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Gas-Induced Water-hammer Loads Calculation for Safety Related Systems

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1. Introduction

NRC Generic Letter 2008-01 requires nuclear power plant operators to evaluate the possibility of non-condensable gas accumulation for the Emergency Core Cooling System, the Residual Heat Removal System and the Containment Spray System. Of particular interest, gas accumulation can result in system pressure transient in pump discharge piping following a pump start. Consequently, this evolves into a gas-water, a water-hammer event and the accompanying force imbalances on the piping segments can be sufficient to challenge the piping supports and restraint. This paper describes an method performing to the water-hammer loads to determine the maximum loading that would occur in the piping system following the safety injection signal and to evaluate its integrity [1].

2. Evaluation Location

UT examination is the general method to identify and quantify gas that has accumulated at a high point. This paper assumes that the inverted-U piping near the rupture disc in High Pressure Safety Injection System has the gas void of 21% in the pipes volume of 4.67ft^3.

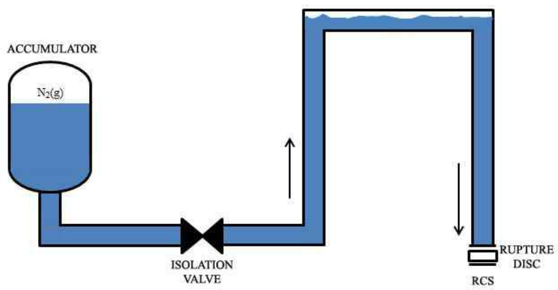

Fig.1 Initial Condition of the High Pressure Safety Injection

3. Calculation

The pressure developed by gas-water water-hammer event are a function of (1) the flow run-up interval, (2) the pump shutoff head pressure, (3) the initial volume of the accumulated gas and (4) the initial pressure of the gas volume. The following problems show how to implement the simplified methodology [2].

For this problem, we consider following parameters

a. A maximum flow rate: $Q_{HPECCMAX}$=650kg/s
b. Accumulator pressure and temperature: $H_{SHUTOFF}$=580.15psid, 30℃
c. A run-up interval: t_{RUNUP}=2sec
d. A initial gas volume: V_{gas}=0.991ft^3
e. An initial gas pressure and temperature: $P_{gas,initial}$=14.7psia, 30℃
f. The velocity of sound in water: C_w=4,582.37ft/s
g. A discharge piping size: $A_{discharge}$=0.6672ft^2
h. The length of the piping high point: L_{HP}=7ft

3.1 Piping Maximum Stress

First we evaluate the gas volume compression to the tank pressure using equation:

$$V_{gas,comp} = V_{gas}\left(\frac{P_{gas,initial}}{P_{gas,initial}+H_{shutoff}}\right)^{(1/1.4)} = 0.070 ft^3 \quad (1)$$

The volume of water added to compress the gas volume during this pressure is 0.991 – 0.070=0.921ft^3. We evaluate the time required to reach accumulator pressure condition is

$$t_{shutoff} = \left(2\bullet\frac{V_{water,comp}\bullet t_{runup}}{Q_{HPECC,\max}}\right)^{0.5} = 0.4\sec \quad (2)$$

From the accumulator linear run-up characteristic given by the equation:

$$Q_{HPECC,\tan k} = Q_{HPECC,\max}\bullet\left(\frac{t_{shutoff}}{t_{runup}}\right) = 4.604 ft^3/s \quad (3)$$

For the specified pipe size and corresponding cross-sectional area, this volumetric flow rate would have a superficial velocity as calculated by:

$$U_s = \left(\frac{Q_{HPECC,\tan k}}{A_{disch\arg e}}\right) = 6.9 ft/s \quad (4)$$

Using this velocity, the water-hammer pressure that would result if this velocity were instantaneously stopped can be calculated written as:

$$\Delta P_{WH} = \left(\frac{\rho_{HPECC}\bullet C_w\bullet U_s}{144\bullet g_c}\right) = 424.586 psi \quad (5)$$

Therefore, the maximum pressure is

$$\Pi_{WH} = H_{shutoff} + P_{gas,initial} + \Delta P_{WH} = 1{,}058.58 psi \quad (6)$$

At half of the pressure increase the gas volume pressure would be;

$$\Pi_{WH} = H_{shutoff} + P_{gas,initial} + \frac{\Delta P_{WH}}{2} = 807.144 psi \quad (7)$$

and the gas volume at this pressure is 0.057ft^3. With the initial parameters defined, the initial gas void fraction is given by;

$$\alpha_o = \frac{V_{gas}}{A_{discharge} \bullet L_{HP}} = 0.212 \qquad (8)$$

and the initial gas density is calculated as;

$$\rho_{go} = \frac{144 \bullet P_{gas,initial} \bullet M_{wg}}{R \bullet (T_{gas,initial} + 460)} = 0.073 \frac{lbm}{ft^3} \qquad (9)$$

for the mixture quality(x) given by:

$$x = 1 \quad \frac{1}{1 + \alpha_o \bullet (\frac{\rho_{go}}{\rho_w})(\frac{L_{go}}{\delta})} = 0.149 \qquad (10)$$

And the two-phase exponent is:

$$n1 = \frac{(1 \quad x) \bullet C_w + x \bullet c_{pg}}{(1 \quad x) \bullet C_w + x \bullet c_{vg}} = 1.012 \qquad (11)$$

With this exponent, the gas volume at the maximum pressure:

$$VM = V_{gas} \bullet (\frac{P_{gas,initial}}{\Pi_{max}})^{(\frac{1}{n1})} = 0.015 ft^3 \qquad (12)$$

Which gives a volume change between these two pressure of VD=0.042ft^3. Dividing this by the pipe flow area results in a length of L_{VD}=0.062ft and dividing this length by the water velocity results in a time of t_{VD}=0.018s. We can calculate the reference pressurization rate as:

$$\frac{dP}{dt})_{WH} = \frac{\Pi_{max} - \Pi}{t_{VD}} = 11{,}723.741 psi \qquad (13)$$

With this maximum force imbalance acting on the piping as follows;

$$F_{HP} = A_{discharge} \bullet \frac{dP}{dt})_{WH} \bullet \frac{L_{HP}}{C_w} = 1{,}720.65 lbf \qquad (14)$$

3.2 Evaluation for the piping allowable stress

For this problem, we consider following parameters:

a. The length of the piping between the piping support: L_t=12.513ft.
b. The density of piping material: ρ_P= 483.84lbm/ft^3
c. Moduli of Elasticity: E=29.4×10^{6}psi
d. Maximum allowable stress: S_h=17.1×10^{3}psi

The effect of pressure, weight, other sustained load must meet requirement as follow [3];

$$B_1(\frac{P_{max} \bullet D_o}{2t}) + B_2(\frac{MA + MB}{Z}) \le 11.8 S_h \qquad (15)$$

The piping loads by internal pressure are given by:

$$PO = 0.5 \bullet \frac{(P_{gas,initail} + H_{shutoff}) \bullet OD_{discharge}}{2 \bullet Th_{discharge}} = 4{,}683.62 psi \qquad (16)$$

and the moment loading on cross section due to weight is given by;

$$MA = L_e \bullet L_t (\rho_p \bullet \pi \bullet \frac{(OD_{discharge}^2 - ID_{discharge}^2)}{4} + \rho_{HPECC} \bullet \pi \bullet \frac{ID_{discharge}^2}{4}) = 7{,}603.753 lbf \bullet ft \qquad (17)$$

$$DW = \frac{2.25 \bullet MA}{Z} = 5{,}499.392 psi$$

Using the equation for water-hammer loads given by:

$$MB = L_e \bullet F_{HP} = 12{,}160.006 lbf \bullet ft \qquad (18)$$

$$WH = \frac{2.25 \bullet MB}{Z} = 8{,}711.188 psi$$

and the maximum loads as follow;

$$S_{max} = PO + DW + WH = 18{,}894.199 psi \qquad (19)$$

Comparing maximum stress to allowable criteria would be;

$$S_{max} = 18894.2 psi \; < S_{allowable} = 30{,}780 psi \qquad (20)$$

4. Results and Discussion

Consequently, measured gas void of 21% (0.991ft^3) satisfy the allowable criteria when the water-hammer load occurs in High Pressure Safety Injection.

Table 1. The Result of Evaluation for Water-hammer Loads.

No.	S_{max}		$S_{allowable}$	
1	PO	4,683.62psi	S_h	17,100psi
2	DW	5,499.39psi	$S_{allowable}$= 1.8×S_h	30,780psi
3	WH	8,711.19psi		
4	S_{max}=PO+DW+WH=18,894.2psi		$S_{allowable}$=30,780psi	

Also, the maximum force imbalance acting on the piping support shows that it not exceed the design loads when the water-hammer event occurs.

Table 2. The Result of Evaluation for the piping support

Piping No.	Support No.	Max. force imbalance	Design Loads	
12W-5	PH-57	1,720lbf	Fy	+18,374lbf -18,374lbf
			Fz	+17,910lbf -17,910lbf

5. Conclusions

For a given gas void volumes in the discharge piping, the result of the calculation shows the maximum loads of 18,894.2psi, which is smaller than the allowable criteria. Also, the maximum peak axial force imbalances acting on the support is 1,720lbf as above.

REFERENCES

[1] USNRC, Managing Gas Accumulation in Emergency Core Cooling, Decay Heat Removal, and Containment Spray Systems, Generic Letter 2008-01, 2008.
[2] Fauske&Associated,Inc., Gas-Voids Pressure Pulsation Program, FAI/08-70 Rev.1, 2008.
[3] ASME, ASME Boiler and Pressure Vessel Code SectionⅢ, 2010.