called film boiling with an un-wetted surface. Hein et al., (1984) reported a relevant curve of the Leidenfrost temperature for forced convection as a function of the pressure. If the mass flux is reduced while keeping the heat flux at the same level, initially the wall temperatures only increase slightly and then rise disproportionately as the mass flux decreases further.

2.3 Agitation on the film interface

IAF destabilization occurs at low and high relative velocities by a vapor film agitation. The agitated region has a very fine structure with a very large surface area. The large interfacial area generated in the agitated region indicates large heat and momentum transfer rates. According to these observations, the occurrence of the agitated region and agitated annuli seems to be a result of the heat transfer from the wall. The heat transfer along the agitated region until a liquid core destabilization is characterized by a considerable increase in the heat transfer coefficient with the length.

2.4 Heat transfer in the vapor film near the critical pressure

It is well understood experimentally that a heat transfer coefficient becomes high near a critical point. Increased heat transfer near a critical state is generally attributed to very large values of the specific heat and the volume coefficient for an expansion which occur in this region. Conventional dimensionless groups have been employed for empirical correlations but there is considerable disagreement as to the proper method to use for an evaluation of properties in the Nusselt, Reynolds, and Prandtl modules.

$$Nu = \left(\frac{\lambda D_h}{k}\right) = a\left(\frac{\rho \upsilon D_h}{\mu}\right)^m \left(\frac{\mu C_p}{k}\right)^n , \quad (1)$$

A rapid change of the properties in the critical region, accentuates this disagreement because of the substantial variations which can occur over a rather narrow temperature or pressure range. The heat transfer coefficient in the IAF flow is larger than that in the film pool boiling despite the thicker vapor film. Increases in the inlet velocity and in the subcooling enhance the heat transfer coefficient. Heat flux, inlet velocity and inlet subcooling only have an influence through the thickness. A decrease in the vapor film thickness reduces the turbulence in the vapor film and allows the thermal conductivity to govern the heat transfer.

3. Results and discussion

The hot subchannel is found in a "matrix subchannel" at the reference test section and a "cold-wall subchannel" for the 4-unheated rods test section. We used the MATRA-α code for the analysis of local conditions from the 5x5 bundle experimental data. The MATRA is a thermal-hydraulic analysis code based on a subchannel approach [2]. The R-134a property routine in REFPROP version 7.0 is incorporated into MATRA-α to calculate the subcooled properties directly. Fig. 3 shows the measured CHF-TPs for the 5x5 bundle experiments. The CHF-TP is affected by both the Reynolds number and the inlet subcooling; The CHF-TP is decreased with the Reynolds number and the inlet subcooling. The effect of the inlet subcooling on the CHF-TP is stronger at a higher Reynolds number (see solid lines in Fig. 3). Meanwhile, at a lower Reynolds number below 200000, the CHF-TP is affected a little by the inlet subcooling. The thermodynamic qualities at the CHF-TP are obtained from the local conditions of the hot subchannels calculated by the Matra-α code.

The CHF-TP data for a matrix subchannel are correlated by the Reynolds number and the enthalpy of a hot subchannel outlet like below;

$$TP_{matrix} = P_c\left(1.0 - \frac{2.8e^{3.83\times10^{-6}\,\mathrm{Re}'}}{h'_{out}}\right) . \quad (2)$$

Where h'_{out} is a hot subchannel outlet enthalpy.

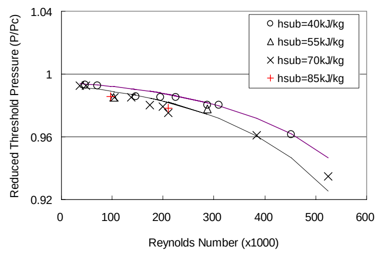


Fig. 3. CHF-TP for the Re and the inlet subcooling

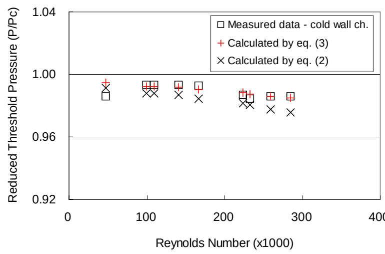


Fig. 4 Measured and predicted CHF-TP

When equation (2) is applied to a "cold-wall subchannel," it totally under-predicts the CHF-TP values as shown in Fig. 4. But, those under-estimated values are corrected very well when we multiplied a cold-wall correction factor $(D_h / D_{he})^{0.5}$ by equation (2),

$$TP_{coldwall} = P_c\left(1.0 - \frac{2.8e^{3.83\times10^{-6}\,\mathrm{Re}'}}{h'_{out}}\sqrt{\frac{D'_h}{D'_{he}}}\right) \quad (3)$$

Where, D'_{he} is a heated equivalent diameter of the cold wall subchannel. In a cold wall subchannel, the local enthalpy near a heater rod is relatively larger than in a matrix subchannel (cold wall effect).

4. Summary

We studied and analyzed the critical heat flux disappearing phenomenon at a sub-critical pressure and found the reason for a critical heat flux disappearance with several experimental evidences. The *inverted annular flow* pattern was revealed as the important stating point for the mechanism of a CHF disappearing phenomenon owing to the fact that it's critical quality is always negative at the CHF-TP condition. We produced CHF-TP correlations for the matrix and cold-wall subchannels, respectively. The prediction performances of those correlations are listed in Table 1.

Table 1. Prediction performances of the CHF-TP correlations

Correlation	Mean	σ	n
Matrix subchannel	1.0000	0.0034	21
Cold-wall subchannel	0.9993	0.0034	9

ACKNOWLEDGEMENTS

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