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Prediction of the minimum point of the pressure drop in a narrow rectangular channel under a transversely non-uniform heat flux

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ABSTRACT

It is necessary to accurately predict the minimum point of pressure drop to ensure the safety of nuclear reactors. However, the non-uniform heat flux distribution along the transverse direction is encountered when the plate-type nuclear fuels are used. This study shows the effect of a transversely non-uniform heat flux on the minimum point of the pressure drop. The pressure drop-flow rate curve under the non-uniform heat flux was obtained by the experiment, and the trend of curve was different with the one of uniform heat flux case. Under the non-uniform heat flux, even when the inlet mass flow rate decreased, the value of the pressure drop was constant for a while with the development of a two-phase flow. With further reduction of inlet mass flow rate, the pressure drop started to decrease until the minimum point of the pressure drop was reached. Moreover, the inlet mass flow rate at the minimum point of pressure drop is much lower than that in the uniform heat flux case. For a detail analysis, the numerical approach is proposed along with the application of multi-channel concept. A single narrow rectangular channel is divided along the transverse direction, and the heat flux is given non-uniformly to the divided channels. Although the pressure drop is separately calculated for each divided channel, the mass is transferred between the channels. In the calculation, the mass flow rate is non-uniformly distributed in the transverse direction. If the mass flow rate is uniformly distributed, the non-uniform heat flux causes an unbalanced pressure drop because of the non-uniform distribution of void fraction. As a result, at the edges where the void fraction is high, the mass flow rate is transferred to the middle of channel to balance the pressure drop in transverse direction. When the void fraction in the middle becomes significantly large, the minimum point of the pressure drop can be obtained.

1. Introduction

In research reactors that use plate-type nuclear fuels, the coolant passes through narrow rectangular channels between the fuel plates. In order to ensure operational standards and safety, several researchers have investigated the thermal–hydraulic characteristics in these narrow rectangular channels. In particular, the pressure drop–flow rate curve has been investigated to avoid the flow instability that occurs at the minimum point of the pressure drop. However, the plate fuel releases more power from its transverse edges (Miller and Ozaltun, 2012). This non-uniform power distribution influences the local boiling phenomenon and results in different thermal–hydraulic characteristics from those obtained under a uniform power distribution (Al-Yahia et al., 2017, Kaminaga et al., 1989). Therefore, it is necessary to investigate the minimum point of the pressure drop under the transversely non-uniform heat flux.

Experimental and predictive researches have been conducted on the minimum point of pressure drop. Whittle and Forgan (1967) experimentally investigated the minimum point of the pressure drop that occurs in subcooled boiling in narrow rectangular channels. The pressure drop–flow rate curve obtained in the case of fixed power is identical to that for the zero-power condition until the minimum pressure drop was investigated. The slope of the curve is changed abruptly from a positive to negative value beyond the point of the minimum pressure drop. In addition, correlations were derived to predict the bulk temperature at the minimum point of the pressure drop. Stelling et al. (1996) developed a simple pressure drop model for the downward flow in a vertical tube and compared the obtained results with their experimental results. The developed model is based on the homogenous model and predicts the pressure drop–flow rate curve accurately. Hainoun and Schaffarth (2001) modified the analysis code ATHLET

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Nomenclature

A	cross-sectional area, [m^2]
C_0	distribution parameter
C_p	heat capacity, [J/(kg K)]
D_h	hydraulic diameter, [m]
f	friction factor, [kg/(m^2 s)]
G	mass flux, [kg/(m^2 s)]
Gz	Graetz number
h	convective heat transfer coefficient, [W/(m^2 K)]
i	enthalpy, [J/kg]
i_{fg}	latent heat of vaporization, [J/kg]
J	superficial velocity, [m/s]
L	channel length, [m]
$\dot{m}$	mass flow rate, [kg/s]
Nu	Nusselt number
P	pressure [bar]
Pr	Prandtl number
q''	heat flux, [W/m^2]
Q	power, [W]
Re	Reynolds number
s	gap of channel, [m]
T	temperature, [°C]
v	fluid velocity, [m/s]
w	channel width, [m]
x	quality
X	Martinelli parameter

Greek symbols

α	void fraction
γ	mass fraction
ΔP	pressure drop, [kPa]
ϕ	two-phase multiplier
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/m s]

Subscripts

A	acceleration
F	friction
g	gas
in	inlet of channel
iso	isothermal
l	liquid
OFI	onset of flow instability
ONB	onset of nucleate boiling
OSV	onset of significant void
out	outlet of channel
sat	saturation
sp	single-phase flow
tp	two-phase flow
w	wall
z	axial position

(Analysis of THermal-hydraulics by Leaks and Transients) to predict the Onset of Flow Instability (OFI) over a wide heat flux range. The modified ATHLET has been validated through a comparison of the results obtained for a narrow rectangular channel with the experimental data, and it exhibited good accuracy. Khater et al. (2007) developed a correlation to predict the heat flux at the OFI in materials testing reactors (MTRs). This correlation is based on the heat balance between the bubble generation and condensation and the force balance at the moment of bubble detachment from the wall. The developed correlation showed a lower deviation from the experimental data than that obtained with the correlation developed by Whittle and Forgan (1967). Hamidouche et al. (2009) investigated the prediction of the pressure drop–flow rate curve using a homogenous model and REALP5 in order to define a margin for the OFI in MTR reactors. The predicted pressure drop–flow rate curve was compared to those of the Oak Ridge National Laboratory thermal hydraulic test loop (ORNL-THTL) experimental results, and it was found that both the homogeneous model and RELAP5 were comparable to the data obtained on using the ORNL-THTL. El-Morshedy (2012) solved the transient equation for the pressure drop in a narrow rectangular channel under the axially non-uniform heat flux. The bulk temperature at the exit of the channel and the flow velocity were defined at the minimum point of the pressure drop. Lee et al. (2013) performed experiments for the downward flow in a narrow rectangular channel with different channel thickness. They found that the gap size has a significant effect on the flow excursion that occurs immediately after the minimum point of pressure drop, and it is triggered by an abrupt change in the flow structure. Yu et al. (2016) experimentally investigated several types of flow instabilities in a vertical narrow rectangular channel. The extant research shows that the margin between the Ledinegg instability and the Pressure Drop Oscillation/ Density Wave Oscillation reduces as the liquid subcooling increases. Furthermore, the correlation obtained by Stoddard et al. (2002) was comparable to the experimental data on the minimum point of the pressure drop although the correlation was based on experiments that comprised the use of horizontal annuli. Ghione et al. (2017) evaluated the existing OFI criteria through a comparison with experimental data. The experiments were performed under a low pressure drop, and axially uniform and non-uniform heat fluxes were applied to the narrow rectangular channel. The experimental data under an axially non-uniform heat flux were more deviated from the OFI criteria than those obtained under a uniform heat flux.

Although the minimum point of the pressure drop was investigated under an axially non-uniform heat flux, it has not been performed for the transversely non-uniform heat flux. In the present study, the minimum point of the pressure drop under the transversely non-uniform heat flux is investigated by predicting the pressure drop–flow rate curve. The pressure drop is calculated using the basic pressure drop equation for the two-phase flow, and the variables in the equation are determined by the correlations for the narrow rectangular channel. Owing to the non-uniform heat flux that causes the unbalanced pressure drop, a numerical solution is required to balance the pressure drop in the transverse direction. For the verification of the prediction, it is compared to the experimental data obtained under both uniform and non-uniform heat flux conditions.

2. Experimental facility and procedure

The schematic of the experimental loop is shown in Fig. 1. Demineralized water circulates through the loop, and the mass flow rate is measured using the mass flow meter. The heat exchanger and preheater are used to set the temperature at the inlet of the test section. The voids generated in the test section would be condensed in the condensing tank, which is open to the atmosphere. The pressure transducer and k-type thermocouple are installed at the inlet and outlet of the test section. The pressure transmitter is installed in the test section to measure the pressure drop where the flow boiling occurs. The electric power applied to the test sec-