Experimental study of onset of nucleate boiling in vertical rectangular channel under forced and natural circulation

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1. Introduction

Sub-cooled flow boiling in the narrow rectangular channel is applied to the many industry field [1] such as supercomputer, heat exchanger and nuclear research reactor. Sub-cooled flow boiling was distinguished to ONB (Onset of Nucleate Boiling), OSV (Onset of Significant Void) and OFI (Onset of Flow Instability) [2-4]. ONB is the location when the wall temperature exceeds saturation temperature of liquid, nucleation firstly occurs on the heated surface. OSV increases void fraction dramatically beyond the ONB. ONB and OSV is stable region, respectively. Further increase with the void fraction, flow instability occurs beyond the stable region. This phenomenon is OFI.

Experiments were performed under the condition of FC (Forced circulation) and NC (Natural circulation). Flow rate of forced circulation was controlled by pump and flow rate of NC [5,6] was formed by difference of density generated between heat source and heat sink. Flow rate of FC is larger than natural circulation. In this paper, ONB region will be analyzed by comparing FC and NC condition. ONB, heat transfer coefficient and bubble behavior such as bubble departure diameter, bubble generation time will be different due to the difference of flow rate. The objective of this paper is that ONB and heat transfer coefficient will be analyzed based on the experimental results. Also bubble behavior such as bubble departure diameter and bubble generation time will calculated using high speed camera and MATLAB.

2. Experimental description

2.1 Test condition

Flow rate, heat flux and inlet temperature can be independent variables in the FC. But in the NC, flow rate is formed by varying heat flux. Therefore, common independent variable is inlet temperature. Flow rate was affected by velocity of pump in the FC. But flow rate of NC was depended by changing inlet temperature due to decrease in the viscosity of coolant when the inlet temperature increased. Table I shows forced and natural circulation test condition. Until now, experiments have been conducted with inlet temperatures of 35 ℃ and 40 ℃ under the condition of FC and NC. The experiment will then be conducted under the FC and NC at an inlet temperature of 45 ℃.

Table I: Test condition of forced and natural circulation

Parameter	Unit	FC	NC
Flow rate	kg/sec	0.015	$2 - 4.5 \times 10^{-3}$
Heat flux	kW/m^2	20 - 110	
Inlet temperature	℃	30 - 45	
Pressure	MPa	0.1 - 0.14	

2.2 Experimental facility

To experiment single- and two-phase in the narrow rectangular channel under the condition of FC and NC, facility was constructed to simulate flat fuel plates of JRR-3 [7,8] which is nuclear research reactor of japan in the Fig 1. This system was constructed to experiment FC and NC loop, respectively.

This system consists of test section, water reservoir, Coriolis flow meter, preheater and data acquisition system (DAQ) and pump. Test loop was filled to demineralized water by using the pump through drain line. When the demineralized water passes test section, mixture of liquid and vapor flows in the water reservoir and then vapor was condensed at the condensing tank. Before the experiment, degassing was performed to water temperature 75 ℃ for 1 hour to reduce the effect of non-condensable gas.
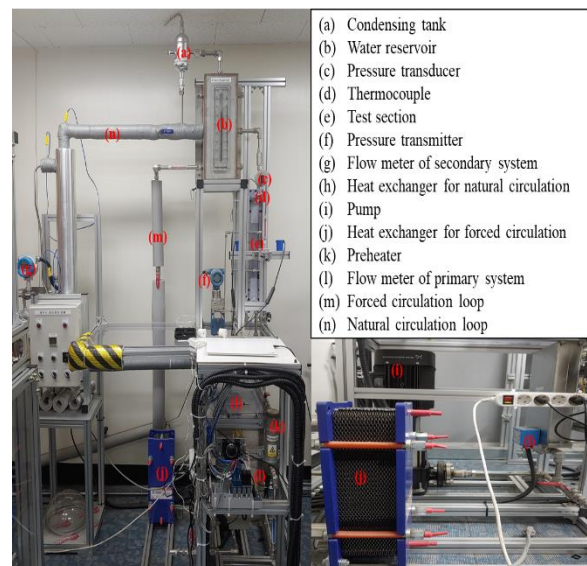

(a) Condensing tank
(b) Water reservoir
(c) Pressure transducer
(d) Thermocouple
(e) Test section
(f) Pressure transmitter
(g) Flow meter of secondary system
(h) Heat exchanger for natural circulation
(i) Pump
(j) Heat exchanger for forced circulation
(k) Preheater
(l) Flow meter of primary system
(m) Forced circulation loop
(n) Natural circulation loop

Figure 1. Experimental facility

2.3 test section

Test section consists of Polycarbonate window, Teflon block, Cartridge heater, Heating block, Cerak-wool insulation and thermocouples. Two cartridge heaters were installed in the test section. Electrical power was controlled by power controller. Test section is uniform heating with one side and the other side is visualization section to investigate the bubble behavior. Gap of cross section flowing coolant is between channel 2.35 mm. The width and length of cross section is 54 mm and 566 mm, respectively.

3. Results and discussions

3.1 ONB measurements
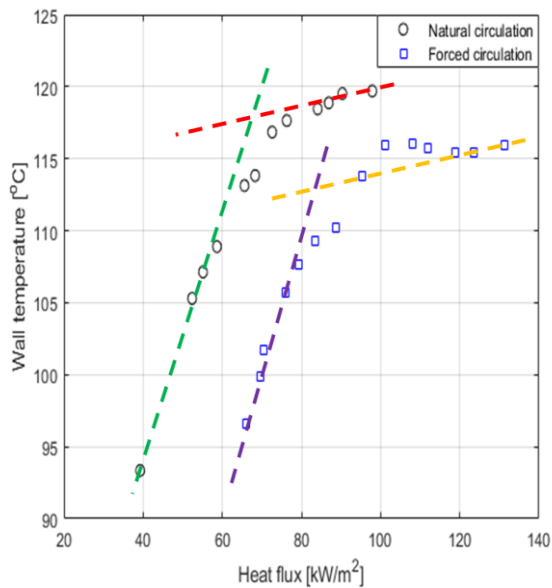
(a) Inlet temperature 35 ℃
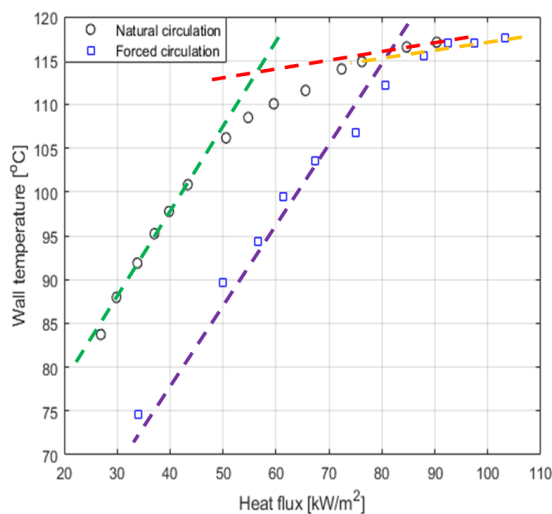
(b) Inlet temperature 40 ℃

Measurement methods of ONB are 1) pressure drop measurement 2) axial wall temperature measurement 3) the slope of the wall temperature-heat flux curve and 4) direct visualization using a high-speed camera. To measure ONB, this paper used 3) and 4). In the FC and NC, ONB was deviated as change of slope between single- and two-phase region. When the inlet temperature increased, heat flux generated ONB on the heated surface is smaller due to increase of the water temperature.

To generate ONB on heated surface, heat flux of FC is larger than that of NC. This reason is difference of cooling rate due to the difference of flow rate.

Difference of flow rate in the FC and NC will affect the heat transfer coefficient and bubble behavior such as bubble departure diameter and bubble generation time. Heat transfer coefficient will calculate using the Newton's cooling law. Also, to investigate bubble behavior, high-speed camera and MATLAB will be used.

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