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공기실을 사용한 압력수두의 완화효과에 대한 분석

An Analysis of Attenuation Effect of Pressure Head Using an Air Chamber

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Abstract

An air chamber is designed to keep the pressure from exceeding a predetermined value, or to prevent low pressures and column separation. Therefore, it can be used to protect against rapid transients in a pipe system following abrupt pump stoppage. In this research, an air chamber was applied to a hypothetical pipe system to analyze attenuation effect of pressure head for different air volumes, locations, chamber areas, coefficients of orifice loss and polytropic exponents. With an increase of air volume, the maximum pressure head at pump site is decreased and the minimum pressure head is increased. For different locations and areas of the chamber, the attenuation effects do not show much difference. Also, as the orifice loss coefficient increases, the maximum pressure head is decreased. For different polytropic exponents, isothermal process shows lower maximum pressure head than that of the adiabatic process.

요지

공기실(air chamber)은 관망에 있어 압력수두가 설계치를 초과하지 않고 또한 최저 압력수두가 발생하지 않도록 하기위해 설계된다. 따라서 공기실은 갑작스런 펌프의 중단에 따르는 순간적인 최고 및 최저 압력수두의 발생을 방지하기위해 사용되어 진다. 본 연구에서는 가상적인 관망에 공기실을 적용하여 공기실의 공기부피, 위치, 면적, 오리피스에서의 손실계수 그리고 polytropic지수의 변화에 따른 압력수두의 완화효과를 분석하였다. 분석결과 공기의 부피가 증가할수록 최고압력수두는 감소하고 최저 압력수두는 증가함을 보여주었으며, 공기실의 위치나 단면적의 변화에 대해서는 완화효과의 변화가 별로 없었다. 또한 오리피스 손실계수를 증가할수록 최고 압력수두가 감소함을 보이고, 공기실의 공기가 등온변화과정을 따를 때가 단열변화과정을 따를 때보다 최고 압력수두가 낮음을 보여주었다.

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1. Introduction

It is well known that an air charged accumulator or air chamber can be used effectively to reduce or eliminate pressure surge to control periodic pressure and flow fluctuations in pipe systems (Wood, 1970; Chaudhry, 1987; Wylie and Streeter, 1993). An air chamber is a vessel having compressed air at its top and having liquid in its lower part (see Fig. 1). An orifice is usually provided between the chamber and the pipeline to restrict the inflow or outflow from the chamber. The air in the chamber contracts or expands due to the inflow or outflow from the chamber. Because of the gradual variation of the flow velocity in the pipeline, the magnitudes of the pressure rise and drop are reduced.

To prevent column separation due to very low minimum pressure in the pipeline, the outflow from the chamber should be as free as possible, while the inflow may be restricted to reduce the size of the chamber. As the air volume may be reduced due to leakage or due to solution in the liquid, an air chamber is used to keep the volume of the air within the limit.

Usually, surge tanks have been used to reduce or eliminate pressure surge in the pipeline. But, air chambers have many advantages over surge tanks. For examples, the volume of an air chamber is smaller than that of an equivalent surge tank and an air chamber can be installed with its axis parallel to the ground slope. Another advantages are that an air chamber can be installed near the pump and that it is cheaper to heat the water in an air chamber in cold climates. However, air chambers need air compressors, auxiliary equipments, and very high initial costs.

In this research, governing equation to apply an air chamber will be derived from known boundary conditions and an air chamber will be applied to a hypothetical pipe system to analyze attenuation effect of pressure head for different air volumes, locations, chamber areas, coefficients of orifice loss and polytropic exponents.

2. Boundary Conditions for an Air Chamber

Applying an air chamber to a hypothetical pipeline, the following equations are obtained at the juction of the chamber with the pipeline (see Fig. 2; Chaudhry, 1987).

Positive and negative characteristic equations for sections (i,n) and (i+1,1)

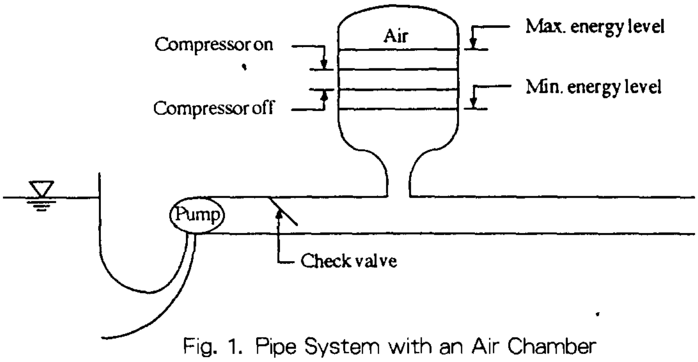

Fig. 1. Pipe System with an Air Chamber

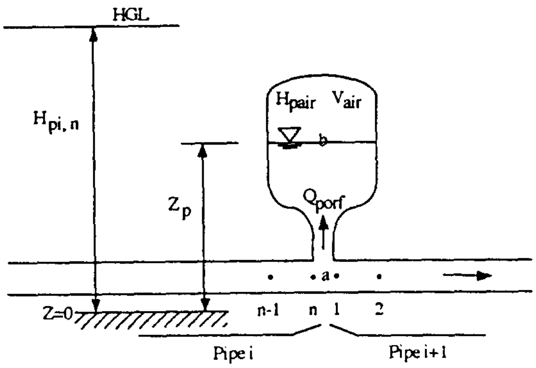

Fig. 2. Pipe System for Simulation

$$H_{pi,n}=C_P-B_iQ_{pi,n} \tag{1}$$

$$H_{pi+1,1}=C_m+B_{i+1}Q_{pi+1,1} \tag{2}$$

in which H = pressure head; Q = flow rate; C_p, C_m = known constants when the equations are applied; B = pipeline characteristic impedance (= a/gA); a = wave propagation velocity; A = pipe cross-sectional area; and g = gravity acceleration.

If the losses at the junction are neglected, then

$$H_{pi,n}=H_{pi+1,1}=H_p \tag{3}$$

Continuity equation

$$Q_{pi,n}=Q_{pi+1,1}=Q_{porf} \tag{4}$$

in whcih Q_{porf} = flow through the air chamber (considered positive into the chamber).

The orifice losses may be expressed as

$$h_{porf}=C_{orf}Q_{porf}\,|\,Q_{porf}\,| \tag{5}$$

in which C_{orf} = coefficient of orifice losses, and h_{porf} = head loss in the orifice for a flow of Q_{porf}.

Considering points (a) and (b) and neglecting the effect of air density, the air pressure can be expressed as

$$H^*_{pair}=H_{pi,n}+H_b-Z_p-h_{porf} \tag{6}$$

in which H^*_{pair} = absolute pressure head of the enclosed air at the end of the time step; H_b = barometric pressure; and Z_p = height of the water surface in the chamber at the end of the time step.

If we use time step Δt, the height of the water surface in the air chamber above the datum at the end of time step is

$$Z_p=Z+0.5(Q_{orf}+Q_{porf})\frac{\Delta t}{A} \tag{7}$$

in which Z = height of the water surface in the chamber at the beginning of the time step, and Q_{orf} = orifice flow at the beginning of time step.

The volume of air in the chamber at the end of the time step is

$$V_{pair}=V_{air}-A(Z_p-Z) \tag{8}$$

in which V_{air}=volume of air at beginning of time step.

If we assume that the air enclosed at the top of the chamber follows the polytropic relation for a perfect gas, then

$$H^{*}_{pair}V^{m}_{pair}=C \tag{9}$$

in which m=exponent in the polytropic gas equation (1.0 for isothermal, 1.4 for adiabatic), and C=constant whose value is determined from the initial conditions (= $H^{*}_{oair}V^{m}_{oair}$).

3. Solution of Governing Equation

We have nine equations and nine unknowns: i.e., $Q_{pi,n}$, $Q_{pi+1,1}$, Q_{porf}, $H_{pi,n}$, $H_{pi+1,1}$, h_{porf}, V_{pair}, H^{*}_{pair} and Z_p. $Q_{pi,n}$ and $Q_{pi+1,1}$ can be obtained from Eqs. (1)-(3), and to get H_p substitute them into Eq. (4). Then,

$$H_p=\frac{\frac{C_p}{B_i}+\frac{C_m}{B_{i+1}}-Q_{porf}}{\frac{1}{B_i}+\frac{1}{B_{i+1}}} \tag{10}$$

Substitute Eqs. (7) and (10) into Eq. (6) to get absolute pressure head of the enclosed air H^{*}_{pair}.

$$H^{*}_{pair}=\frac{\frac{C_p}{B_i}+\frac{C_m}{B_{i+1}}-Q_{porf}}{\frac{1}{B_i}+\frac{1}{B_{i+1}}}-Z-0.5(Q_{orf}+Q_{porf})\frac{\Delta t}{A}$$
$$-C_{orf}Q_{porf}\,|\,Q_{porf}\,|\,+H_p \tag{11a}$$

$$=C_2+C_3Q_{porf}-C_{orf}Q_{porf}\,|\,Q_{porf}\,| \tag{11b}$$

where

$$C_1=\frac{1}{B_i}+\frac{1}{B_{i+1}} \tag{12a}$$

$$C_2=\frac{C_p}{B_i}+\frac{C_m}{B_{i+1}}-Z-0.5Q_{orf}\frac{\Delta t}{A}+H_b \tag{12b}$$

$$C_3=-\frac{1}{C_1}-0.5\frac{\Delta t}{A} \tag{12c}$$

Substitute Eqs. (8) and (11b) into Eq. (9)

$$[C_2+C_3Q_{porf}-C_{orf}Q_{porf}\,|\,Q_{porf}\,|\,]$$
$$X[V_{air}-0.5(Q_{orf}+Q_{porf})\Delta t]^{m}=C \tag{13a}$$

where

$$C_4=V_{air}-0.5Q_{orf}\Delta t \tag{13b}$$

$$C_5=-0.5\Delta t \tag{13c}$$

Eq. (13a) can be rewritten as

$$F=[C_2+C_3Q_{porf}-C_{orf}Q_{porf}\,|\,Q_{porf}\,|\,]$$
$$X[C_4+C_5Q_{porf}]^{m}-C=0 \tag{14}$$

The solution to this equation is found numerically by the Newton-Raphson method.

$$F+F\Delta Q_{porf}=0 \tag{15a}$$

$$\Delta Q_{porf}=-\frac{F}{F'} \tag{15b}$$

The derivative of F is

$$\frac{dF}{dQ_{porf}}=[C_3-2C_{orf}\,|\,Q_{porf}\,|\,][C_4+C_5Q_{porf}]^{m}$$
$$+[C_2+C_3Q_{porf}-C_{orf}Q_{porf}\,|\,Q_{porf}\,|\,]$$
$$Xm[C_4+C_5Q_{porf}]^{m-1}C_5=0 \tag{16}$$

Then the substitution statement

$$Q_{porf} = Q_{porf} + \varDelta Q_{porf} \qquad (17)$$

yields an improved value of Q_{porf}. This procedure is repeated either a fixed number of times or until the tolerance TOL is met.

$$|\varDelta Q_{porf}| < TOL \qquad (18)$$

In this research, a program of characteristics method in series of pipes was adapted from Wylie and Streeter (1993) and Wylie (1983) for this analysis, and modified to apply an air chamber to a hypothetical pipe system to analyze attenuation effect of pressure head for different air volumes, locations, chamber areas, coefficients of orifice loss and polytropic exponents.

4. Simulation using an Air Chamber

To analyze attenuation effect of pressure head at pump site, an air chamber is installed to a hypothetical pipe system (Suda, 1991). The attenuation effect of an air chamber can be analyzed by changing following parameters i.e. volume, location, chamber area, coefficient of orifice loss and polytropic exponent. In this analysis pump stopped at t =0 and valve parameter decreased linearly until t=20 sec., and stayed at dimensionless

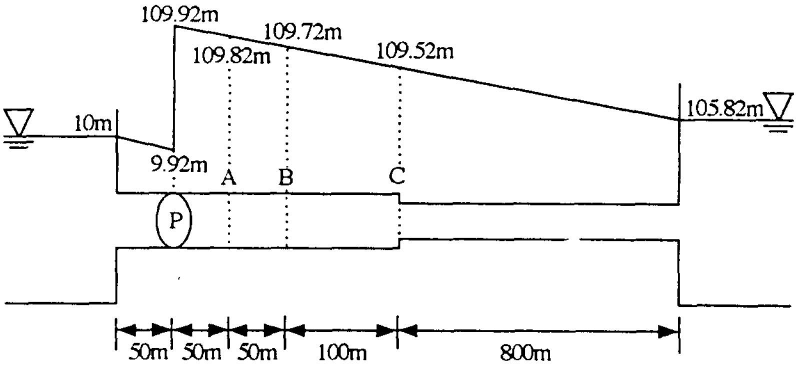

Fig. 3. Initial Condition of Pipe System for Simulation

Table 1. Pump Data for This Analysis

Descriptions	Values
Upstream reservoir head	$H_{ur}=10m$
Nominal discharge of the pump	$Q_n=2m^3/sec$
Nominal head of the pump	$H_n=100m$
Nominal rotational speed of the pump	$W_n=1450rpm$
Nominal shaft torque of the pump	$T_n=600kgm^2/sec^2$
Mass of rotaty parts times square of radius of gyration	$WRg^2=38.7kgm^2$
Wide-open head loss coefficient	$k_o=0.1$
Valve head drop	$k_o\frac{V^2}{2g}=0.01594m$
Ns=25 SI unit	

Table 2. Pipe Data for This Analysis

Pipe	Length(m)	Diameter(m)	Friction Coeff.	a (m/s)
1	50	1.2	0.012	1000
2	50	1.2	0.015	1000
3	50	1.2	0.015	1000
4	100	1.2	0.015	1000
5	800	1.0	0.014	1200

Table 3. Air Chamber Data for This Analysis

Descriptions	Values
Water level in the chamber	$Z=15m$
Chamber area	$A=3m^2$
Polytropic exponent	$m=1.0-1.4$
Coefficient of orifice losses	$C_{orf}=0.002$
Barometric pressure head	$H_b=10.33m$
Air volume	$V_{air}=30m^3$

valve opening=0.005 (Azoury et al., 1986; Goldberg, 1987). The hypothetical piping system of this analysis is shown in Fig. 3.

Pump, pipe and air chamber datas for this analysis are listed in Tables 1, 2, and 3.

From Table 2, head losses can be calculated as follows: $H_1=(fLV^2)/(2gd)=(0.012x50x3.127)/(1.2x2x9.81)=0.08m$; $H_2=H_3=0.1m$; $H_4=0.2m$; and $H_5=3.7m$. If we install an air chamber at 50m downstr eam from the pump(location A), then $H^{*}_{pair}=H_p-Z_p-h_{orf}+H_b=105.13m$.

5. Analysis of Attenuation Effect

In order to analyze the attenuation effect for different air volume in chamber, air volume was changed from $1m^3$ to $500m^3$ and other parameters used are $m=1.2$, $A=3m^2$, $f=0.002$ (from now on f means coefficient of orifice losses C_{orf}). For this case an air chamber was installed at 50m downstream from the pump. Fig. 4. shows that the time history of pressure head at the pump with and without the air chamber. As expected, the pressure heads are almost the same when we use an air volume of $1m^3$. With an increase of air volume, it is found that the maximum pressure head is decreased and the minimum pressure head is increased. Also the period of the peak is increased with incereases of the air volume. For the case of an air volume of $500m^3$, the air chamber accomodates almost all of the pressure surge.

To find the attenuation effect for different locations of air chamber, three locations were selected(i.e. locations A, B, and C). In this analysis air volume of $30m^3$ was used and other parameters were unchanged. Fig. 5. shows that the attenuation effect of the location is minor. So, we can find that the location of the air chamber does not show much effect in the attenuation of pressure head. As mentioned in the introduction, the advantage of an air chamber is that it can be installed near the pump without any distinguishable effect.

Fig. 6. shows the effect of the number of

air chambers. First, three air chambers having the same volume of 10m^3 (total volume is 30m^3) were installed at three different locations (location A, B, and C). In this case the maximum pressure head at pump is about 180m. Second, one air chamber (volume of 10m^3) was installed at 50m downstream of the pump(location A). This case shows a maximum pressure head of about 185m. Therefore, it can be concluded that the

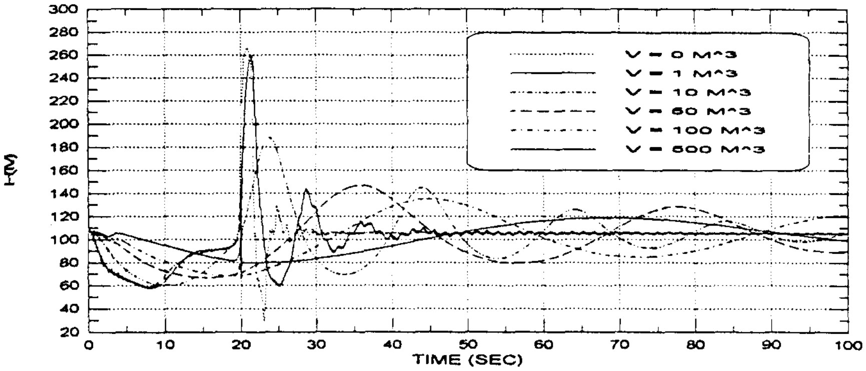

Fig. 4. Attenuation Effect for Different Air Chamber Volumes

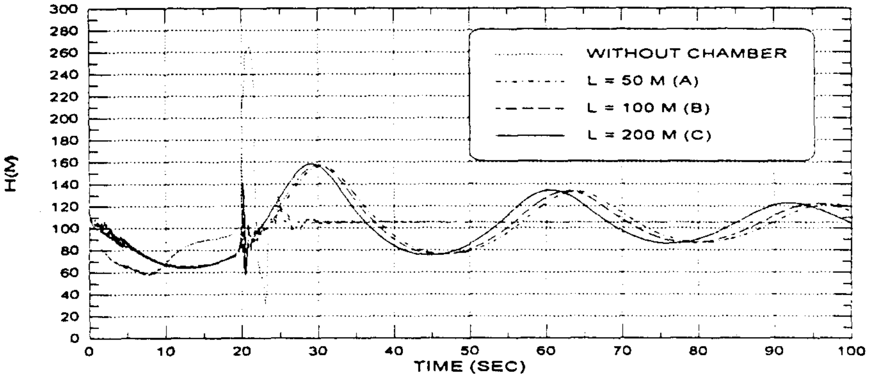

Fig. 5. Attenuation Effect for Different Air Chamber Locations

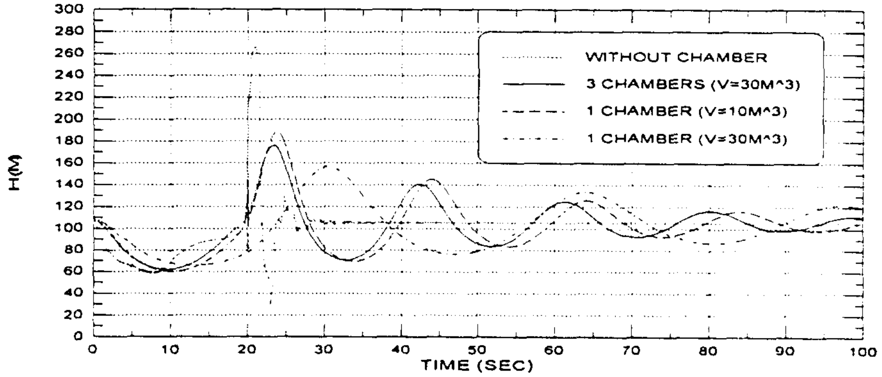

Fig. 6. Attenuation Effect for Separated Chambers

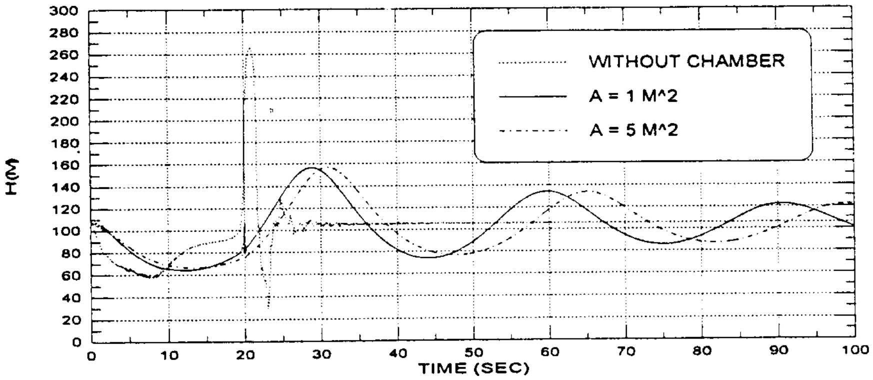

Fig. 7. Attenuation Effect for Different Air Chamber Areas

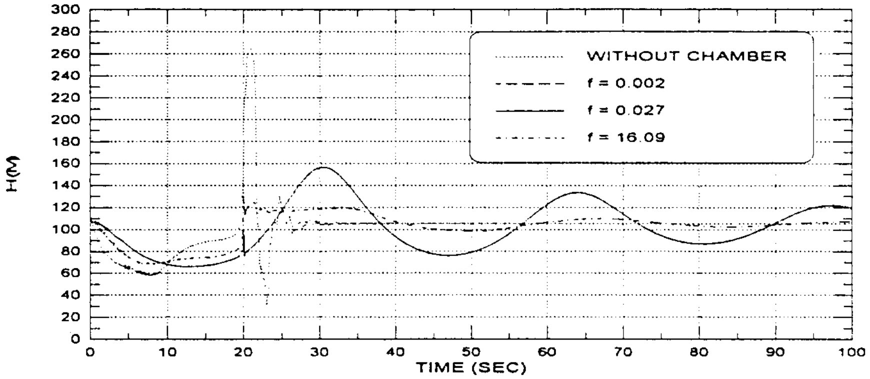

Fig. 8. Attenuation Effect for Different Coefficients of Orifice Loss

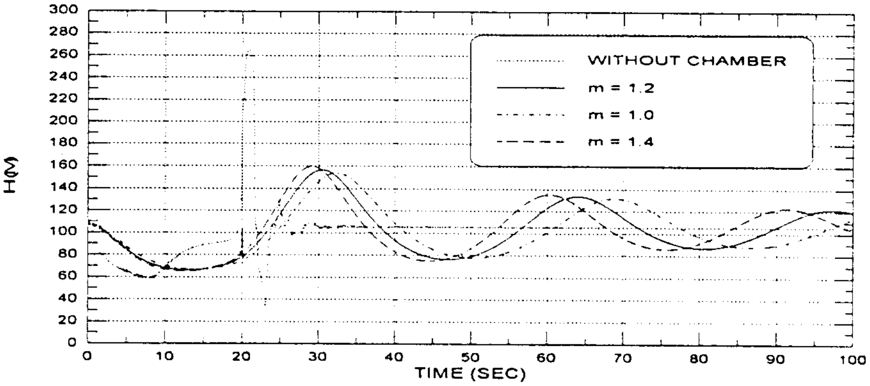

Fig. 9. Attenuation Effect for Different Polytropic Exponents

separation of the air chambers does not greatly improve on the performance of one chamber.

Fig. 7. shows the attenuation effect of an air chamber with the variation of chamber area. Both cases ($1m^2$ and $5m^2$) show almost the same maximum and nimimum pressure heads, showing that the attenuation effect does not depend on the chamber area, but rather on the chamber volume. Also, to find

the attenuation effect for different coefficients of orifice loss, three different orifice diameters were selected. From the orifice head loss equation, we can estimate coefficient of orifice loss corresponding to the orifice diameter.

$$h_{porf} = C_{orf} Q_{porf} \mid Q_{porf} \mid = \left[\frac{1}{C_v} - 1 \right] \frac{Q^2}{2gA^2} \qquad (19)$$

Therefore

$$C_{orf} = \left[\frac{1}{C_v} - 1 \right] \frac{1}{2gA^2} \qquad (20)$$

If the orifice is round, C_v is 0.99. The estimated coefficients of orifice loss are: $C_{orf} = 16.09$ (D=0.1m); $C_{orf} = 0.027$ (D=0.5m); and $C_{orf} = 0.002$ (D=1m). When the coefficients are small ($C_{orf} = 0.027$ and 0.002), pressure head did not show much difference. However, in the case of $C_{orf} = 16.09$, the maximum pressure head was decreased. Fig. 8. shows the attenuation effect of the pressure head for the different coefficiens of orifice loss. In this analysis, constant orifice loss coefficient for the inflow and outflow from the chamber was used. But, if the orifice is of differential type, C_{orf} should have different values for the inflow and outflow from the chamber.

Finally, polytropic exponent m was changed from 1.0 (isothermal) to 1.4 (adiabatic) to see the attenuation effect, and Fig. 9. shows the result. When m=1.4 was used, the maximum pressure head is a little higher than the case for m=1.0. This means that if the air in the chamber follows an isothermal process, the air is more flexible and accomodates more of a pressure surge than that of an adiabatic process.

6. Conclusions

An air chamber plays an important role in the protection of pipe system against rapid transient following abrupt pump stoppage. In this research, governing equation to apply an air chamber was derived from known boundary conditions and an air chamber was applied to a hypothetical pipe system to analyze attenuation effect of pressure head at pump site. For different air volumes, locations, chamber areas, coefficients of orifice loss and polytropic exponents, attenuation effect of pressure head was analyzed and following results were obtained:

1) Attenuation effect is increased as air volume of chamber increases.
2) Location of an air chamber does not show much difference in the attenuation effect.
3) Attenuation effect does not depend on the chamber area, but rather on the chamber volume.
4) Attenuation effect is increased as the coefficient of orifice loss increases.
5) If the air in the chamber follows an isothermal process, attenuation effect is increased.

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