A Feasibility Study on the Application of 1D-Computational Fluid Dynamics to Small Line Break Analysis

Young Long Lee [a*], Yong Sang Ko [a], Kun Woo Yi [a], Kyong In Ju [a]
[a]*KEPCO Engineering & Construction Company, Inc.,*
989-111, Daedeokdaero Yuseong-gu, Daejeon, 34057, KOREA
[*]*Corresponding author: yllee@kepco-enc.com*

1. Introduction

10 CFR 50, Appendix A – General Design Criterion 33 for Nuclear Power Plants requires the system to supply reactor coolant makeup for protection against small breaks in the reactor coolant pressure boundary shall be provided.

One charging pump of the chemical and volume control system (CVCS) has sufficient capacity to make up the inventory lost to the containment due to a small reactor coolant system (RCS) line break. These lines have flow restricting orifices installed in their RCS nozzles to limit leakage in the event of a small line break. The leakage rate from a small line break is one of the important parameters to size the charging pump at rate conditions [1].

The leakage rate can be evaluated by hand calculations or computer codes based on Henry-Fauske critical flow model.

The purpose of this paper is to simulate the leakage rate from a small line break using FloMASTER [2], the commercial 1D-Computational Fluid Dynamics (CFD) solution and to evaluate it by comparing with the results of RELAP5 computer code [3].

In this study, the applicability of FloMASTER is to be confirmed in the preliminary design phase by comparing with the results of FloMASTER two-phase simulation and RELAP5 computer code for small line break analysis

2. Methods and Results

FloMASTER is a general purpose 1D-CFD solution for modeling and analysis of fluid mechanics in complex piping systems of any scale.

The transient analysis is performed using FloMASTER two-phase simulation. It is assumed that a small line break at the pressurizer occurs during 100% power operation and reactor coolant is discharged into the containment atmosphere through a small line break.

2.1 Small Line Break Model

In the event of a small line break, a critical flow occurs due to high differential pressures suddenly connected and the leakage flow can be evaluated through Henry-Fauske model, or Modified Henry-Fauske model [4-7].

Henry-Fauske model of two-phase flow through long channels is the basis for the thermal-hydraulic analysis of critical flow. Henry's mass flux equation is given in Equations (1) and (2).

$$G_c{}^2 - \frac{1}{\left[\dfrac{X_c v_{gc}}{\gamma_o p_c} - (v_{gc} - v_{Lc}) N \dfrac{dX_E}{dp}\right]_c} = 0 \qquad (1)$$

$$p_c + p_e + p_a + p_f + p_k + p_{aa} - p_o = 0 \qquad (2)$$

In Equation (1), subscript "c" and "o" are values for the exit and entrance plane. p_c and p_o mean the pressures of exit and entrance plane. G_c is mass flux of the fluid at crack exit plane. X_c is quality at exit plane. X_E is equilibrium fluid quality, v_{gc} and v_{Lc} mean specific volume of saturated vapor and liquid at exit plane. γ_o is the isentropic expansion coefficient. N is thermal non-equilibrium factor and applies N = 20 for $X_E < 0.05$, N = 1.0 for $X_E \geq 0.05$ [2].

Equation (2) shows the relations between pressure at the entrance plane and pressure loss at the exit plane. p_e means pressure loss due to entrance effects, p_f is pressure loss due to friction. p_k is pressure loss due to protrusions in the crack path, p_a is pressure loss due to acceleration, p_{aa} is pressure loss due to area change acceleration. If leakage path is constant, p_{aa} becomes zero.

In Equations (1) and (2), unknown factors G_c and p_c are obtained. The leakage rate is calculated by multiplying G_c with the cross-sectional flow area at crack exit plane, A_c.

The entrance pressure losses, p_e are given by Equation (3) where C_D is the coefficient of discharge. A coefficient of discharge C_D between 0.62 and 0.95 should be chosen based on the judgment of the designer as to how round the entrance edges are in comparison to the C_D.

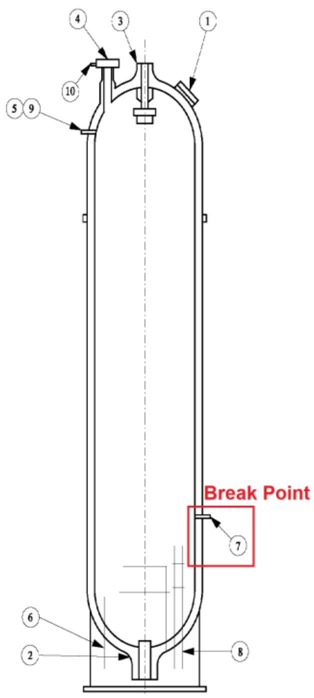
In hand calculation, the leakage rate is calculated by multiplying G_o with the cross-sectional flow area at crack entrance plane, A_o. The coefficient of discharge, C_D and entrance pressure losses, p_e are given conservatively.

$$p_e = \frac{G_o{}^2 v_{Lo}}{2C_D{}^2} \qquad (3)$$

2.2 Analysis Model and Initial Conditions

A flash tank is an evaporator of the boiler or steam-jet system and is usually a large-volume vessel where large water-surface area is needed for efficient evaporative cooling action. Warm water returning from the process is sprayed into the flash tank chamber through nozzles and the effluent is pumped to the bottom line of flash tank [8].

Analysis model for small line break is as shown in Figure 1. FloMASTER network diagram is constructed as in Figure 2 based on the analysis model of Figure 1. The two-phase transient was simulated for 600 seconds. Flash Tank module, such as pressurizer when a small line break occurs, is a component that continuously separates compressed water into condensate water and steam from the boiler or steam-jet system. A small line break is simulated by suddenly opening virtual valves (Cv = 0) and giving abrupt flow area change.



No.	Nozzle	No.	Nozzle
1	Manway	6	Level-lower
2	Surge	7	Temperature
3	Spray	8	Heater
4	POSRV	9	Pressure
5	Level-upper	10	RCGVS

Fig. 1. Pressurizer break point for system modeling [1]

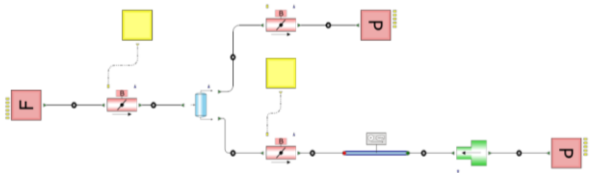


Fig. 2. FloMASTER network diagram for system modeling

The diameter and length for small lines are listed in Table I and the initial conditions for the simulations are listed in Table II.

Table I: Areas and Length for Small Line Break

	Diameter	Length
OL4	20 mm (0.787 inch)	25.4 mm (1 inch)
EUR	10 mm (0.394 inch)	25.4 mm (1 inch)
KSNP	5.56 mm (7/32 inch)	25.4 mm (1 inch)

Table II: Initial Conditions for the Simulations

	OL4[1]	EUR[2]	KSNP[3]
Fluid Model	Separated Mixture Model	Separated Mixture Model	Separated Mixture Model
Heat Transfer Model	Adiabatic	Adiabatic	Adiabatic
Pressure	2,250 psia (15.5MPa)	2,250 psia (15.5MPa)	2,250 psia (15.5MPa)
Temp.	653°F (345°C)	653°F (345°C)	653°F (345°C)
Liquid Volume	1155 ft^3 (32.71 m^3)	912 ft^3 (25.83 m^3)	912 ft^3 (25.83 m^3)
Valve Opening Time	Start 1 sec End 2 sec	Start 1 sec End 2 sec	Start 1 sec End 2 sec
Time Step	0.5 sec	0.5 sec	0.5 sec
Transient Time	600 sec	600 sec	600 sec

[1] Olkiluoto Nuclear Power Plant Unit 4 (EU-APR1400)
[2] European Utility Requirements for LWR Nuclear Power Plants
[3] Korea Standard Nuclear Power Plant

2.3 Analysis Results and Evaluation

The results of the transient analysis for the cases listed in Tables I and II are as shown in Figure 3. The maximum leakage rate is reached immediately after the event (i.e., after opening the valves), and it is proportional to the break area. Maximum leakage rates between FloMASTER, RELAP5 computer codes and hand calculations are compared in Table III.

RELAP5 and hand calculation analysis results are based on the Henry-Fauske model and initial conditions are as listed in Tables IV and V.

Table III: Comparison of Maximum Leakage

	FloMASTER	RELAP5	Hand Calculation (C_D = Min.0.62 / Max.0.95)
OL4	25.837 kg/s (56.961 lb/s)	30.176 kg/s (66.563 lb/s)	26.361 kg/s (58.115 lb/s) ~ 40.391 kg/s (89.047 lb/s)
EUR	6.447 kg/s (14.213 lb/s)	7.544 kg/s (16.632 lb/s)	6.590 kg/s (14.529 lb/s) ~ 10.098 kg/s (22.262 lb/s)
KSNP	1.987 kg/s (4.381 lb/s)	2.329 kg/s (5.135 lb/s)	2.037 kg/s (4.491 lb/s) ~ 3.122 kg/s (6.883 lb/s)

Table IV: Initial Conditions for RELAP5

Initial Conditions	Parameter
Choking Option	On
Area Change Option	Abrupt Area Change
Discharge coefficient, Cd	1.999

Table V: Initial Conditions for Hand Calculations

Initial Conditions	Parameter
Entrance Pressure Losses, p_e	2235.5 psid (15.4 MPa)
Coefficient of Discharge, C_D	0.62~0.95

The leakage rate of FloMASTER is 86% less than that of RELAP5 and 64% (C_D=0.95) to 98% (C_D=0.62) less than those of hand calculations.

In the results, the leakage rate using FloMASTER is approximately equal to the minimum leakage rate using hand calculation (C_D=0.62). The leakage rate using RELAP5, computer code for safety analyses, shows that the leakage rate is at least 25% to up to 36% less than maximum leakage rate (C_D=0.95) using hand calculation. These results are considered to quantify design margin.

In KSNP reactor, one charging pump capacity [8.486 kg/s (18.708 lb/s)] has sufficient design margin to cover the above maximum leakage rate [3.122 kg/s (6.883 lb/s)]. In EUR and OL4, the maximum leakage rates are respectively 10.098 kg/s (22.262 lb/s) and 40.391 kg/s (89.047 lb/s), equal to or greater than one charging pump capacity [10.286 kg/s (22.677 lb/s)] of APR1400 reactor. The charging pump capacity is expected to be larger than the charging pump capacity of APR1400 reactor when designing OL4 reactor.

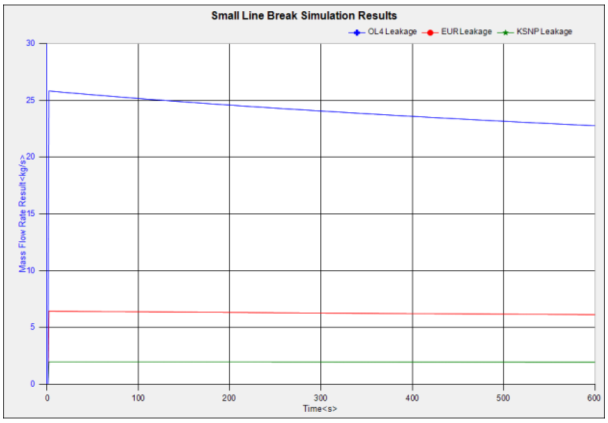


Fig.3. Results of transient simulation.

3. Conclusions

This paper calculated the leakage rate in a small line break using commercial 1D-CFD solution FloMASTER and RELAP5 computer codes. It was identified that FloMASTER has less leakage than RELAP5.

The results show that one charging pump of KSNP reactor has sufficient capacity to include the leakage rate from FloMASTER, RELAP5 and hand calculation. KSNP reactor is evaluated to have sufficient design margin. The leakage rate of OL4 reactor is also expected to require one charging pump capacity larger than rated capacity of APR1400 reactor.

In conclusion, the results between FloMASTER and RELAP5 are about 15% different, so it is estimated that FloMASTER is utilized in preliminary design phase.

REFERENCES

[1] Final Safety Analysis Report for Shin Hanul Nuclear Power Plant Unit 1 and 2.
[2] Simcenter Flomaster Components Reference Manual-Software Version 2019.3, Siemens, Nov. 2019.
[3] US NRC, RELAP5/MOD3.3 Code Manual, Vol.II: Appendix A – Input Requirements, NUREG/CR-5535, 2012.
[4] D. D. Paul, J. Ahmad, P. M. Scott, L. F. Flanigan, and G. M. Wilkowski, Evaluation and Refinement of Leak-Rate Estimation Models, NUREG/CR-5128, Rev.01.
[5] Henry, R. E., 1970, The Two-Phase Critical Discharge of Initially Saturated or Subcooled Liquid, Nuclear Science and Engineering, Vol. 41, pp. 336~342.
[6] Henry, R. E. and Fauske, H. K., 1970, Two-Phase Critical Flow at Low Qualities, Part 1: Experimental, Nuclear Science and Engineering, Vol. 41, pp. 79~91.
[7] Henry, R. E. and Fauske, H. K., 1970, "Two-Phase Critical Flow at Low Qualities, Part II: Analysis," Nuclear Science and Engineering, Vol. 41, pp. 92~98.
[8] Robert H. Perry, Don W. Green, Perry's Chemical Engineers' Handbook, Mc Graw Hill, 2007.