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Study on Pool Surface Evaporation and Model Evaluation

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1. Introduction

Pool surface evaporation is a phenomenon of interest in various fields such as oceanography, atmospheric meteorology, chemistry, and nuclear engineering. In particular, in the field of nuclear engineering, interest in pool surface evaporation after Fukushima Daiichi Nuclear Power Unit 4 is increasing.

In the thermal-hydraulics analysis code, the pool surface heat transfer model was derived from a similar concept. However, due to differences in model implementation methods and various additional effects each code shows different calculation results. This study analyzed the effect of 1) pool surface temperature, 2) effective area between pool surface and atmosphere, and 3) suction effect on pool surface heat transfer model. For this analysis, the pool surface heat transfer model [1] based on HMTA (Heat and Mass Transfer Analogy) was implemented into the CAP code. And using this model as a default model, the effect of the above three on pool heat transfer was analyzed through comparing CAP calculation results and Boelter experiment [2].

2. Pool Surface Evaporation Model

Figure 1 shows the distribution of the pressure and temperature near the pool surface. In the figure, the subscripts a, g, s, l, and gli refer air, gas-mixture, steam, liquid, and gas-liquid interfaces, respectively. Heat and mass transfer between pool and atmosphere occurs through the pool surface. Equation (1) shows the heat flux which is transferred to the pool surface.

$$q_{surf} = (q_{g\to gli} + q_{l\to gli}) \tag{1}$$

- $q_{g\to gli}$: heat flux from atmosphere to the pool surface [W/m^2]
- $q_{l\to gli}$: heat flux from pool to the pool surface [W/m^2]

The mass transfer can be calculated by dividing the heat flux (q_{surf}) by latent heat, or using HMTA. Eq. (2) shows mass flux, calculated using HMTA [2].

$$\Gamma''_{mass} = h_m(\rho_{stm@T_{gli}} - \rho_{stm}) \tag{2}$$

- h_m: mass transfer coefficient [m/s]
- $\rho_{stm@T_{gli}}$: steam density at pool surface [kg/m^3]
- ρ_{stm}: steam density at atmosphere [kg/m^3]

where, h_m was calculated using below assumption:

$$Sh = \frac{h_m}{D_{sg}/L_c} = Nu = \frac{h}{k/L_c} \tag{3}$$

- D_{sg}: diffusivity [m^2/s]
- L_c: characteristic length [m]

2.1 Pool Surface Temperature

Equation (4) shows mass flux, calculated by dividing the heat flux by latent heat.

$$\Gamma''_{heat} = (q_{g\to gli} + q_{l\to gli})/h_{fg} \tag{4}$$

where,

$$q_{g\to gli} = h_{g\to gli}(T_g - T_{gli}) \tag{5}$$

$$q_{l\to gli} = h_{l\to gli}(T_l - T_{gli}) \tag{6}$$

Since Equations (2) and (4) must have the same value, the pool surface temperature (T_{gli}) is a value that satisfies both equations. Contrary of this, CONTEMPT-LT assumes the pool surface temperature as pool bulk temperature.

2.2 Effective Area

Since the contact area between the pool surface and steam is equal to the total surface area multiplied by steam mole fraction, MARS and SPACE multiplied heat flux by steam mole fraction as in Equation (7).

$$q'_{g\to gli} = q_{g\to gli}(P_{stm@T_{gli}}/P) \tag{7}$$

- $P_{stm@T_{gli}}$: steam pressure at pool surface [Pa]
- P: total pressure [Pa]

2.3 Suction Effect

In this study, among suction effect model the Collier's model [3] was used. Collier suction effect model is as follows:

$$h' = h\Phi \tag{8}$$

where,

$$\Phi = \frac{\lambda}{1.0 - e^{-\lambda}} \tag{9}$$

$$\lambda = \frac{\Gamma''_{mass} c_{pg}}{h_{g\to gli}} \tag{10}$$

In the above equation, Γ''_{mass} is the mass flux between pool and atmosphere, and has a negative value when pool evaporation occurs.

In this study, the default model was designed as shown in Equations (2), and 6 sub-models reflecting the above three differences were implemented into CAP.

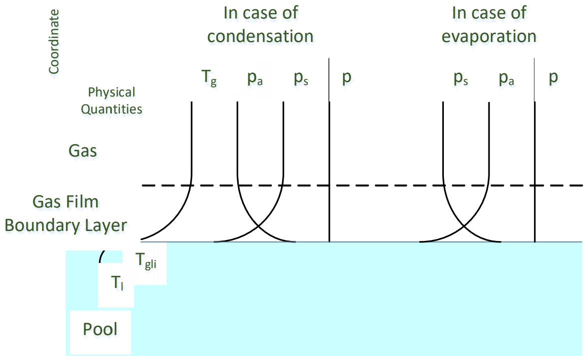

Fig. 1. Distribution of Pressure and Temperature near the Pool Surface

3. Boelter Test [2]

The Boelter experiment is a pool evaporation experiment performed in a 1.0 ft diameter pool. Figure 2 schematically shows the experiment setup. The pool is housed in a 5 x 5 x 7 ft chamber. There is an electric heater inside the pool to keep the pool temperature constant. And all measuring instruments are located inside the chamber. The experiment was performed 43 test sets under the following conditions, and pool evaporation rate was provided as experimental data.

- pressure: 1.0 bar
- pool temperature: 24.0 ~ 94.2 ℃
- atmosphere temperature: 17.2 ~ 26.8 ℃
- relative humidity: 59 ~ 98 %

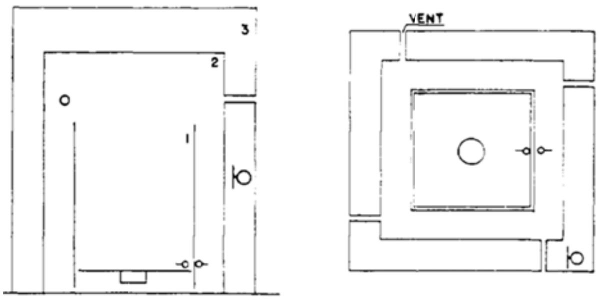

Fig. 2. Boelter Experimental Setup

4. CAP Modeling & Analysis Results

Figure 3 shows the CAP modeling for the Boelter experiment. In order to maintain constant pool and atmospheric thermodynamic conditions, the height of LVol was set large.

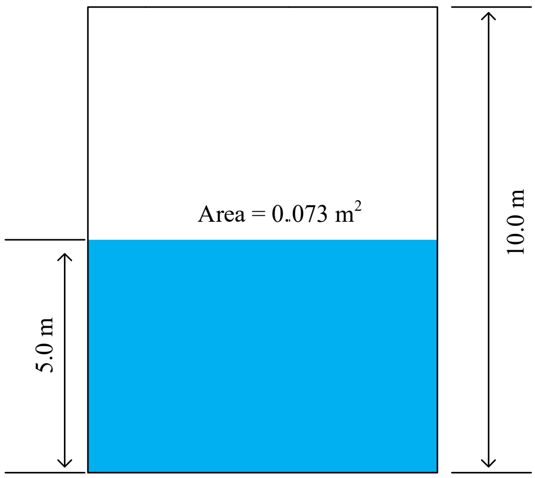

Fig. 3. CAP Modeling

Table I summarized the sub-models implemented to analyze the effect of the three below.

- pool surface temperature
- effective area between pool and atmosphere
- suction effect

The pool surface temperature satisfying Equations (2) and (4) applied to model 1 ~ 3. On the other hand, pool bulk temperature was applied to model 4 ~ 6 as the pool surface temperature. Model 2 and 5 consider the effective area, and model 3 and 6 consider the suction effect.

Table I: Sub-models of Pool Surface Heat Transfer Model

Model No.	Surface Temperature	Effective Area	Suction Effect
1	T_{gli}	-	-
2	T_{gli}	Eq. (7)	-
3	T_{gli}	-	Eq. (8)
4	T_{pool}	-	-
5	T_{pool}	Eq. (7)	-
6	T_{pool}	-	Eq. (8)

Figure 4 shows the comparison results between the predicted values of model 1 ~ 3 and the experimental data. All three models predict experimental data well in the low steam mole fraction region, but under-predict in high steam mole fraction region. Also, no significant differences could be identified between these models. Figure 5 shows the comparison results of the predicted values of model 4 ~ 6 with the experimental data. In high steam mole fraction region, as in model 1 ~ 3, model 4 ~ 6 under-predicted the experimental data. However, overall, model 4 ~ 6 predicted evaporation rate higher than that of model 1 ~ 3.

The effect on the pool surface temperature can be confirmed in model 1 and model 4. Since the pool surface temperature is between that of pool and atmosphere, model 1 has lower temperature difference than model 4. Therefore, model 1 predicts evaporation rate lower than that of model 4. It is noteworthy that model 4 predicted the experimental data more similarly than model 1.

The effect on effective area can be confirmed in model 1 and model 2. In case of effective area is applied, the heat ($q_{g\to gli}$) becomes smaller (see Eq. (7)). Since $q_{g\to gli}$ is negative under the conditions of pool surface evaporation occurs, model 2, applying the effective area, predicted evaporation rate higher than model 1. However, the effective area had little effect on the evaporation rate. In this study, the effective area was implemented to affect only the heat flux as shown in Eq. (7), so there was no effect on the effective area in Model 5.

Finally, the effect on the suction effect can be confirmed in model 1,3 and model 4,6. In case of the suction effect is applied, the heat transfer coefficient and the mass transfer coefficient decrease. Therefore, the model with the suction effect predicts a lower evaporation rate than the model without suction effect. It should be noted that the difference between model 1 and 3 is significantly lower than that of between model 4 and 6. This is because the effect on the suction effect is canceled in the process of calculating pool surface temperature by iterative method. In order for the evaporation rate to decrease, the heat transferred from pool to pool surface ($q_{l\to gli}$) must decrease, so the surface temperature is higher than before. As the pool surface temperature increases, the evaporation rate increases since steam density difference between the pool surface and the atmosphere increases.

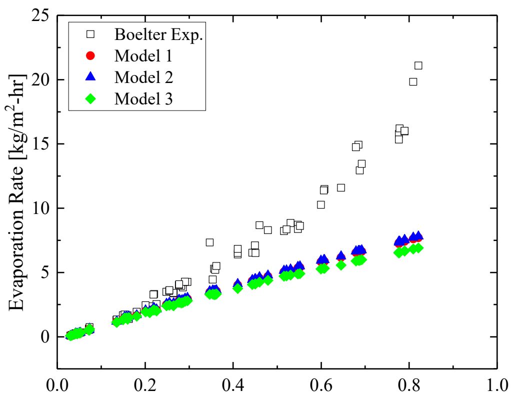

Fig. 4. Comparison Results (Model 1 ~ 3)

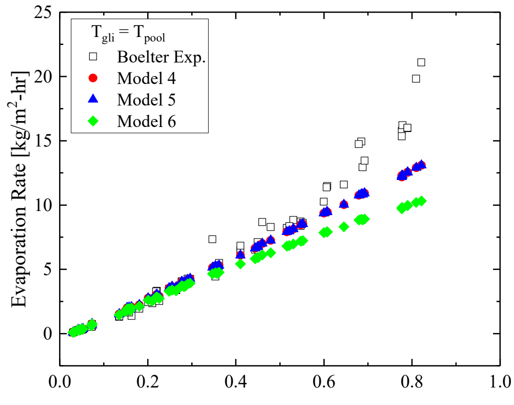

Fig. 5. Comparison Results (Model 4 ~ 6)

5. Conclusion

In this study, the default pool surface heat transfer model was designed based on HMTA. In order to analyze the effects of 1) pool surface temperature, 2) effective area between the pool surface and the atmosphere, and 3) suction effect on surface heat transfer, 6 sub-models reflecting the above three effects in the default model were implemented in CAP. These sub-models were compared with the Boelter pool evaporation experiment. The pool surface temperature (T_{gli}) had the greatest effect on the pool evaporation among the three differences. The effective area had little effect on the pool evaporation. Finally, in case of pool surface temperature was calculated iterative, the suction effect had little effect on pool evaporation. On the other hand, the suction effect had a great effect on the pool evaporation, assuming that the pool surface temperature is same as the pool temperature.

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