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Investigations on the Steam Condensation in a Vertical Tube Geometry

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1. Introduction

In case of accidents that threats containment integrity, such as Station Black Out (SBO), it is able to depressurize containment using exterior-surface condensation in presence of non-condensable gases, which is named as Passive Containment Cooling System (PCCS). It is very important to precisely predict heat removal capability PCCS, as it affects safety and economics.

A few investigations have conducted by various researchers, such as JNU [1], A. Dehbi [2], Kawakubo [3], and P. Tong [5], to find out the effect of non-condensables, subcooling and pressure. However, the effect of curvature is not yet experimentally and numerically studied. It is reported that the effect of curvature exists at single-phase condition, yet it is not studied that if it can applicable to two-phase condensation in presence of non-condensables.

In this paper, various experimental data are collected to analyze if it is able to observe curvature effect. However, it is hard to analyze experimental data, as the geometry, experimental conditions and means of measurement differs. To check if the differences between experiments are curvature effect, each experiment is compared with CFD simulation result using a commercial CFD code, STAR-CCM+.

2. Correlations for vertical tube curvature effect

Cebeci theoretically shown the existence of curvature effect in vertical cylinder, single-phase fluid flow condition. Popiel derived the average Nusselt number correlation, based on Cebeci's theoretical result: [4]

$$\frac{Nu_H}{Nu_{H,FP}} = 1 + A \cdot [32^{0.5} Gr_H^{-0.25} \frac{H}{D}]^B \qquad (1)$$

where

$$A = 0.0571322 + 0.20305 \cdot \Pr^{-0.43}$$
$$B = 0.9165 - 0.0043 \Pr^{0.5} + 0.01333 \ln(\Pr) + 0.0004809 / \Pr \qquad (2)$$

The correlation is valid for Pr=0.01 to 100 and Gr<4E9. A comparison equation between 1cm and 4cm outer diameter cylinder using equation (1) is derived as:

$$\frac{Nu_{H,1cm}}{Nu_{H,4cm}} = \frac{1 + A \cdot [32^{0.5} Gr_H^{-0.25} \frac{H}{D_{1cm}}]^B}{1 + A \cdot [32^{0.5} Gr_H^{-0.25} \frac{H}{D_{4cm}}]^B} \qquad (3)$$

'H', 'D', 'FP' represents for length, diameter of cylinder, flat plate, respectively. In case of air, using Pr=0.72 and Gr=4e9, the 1cm-to-4cm ratio calculated as 1.37, while the ratio of steam, using Pr=1.06 and Gr=4e9, is calculated as 1.33. For water, using Pr=6 and same Grashof number, the ratio is 1.21.

From given correlations and comparison results, it is able to predict the existence of curvature effect. Thinking two-phase as an imaginary mixture of water and steam, the curvature effect is somewhat between 1.21 and 1.33. However, it is unknown how condensation phenomenon will affect curvature effect.

3. Various condensation experiments

A few experiments are conducted for various non-condensables, wall subcooling and pressure condition. In this paper, experiments of exterior surface condensation in presence of non-condensables are collected.

The geometry of experiment facilities can be generalized as fig. 1, with difference of diameter and length of pressure vessel.

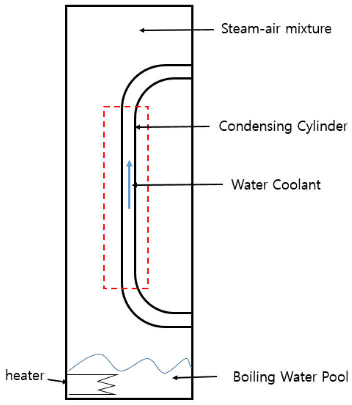

Fig 1. Geometry of experiment facilities

Specific geometry of experiment facilities are written in table 1. Bulk and Tube represent for pressure vessel and condensing cylinder, respectively.

Table Ⅰ: Specific geometry of experiment facilities

Name	Bulk diameter	Bulk height	Tube diameter	Tube height
JNU	0.61 m	1.95 m	1cm/4cm	1 m
Kawakubo	0.492 m	2.7 m	1cm	1 m
A. Dehbi	0.45 m	5 m	4cm	3.5 m
P. Tong	0.245 m	Approx. 2.5 m	4cm	2 m

It is known that pressure, air mass fraction and subcooling affects the heat transfer coefficient. To analyze only about curvature effect, effect of air mass fraction, pressure and subcooling should be eliminated.

The range of air mass fraction and pressure is written in table 2.

Table Ⅱ: Pressure and air mass fraction conditions

Name	Pressure	Air Mass Fraction Range
JNU_4cm	4 bar	0.1 to 0.8
JNU_1cm	4 bar	0.1 to 0.8
Kawakubo	4 bar	0.1 to 0.5
A. Dehbi	4.5 bar	0.3 to 0.86
P. Tong	4 bar	0.18 to 0.8

In this paper, air mass fraction range, 0.3 to 0.5 is taken into consideration. For elimination of pressure effect, pressure condition of experiments except Dehbi's are limited to 4 bar. The experiment data of Dehbi's 4.5 bar condition can be converted into 4.0 bar condition, using his own correlation:

$$h_{Dehbi,tube} = 1.25 \cdot \frac{L^{0.05}[(3.7+28.7P)-(2438+458.3P)\log W_{air}}{(T_{\infty,sat}-T_{wall})^{0.25}} \quad (4)$$

Using experiment conditions, the average 4 to 4.5 bar ratio is calculated as 0.944.

Lastly, subcooling effect should be taken into account. Each experiment have its own subcooling value, making it difficult to analyze curvature effect. In case of JNU, Kawakubo and Dehbi's experiments, the subcooling is specified, whereas P. Tong's is given as range. The range of each experiment is listed in table 3.

Table Ⅲ: Subcooling range of experiments

Name	Subcooling Range
JNU	36.2K to 56.4K
Kawakubo	20K and 30K
A. Dehbi	22.3K to 29.7K
P. Tong	13K to 25K

A general form of heat transfer coefficient in presence of non-condensables is given as:

$$h = (T_{bulk}-T_{wall})^{a} \cdot f(W_{air}, P) \quad (5)$$

Generally, -0.25 is used for index 'a', from theoretical study of laminar pure steam condensation solution. In this study, to eliminate effect of subcooling, a modified heat transfer coefficient for this study is defined by dividing heat transfer coefficient with subcooling effect term, that is,

$$h_{mod} = \frac{h}{(T_{bulk}-T_{wall})^{-0.25}} = f(W_a, P_{4bar}) \quad (6)$$

The modified heat transfer coefficient of various experiments, with pressure and subcooling effect eliminated by using eq. (4) and eq. (6), are plotted in fig. 2. In graph, 'dT' represents for wall subcooling. Due to its subcooling uncertainty of Pan Tong's experiment, possible modified heat transfer coefficient expressed as shaded area.

It is able to observe the range of 1cm diameter experiments, from Kawakubo's to JNU_1cm, is located slightly above the range of 4cm diameter experiments, from JNU_4cm to Dehbi's. However, due to scattered experiment results, two ranges are overlapped much, making it hard to observe a clear curvature effect from data.

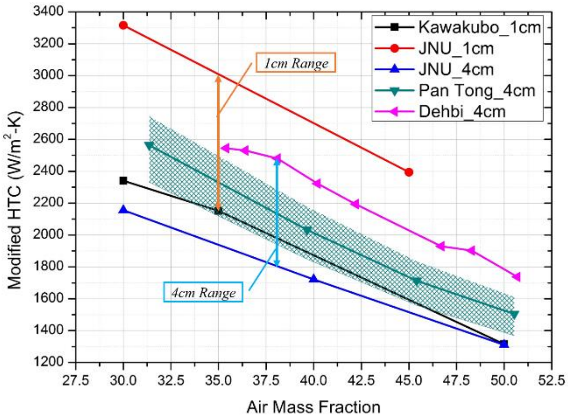

Fig 2. Modified heat transfer coefficient of experiments

4. CFD simulation of experiments

To evaluate and see if curvature effect exists in numerical calculation, using STAR-CCM+, a commercial CFD code, all experiments are simulated. STAR-CCM+ creates two-dimensional shell region in vicinity of wall surface to calculate condensation. Total evaporation and condensation rate with bird suction factor for vigorous condensation at fluid film is written as:

$$\dot{m}_{condensation,i} = -\frac{\left(Y_{g_c}-Y_{g_s}\right)\rho_{g_s} D_{g,i}}{1-Y_{g_s}} \frac{\ln(1+B)}{B} \quad (7)$$

Suction factor B is written as:

$$B = \frac{Y_{g_s}-Y_{g_s,\infty}}{1-Y_{g_s}} \quad (8)$$

and it is assumed that

$$Y_{g,\infty} \approx Y_{g,c} \quad (9)$$

Subscripts 'i', 'g', 'c' and 's' represents for interfacial, gas, cell and surface, respectively.

For CFD simulation, a quarter of each experiment facility is modeled using prism layer and polyhedral mesher. For every simulation, wall Y+ value is kept below 1. Detailed physics settings are listed in table 4.

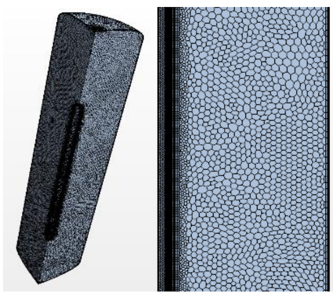

Fig 3. Mesh grid used for simulation.

Table Ⅳ: Physics settings for CFD simulation

Physics	Value
Time step	0.001 sec
Turbulence model	SST K-omega model

Condensation heat transfer coefficient is very sensitive to diffusion model. To adjust diffusion model, user defined diffusion model is applied for simulation. Chosen diffusion model is one that used in MELCOR code:

$$D = 4.7931 \cdot 10^{-5} \left[\frac{T^{1.9}}{P} \right] \qquad (10)$$

Shown in eq. (8) and eq. (9), STAR-CCM+ does not use bulk steam mass fraction but uses a cell value right beyond shell region. This results in lack of steam supply, making STAR-CCM+ underestimate. Defining suction factor not only in shell region, but also in bulk region might compensate. Modified diffusion model for bulk region is defined as:

$$4.7931 \cdot 10^{-5} \left[\frac{T^{1.9}}{P} \right] \cdot \frac{\ln(1+B)}{B} \qquad (11)$$

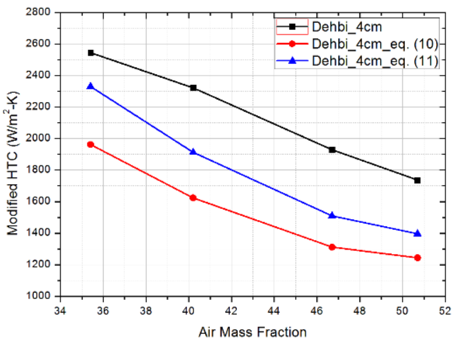

Fig 4. CFD simulation result of Dehbi's experiment

It is shown in fig. 4 that CFD significantly under-predicts heat transfer coefficient in case of Dehbi's experiment, yet CFD is able to calculate the trend along air mass fraction.

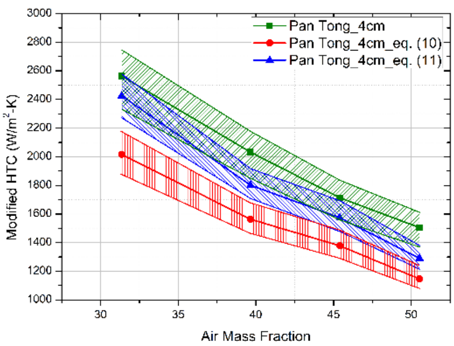

Fig 5. CFD simulation result of P. Tong's experiment

In case of P. Tong's experiment, due to its uncertainty of subcooling, a range of subcooling are simulated. It is shown in fig. 5 that CFD significantly under-predicts heat transfer coefficient at all subcooling without usage of eq. (10). When eq. (11) is applied, the CFD calculation result partially overlapped with range of experiment.

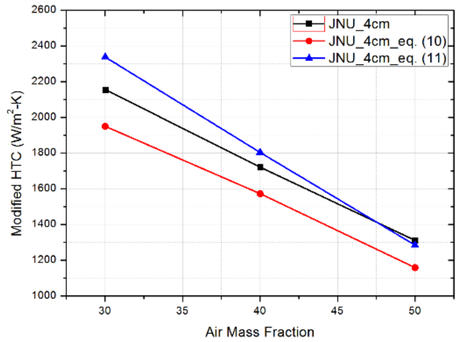

Fig 6. CFD simulation result of 4cm tube by JNU

It is shown in fig. 6 that CFD under-predict heat transfer coefficient at 4cm diameter JNU experiment just like P. Tong's experiment. When eq. (11) applied, CFD overestimates at low air mass fraction and underestimates at high air mass fraction.

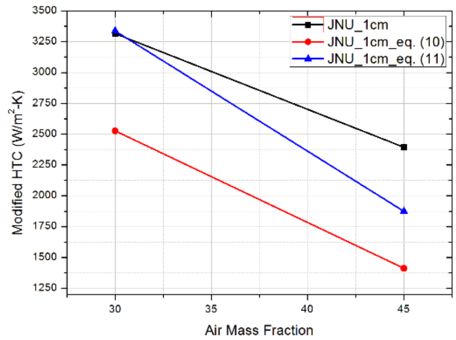

Fig 7. CFD simulation result of 1cm tube by JNU

For 1cm diameter experiment conducted by JNU, CFD significantly underestimate. However, usage of eq. (11) reasonably predicts the heat transfer coefficient at low air mass fraction. However, as seen in 1cm experiment of JNU, CFD underestimate at high air mass fraction.

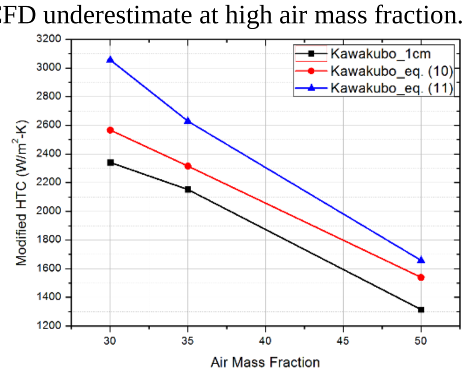

Fig 8. CFD simulation result of Kawakubo's experiment

Unlike any other experiment, CFD overestimates heat transfer coefficient. Without using eq. (11), the trend along air mass fraction of CFD simulation is similar to experiment data, yet the usage of eq. (11) makes CFD to overestimate at low air mass fraction.

5. 1cm-to-4cm comparison and discussion

In this study, 1cm-to-4cm ratio is compared for evaluation of curvature effect in experiment and CFD. Data without value at chosen air mass fraction was calculated by linear curve fitting. All values for comparison between experiments are calculated based on modified heat transfer coefficient; i.e., subcooling and pressure effects are eliminated. As mentioned, the experiment of P. Tong is expressed as shaded area.

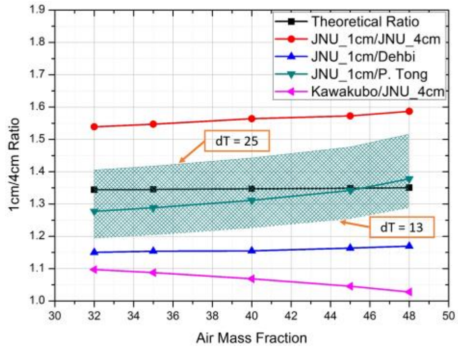

Fig 9. 1cm-to-4cm ratio of experiments

The ratio between 1cm and 4cm experiments shows the existence of curvature effect. However, the experimental ratio scatters a lot, minimum 1.02 to maximum 1.6. From this result, it can be assumed that Dehbi's experiment and P. Tong's experiment measured relatively high heat transfer coefficient compared with 4cm diameter experiment of JNU.

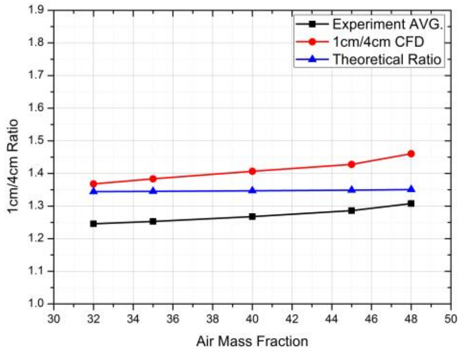

Fig 10. CFD 1cm-to-4cm ratio of CFD with eq. (11)

As it is able to change subcooling and pressure freely in CFD, a 4-bar, subcooling 30K is simulated for investigation only about curvature effect. In fig.10, it is shown that CFD tends to overestimate the curvature effect, while average of experiments tends to underestimate. Overall trend versus air mass fraction is similar with average of all experiments listed in fig. 9.

Interesting point is, as air mass fraction gets higher, curvature effect reinforces, both in experiment and CFD. In theory of Popiel derived for single-phase condition, no such phenomenon is observed.

6. Conclusions

In this paper, with correlations derived from prior studies, we found the existence of curvature effect under PCCS operating condition. However, it is unable to find out a clear curvature effect at experiment data as they scatter much. As a means of comparison reference between experiment, CFD code is used.

From comparison between CFD and experiment, we could confirm the existence of curvature effect. However, measured heat transfer coefficients of Kawakubo's experiment are relatively low, whereas Dehbi's measurement data are relatively high. Also, considering that usage of eq. (11) overly supplies steam to condensing shell region, heat transfer coefficients of Pan Tong's measured relatively high, but not as much that of Dehbi's. A further experimental identification is needed for evaluation.

Currently, CFD code calculates the curvature effect. Overall trend versus air mass fraction is similar with average of experiment. In high air mass fraction, CFD and experiment shows higher curvature effect; theory of Popiel doesn't show such phenomenon, implying a need of further research.

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REFERENCES

[1] D.-W. Jerng, Y-G Lee, B-J. Yun, et al., "A study on heat transfer model and performance of Passive systems for nuclear power plant containment cooling", National Research Foundation of Korea, 2015

[2] A. Dehbi, "Prediction of steam condensation in the presence of noncondensable gases using a CFD-based approach", *Nuclear Engineering and Design*, Vol. 258, pp 199-210 (2013)

[3] M. Kawakubo et al., "An Experimental Study on the cooling Characteristics of Passive Containment Cooling Systems", *Journal of Nuclear Science and Technology*, Vol. 46, pp 339-345 (2009).

[4] C.O. Popiel, "Free Convection Heat Transfer from Vertical Slender Cylinders: A Review", *Heat transfer Engineering*, 29(6), pp. 521-536 (2008).

[5] Pan Tong et al., "An experimental investigation of pure steam and steam-air mixtures condensation outside a vertical pin-fin tube", *Experimental Thermal and Fluid Science*, Vol. 69, pp 141-148 (2015).