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Evaluation of Condensation Models for the Outer Wall under Pure Steam Condition

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1. Introduction

i-SMR (Innovative Small Modular Reactor) adopts a Passive Containment Cooling System (PCCS) to prevent the increase of pressure inside of a containment vessel in the postulated SBLOCA (Small Break Loss of Coolant Accident). In the nominal condition of the i-SMR, the containment maintains almost vacuum condition and it is exposed to steam in the SBLOCA. Therefore, the evaluation of prediction capability of steam condensation models adopted in the safety analysis code is necessary.

Present study was conducted to investigate the steam condensation in the PCCS. For this, available condensation models and experimental data for pure steam condensation were collected from open literature. Finally, the steam condensation models were evaluated against the experimental data

2. Steam condensation models

Although the containment of i-SMR is designed to be operated at the vacuum condition, small amount of air is expected in the actual condition. Therefore, existing correlations for condensation of steam mixed with non-condensable gas as well as for pure steam on a vertical plate or tube were reviewed and evaluated in this study.

Fig. 1 illustrates the filmwise condensation process on the vertical condenser wall, which includes two distinct regions for the condensate film and diffusion layer, respectively. And the total heat transfer coefficient can be calculated as follows:

$$h_{total} = \frac{h_{film}+h_{diff}}{h_{film}h_{diff}} \quad (1)$$

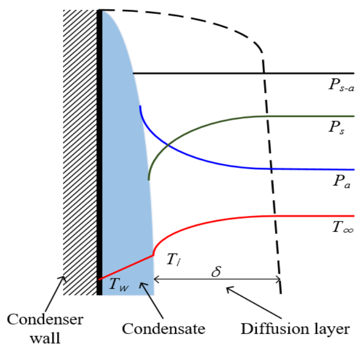

Fig. 1. Filmwise condensation in the presence of non-condensable gas

2.1 Condensation models for condensate film region

The steam condenses on the cold wall and flows downward as a liquid film as shown in Fig. 2. It can be categorized as laminar, laminar-wavy, and turbulent film regime according to the film Reynolds number (Re_{film}). The widely used condensation heat transfer correlations for each condensate film regimes were reviewed and tabulated in Table I. Among them, Nusselt [1] model was adopted in the best estimate code, MARS-KS [8].

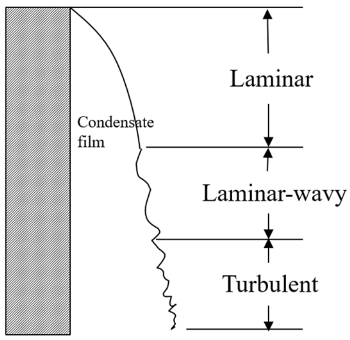

Fig. 2. Flow regimes of condensate film

Table I: Existing correlations for condensation film

Nusselt [1] (laminar)
$h_{film} = 1.47 k_{film} Re_{film}^{-1/3} \left[\frac{\mu_l^2}{g\rho_l(\rho_l-\rho_g)}\right]^{-1/3}, Re_{film} \le 30$
Kutateladze[2] (Laminar-wavy)
$h_{film} = \frac{k_{film} Re_{film}^{-1/3}}{1.08 Re_{film}^{1.22}-5.2} \left[\frac{\mu_l^2}{g\rho_l(\rho_l-\rho_g)}\right]^{-1/3},\ 30 < Re_{film} \le 1800$
Labuntsov[3] (turbulent)
$h_{film} = \frac{k_{film} Re_{film}^{-1/3}}{8750+58 Pr_{film}^{-0.5}(Re_{film}^{0.75}-253)} \left[\frac{\mu_l^2}{g\rho_l(\rho_l-\rho_g)}\right]^{-1/3}, Re_{film} > 1800$

2.2 Condensation models for gas diffusion region

In the presence of non-condensable gas, the diffusion layer of the gas is formed as shown in Fig. 1. MARS-KS [8] adopted Churchill and Chu [9] model. Recently, Kang et al. [4] developed a condensation model applicable to steam-air mixed gas condition. The two correlations are summarized in Table II.

Table II: Existing correlations for the diffusion layer region

Churchill and Chu [9]	$h_{diff} = (0.825 + \frac{0.387 Ra_L^{1/6}}{(1+(\frac{0.492}{SC})^{9/16})^{8/27}})^2 \frac{D_{s-a}}{L}$
Kang et al. [4]	$h_{diff} = \rho_{s-a} D_{s-a} \frac{h_{fg}}{T_\infty - T_i} \frac{W_{s,\infty} - W_{s,i}}{1 - W_{s,i}} \frac{Sh_L}{L}$ $Sh_L = 0.19 Ra_L^{0.3} \theta_{suction} \eta_{curvature} (1 + 0.2 AR^{0.8})$

3. Evaluations

The aforementioned condensation models were evaluated against experimental data obtained in the pure steam conditions as in Table III.

Table III: Experimental condition of available pure steam condensation data

Experiment	thermal-hydraulic parameters		
	$P_{s\text{-}a}$ (kPa)	$W_{a,\infty}$ (-)	$\Delta T_{w,sub}$ (K)
Kang et al. [4]	200-600	Almost pure (0.005-0.02)	10.4–35.1
Bian et al. [5]	200-1600	Pure steam	50.0-90.0
Fan et al. [6]	400-500	Pure steam	11.8-31.6
Tong et al. [7]	600	Pure steam	5.2-20.9

3.1 Evaluation of film condensation models

The evaluation results of three models introduced in previous section are shown in Fig. 3. In case of Kang et al. [4] data, Nusselt [1] model showed the best prediction result. For the Bian et al. [5] data, which was obtained in high pressure condition, Labuntsov [3] model showed the best prediction performance among the models. However, all models showed a significant discrepancy in cases of Fan et al. [6] and Tong et al. data [7]. The film condensation models were developed theoretically or based on the experimental data, therefore the significant discrepancy with Fan et al. [6] and Tong et al. [7] data can be attributed to the uncertainty of the two experimental data. However, it requires more confirmation on the quality of the two kinds of data.

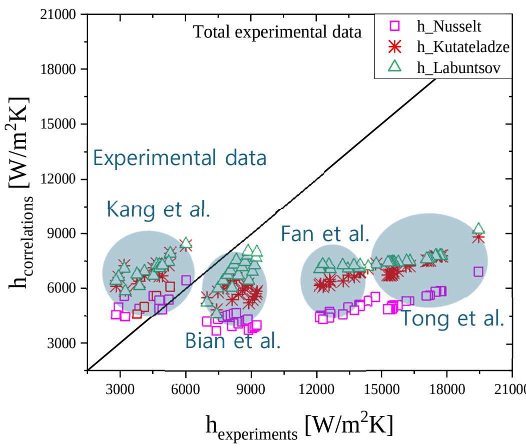

Fig. 3. Evaluation results of condensate film heat transfer coefficient models for pure steam condensation

3.2 Evaluation of Kang et al. models for gas diffusion region

Fig. 4 represents the evaluation results of the Kang et al. [4] condensation model using their experimental data. A notable thing is the model was developed by using the condensation data in the steam-air condition. In spite of this fact, the model well predicted the experimental data obtained in the pure steam condition as shown in the Fig. 4.

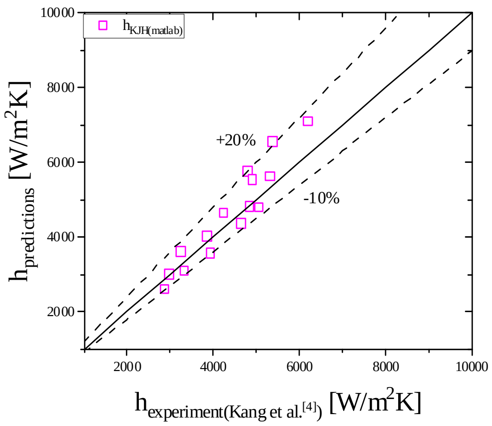

Fig. 4. Evaluation result of the Kang et al.[4] model

3.3 Evaluation with MARS code

Applicability of MARS-KS [8] to the pure steam condensation was evaluated against Kang et al. [4] experimental data. Additionally, we implemented the Kang et al. [4] condensation model into the MARS-KS, and also evaluated. For this, the versions of the MARS-KS were classified as the original MARS and a modified MARS which incorporates the Kang et al. model as described in Table IV.

The nodalization for low pressure calculation is designed to represent the experiments and is illustrated in Fig. 5. In the calculation, the air mass fraction of the test section is set as the initial condition, while the boundary condition is set by constant heat flux and condenser wall temperature. . From this calculation, we obtained steady state condensation heat transfer coefficient of the condensing tube and compared with experimental data. Analysis condition is summarized in Table V.

The evaluation results were shown in Fig. 6. It indicates that the modified MARS showed better result with MAPE 11.3%. However, both two MARS overpredicted the experimental data in the high-pressure region. It shows that both the Kang et al. [4] model and original MARS should be improved for the application to the condensation in the pure steam condition.

For parametric study of the PCCS for i-SMR, we extended present calculation to the pure steam condition for high pressure ranging from 10 to 40 bar. More detailed analysis conditions are summarized in Table V.

The nodalization is changed from the previous one as depicted in Fig. 7. A time-dependent volume was utilized to establish target pressure in the test section, and wall subcooling was controlled by changing the inlet coolant temperature of the secondary side. The evaluation results are shown in Fig. 8. Similar to the results in Fig. 6, the modified MARS showed lower condensation heat transfer coefficient than that of original MARS. It shows again the necessity of experimental data obtained in the high pressure pure steam condition and development of relevant condensation model by using the data.

Table IV: Model set of two MARS code

	h_{film}	h_{diff}
Original MARS	Max(Nusselt [1], Shah [10])	Churchill and Chu [9]
Modified MARS	Table I	Kang et al. [4]

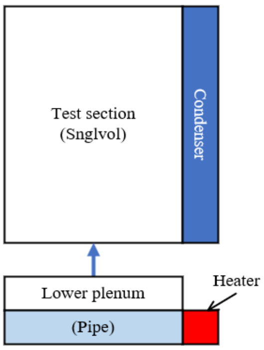

Fig. 5. MARS nodalization for low pressure analysis

Table V: MARS analysis conditions

	Low pressure analysis	High pressure analysis
Experimental data	Kang et al. [4]	X
$P[kPa]$	200 – 600	1000 – 4000
W_a	0.005 – 0.02	0.002 – 0.004
$\Delta T_{wall,sub}[K]$	10.2 – 35.1	18.9 – 58.0

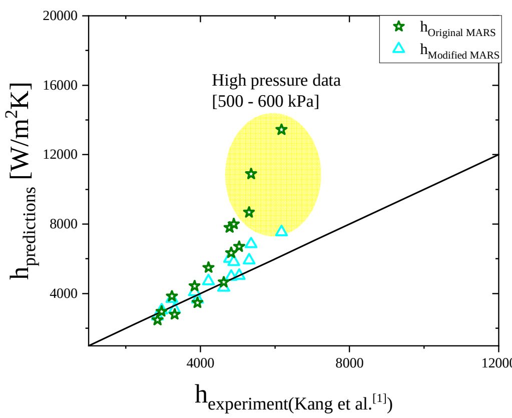

Fig. 6. Comparison of Original and Modified MARS code against Kang et al. [4] data

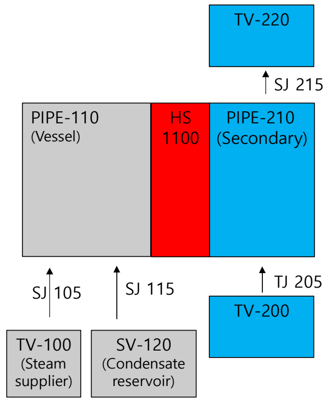

Fig. 7. MARS nodalization for high pressure analysis

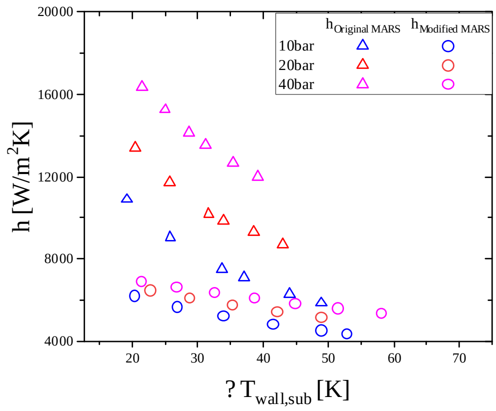

Fig. 8. Exploratory calculation results of MARS for high pressure pure steam condition

4. Conclusions

Available condensation heat transfer coefficient models were investigated and evaluated in the pure steam condition. Additionally, Kang et al. [4] model, which was developed under the presence of non-condensable gas, was evaluated with the pure steam experimental data. Furthermore, the model was implemented into MARS code and then evaluated together with the original MARS code. The evaluation results showed that evaluated correlations had unsatisfactory prediction performance. On the other hand, Kang et al. [4] model showed reasonable prediction results in pure steam conditions even though their model was developed under the presence of non-condensable gas condition. However, present study shows the necessity of experimental data obtained in the high pressure pure steam condition and development of relevant condensation model by using the data.

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