Redefinition of *Ra'* for the 2D experimental facility simulating IVR-ERVC

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1. Introduction

In a severe accident, molten fuels relocate and stratify into the upper metallic layer and lower mixture layer by the difference of density. The decay heat generated from mixture layer should be cooled properly so as to retain the core melt safely in the vessel (IVR-ERVC: In Vessel Retention-External Reactor Vessel Cooling).

There are several studies simulating the IVR-ERVC phenomena with 3D and 2D experimental facilities. Since the mixture layer generates the decay heat continuously, the volumetric heat source should be established. The modified Rayleigh number, *Ra'* was defined as the product of *Ra* and Damköhler number to incorporate the internal heat generation. We discovered that the existing definition of *Ra'* is improper for the 2D tests. This study discusses the problem of the existing definition of *Ra'* for the 2D experiments and redefines it.

We performed mass transfer experiments based on the analogy between heat and mass transfer with 2D and 3D facilities. The experimental facilities are semi-circular for 2D and hemi-spherical for 3D (MassTER-OP3 and MassTER-OP2: Mass Transfer Experimental Rig for a 3D and 2D Oxide Pool).

2. Theoretical Background

2.1 Definition of Ra'

In order to incorporate the decay heat emitted in the mixture layer, the expression for interal heat generation is needed replacing the temperature difference expression for traditional *Ra*. Thus *Ra'* is used to describe the natural convection heat transfer phenomena involving the internal heat source.

$$Ra' = Ra \times Da \ , \tag{1}$$

$$\text{Damköhler number } (Da) = \frac{q''' H^2}{k \Delta T} \ \text{and} \tag{2}$$

$$Ra' = \frac{g\beta \Delta T H^3}{\alpha \nu} \times \frac{q''' H^2}{k \Delta T} = \frac{g\beta q''' H^5}{\alpha \nu k} \tag{3}$$

2.2 Previous studies

2.2.1 Three-dimensional experiments

Asifa and Dhir [1] experimented the natural convection heat transfer phenomena with the 3D hemispherical facility (UCLA). The developed correlation was in the *Ra'* range of 2×10^{10} and 1.1×10^{14}.

$$Nu_{dn} = 0.54\,(Ra')^{0.2}\,(H/R_e)^{0.25} \tag{4}$$

Theofanous and Angelini [2] performed the experiments in the 3D hemispherical pool (ACOPO). They developed the correlations with the *Ra'* range of 1×10^{12} and 2×10^{16}.

$$Nu_{up} = 1.95\,Ra'^{\,0.18} \tag{5}$$

$$Nu_{dn} = 0.3\,Ra'^{\,0.22} \tag{6}$$

2.2.2 Two-dimensional experiments

Lee et al. [3] performed the natural convection heat transfer experiments in a 2D semi-circular pool (SIGMA CP). They developed the heat transfer correlations in the *Ra'* range of 5.71×10^{6} and 7.04×10^{11}.

$$Nu_{up} = 0.31(Ra'_H Pr^{-0.36})^{0.245} \tag{7}$$

$$Nu_{dn} = 0.219(Ra'_H Pr^{-0.215})^{0.235} \tag{8}$$

Bonnet and Seiler [4] investigated the natural convection heat transfer using a 2D semi-circular experiment facility (BALI). The correlation was developed with the *Ra'* of $10^{15} - 10^{17}$.

$$Nu_{up} = 0.383\,Ra'^{\,0.233} \tag{9}$$

$$Nu_{dn} = 0.116\,Ra'^{\,0.25}\,(H/R_e)^{0.32} \tag{10}$$

3. Redefinition of *Ra'*

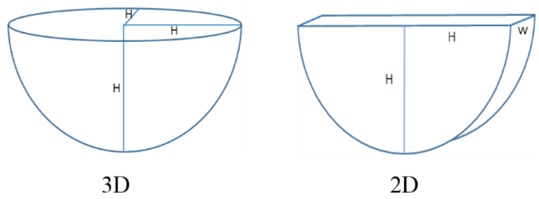

Fig. 1. Geometries of experimental facilities.

Fig. 1 presents the geometries of semi-circular (2D) and hemi-spherical (3D) experimental apparatuses. The characteristic length for the 3D facility is only height (H). For the 2D facility, width (W) should also be taken into account to decide the volume.

The volumetric heat flux (q''') was defined as below.

$$q''' = \frac{q}{H^3} \tag{11}$$

This definition is proper for the 3D facility. However, it is not suitable for the 2D facility, because it neglects the width. Hence, the volume of the 2D facility should be properly defined using *d* and *H* so as to compare the results of 2D and 3D experiments.

Table I: Definitions of q/V, q''' and *Ra'*

	$\frac{q}{V}$	q'''	Ra'
3D	$\frac{q}{\frac{2}{3}\pi H^3}$	$q'''_{3D} = \frac{q}{H^3}$	$Ra'_{3D} = \frac{g\beta H^2 q}{\alpha\nu k}$
2D	$\frac{q}{\frac{1}{2}\pi H^2 d}$	$q'''_{2D} = \frac{4}{3}\times\frac{q}{H^2 d}$	$Ra'_{2D} = \frac{4}{3}\frac{g\beta H^3 q}{\alpha\nu k d}$

Table 1 summaries definitions of *q*/V, *q'''* and *Ra'* for the 3D facility and 2D facility. As mentioned, the volumetric heat flux for the 3D facility (q'''_{3D}) was already defined as

$$q'''_{3D} = \frac{q}{H^3}. \tag{11}$$

Expressed using volume of a facility (V), it becomes

$$q'''_{3D} = \frac{q}{V}\times\frac{2}{3}\pi \tag{12}$$

$$\text{for} \quad V = \frac{2}{3}\pi H^3. \tag{13}$$

Like this, the volumetric heat flux for a 2D facility (q'''_{2D}) could be redefined as

$$q'''_{2D} = \frac{q}{V}\times\frac{2}{3}\pi \tag{13}$$

$$\text{for} \quad V = \frac{1}{2}\pi H^2 d. \tag{14}$$

And then,

$$q'''_{2D} = \frac{4}{3}\times\frac{q}{H^2 d}. \tag{15}$$

Thus

$$Ra'_{2D} = \frac{g\beta\Delta T H^3}{\alpha\nu}\times\frac{4}{3}\frac{qH^2}{k\Delta T H^2 d} = \frac{4}{3}\frac{g\beta H^3 q}{\alpha\nu k d}. \tag{16}$$

Consequently,

$$Ra'_{2D} = Ra'_{3D}\times\frac{4}{3}\frac{H}{d}. \tag{17}$$

4. Experiments

4.1 Methodology

This study performed mass transfer experiment using the electroplating system based on analogy between heat and mass transfer. *Nu* and *Pr* of heat transfer analogy with *Sh* and *Sc* of mass transfer, respectively.

A mass transfer experiment using the electroplating system is performed first by Levich [5], and Selman [6] organized mass transfer correlations under different conditions after that. A more detailed explanation of the methodology can be found in Chung et al [7]. Because it is difficult to know the concentration of copper ion on the cathode surface, we used limiting current technique. When the potential between electrodes increases continuously, the current increases until the plateau region, which is steady despite the applied voltage increases. The current in plateau region is the limiting current. In limiting current, the concentration of copper ion on the cathode surface is almost zero. Therefore, mass transfer coefficient h_m is defined as below.

$$h_m = \frac{(1-t_{Cu^{2+}})I_{\lim}}{nFC_b} \tag{18}$$

4.2 Experimental facility

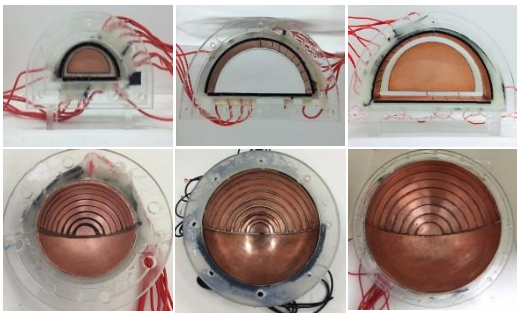

Fig. 2. Experimental facility of MassTER-OP2 and MassTER-OP3.

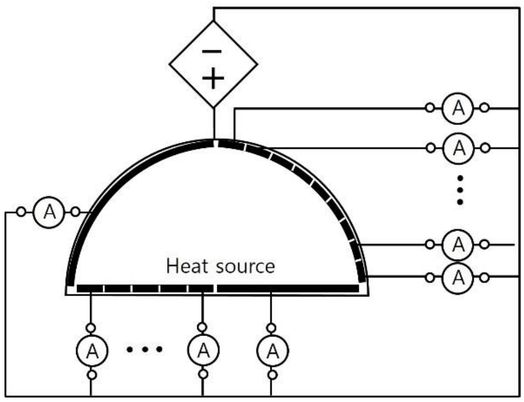

Fig. 3. Experimental circuit.

Fig. 2 indicates the experimental facilities of MassTER-OP3 and MassTER-OP2. MassTER-OP3 are hemi-spherical facilities (3D) where Ra'_{3D} is 1.81×10^{13}, 4.24×10^{14} and 3.05×10^{15}. MassTER-OP2 facilities are semi-circular shaped, where Ra'_{2D} is respectively 7.15×10^{12}, 1.74×10^{14} and 1.41×10^{15}.

The copper is lined on the inner wall of upper and curved side. In order to measure local current, half of the copper is divided by 4pieces on upper side and 9 pieces on curved side. Volumetric heat source is fixed on the flat side wall for MassTER-OP2 and on the inner center of hemisphere for MassTER-OP3. The facility is filled with sulfuric acid–copper sulfate (H_2SO_4–$CuSO_4$) fluid.

Fig. 3 shows the system circuit. The multi-meter is connected with cathode copper in parallel.

5. Results and discussion

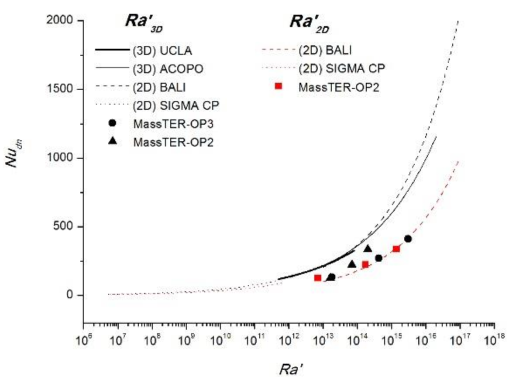

Fig. 4. A comparison of measured Nu_{dn} with existing correlations for Ra'_{3D} and Ra'_{2D}.

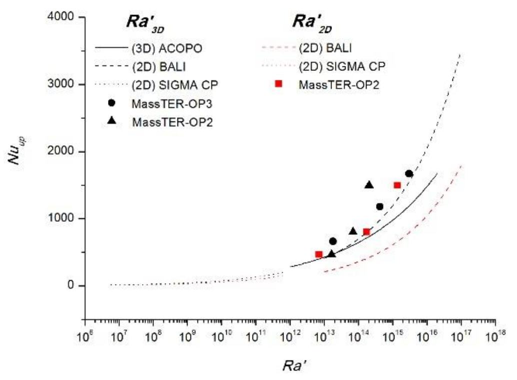

Fig. 5. A comparison of measured Nu_{up} with existing correlations for Ra'_{3D} and Ra'_{2D}.

Fig. 4 compares the Nu_{dn} of MassTER-OP experiments with existing correlations for the curved surface for Ra'_{3D} and Ra'_{2D}. And Fig. 5 compares the Nu_{up} of MassTER-OP experiments with existing correlations for the top plate for Ra'_{3D} and Ra'_{2D}. The black lines are 3D (UCLA, ACOPO) and 2D (BALI, SIGMA CP) correlations in their original forms using the Rayleigh number definition for 3D, Ra'_{3D}. The red lines are 2D correlations using the new Rayleigh number definition for 2D, Ra'_{2D}. The black circles and the black triangles indicate Nu_{dn} of MassTER-OP3 and MassTER-OP2 using the original definition of the Rayleigh number definition for 3D, Ra'_{3D}. The red squares indicate Nu_{dn} of MassTER-OP2 using the new Rayleigh number definition for 2D, Ra'_{2D}.

The present experimental results agree with the modified correlation of the BALI experiment for curved surface and agree with the original correlation of the BALI experiment for the top plate. Comparing with other experiments, the current results underestimate the heat flux for the curved surface and overestimate the heat flux for the top plate.

In both Fig. 4 and Fig. 5, the black circles (3D experiments) and the red squares (2D experiments with new definition of Ra'_{2D}) show consistency. The black triangles (2D experiments using the existing definition of Ra'_{3D}) show different trend against the black circles. This means the new definition of Ra'_{2D} is proper for 2D experiments in terms of comparing the results with 3D experiments.

6. Conclusions

This study simulated oxide pool using 3D and 2D facilities and performed mass transfer experiments based on the heat and mass transfer analogy concept. We found the existing definition of *Ra'* is not proper for 2D facility so as to compare with 3D results and redefined Ra'_{2D} for 2D facility. Then, we applied the redefined Ra'_{2D} to the all 2D results including MassTER-OP2, and compared with MassTER-OP3 results and 3D correlations. In the both curved surface and top plate, *Nu* trend of MassTER-OP2 for redefined Ra'_{2D} agreed with that of MassTER-OP3 more than that for Ra'_{3D}.

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