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A study on prediction methods of the critical heat flux for upward flow in a vertical narrow rectangular channel

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HIGHLIGHTS

- The empirical CHF correlations for upward flow in a vertical narrow rectangular channel were reviewed, for high pressure condition over 40 bar.
- New Correlation-A/B, which were derived by ACE algorithm, show much more improved prediction errors than other previous CHF correlations.
- The Look-Up Table (LUT) of ACEL predicts CHF as well as New Correlations.
- Comparative analysis shows that LUT with correction factors has potential application greater than New Correlations, for low pressure condition.

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ABSTRACT

The previous empirical CHF correlations for upward flow in a vertical narrow rectangular channel which is uniformly heated from both wide sides were reviewed and analyzed by using the experimental data points at pressure condition over 40 bar. The new correlations, that is, Simple Correlation and New Correlation-A/B were derived and proposed by using simple regression and ACE algorithm, and it was shown that they have more improved prediction errors than the other previous correlations. The Look-Up Table (LUT) of AECL also estimates CHF as well as New Correlation—A/B even though LUT was generated from the CHF data points in circular channels. As a result of comparative assessments of LUT and the empirical correlation of low pressure condition, it is reasonably concluded that for wider pressure condition, LUT with proper correction factors is the most pragmatic and universal CHF prediction method for rectangular channel in this study.

1. Introduction

1.1. Background of researches

Plate-type fuel has been studied and used in not only researches but also actual reactors for a long time, since it was installed in the first commercial reactor, Shippingport PWR (Clayton, 1993). Compared with the general, circular rod-type fuel, plate-type fuel has a higher ratio of heat transfer area to its volume. This characteristic can keep its central temperature lower, and make the power density of a reactor core higher, than a circular rod-type fuel. This is the main reason a research reactor, whose purpose is to generate higher neutron-flux for various research fields, adopts a plate-type fuel. Also, by increasing its power density, the load following characteristics of a reactor can be improved. In addition, a plate-type fuel has better structural robustness and stronger resistance to earthquake or other external shock.

Fig. 1 shows a typical fuel assembly composed of plate-type fuels and a modeling concept of its primary coolant channel. In this figure, the cross section shape of the primary coolant channel between fuels is a narrow rectangle, and coolant is heated from both wide sides. The narrow rectangle is a representative non-circular channel shape.

It is well known that the thermal-hydraulic characteristics of a non-circular shape channel are different than those of a circular shape channel. So it can be expected that the critical heat flux (CHF) characteristics in a narrow rectangular channel are different than those of a circular channel. The trend of CHF in a rectangular channel has been reported to be not qualitatively much different from that of a circular channel, according to thermal-hydraulic parameters such as inlet subcooling, mass flux, etc. But little is known about the quantitative differences between the two channels.

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Nomenclature

A	cross section area of channel (m^2)
A_h	heated surface area (m^2)
AR	aspect ratio
AR_{he}	heated aspect ratio
b	width of channel (m)
Bi	Biot number
Bo	Buoyancy number
D_e	hydraulic equivalent diameter (m)
D_{he}	heated equivalent diameter (m)
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
h	convection heat transfer coefficient (kW/m^2K)
h_{fg}	latent heat of vaporization (kJ/kg)
Δh_{in}	inlet subcooling (kJ/kg)
k	thermal conductivity (kW/mK)
L	length of channel (m)
p	pressure (bar)
q_c	critical heat flux (kW/m^2)
s	gap of channel (m)
V_h	heater volume (m^3)
w	width of heater (m)
We	Weber number
X	quality

Greek letters

α	void fraction
λ	characteristic length m $\lambda = \sqrt{\sigma/\left(\rho_f - \rho_g\right)g}$
ρ	density (kg/m^3)
σ	surface tension (N/m)
ϕ_{BO}, ϕ_c	critical heat flux (kw/m^2)

Superscript

*	dimensionless (variable)

Subscript

f	liquid phase
g	vapor phase

Numerous studies on the CHF in a research reactor's core and a micro-scale rectangular channel have been carried out recently. But for the former, there is little published experimental data. For the latter, the thermal-hydraulic phenomena of a micro-scale channel are known to be different from those of the coolant channel in a commercial reactor core, because surface tension is dominant in micro-scale. For this reason, the latter is excluded from the scope of this study.

The purposes of this paper are to review previous research on the CHF in a narrow rectangular channel, carry out assessments of some of the CHF prediction methods and distinguish the better prediction method. We consider a variety of studies on the CHF in a narrow rectangular channel, depending on various conditions, such as pressure, the number of heated surfaces, flow driving method, flow direction, etc. But it must be noted that the conditions for CHF in this paper are limited to the forced upward flow of water in a vertical narrow rectangular channel which is uniformly heated from both wide sides. In particular, the pressure condition is over 40 bar, relatively high.

1.2. Previous researches

Representative studies on the CHF of upward flow in a vertical narrow rectangular channel and the empirical correlations proposed by these researches are summarized in Table 1. On the whole, the pressure condition in these investigations is relatively high.

DeBortoli et al. (1958), Goldman and Thomas (1961) and Tong (1972) proposed the CHF design equations, which conservatively estimated the CHF in a vertical narrow rectangular channel and can be applicable to high pressure and restricted mass flux condition. Macbeth (1963) analyzed the CHF data set of DeBortoli et al. and suggested the CHF correlation which was applicable to a wider range of pressure conditions than the design equations. But that work has the fault that its constant coefficients are defined at specific discrete pressure conditions, so CHF cannot be calculated for all continuous pressure conditions. Tong (1967) supposed the W-3 correlation which can be applied to both circular and rectangular channels. Unlike other correlations, this was developed as a local parameter CHF correlation, but the applicable range of this correlation is also very limited. More recently (Katto, 1981) derived a rectangular channel CHF correlation which was originally founded on a circular channel CHF correlation. Although this is an inlet conditional correlation, there is no clear statement about the application range limit except pressure condition. For this reason, Katto's correlation is thought to be relatively more universal than other previous correlations.

2. Review of empirical correlations

2.1. Review of previous correlations

From an engineering viewpoint, the CHF prediction methods are pragmatically very meaningful, so a considerable number of studies have employed them over the past decades. The CHF prediction methodologies are categorized into empirical correlation, look-up

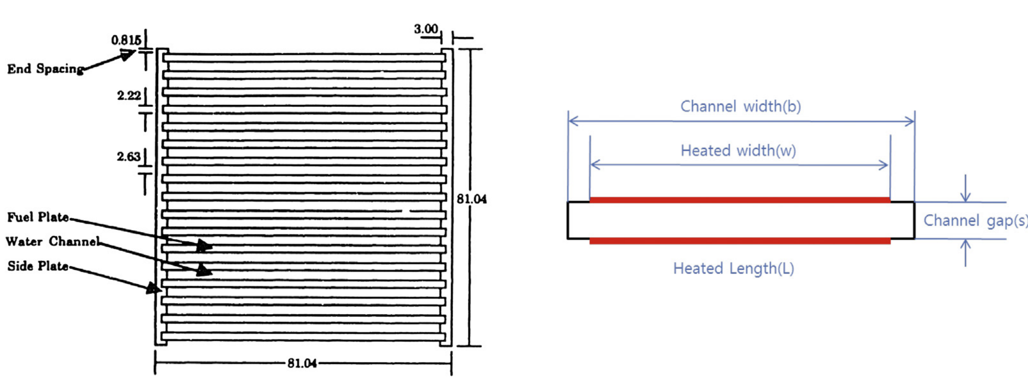

Fig. 1. Assembly of plate-type fuels and rectangular channel simulator.