Steady-State Analyses of Fluid Flow Characteristics for AFWS in PWR using Simplified CFD Methods

Sang-Kyu Lee, Nam-Seok Kim, Byung-Soo Shin, and O-Hyun Keum

***Abstract*—** The method of modeling and simulation for evaluating hydrodynamic characteristics of auxiliary feed water system (AFWS) in pressurized water reactor was represented in this paper. One dimensional thermo-fluid simulation code (Flowmaster) was used in both normal and abnormal condition. The real geometry and performance data of each component in AFWS is used to make the present model and calculate under normal steady-state condition. A comparison of the results showed a good agreement with measurements and it indicates that the proposed methodology is reasonable.

***Keywords*—** Auxiliary Feed Water, Computational Fluid Dynamics, Flowmaster, Nuclear Power Plant

I. INTRODUCTION

A Pressurized Water Reactor consists of primary system and secondary system. Primary systems transfer the heat produced in the reactor to the steam generator. Secondary system removes the heat as a heat sink and consists of main steam system, condensate system, main feed water system, etc. Main Feed Water System (MFWS) provides the steam generators with heated water during normal operation. Auxiliary Feed Water System (AFWS) has function to supply feedwater to the steam generators when main feed water system is inoperable. Also AFWS is used to supply feedwater to the steam generators during hot standby conditions and reactor cool-down to the point where the Shutdown Cooling System (SCS) starts operation. AFWS is divided into main line and recirculation line, and consists of auxiliary feedwater pumps, condensate storage tank, orifices, block valves, flow control valves, etc. Main line is connected to steam generator and recirculation line is connected to condensate storage tank.

In this paper, pre-operational test data through recirculation line were compared with simulation data using Flowmaster at the several cases from 0% to 40% opening ratio of regulating valve including rated flow condition.

II. ANALYSIS METHODS

Generally, continuity and momentum equations are used for calculating pressure and velocity in a pipe. These two governing equations are represented:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v)}{\partial x}=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+\frac{\partial(\rho v^2)}{\partial x}=-\frac{\partial p}{\partial x}-\frac{f\rho}{2D}v|v|-\rho g\sin\theta \tag{2}$$

where p is the pressure, v is the velocity of fluid, g is gravity, D is the pipe diameter, f is Darcy-Weisbach friction factor and ρ is the fluid density

With incompressible steady-state condition, equations (1) and (2) are simplified to a formulation of Bernoulli equation, and pressure differences are derived as below:

$$p_1-p_2=\frac{f\rho l}{2D}v|v|+\rho g(z_2-z_1) \tag{3}$$

And it is expressed as mass flow:

$$\dot{m}=\sqrt{\frac{\rho\pi^2D^5\left[(p_1-p_2)+\rho(z_1-z_2)\right]}{8\rho fl}} \tag{4}$$

Equation (3) can be more simplified in the form of a loss coefficient K, by assuming an elevation between inlet and outlet is same:

$$p_1-p_2=K\cdot\left(\frac{1}{2}\rho\cdot v|v|\right) \tag{5}$$

The loss coefficient, K, is an empirical correlation factor, such as Zagarola, Colebook & White, etc. It is determined by characteristics of geometry. Equation (5) is not only applicable to a pipe, but also other components.

III. ONE DIMENSIONAL MODELING FOR AFWS

Flowmaster - one dimensional commercial CFD code was used for modeling of fluid characteristics in AFWS. AFWS consisted of main line and recirculation line. However, as the scope of this study was the comparison of simulation results with a pre-operational test data through a recirculation line, only recirculation line was modeled. A real geometry of recirculation line is illustrated in Fig. 1.

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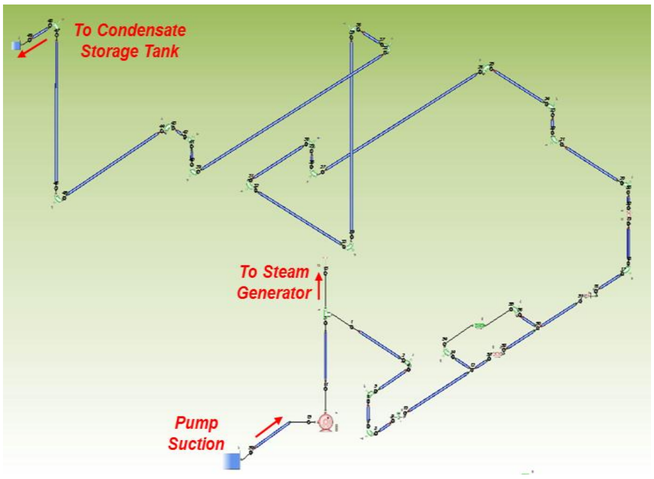

Fig. 1 Geometry of a recirculation line in AFWS

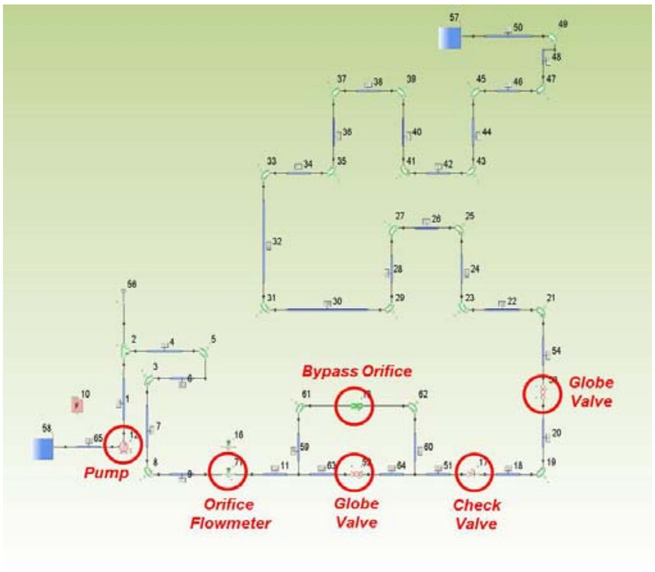

Fig. 2 Simple schematic using Flowmaster

The system consists of a centrifugal type pump, orifice flowmeter, bypass orifice, valves, elbows and pipes. Flowmaster has only one-dimensional information, and thus the simple schematic representation of a recirculation line has been produced and is presented in Fig. 2.

One-dimensional model of AFWS commences at the suction of auxiliary feedwater pump with proper straight pipeline and terminates at the upstream of condensate storage tank. Both the inlet and outlet boundary conditions are specified as a constant total pressure representing the local system pressure. The main line is modeled as simple ended boundary.

A summary of modeling techniques used to represent AFWS can be described for each component as below:

A. Pipe Friction

The equation for calculating pressure difference in pipe was defined as follow:

$$p_2 - p_1 = K_{pipe}\frac{\dot{m}_1|\dot{m}_1|}{2\rho A^2} \tag{6}$$

where P_1 and P_2 are pressure at inlet and outlet in a pipe, K_{pipe} is non-dimensional loss coefficient, and A is a pipe cross-sectional area.

For calculating loss coefficient which is represented by friction factor in equation (7), the Colebrook-White correlation is used:

$$K_{pipe} = \frac{L}{D}\cdot\frac{0.25}{\left[\log\left(\frac{k}{3.7D}+\frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \tag{7}$$

where k is roughness and Re is Reynolds number.

B. Valve Friction

The pressure equation is similar to Eq. (6), and loss coefficient is defined as below:

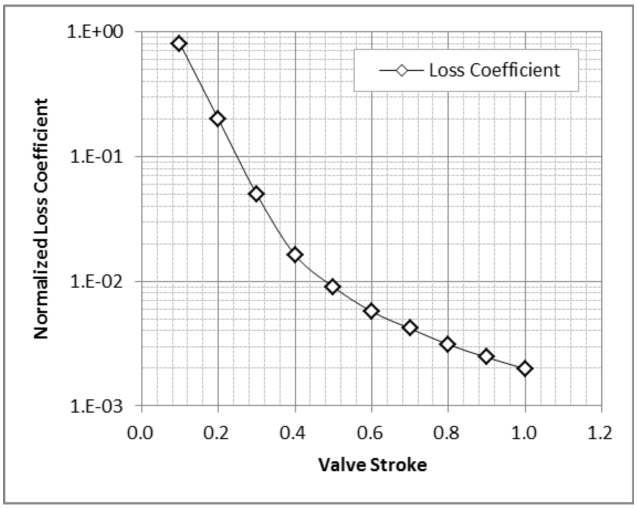

Fig. 3 Loss coefficient for valves

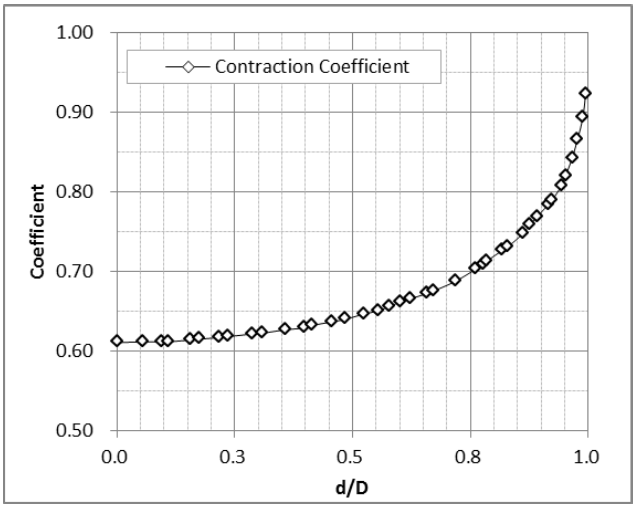

Fig. 4 Orifice contraction coefficients

$$K_{valve} = \frac{C_1 \pi^2 D^4}{C_v^2} \tag{8}$$

where C_1 is an empirical coefficient and C_v is a flow coefficient defined as the rate of flow that will generate a pressure drop of 1 psi across the valve. Fig. 3 shows a loss coefficient of control valves for this study. The x-axis indicates a valve opening ratio and y-axis indicates a normalized loss coefficient values.

C. Orifice Friction

The orifices are modeled by Miller approximation, as represented in Eq. (9).

$$K = C_{\mathrm{Re}} \cdot \left\{ 1 - \left(\frac{d_0}{D} \right)^2 C_c \right\}^2 \frac{1}{\left(\frac{d_0}{D} \right)^4 C_c^2} \tag{9}$$

where d is an orifice diameter, C_c is a contraction coefficient, and C_{Re} is a correction factor determined by Reynolds number. Fig. 4 shows an orifice contraction coefficient for this paper.

IV. RESULTS

For verifying the analysis model, incompressible steady-state simulations with 0.0% of the valve stroke were carried out. The simulation results were compared with measured values in the aspects of volume flow rate and total developed head.

Table I shows the comparison of each results. Quantitative deviations were calculated by test data. In Table I, TDH* is the normalized value of total developed head which is calculated by the maximum and minimum measured values. Comparing with the test data, calculation results are matching within ±1.0% deviation.

The next stage will be to simulate, and predict an opening position of control valve, as the estimated volume flow rates are similar to the measurements (26.5, 32.8, and 41.0 *[l/s]*) within ±1.0%. The results are summarized in Table II. It can be seen that the predicted valve strokes are estimated to 23.0%, 32.0%, and 43.0%. It means that the current analysis model has been slightly underestimated in the aspect of volume flow rates, that is volume flow rates will be predicted lower than 26.5, 32.8, and 41.0 *[l/s]* if valve opening ratios are set to 22.0, 30.0, and 40.0%, respectively. The normalized values for total developed head were estimated within about ±3.0%.

Additionally, four different cases of various volume flow rate were simulated and compared in Table III. The deviations of all the calculated values are presented within ±1.0%.

Fig. 5 shows the numerical and experimental results of total developed head along the volume flow rate. Above all measured and simulated values in Table I, II, and III are illustrated as triangle and circular with dotted line, respectively. As considering an uncertainty of experiments, it can be concluded that the current analysis method is well developed

Finally, the friction loss of system is calculated with rated flow condition and shown in Fig. 6. A solid line with circle sign is a pump performance curve, a dotted line with triangle is a friction loss for a system, and a point where the intersection of two curves defines the operating point of the system.

V. CONCLUSION

The present study represents modeling and simulation of auxiliary feedwater system in typical pressurized water reactor using one-dimensional numerical method. In the first part of the work, a real geometry and performance data of each component were modeled by commercial software, Flowmaster.

TABLE I
SIMULATION RESULTS WITH 0.0% VALVE OPEN

	Simulation	Measurement	Deviation
Volume Flow [l/s]	*16.8*	*16.7*	*+0.5%*
TDH [-]*	*0.947*	*0.952*	*-0.5%*

*TDH** : Normalized Values for Total Developed Head

TABLE II
SIMULATION RESULTS UNDER 26.5, 32.8, AND 41.0 L/S VOLUME FLOW RATES

	Simulation	Measurement	Deviation
Volume Flow [l/s]	*26.3*	*26.5*	*-0.8%*
TDH [-]*	*0.888*	*0.888*	*0.0%*
Valve Opening [%]	*23.0*	*22.0*	*+4.5%*
Volume Flow [l/s]	*33.0*	*32.8*	*+0.6%*
TDH [-]*	*0.810*	*0.821*	*-1.4%*
Valve Opening [%]	*32.0*	*30.0*	*+6.7%*
Volume Flow [l/s]	*40.9*	*41.0*	*-0.3%*
TDH [-]*	*0.683*	*0.703*	*-2.7%*
Valve Opening [%]	*43.0*	*40.0*	*+7.5%*

TABLE III
COMPARISON OF VOLUME FLOW RATE WITH VARIOUS CONDITIONS

No	Simulation	Measurement	Deviation
1	*23.0*	*23.0*	*-0.1%*
2	*25.1*	*25.1*	*-0.2%*
3	*28.4*	*28.2*	*+0.6%*
4	*30.6*	*30.4*	*+0.8%*

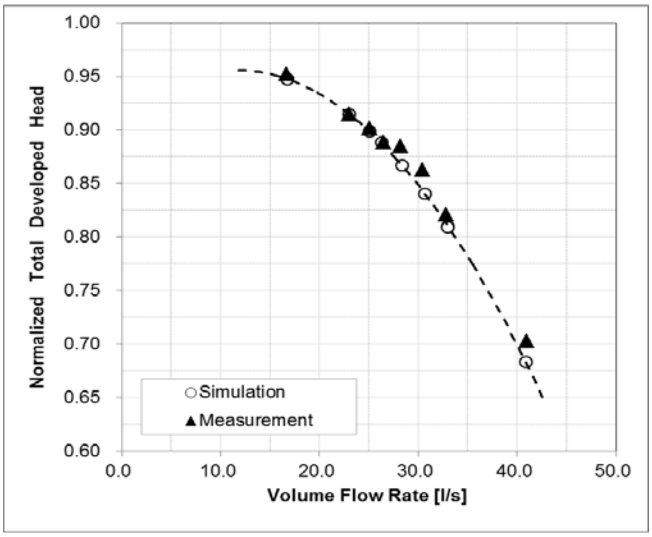

Fig. 5 Comparison with Measurements

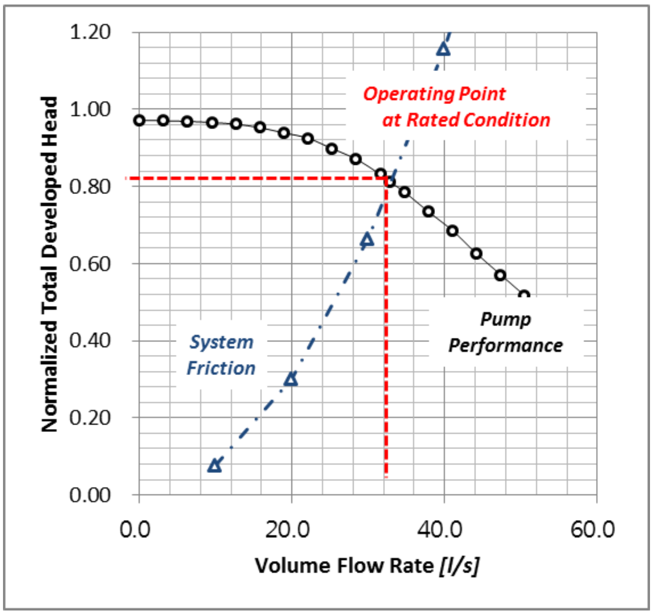

Fig. 6 Prediction of operating point

Then incompressible steady-state simulations were performed and the results were compared. As a result, the present analysis model was good agreement with measurements and well described fluid characteristics of the original system. Additionally, as applying to transient simulation, it is expected to provide an insight, which is to analyze effects of transient response caused by failures of component, change of arrangement, etc.

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