Design of the test apparatus for flow boiling on downward-facing inclined wall for application of IVR-ERVC

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1. Introduction

For APR1400 (Advanced Power Reactor 1400), external reactor vessel cooling (ERVC) in submerged water is adopted as an effective severe accident management strategy for in-vessel retention (IVR) of molten corium to secure the reactor's integrity and prevent releasing radioactive materials out of the reactor. However, as the thermal power increases up 4000 MWth, technical applicability of the IVR-ERVC strategy should still be validated.

For this validation, many studies using computational fluid dynamics (CFD) have been conducted over the past years. Using three-dimensional CFD, ones can analyze detailed flow field and local heat transfer in the flow channel between the lower head of the reactor vessel and the reactor cavity [1-3].

The present wall boiling model in current CFD codes was formulated based on the assumption of well-separated isolated bubbles on an upward-facing heated wall [4], whereas boiling on the downward-facing wall of the lower head is characterized by the presence of vapor slugs which are cyclically generated from the coalescence of neighboring isolated bubbles and transported downstream [5]. This kind of discrepancy may introduce considerable errors in thermal-hydraulic analysis using CFD to assess the applicability of the IVR-ERVC strategy to APR1400.

Recently, Kim [6] experimentally studied the wall boiling heat transfer characteristics on a downward-facing heated wall only at an inclination angle of 10°, which can be seen in core catcher. Using obtained experimental results, he could propose modified wall boiling model of CFD for application to the core catcher. Similar experimental studies and model improvements are desired for reliable three-dimensional CFD analysis of IVR-ERVC, which has downward-facing heated wall inclined from horizontal to vertical.

The purpose of this study is to determine dimensions of a flow boiling test apparatus on a downward-facing heated wall and experimental conditions for thermal-hydraulic similarities.

2. Design Approach of Test Apparatus

In order to reproduce localized thermal-hydraulic conditions at each location on the hemispherical lower head of the reactor pressure vessel (*R*=2.5 m), a flow boiling test section with a relatively short downward-facing heated wall was designed. Inclination of the downward-facing wall varied from horizontal to vertical with an interval of 15°, as shown in Fig. 1.

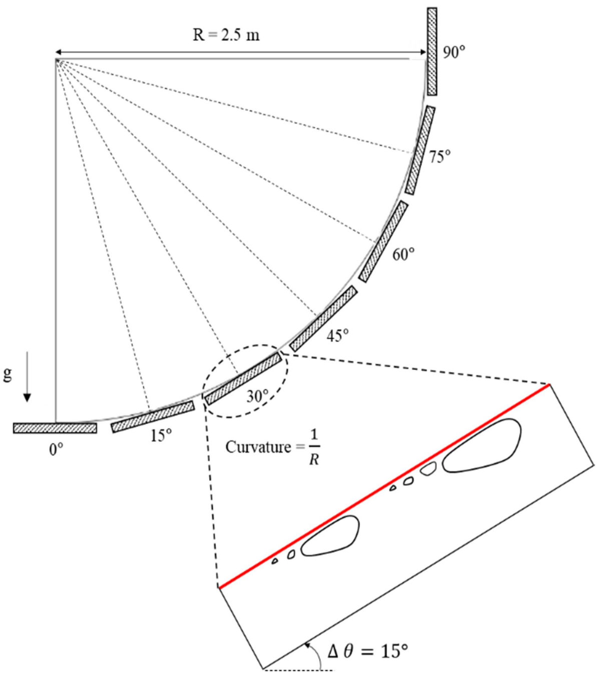

Fig. 1. Design approach of the flow boiling test apparatus on a downward-facing heated wall relevant to three-dimensional CFD analysis for IVR-ERVC

3. Similarity Analysis

3.1 Buckingham Pi-theorem for APR1400

Under severe accident conditions in APR1400, the cooling water is supplied from the In-containment Refueling Water Storage Tank (IRWST) to the reactor cavity. When the initial cooling water contact with external reactor vessel, generated isolated bubbles due to nucleate boiling on the downward-facing external wall of the reactor vessel do not lift off, merge each other and slide downstream in forms of slug bubbles. Therefore, the resulting boiling phenomenon of interest in this study should be characterized by slug bubble [5].

For thermal-hydraulic similarity, dimensional analysis was performed using Buckingham Pi-theorem. Fourteen independent parameters that can affect boiling heat transfer on a downward-facing heated wall were considered (*n*=14): heat flux (q''), heated length (L), channel diameter (d), conditions of working fluid (V, ΔT), fluid properties ($\rho_f, \rho_g, \sigma, \mu_f, h_{fg}, C_p$), gravity ($g$), inclined angle ($\theta$) and void fraction ($\alpha$), as summarized in Table. 1. The inclined angle and void fraction parameters are matched equivalently between APR1400 and the test apparatus. Thus, the total number of the remaining dimensional parameters is twelve (*n*=12). The repeating parameters are ρ_f, V, d and ΔT (*m*=4). Primary dimensions are mass, length, time and temperature (*r*=4). According to Buckingham Pi-theorem (*n*-*m*=8), eight dimensionless numbers were transformed as listed in Table. 2.

On a closer view in Table. 2, Reynolds number is a significant dimensionless number to maintain dynamic similitude of fluid flow. Froude number defined as the ratio of the inertia force and the gravitational force. When the Froude number is lower than 1, the buoyancy force will strongly affect hydrodynamics on downward-facing as the inclination angle changed. Weber number represents the ratio of inertia force to surface tension force which is useful to analyze the interface of fluid flows between two different fluids. It is quite important in determining the dominant energy between kinetic energy and surface tension energy. Eckert number is useful in determining the relative importance of heat transfer and the kinetic energy of flow. E_r number is defined as the ratio of kinetic energy with respect to thermal energy which is required for phase change from liquid to vapor. The meaningless dimensionless number describes the ratio of heat flux to kinetic energy. Channel ratio is related to the flow developing along the heated length and density ratio is the fundamental properties of working fluid.

Table 1. List of independent boiling parameters for subcooled flow boiling on downward-facing heated wall with various inclination angle

Parameters	Meaning
q''	Heat flux
L	Heated length
d	Hydraulic diameter
V	Flow velocity
ΔT	Subcooled
ρ_f	Density of fluid
ρ_g	Density of gas
σ	Surface tension
μ_f	Fluid viscosity
h_{fg}	Evaporation heat
C_p	Heat capacity
g	Gravitational force
θ	Wall orientation
α	Void fraction

Table 2. Buckingham Pi group for APR1400

Pi group	Meaning	Comments
$\frac{\rho V d}{\mu}$	Reynolds number	Flow pattern
$\frac{V^2}{gd}$	Froude number	Inertial vs gravity
$\frac{\rho_f V^2 d}{\sigma}$	Weber number	Inertial vs surface tension
$\frac{V^2}{C_p \Delta T}$	Eckert number	Convective heat transfer
$\frac{V^2}{h_{fg}}$	E_r number	Ratio of thermal to kinetic energy
$\frac{q''}{V^3 \rho_f}$	Meaningless	Ratio of heat to kinetic energy
$\frac{L}{d}$	Channel ratio	Flow development
$\frac{\rho_f}{\rho_g}$	Density ratio	Two-phase

4. Results

To maintain thermal-hydraulic similarity with ERVC in APR1400, dimensions of the test apparatus and experimental conditions were determined from similarity analysis results using Buckingham Pi-theorem. The obtained values of the principle dimensionless numbers for APR1400 and the test apparatus are summarized in Table. 3. From the obtained values, seven dimensionless numbers were preserved among them except for the Reynolds number. The detailed analysis was explained as following.

4.1 Dimensions of flow boiling test apparatus

The dimensions of the test apparatus were determined using Reynold number and L/d dimensionless number. *Re* is a criterion for similarity of fluid behavior, either laminar flow or turbulent flow. From the obtained value of Reynolds number in APR1400 (>150,000), the flow pattern is fully turbulent. Hydraulic diameter of the test apparatus was set to be 13 mm and corresponding Reynolds number (>9,000) is large enough to maintain same turbulent flow condition. The height of the test apparatus as flow channel should be larger than the two-phase flow boundary layer thickness to avoid distortion of slug bubbles. In this work, the height was set as 20 mm. The length of the heating area in the test apparatus was determined to have the same value of *L/d* as that of a piece of the lower head in Fig. 1. As a result, the dimensions of the flow boiling test apparatus were determined as 10 mm (W) × 20 mm (H) × 130 mm (L).

4.2 Experimental conditions

As shown in Table. 3, fluid velocity (*V*) is the dominant parameter in *Fr, We, Eckert* and E_r numbers as the power of square or cube. Thus, to match the values of the dimensionless numbers, the fluid velocity should be equal. Park et al. [7] conducted thermal-hydraulic analysis using RELAP5/MOD3 to predict mass flow rate and heat flux under IVR-ERVC condition in APR1400. They found that the mass flow rate in ERVC of APR1400 varies in the range between 800 kg/s and 1400 kg/s. The corresponding mass flux is in the range of 200 – 500 $\mathrm{kg/m^2s}$, from which the flow velocity of the test apparatus was determined.

Heat flux condition is determined using $\frac{q''}{V^3\rho_f}$ dimensionless number. Thus, once the same working fluid and fluid velocity were predetermined, the value of heat flux also should be same. Park et al. reported in the analysis that the heat flux value on the hemispherical lower head of the reactor pressure vessel can increase up to 1400 $\mathrm{kW/m^2}$. The same heat flux condition should be considered in the test apparatus.

To simulate same localized thermal-hydraulic characteristics at each location on the hemispherical lower head of the reactor pressure vessel, the test section was designed to be inclined from 0° (downward) to 90° (vertical) at an interval of 15° using a rotatable optical table. Void fraction of two-phase flow at the test section was set to be same as that at the corresponding point of the hemispherical lower head, using a set of preheaters. To insure fully development of the two-phase flow, an adiabatic entrance flow region of 500 mm in length was placed between the preheaters and the test section. The entrance length was calculated by Eq. (1) for turbulent flow [9].

$$\frac{l}{D_h} = 4.4Re^{1/6} \quad (1)$$

5. Conclusions

To simulate the thermal-hydraulic similarities on external reactor vessel in ERVC conditions, the dimensions of a flow boiling test apparatus on downward-facing heated wall and experimental conditions were determined using Buckingham Pi-theorem. The obtained main results are summarized as follows:

- From the similarity analysis using Buckingham Pi-theorem, hydraulic diameter of the test apparatus was set to be 13 mm and corresponding Reynolds number (>9,000) is the same turbulent flow condition with APR1400.
- The dimensions of a flow boiling test apparatus were determined by Re and $\frac{L}{d}$ dimensionless numbers. The dimensions of test apparatus were 10 mm (w) × 20 mm (H) × 130 mm (L).
- The experimental conditions of test apparatus were established that the mass flux was in the range of 200 – 500 $\mathrm{kg/s}$ and heat flux was up to 1400 $\mathrm{kW/m^2}$.

Table 3. Comparison of dimensionless group and independent boiling parameters between APR1400 and test section

Dimensionless number	APR1400 [8]	Test section	Comments
Buckingham Pi-theorem for APR1400			
$\frac{\rho V d(D)}{\mu}$	157,140 – 192,742	9,464 – 23,661	Turbulent flow conditions
$\frac{V^2}{gd}$	0.02 – 0.36	0.22 – 1.38	Influence of buoyancy force to fluid motion
$\frac{\rho V^2 L_b}{\sigma}$	53 - 673	9 - 59	Used to analyze the formation of bubbles We > 1, Inertial force is stronger than surface tension
$\frac{V^2}{C_p \Delta T}$	1.03×10^{-5} -6.47×10^{-5}	1.03×10^{-5} -6.47×10^{-5}	Ratio of the kinetic energy to the enthalpy driving force for heat transfer
$\frac{V^2}{h_{fg}}$	1.21×10^{-7} -1.92×10^{-8}	1.21×10^{-7} -1.92×10^{-8}	Ratio of thermal to kinetic energies
$\frac{q''}{V^3\rho}$	-	-	Heat flux to kinetic energies of bubble
$\frac{L}{d}$	4.3 – 8.6	9.75	Flow development
$\frac{\rho_f}{\rho_g}$	-	-	T = Saturated condition P = Atmospheric pressure
Independent boiling parameters			
α	0 – 0.8	0 – 0.8	Inlet void fraction
θ	0 – 90 °	0 – 90 °	Inclination angle

- The inclination angle was controlled from 0 ° (downward) to 90° (vertical) with an intervals of 15°.
- Entrance region was designed with 500 mm to insure fully development of the two-phase flow in turbulent flow condition.

Experiments will be conducted to investigate slug-bubble flow boiling phenomena on downward-facing heated walls applicable to IVR-ERVC, and obtained results will be utilized to improve wall boiling model in CFD for a downward-facing heated wall.

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