Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

Discussion on the Heat and Mass Transfer Model on the Pool Surface

Soon-Joon HONG[a*], Yeon-Jun CHOO[a], Sang-Jun HA[b]
[a]*FNC Tech., Heungdeok IT Valley, Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 446-908, Korea*
[b]*KHNP Central Research Institute, 28-1, Jang-dong, Yuseong-gu, Daejeon, 305-343, Korea*
[*]*Corresponding author: sjhong90@fnctech.com*

1. Introduction

Heat transfer on the pool surface involves the evaporation and condensation of steam in the presence of non-condensable gas. It is a kind of inter-phase heat transfer. This phenomenon has been regarded as less important on the thermal hydraulic behaviors such as pressure, temperature, hydrogen distribution, and so on in the nuclear reactor containment building [1, 2]. So there are very limited studies on the pool surface heat transfer. However, as new advanced reactors such as APR1400, AP1000, and so on adopt In-containment refueling water storage tank (IRWST), this phenomenon attracts the increased concern. As a matter of fact, several RAIs (requests for additional information) during the licensing review of the developed CAP have been presented [3]. And early in 2000s the steam condensation on the water surface of IRWST was a concern of APR1400 design [4]. Such an increased concern is believed because it is a newly adopted system.

This study discusses the pool surface heat transfer by reviewing the models of several well-known containment analysis codes, and conducting the sensitivities.

2. Heat transfer model in containment analysis codes

2.1 CONTEMPT-LT & CONTEMPT4 Codes

CONTEMPT-LT and CONTEMPT4 Codes calculate the pressure and temperature (PT) of a compartment by accounting for heat addition to each phase (atmosphere and pool). The heat is transferred to/from heat conductors and between phases. Mass transfer is also accompanied and accounted for according to the latent heat transfers. The heat between the atmosphere and the pool is directly transferred without going by way of the interface.

The heat flux between the atmosphere and the pool is composed of sensible heat transfer and latent heat transfer. The formula is given by

$$\dot{q}'' = c_1 h_b (T_g - T_b) + [c_2 K_b M_g (i_{fg} + i_f)(x_g - x_b)]/x_{am} \quad (1)$$

, where

$\dot{q}''$: surface heat flux
c_1: input heat transfer multiplier constant
h_b: Sensible heat transfer coefficient at interface
T_g: vapor temperature
T_b: interface temperature
c_2: input mass transfer multiplier constant
K_b: mass transfer coefficient
M_g: molecular weight of water
i_{fg}: latent heat of vaporization
i_f: specific internal enthalpy of fluid transferred
x_g: mole fraction of vapor in bulk
x_b: mole fraction of vapor at boundary(interface)
x_{am}: logarithm mean mole fraction of noncondensable gases

2.2 GOTHIC Code

GOTHIC Code is based on three-fluid (gas, continuous liquid, and dispersed droplet) equation set and the phase change occurs at the interface [7]. For the interfacial heat transfer, all the heat from each phase at first transfers to the interface, and the net excess heat remaining at the interface results in the phase change in order to use up the remaining heat. Thus, the heat transfer model at the pool surface is composed of heat transfer model between interface and liquid, and that between interface and gas (vapor).

<u>Between vapor and interface</u>

$$Nu_{vl}(D_h) = \max\begin{pmatrix} 0.036 Re_v^{\frac{4}{5}} Pr_v^{\frac{1}{3}} \\ 0.21 (Gr_v Pr_v)^{\frac{1}{3}} \\ \dfrac{D_h}{L} \end{pmatrix} \Theta_T$$

, where

Nu: Nusselt number
Re: Reynolds number
Pr: Prandtl number
Gr: Grashof number
D_h: Pool hydraulic diameter
Θ_T: correction factor by Bird
L: Effective diffusion length

Subscript v and l means vapor phase and liquid phase, respectively.

<u>Between liquid and interface</u>

$$Nu_{ll}(D_h) = \max\begin{pmatrix} \dfrac{2D_h}{(Pool\ Depth)} \\ 0.13 (Gr_v Pr_v)^{\frac{1}{3}} \end{pmatrix} \quad (3)$$

<u>Mass transfer at interface</u>

$$Nu_{ml}(D_h) = \max\begin{pmatrix} 0.036Re^{\frac{4}{5}}Pr_v^{\frac{1}{3}} \\ 0.21(Gr_vPr_v)^{\frac{1}{3}} \\ \frac{D_h}{L} \end{pmatrix}\Theta_T \quad (4)$$

2.3 CAP Code

Governing equation set of CAP is also based on the three-fluid model, and the heat/mass transfer calculation is conceptually similar to GOTHIC. In CAP no correction factor is adopted unlike to GOTHIC.

Between liquid and interface

$$\mathrm{Nu_{gli\leftrightarrow l}} = \max(\mathrm{Nu^{forced}}, \mathrm{Nu^{natural}}, \frac{\mathrm{2D_h}}{\mathrm{Pool\ Depth}}) \quad (5)$$

$$Nu^{forced} = St_lRe_lPr_l \quad (6)$$

$$Nu^{natural} = \begin{cases} 0.27Ra^{\frac{1}{4}} \quad for\ 10^5 \le Ra \le 10^{10} \quad \text{cooling} \\ \begin{cases} 0.54Ra^{\frac{1}{4}} \quad for\ 10^5 \le Ra \le 10^7 \\ 0.15Ra^{\frac{1}{3}} \quad for\ 10^7 \le Ra \le 10^{11} \end{cases} \text{heating} \end{cases} \quad (7)$$

, where
St: Stanton number
Ra: Rayleigh number

Between gas and interface

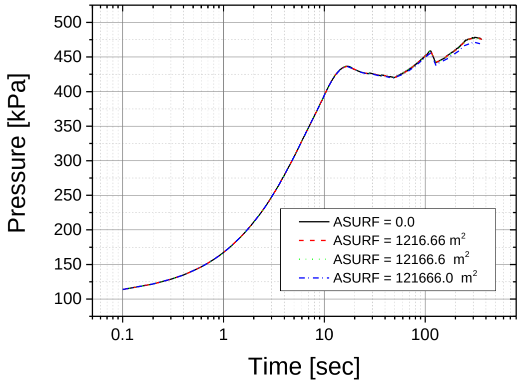
$$Nu_{gli\leftrightarrow g} = \max(Nu^{forced}, Nu^{natural}, \frac{2D_h}{L}) \quad (8)$$

$$Nu^{forced} = St_gRe_gPr_g \quad (9)$$

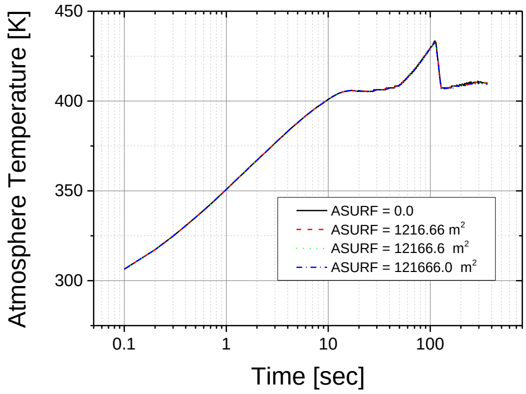
$$Nu^{natural} = \begin{cases} 0.27Ra^{\frac{1}{4}} \quad for\ 10^5 \le Ra \le 10^{10} \quad \text{heating} \\ \begin{cases} 0.54Ra^{\frac{1}{4}} \quad for\ 10^5 \le Ra \le 10^7 \\ 0.15Ra^{\frac{1}{3}} \quad for\ 10^7 \le Ra \le 10^{11} \end{cases} \text{cooling} \end{cases} \quad (10)$$

3. Pressures and temperature sensitivity

In order to check the importance of the pool surface heat transfer on the containment pressure and temperature, sensitivity analyses of pool surface area was conducted using CONTEMPT-LT/028-A, which has been traditionally used for the containment PT analysis. It was conducted for SKN3&4 discharge leg break accident with maximum emergency core cooling system (ECCS) flow for maximum PT analysis. The heat transfer area was changed to 0 times (no heat transfer), 10 times, and 100 times. As shown in Fig. 1 the sensitivity is nearly negligible.



(a) Pressure

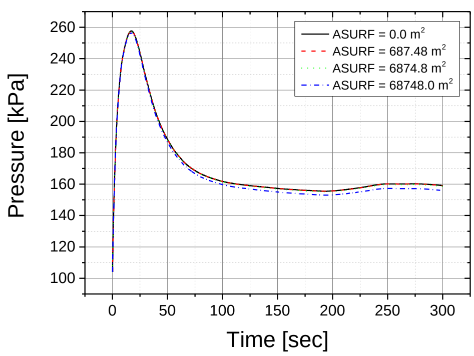


(b) Temperature

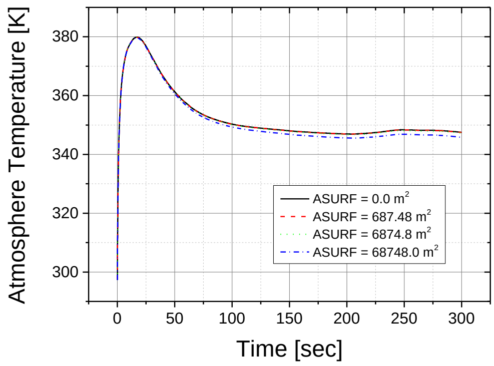
Fig. 1 Sensitivity for the heat transfer area for discharge leg break with maximum ECCS flow for max. PT analysis

Fig. 2 shows the sensitivity for the minimum PT analysis (ECCS performance analysis). It also shows very little effect according to the change of pool surface area.

From these two analyses, the pool surface heat transfer is not so important phenomena in containment PT analysis, as OECD/NEA PIRT suggested.



(a) Pressure



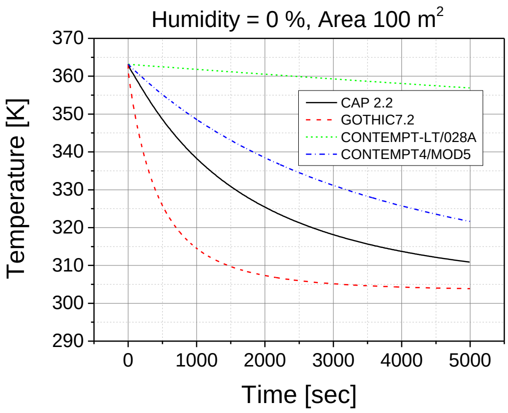
(b) Temperature

Fig. 2 Sensitivity for the heat transfer area for min. PT analysis

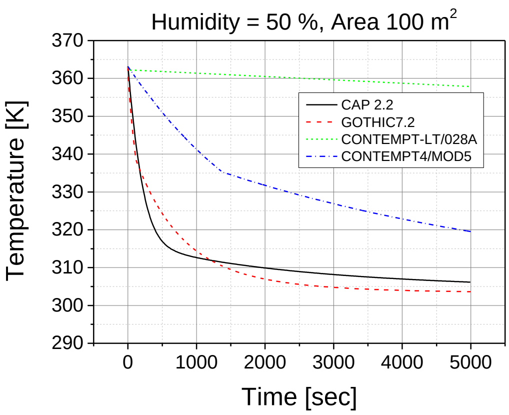
4. Sensitivity for latent heat transfer

4.1 Humidity effect

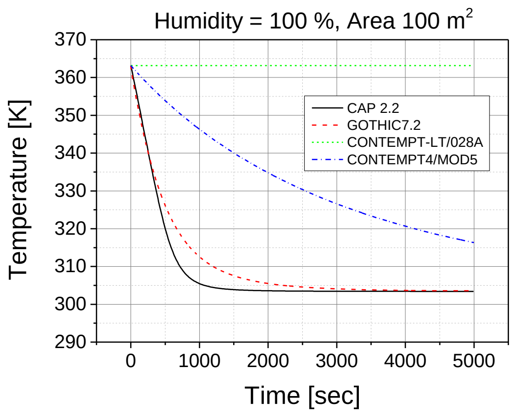
The effect of atmosphere humidity on the heat transfer was analyzed. The relative humidity was set 0%, 50%, and 100%.



(a) Humidity = 0 % and Interfacial Area = 100 m^2



(b) Humidity = 50 % and Interfacial Area = 100 m^2



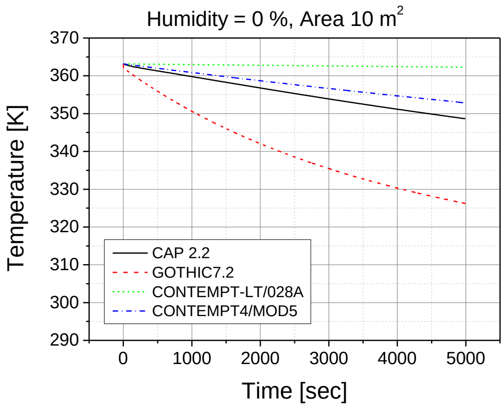
(c) Humidity = 100 % and Interfacial Area = 100 m^2

Fig. 3 Sensitivity of humidity

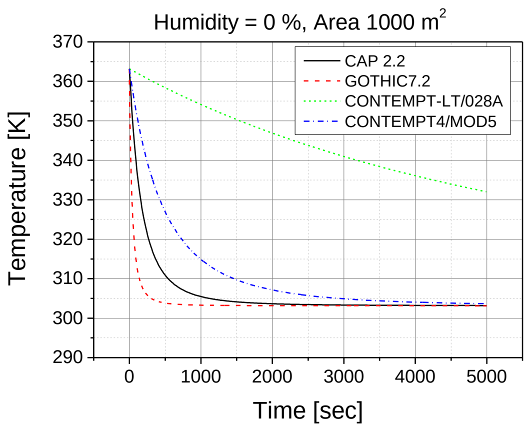
The results were different from code to code as shown in Fig. 3. For a low humidity CAP and GOTHIC showed large difference. But CONTEMPT series showed lower heat transfer than the two codes regardless of the humidity. CONTEMPT4/MOD5 showed closer result to GOTHIC and CAP than CONTEMP-LT/28-A, but still showed large gap compared to CAP and GOTHIC.

4.2 Area effect

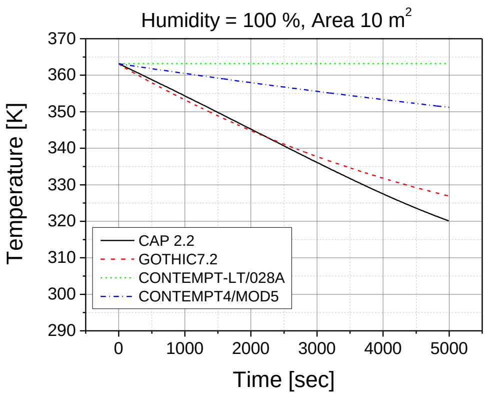
The reference case uses 100m^2 for heat transfer area. And the sensitivity was carried out for 0.1times and 10 times of the reference area. All the codes shows that the heat/mass transfer increases as the heat transfer area increases as shown in Fig. 4. CONTMEPT-LT/028A shows the lowest heat transfer among the three.



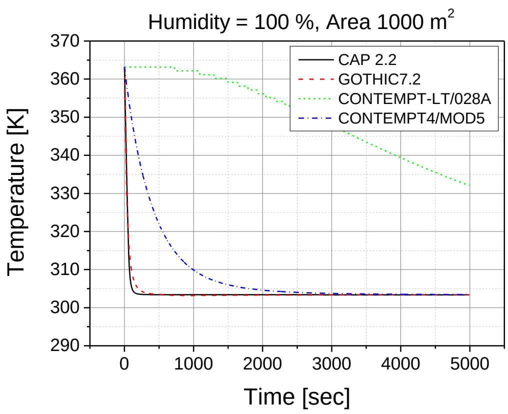
(a) Humidity = 0 % and Interfacial Area = 10 m^2



(b) Humidity = 0 % and Interfacial Area = 1000 m^2



(c) Humidity = 100 % and Interfacial Area = 10 m^2



(d) Humidity = 100 % and Interfacial Area = 1000 m^2

Fig. 4 Sensitivity of heat transfer area

4.3 Analysis on the latent heat transfer

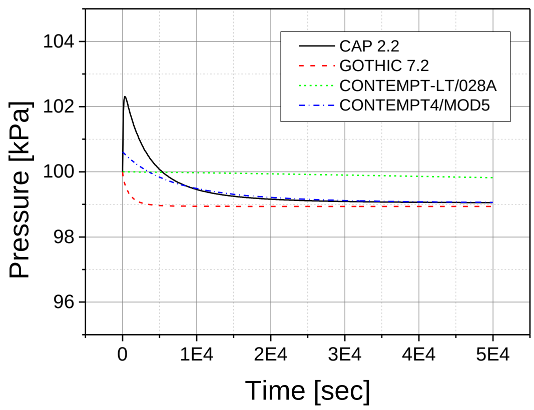
CONTEMPT-LT/028-A shows qualitatively similar trend with CAP and GOTHIC, but the quantitative values are too largely different to compare each other. Thus the comparison between CAP and GOTHIC is believed important.

For the lower humidity, CAP result locates between GOTHIC and CONTEMPT4/MOD5. But as the humidity increases, CAP gets similar to GOTHIC, whereas CONTEMPT4/MOD5 shows still lower heat transfer than the two. For the heat transfer area sensitivity, CAP gets similar to GOTHIC as the area increases, but CONTEMPT4/MOD5 still shows large gap.

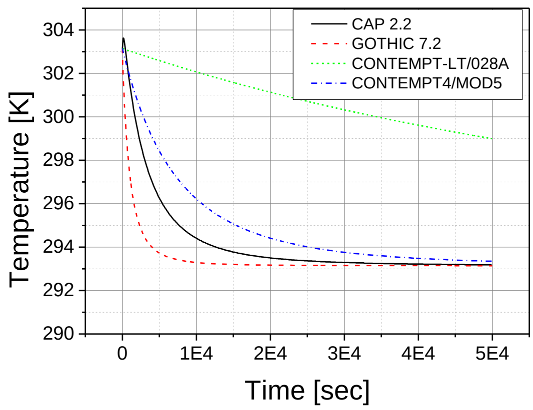
In summary, CAP gets similar to GOTHIC as the humidity increases or as the heat transfer area increases. But when the humidity is lower or when the heat transfer area is small CAP becomes similar to CONTEMPT4/MOD5. Conclusively CAP shows the middle value between GOTHIC and CONTEMPT4/MOD5.

5. Sensitivity for sensible heat transfer

Latent heat transfer between pool surface and atmosphere is expected dominant when the pool temperature is low and the vapor in the high temperature atmosphere condenses. Latent heat transfer and sensible heat transfer will concur as the temperature difference between the pool and the atmosphere is present. However, if the humidity is high (~100%) and the pool temperature is higher than the atmosphere temperature, the evaporation will be very small and the sensible heat transfer will be surely dominant.



(a) Pressure trend



(b) Temperature trend

Fig. 5 Sensible heat transfer

This study analyzed the case the mass transfer at the pool surface is small. The geometric conditions were set same to the case of latent heat transfer analysis. And the temperature difference between the pool and the atmosphere was set 10.0K: Atmosphere was set 303.15K, and the pool 293.15. At the initial time the relative humidity were set 0%, and the humidity will increase as the time goes on.

Similar trend to the latent heat transfer case was shown as shown in Fig. 5.

6. Conclusions

This study discussed the pool surface heat transfer. The related models of CAP, GOTHIC, CONTEMPT-LT, and CONTEMPT4 were compared. The sensitivity of heat transfer coefficient for SKN3&4 using conventional code CONTEMPT-LT/028-A showed little effect. And the sensitivity of relative humidity and heat transfer area for latent heat transfer shows that CAP locates between GOTHIC and CONTEMPT4/MOD. The sensitivity for sensible heat transfer also shows similar trend. Conclusively, current CAP model of pool surface heat transfer has no fatal defect.

For the future application to new designs such as passive containment cooling system (PCCS), more elaborate model is surely required. And it should be done in the consideration of best-estimate approach and conservative approach.

ACKNOWLEDGEMENT

This work has been carried out under the support from the Ministry of Trade, Industry and Energy (MOTIE) and Korea Institute of Energy Technology Evaluation and Planning (KETEP) of the Korean government.

REFERENCES

[1] Karwat, H., et al., SOAR on Containment Thermalhydraulics and Hydrogen Distribution, Report by an OECD/NEA Group of Experts, 1999.
[2] S.J. Hong et al., PIRT for CAP development, Future and Challenge Company, 2016.
[3] KHNP, Topical report on the CAP code for nuclear power plant design, Korea Hydro & Nuclear Power Company, 2016
[4] KHNP, Model development and evaluation of containment back pressure by IRWST damper of APR1400, Korea Hydro & Nuclear Power Company, 2004
[5] Hargroves, D.W., et al., CONTEMPT-LT/028-A Computer Program for Predicting Containment Pressure-temperature Response to a Loss-of-Coolant Accident, Idaho National Engineering Laboratory, NUREG/CR-0255, TREE-1279, 1979
[6] Lin et al., A multicompartment containment system analysis program, U.S. Nuclear Regulatory Commission, NUREG/CR-3716, BNL-NUREG-51754, 1984
[7] Rahn F., GOTHIC Containment Analysis Package Qualification Report Version 7.2, NAI8907-09 Rev 9, EPRI, 2006.