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Assessment of Analytic Waterhammer Pressure Model of FAI/08-70

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1. Introduction

Recently, accumulation of non-condensable gas in the safety related systems in the nuclear power plants has received wide attention because waterhammer effect due to accumulation of non-condensable gas can give inadvertent opening of relief valves installed on the safety related systems or excessive loading on the piping/supporters, which endanger the integrity or function of the safety related systems.[1,2] Therefore, Korea Institute of Nuclear Safety (KINS) has taken some regulatory steps to solve this safety issue since few years ago and responding to this regulatory action, Korea Hydro & Nuclear Power (KHNP) has been doing various evaluations related to this safety issue as well.

In evaluating waterhammer effect on the safety related systems, methods developed by the US utility are likely to be adopted in Korea. For example, the US utility developed specific methods to evaluate pressure and loading transient on piping due to waterhammer as in FAI/08-70[2]. The methods of FAI/08-70[2] would be applied in Korea when any regulatory request on the evaluation of waterhammer effect due to the non-condensable gas accumulation in the safety related systems. Specifically, FAI/08-70[2] gives an analytic model which can be used to analyze the maximum transient pressure and maximum transient loading on the piping of the safety-related systems due to the non-condensable induced waterhammer effect.[3]

Therefore, it seems to be meaningful to review the FAI/08-70[2] methods and attempt to apply the methods to a specific case to see if they really give reasonable estimate before the application of FAI/08-70[2] methods to domestic nuclear power plants. For this purpose, in the present study, we review the analytic model for pressure transient evaluation in detail first and then apply this model to a specific case about which experimental data were taken to check adequacy of the analytic model of pressure transient. Especially, we focus on waterhammer at the high level piping locations downstream of safety-related pump. (See, Figure 1.) In this geometry, waterhammer would be initiated by pump start.[3]

2. Analytic Model for Pressure Transient

In FAI/08-70[2], two stage approach has been taken in developing an analytic model for pressure transient. That is, accelerating phase and decelerating phase are introduced and specific modeling is made for each phase. Here, acceleration phase implies a period during which fluids within piping would accelerate by pump start and deceleration phase implies a period at which fluids within piping start to decelerate due to the compression of non-condensable gas in the piping and impact of fluids against the end of piping. Specific modelings applied for each phase are explained below in detail.

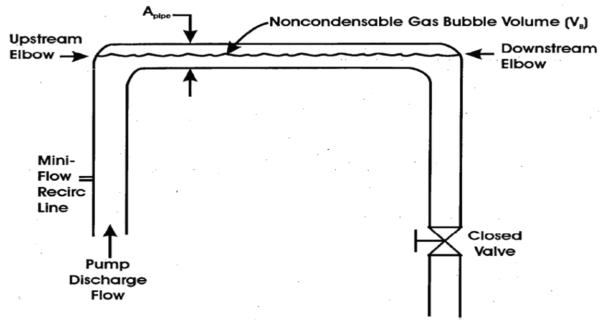

Fig. 1. Physical Geometry for Analytic Pressure Transient Model.

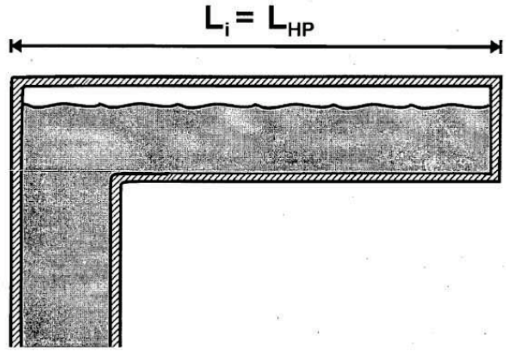

Fig. 2a. Schematic of Early Stage of Acceleration Phase

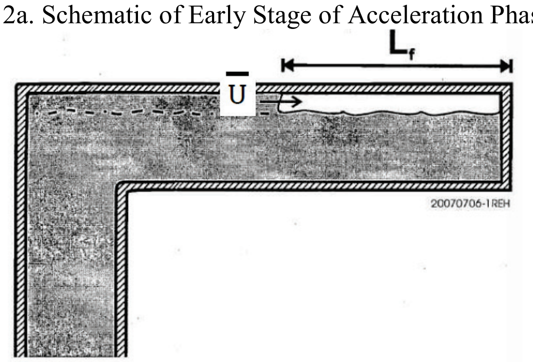

Fig. 2b. Schematic of Later Stage of Acceleration Phase

2.1 Modeling for Acceleration Phase

Figure 2a and 2b show two schematics which are used for the modeling of acceleration phase. Specific modeling steps taken in the acceleration phase are as follows

1. As the pump starts, fluids in the piping begin to move to the downstream elbow. (See, Figure 1.) And at the same time, fluids also begin to compress non-condensable gas within the piping. It is assumed that the maximum pressure of non-condensable gas attainable at the later stage of acceleration phase would be summation of an initial system pressure and a shutoff pressure of the pump.

2. It is assumed that the compression of non-condensable gas follows isentropic process. Therefore, the following equation holds.

$$P_i V_i^{\gamma} = P_f V_f^{\gamma} \quad (1)$$

Here, P is pressure of non-condensable gas, V is volume of non-condensable gas and $\gamma(= 1.4)$ is specific heat ratio. Subscripts, i, f indicate initial and final states of the compression process.

3. Maximum pump discharge flow occurs at the later stage of acceleration phase and it is given as below.

$$Q_{pump}(t) = Q \cdot Min\left[1, \left(\frac{t}{t_{run-up}}\right)\right] \quad (2)$$

Here, Q_{pump} is pump discharge flow at time, t, Q is discharge flow at fully run-up condition of the pump(i.e. normal operating condition) and t_{run-up} is pump run-up time.

4. According to Eq. (2), discharge flow during the pump run-up period is given by

$$V_{run-up} = \int_0^{t_{run-up}} Q_{pump}(t)dt = \frac{Q}{2} t_{run-up}. \quad (3)$$

Here, V_{run-up} represents accumulated discharge flow during the pump run-up period.

5. It is also assumed the later stage of acceleration phase ends when the accumulated pump discharge flow equals to the maximum volume decrease of non-condensable gas during the compression period and waterhammer occurs at this end which is designated as waterhammer generation time, t_{WH}. Therefore, according to this assumption, the following equation holds

$$\Delta V = \int_0^{t_{WH}} Q_{pump}(t)dt \quad (4)$$

Here, $\Delta V(= V_i - V_f)$represents volume change of non-condensable gas.

6. If ΔV is less than V_{run-up}, it implies t_{WH} is less than t_{run-up}, therefore Q_{pump} is given by

$$Q_{pump}(t) = Q \frac{t}{t_{run-up}}. \quad (5)$$

Therefore, applying Eq. (5) to Eq. (4) and rearranging gives

$$\Delta V = \frac{Q}{2} \frac{t_{WH}^2}{t_{run-up}} \quad (6)$$

As a result, waterhammer generation time t_{WH} can be given by

$$t_{WH} = \left(\frac{\Delta V \cdot 2 \cdot t_{run-up}}{Q}\right)^{1/2}. \quad (7)$$

It should be noted that Eq. (7) holds only when t_{WH} is less than t_{run-up} because Eq. (5) is used in the derivation of Eq. (7).

2.2 Modeling for Deceleration Phase

Fluids velocity would be accelerated until the later stage of acceleration phase and then it starts to decelerate because of the compression of non-condensable gas and the impact of fluids against the end of the piping. As a result, fluids come to stop and waterhammer pressure occurs. In FAI/08-70[2], the waterhammer pressure at the deceleration phase is assumed as below.

$$\Delta P = \rho C_w \overline{U} \cdot \alpha_i \quad (8)$$

Here, ΔP is waterhammer pressure, ρ is density of fluids (i.e. density of water), C_w is speed of sound in the fluids, $\overline{U}$ is local front velocity of fluids (See, Figure 2b.) and α_i is initial void fraction of piping.

Eq. (8) can be transformed further if we introduce superficial velocity, U_s. Since the superficial velocity and the local front velocity are defined respectively by

$$U_s \equiv \frac{Q_t}{A_{pipe}} \text{ and } \overline{U} \equiv \frac{Q_t}{A_g}, \quad (9a,b)$$

they are related each other as follows

$$\frac{\overline{U}}{U_s} = \frac{Q_t}{A_g} \times \frac{A_{pipe}}{Q_t} = \frac{A_{pipe}}{A_g} = \frac{1}{\alpha_i} \rightarrow \overline{U} \cdot \alpha_i = U_s. \quad (10)$$

Here, Q_t is total flow of fluids due to the pump operation (that is, a summation of water flow and non-condensable gas flow), A_{pipe} is cross sectional area of pipe and A_g is cross sectional area of pipe occupied by non-condensable gas.

Therefore, Eq. (8) can be rewritten as below by use of Eq. (10)

$$\Delta P = \rho C_w U_s. \quad (11)$$

This is similar to ordinary waterhammer equation. [4]

3. Application of the Analytic Model to a Specific Waterhammer Experimental Data

Until now, the analytic model of waterhammer pressure of FAI/08-70[2] is reviewed in detail. From now on, we apply the model to a specific case to see if the model really gives reasonable estimate of waterhammer pressure due to the accumulation of non-condensable gas in the safety related piping.

In FAI/08-70[2], a lot of gas-water waterhammer experiments which were conducted for various experimental parameters conditions are also included. Among them, as a representative experiment to check the validity of the analytic model, we take the number 52A experiment. The 52A experiment which adopts flushed initial condition was conducted at a test section with a short vertical piping length of 9inch and an elevated level piping length of 51inch. Fig. 3 shows the test section used for the 52A experiment. Fig. 4 also shows an overall structure of experiment apparatus and the specific location for the test section of the experiment 52A to be installed. It should be noted that the red dotted region of Fig. 4 was replaced by the test section of Fig. 3 during the 52A experiment.

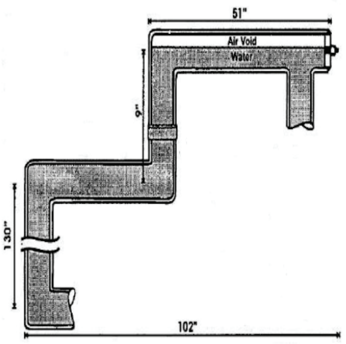

Fig. 3. Schematic of Test Section for Experiment 52A.

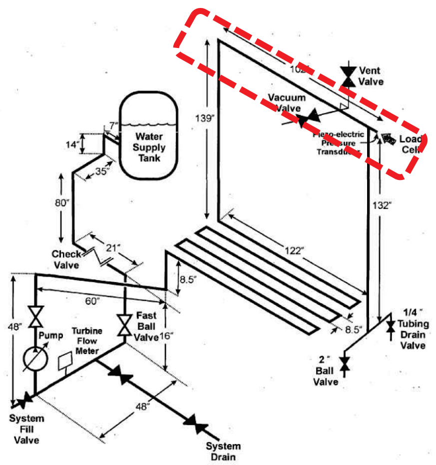

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Fig. 4. Schematic of Experiment Apparatus of FAI/08-70[2].

Table I also shows major parameters used to assess the experiment 52A. According to data given in Table I, waterhammer pressure for the experiment 52A can be determined as follows.

Table I: Major Parameters Used for Assessment of the Experiment 52A.

Parameters	Values	References
Nominal flow rate(Q)	0.14202ft^3/sec	Pump characteristics
Run-up interval($t_{run\text{-}up}$)	1.0sec	Pump characteristics
Pump shutoff head@elevation of NC gas bubble	27.0psid	Pump characteristics+ piping level
Initial NC gas volume(V_i)	0.071ft^3	System characteristics
Initial NC gas pressure(P_i)	2.5psia	System characteristics
Velocity of sound in water(C_w)	4,872ft/sec	Medium characteristics
Cross sectional area of pipe(A_{pipe})	0.02330ft^2 (2" Scedule 40)	Piping characteristics

*NC implies "Non-condensable"

At the later stage of acceleration phase, maximum pressure of non-condensable gas attainable would be sum of the pump shutoff head at the pliping high point and the initial non-condensable gas pressure which is the same as the initial system pressure. Therefore, the final pressure of non-condensable is given by

$$P_f = P_i + P_{shutoff} = 2.5 + 27.0 = 29.5psia.$$

Since all parameters in Eq. (1) except V_f are given, V_f is determined as

$$V_f = V_i \left(\frac{P_i}{P_f}\right)^{1/\gamma} = 0.071 \left(\frac{2.5}{29.5}\right)^{1/1.4} = 0.01218ft^3.$$

Consequently, volume decrease of non-condensable gas due to the pump start is calculated as

$$\Delta V = V_i - V_f = 0.071 - 0.01218 = 0.058821ft^3.$$

Since above volume decrease would be the same as the accumulated discharge flow until the later stage of acceleration phase, Eq. (7) can be used to determine the waterhammer generation time, t_{WH}. It is given by

$$t_{WH} = \left(\frac{\Delta V \cdot 2 \cdot t_{run-up}}{Q}\right)^{\frac{1}{2}}$$
$$= \left(\frac{0.058821 \cdot 2 \cdot 1.0}{0.14202}\right)^{1/2} = 0.9101sec.$$

Note that since above result shows t_{WH}(= $0.9101sec$) is less than t_{run-up}(=1.0sec), it is justified to use Eq. (7).

Furthermore, the pump discharge flow at t_{WH} and the superficial velocity are given below, respectively.

$$Q_{pump}(t_{WH}) = Q\frac{t_{WH}}{t_{run-up}} = 0.14202\frac{0.9101}{1.0} = 0.1292576 ft^3/sec$$

$$U_s = \frac{Q_{pump}}{A_{pipe}} = \frac{0.1292576}{0.02330} = 5.55 ft/sec$$

Consequently, waterhammer pressure due to non-condensable gas compression by the pump start is given by Eq. (11).

$$\Delta P = \rho C_w U_s = \frac{62.3}{(144 \times 32.2)} \cdot 4872 \cdot 5.55 = 363.3 psid$$

Here, the speed of sound in the water is used with the value at 70°F which is the temperature of fluids of the experiment 52A. Finally, the maximum absolute pressure attainable with the piping system due to waterhammer is given by

$$P_{peak} = \Delta P + P_f = 363.3 + 29.5 = 392.8 psia.$$

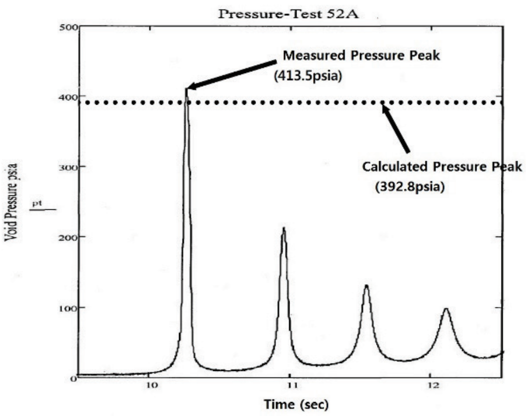

Fig. 5. Comparison of experimental data and analytic calculation for the experiment 52A.

Figure 5 shows the comparison between the measured peak pressure and the calculated peak pressure by the analytic model. Measured peak pressure of the experiment 52A is 413.5psia. Otherwise, the calculated peak pressure is 382.8psia which is a little bit less than the measured peak pressure of the experiment 52A. The extent of less prediction of the analytic model is given by

$$\frac{(413.5-392.8)}{392.8} \times 100 = 5.27\%.$$

These findings show that the analytic model of waterhammer pressure can give a close estimate of the real peak pressure but unfortunately, it cannot give conservative estimate of the peak pressure. For the experiment 52A, 5.27% of non-conservatism is identified in the present study

4. Conclusions

In the present study, analytic waterhammer pressure model of FAI/08-70[2] is reviewed in detail and the model is applied to the specific experiment of FAI/08-70[2] to see if the analytic waterhammer pressure model really gives reasonable estimate of the peak waterhammer pressure.

Specifically, we assess the experiment 52A of FAI/08-70[2] which adopts flushed initial condition with a short rising piping length and a high level piping length of 51inch.

The calculated analytic waterhammer pressure peak shows a close agreement with the measured experimental data of 52A. Unfortunately, however, the theoretical value is a little bit less than that of the experimental value. This implies the analytic model of FAI/08-70[2] is not conservative. Therefore, care should be made when this analytic method is applied to evaluate the waterhammer peak pressure of the safety related systems due to non-condensable gas accumulation.

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