Comparison of CAP 3.0 and CONTEMPT-LT/028 evaporation models in an indoor pool

Yong-Ju Cho[a], Sun-Hong Yoon[a], Jae-Seung Moon[b], Sang-Gyu Lee[b]*
[a]KEPCO-E&C, Nuclear Technology Research Dept, 269 Hyeoksin-ro, Gimcheon-si, 39660
[b]KEPCO-E&C, Nuclear Engineering Dept, 269 Hyeoksin-ro, Gimcheon-si, 39660
[*]Corresponding author: cyongju93@kepco-enc.com

1. Introduction

Evaporation is an important role in assessment of the minimum requiring water level of operating the Cooling Spray Pump and affects the atmosphere pressure and temperature of the nuclear containment because the Sump temperature is higher than that of the atmosphere temperature in the case of a LOCA. The mechanism of this evaporation is atmosphere-water molecular movement, which rapidly saturates the very thin atmosphere layer. If convective flow in the air is negligible, further evaporation proceeds entirely by molecular diffusion, which the evaporation process is governed solely by the molecular diffusion, which is a very slow process **[1]**. In this paper, Smith, et al. evaporation experiment was simulated with CAP3.0 and CONTEMPT-LT/028, and the gas-liquid interface evaporation rate was investigated. In addition, it was compared with the widely used Shah's evaporation model. Finally, the gas-liquid interface mass rate of the two codes was checked by simulating the Loss of Coolant Accident (LOCA).

In order to assess the evaporation models of CONTEMPT-LT/028 and CAP3.0, which analysis environmental conditions of the containment at LOCA for a long period of time, Smith's test (i.e. Smith, et al. evaporation experiment) was simulated by CONTEMPT-LT/028 and CAP3.0. This Smith's test differs from the outdoor pool evaporation experiment, where the evaporation rate may be excessive due to forced convection because it was performed in an internal large poor. In addition, this paper assesses evaporation model with the widely used Shah's evaporation model (2012), and finally evaluated how the simulation results differ when the results simulate the LOCA.

2. Evaporation model in containment analysis codes

2.1 CONTEMPT-LT/028

The atmosphere pressure and temperature assessment of the OPR1000 and APR1400 containment under construction and operation is being assessed by the methodology based on the CONTEMPT-LT/028 computer simulation code. In CONTEMPT-LT/028, the Colburn-Hougen model is used for heat transfer between the atmosphere of the containment and sump. The model is divided into the sensible heat transferred by the temperature gradient and the latent heat of mass transferred by the gradient of molecular.

$$q'' = C_1 h_b (T_g - T_b) + [C_2 K_b M_g (i_{fg} + i_f)(x_g - x_b)]/x_{am} \tag{1}$$

, where
q'' = surface flux
h_b = sensible heat transfer coefficient at interface for small mass transfer coditions
T_g = atomoshphere temperature
T_b = boundary temperature
C_1 = input heat transfer multiplier constant
C_2 = input mass transer multiplier constant
K_b = mass transfer coefficient
M_g = molecular weight of water
i_f = specific internal enthalpy of fluid transferred
i_{fg} = latent heat of vaporization
x_g = mole fraction of vapor in bulk
x_b = mole fraction of vapor at boundary
x_{am} = logarithmic mean mole fraction of air

The constants C_1 and C_2 are constants that the Program User can consider the effect of either one of heat transfer and mass transfer or the ratio of the two effects.

The sensible heat transfer coefficient h_b is obtained as follows, and the subscript b means the boundary.

<u>Heated surface, turbulent range</u>, $2 \times 10^7 < \mathrm{Gr\,Pr} < 3 \times 10^{10}$

$$\frac{h_b L}{K_b} = 0.14(\mathrm{Gr\,Pr})_b^{1/3} \tag{2}$$

<u>Heated surface, laminar range</u>, $10^5 < \mathrm{Gr\,Pr} < 3 \times 10^7$

$$\frac{h_b L}{K_b} = 0.54(\mathrm{Gr\,Pr})_b^{1/4} \tag{3}$$

<u>Cooled surface, laminar range</u>, $3 \times 10^5 < \mathrm{Gr\,Pr} < 3 \times 10^{10}$

$$\frac{h_b L}{K_b} = 0.27(\mathrm{Gr\,Pr})_b^{1/4} \tag{4}$$

The mass transfer coefficient is obtained by Chilton-Colburn Analogy **[2]**.

$$K_b = \frac{h_b}{C_{pg} M_g}\left(\frac{Pr}{Sc}\right)^{2/3} \tag{5}$$

K_b = mass transfer coefficient
Pr = Prandtl number
Sc = Schmidt number
C_{pg} = Specific heat of vapor region
M_g = molecular weight of water

2.2 CAP 3.0

CAP 3.0 is a transient analysis simulation code for thermal hydraulic behavior analysis in the containment of a nuclear power plant. A one-dimensional flow model based on the two-phase, three-phase flow field governing equation is used. The heat transfer and mass transfer at the gas-liquid interface of the CAP 3.0 are calculated as follows **[3]**.

$$Q_{total} = Q_{g\to gli} + Q_{l\to gli} + \Gamma_l \Delta h_{sl}$$
$$Q_{g\to gli} = h_{g\leftrightarrow gli} A_{gli}(T_g - T_{gli})$$
$$Q_{l\to gli} = h_{l\leftrightarrow gli} A_{gli}(T_g - T_{gli})$$
$$\Gamma_l = h_m A_{gli}(\rho_{s,gli} - \rho_{s,g}) \quad (6)$$

Γ_l = Phase change rate at the interface
Δh_{sl} = Heat associated with the phase change
gli = gas − liquid interface
A_{gli} = gas-liquid interface area
h_m = mass transfer coefficient

Each heat transfer coefficient is obtained as a Nusselt number, and the mass transfer coefficient is obtained by the Chilton-Colburn Analogy **[4]**.

<u>Between liquid and interface</u>

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

$$Nu^{forced} = St_l Re_l Pr_l$$

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

, where
St = Stanton number
Ra = Rayleigh number
Pr = Prandtl number

<u>Between gas and interface</u>

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

$$Nu^{forced} = St_g Re_g Pr_g$$

$$Nu^{natural} = \begin{cases} 0.27Ra^{\frac{1}{4}} & for\ 10^5 \le Ra \le 10^{10} \quad \text{cooling} \\ \begin{cases} 0.54Ra^{\frac{1}{4}} & for\ 10^5 \le Ra \le 10^7 \\ 0.15Ra^{\frac{1}{3}} & for\ 10^7 \le Ra \le 10^{11} \end{cases} & \text{heating} \end{cases}$$
(8)

, where
St = Stanton number
Ra = Rayleigh number
Pr = Prandtl number

<u>Chilton-Colburn analogy</u>

$$\frac{h_m}{h} = \frac{1}{\rho_g c_{p,g}}\left(\frac{Pr}{Sc}\right)^{2/3} \quad (9)$$

2.3 Shah's model

For outdoor tanks, forced convection occurs, but for indoor pools, natural convection mechanism is dominant. Most published evaporation models only consider forced convection. However, the Shah model can consider natural convection and is used in various fields.

This model was revised in 2012 as the final version and is mainly used for unmanned outdoor/indoor swimming pools, water tanks with hot water such as spent fuel pool, water tanks used to shut off heat in cooling systems, containers/tanks with low water level etc **[1].**

$$E = C\rho_w(\rho_w - \rho_r)^{\frac{1}{3}}(W_w - W_r) \quad \text{for natural convection}$$

$$E = b(\rho_w - \rho_r) \quad \text{for considering forced convection (10)}$$

with C = 35 in SI units and C = 290 in I-P units, b = 0.00005 in SI and b = 0.0346 in I-P units.

, where
E = rate of evaporation under actual conditions, kg/m^2 ·h (lb/ft^2· h)
ρ = density of air, mass of dry air per unit volume of moist air, kg/m^3(This is the density in psychrometric charts and tables)
W = specific humidity of air, kg of moisture/kg of air (lb of moisture/lb of air)
r = at room temperature and humidity
w = saturated at water surface temperature

3. Description of the Smith's test

Among several indoor evaporation rate experiments, Smith's test is selected. The Smith's test is an indoor pool evaporation rate experiment supported by the U.S Department of Energy.

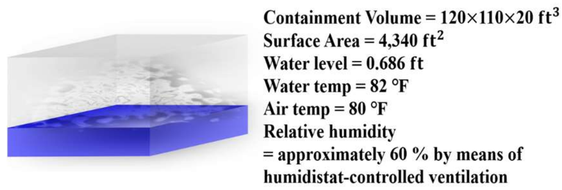

Fig. 1 – Experiment conditions of Smith's Test

The volume of the experimental facility is 120 ft x 110 ft x 20 ft and the pool surface area was 4,340 ft^2 and the height was 0.686 ft. The water temperature was typically designed to be maintained at 82°F by a thermostat, the air temperature at 80°F, and about 60% relative humidity with ventilation. The experiment was carried out for 68.4 hours, and the values of water temperature, relative humidity, atmospheric pressure, evaporation rate, and heat of evaporation were measured **[5] (Fig. 1, Table. 1)**.

Table. 1
Results of Smith's Test

TIME HR	TEMPERATURES - DEG F Air DB	Air WB	WATER	RH %	Vapor Pressure-IN MM HG WATER	AIR	DIFF
0	80	--	82	--	--	--	--
2.4	78	67	83	59	1.14	0.57	0.57
3.6	78	68	83	61	1.14	0.60	0.54
8.7	79	67	83	57	1.14	0.55	0.59
20.9	76	67	83	64	1.14	0.58	0.56
26.8	77	65	83	55	1.14	0.52	0.62
28.9	78	66	83	55	1.14	0.54	0.60
32.4	80	68	83	57	1.14	0.58	0.56
45.4	77	67	83	61	1.14	0.58	0.56
52.2	77	68	83	65	1.14	0.61	0.53
56.4	78	66	83	55	1.14	0.54	0.60
68.4	76	66	83	59	1.14	0.52	0.62

Level FT	CUM EVAP* LBS	EVAP RATE* LBS/HR-FT^2	CUM HEAT BTU/FT^2	HEAT EVAP** BTU/FT^2	EVAP RATE** LBS/HR-FT^2
0.686	--	--	--	--	--
0.683	813	0.078	241	231	0.092
0.682	1084	0.069	321	306	0.081
0.680	1626	0.043	642	605	0.066
0.672	3794	0.042	1231	1141	0.052
0.669	4607	0.040	1633	1518	0.054
0.667	5149	0.041	1753	1629	0.054
0.666	5420	0.039	1954	1815	0.053
0.658	7588	0.039	2623	2428	0.051
0.654	8672	0.038	2804	2580	0.047
0.650	9756	0.040	2829	2586	0.044
0.643	11696	0.039***	3480	3186	0.044

Notes :
* Determined by water level change
** Determined by adjusted heat supply rate
*** Final results of test

4. Description of the simulation code modelling and assessment

In order to, simulate Smith's test, an electric heater is simulated on the bottom of the tank. Instead of the humidity and temperature control device, the volume is set to $1.0\times \mathrm{E}+11\ \mathrm{ft}^3$, but pool geometry is same as the experiment, and the atmospheric temperature and pressure relative humidity were fixed.

The temperature of the atmosphere and the temperature of the pool are set to the average of the experimental atmosphere temperature 78 °F and water temperature 83 °F, and the trend is observed for 68.4 hours **(Fig. 2)**.

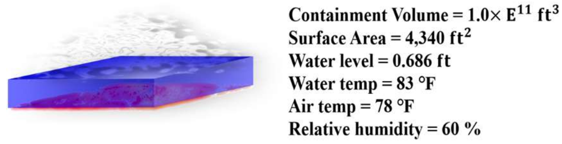

Fig. 2 - Pool Evaporation Modelling

As a result, the evaporation rate of CONTEMPT-LT/028 averaged $0.00106\ \mathrm{lb/hr-ft^2}$ for 68.4 hours, and CAP 3.0 is 2.14E-11 $\mathrm{lb\backslash hr-ft^2}$. Smith's test compared with the test results, CONTEMPT-LT/028 showed an average of 84.1 times the evaporation rate (smith's test average evaporation rate/CONTEMPT-LT/028 average evaporation rate) and CAP 3.0 showed an average of 2.71E+09 times. The results of CONTEMPT-LT/028 and CAP 3.0 are showed in tables and graphs **(Table. 2, Table. 3, Fig. 3)**.

Additionally, when compared with the widely used Shah model (2012), CAP 3.0 and CONTEMPT-LT/028 both simulation codes produce relatively lower evaporation rates than Shah's model and Smith's test **[1]**. The percent deviation of the final test result was 17.0%, while the average of CONTEMPT-LT/028 percent deviation was 98.0%, and the average of CAP 3.0 was 100% of percent deviation.

Table. 2
CONTEMPT-LT/028 Results of Pool Evaporation*

Time HR	Evaporation Rate LBS/HR-FT^2	RH %	ATM Psi	Steam Pressure Psi	Atmos Temp F	Sump Temp F	Percent deviation (%)
0	--	60.0	14.7	--	78.0	83.0	
2.4	1.13E-03	60.0	14.7	0.266	78.0	83.1	98.8
3.6	1.14E-03	60.0	14.7	0.266	78.0	83.1	98.6
8.7	1.15E-03	60.0	14.7	0.266	78.0	83.2	80.0
20.9	1.14E-03	60.0	14.7	0.266	78.0	83.1	80.7
26.8	1.13E-03	60.0	14.7	0.266	78.0	83.0	81.4
28.9	1.12E-03	60.0	14.7	0.266	78.0	83.0	82.1
32.4	1.11E-03	60.0	14.7	0.266	78.0	82.6	82.9
45.4	1.07E-03	60.0	14.7	0.266	78.0	82.6	86.0
52.2	1.05E-03	60.0	14.7	0.266	78.0	82.5	87.6
56.4	1.03E-03	60.0	14.7	0.266	78.0	82.4	89.3
68.4	9.94E-04	60.0	14.7	0.266	78.0	82.1	92.6

Notes :
* The average of the values from the second decimal place

Table. 3
CAP 3.0 Results of Pool Evaporation*

Time HR	Evaporation Rate lb/hr-ft^2	RH %	ATM Psi	Steam Pressure Psi	Atmos Temp F	Sump Temp F	Percent deviation (%)
0	--	60.0	14.7	--	78.0	83.0	
2.4	2.14E-11	60.0	14.7	0.285	78.0	83.1	100
3.6	2.14E-11	60.0	14.7	0.285	78.0	83.1	100
8.7	2.14E-11	60.0	14.7	0.285	78.0	83.2	100
20.9	2.14E-11	60.0	14.7	0.285	78.0	83.1	100
26.8	2.14E-11	60.0	14.7	0.285	78.0	83.0	100
28.9	2.14E-11	60.0	14.7	0.285	78.0	83.0	100
32.4	2.14E-11	60.0	14.7	0.285	78.0	82.6	100
45.4	2.14E-11	60.0	14.7	0.285	78.0	82.6	100
52.2	2.14E-11	60.0	14.7	0.285	78.0	82.5	100
56.4	2.14E-11	60.0	14.7	0.285	78.0	82.4	100
68.4	2.14E-11	60.0	14.7	0.285	78.0	82.1	100

Notes :
* Using linear interpolation

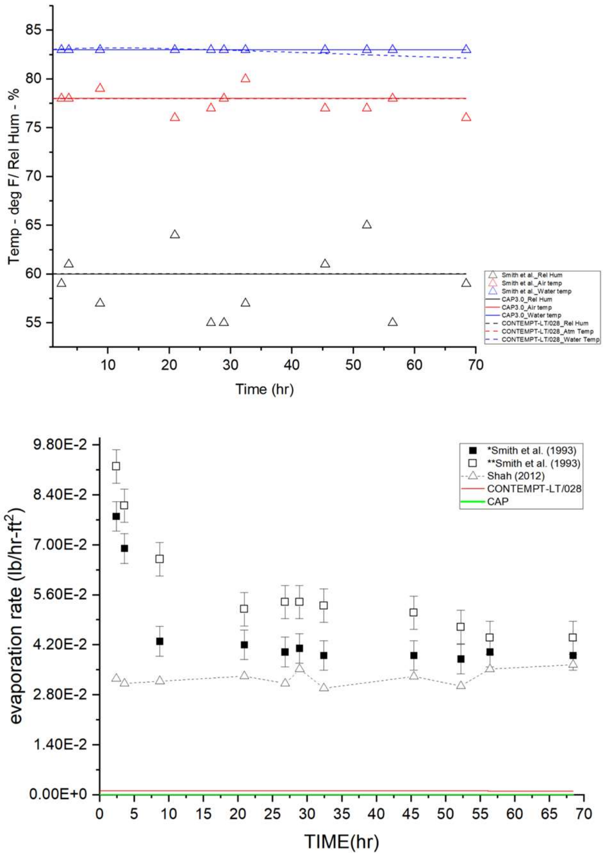

Fig. 3 - The recorded trends of temperature, relative humidity and evaporation rate during a 68-hour test period

For Shin-Kori Units 5 and 6, the evaluation results of the two codes were compared and analyzed at the LOCA accident. As a condition of Shin-Kori Units 5 and 6 LOCA, no heat structure was simulated, and we assumed that the Cooling Spray was not operated to consider only the evaporation and condensation models between the CONTEMPT-LT/028 and CAP 3.0 codes.

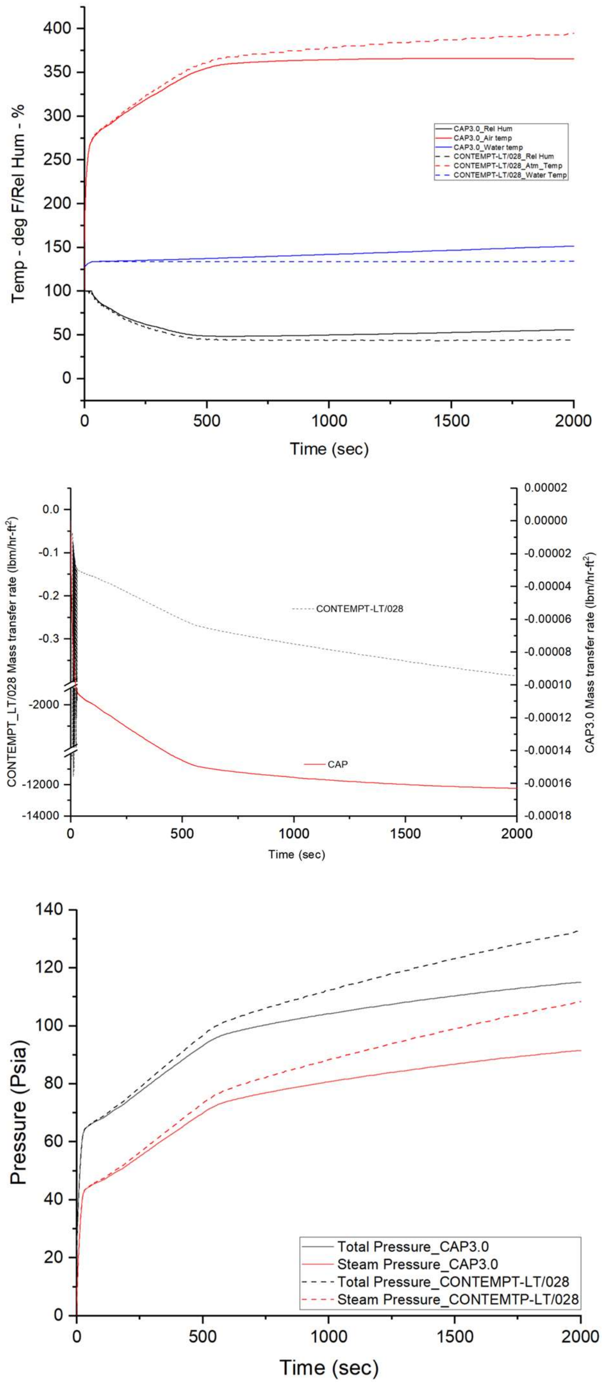

Fig. 4 - The recorded trends between CAP3.0 and CONTEMPT-LT/028 during LOCA (without heat structures and turning off Cooling Spray)

The Smith's test difference result in evaporation and condensation mass transfer between the two simulation codes shown in the experiment is similar in the case of the LOCA. The mass transfer rate of CAP3.0 is much smaller than that of CONTEMPT-LT/028 (if the mass transfer rate is negative, condensed and if positive, evaporated). However, pressure and the temperature of CAP 3.0 changed faster than CONTEMPT-LT/028.

The fact that the gradient of pressure and temperature showed non-proportional results despite relatively smaller mass transfer amount means that the effect of temperature and pressure change due to sensible heat is greater than the effect on the phase change of water. It also means that the heat transfer coefficients $h_{g\leftrightarrow gli}$, and $h_{l\leftrightarrow gli}$ of the Pool interface model of CAP 3.0 are larger than the heat transfer coefficients h_b of CONTEMPT-LT/28 **(Fig. 4)**.

5. Conclusion

Smith's test data and LOCA simulations showed that there is a big difference in the mass transfer rate for both CAP 3.0 and CONTEMPT-LT/28 codes. From the assessment of the minimum water level of the cooling spray pump operation and the mass and energy (M/E) emission of the accident analysis, it is conservative when the evaporation is large.

Also, in LOCA, since the mass transfer rate is small, it is judged that sensible heat has a greater effect on pressure and temperature than latent heat. It seems necessary to evaluate the effects of the latent heat and sensible heat of the tank interface and allow the user to select the evaporation model.

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