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A Numerical Study on the Reduction of Water Hammering in a Simple Water Supply Pipe System

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Key words: Water hammer, Air chamber, Water supply pipe system, Computer simulation

Abstract

A numerical study has been conducted to characterize the transient pressure in a simple water supply pipe system with an air chamber by utilizing a commercial code that employs the method of characteristics. Some results produced for validation in the study agree quite well with the previously reported. Several parameters are then varied. Among them are the valve closure time, the wave speed, the static pressure, the polytropic exponent, the air chamber volume, the diameter and the shape of orifice in the air chamber, etc, while the water temperature and velocity are kept constant at 20℃ and 0.8 m/s, respectively. Results reported in this parametric study may be useful to understand the unsteady behavior of the system.

Nomenclature

a : Wave speed [m/s]

d_0 : Orifice diameter [mm]

H_w : Initial water level in air chamber [mm]

L : Length of air chamber [mm]

L_0 : Orifice length of long-edged orifice [mm]

n : Polytropic exponent

T_v : Valve closure time [s]

p : Water hammer pressure [bar]

p_s : Static pressure [bar]

V : Volume of air chamber [cm^3]

1. Introduction

In a building water supply pipe system, either the quick closure of valves or the startup and trip of pumps results in severe transient pressure of the fluid flow in the pipe system. Vibration and noise generated by these pressure waves with high amplitude cause the environmental problems in a building, against the demand to have green, convenient and comfortable building environment. The problems by the water hammer are more serious in high-rise and large buildings with inevitably high supply pressure of water.$^{(1)}$ Typical gadgets

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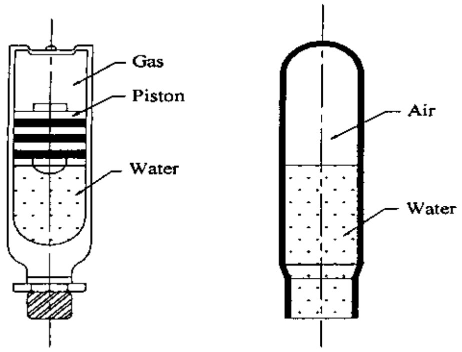


(a) Piston-type water hammer arrester (b) Air chamber

Fig. 1 Typical gadgets used for reducing the water hammer.

used for reducing the water hammer pressure in the systems are water hammer arresters and air chambers (see Fig. 1). In advanced foreign countries, methods for designing the air chambers and for predicting their performances were well established; for example, a commercial computer code(2) was developed for their designs. Also, related standards and codes(3-5) of the water hammer arresters were formulated in 1960s, and since then, their standardized products have been being used widely. Here in Korea, the former ones that are simpler in structure than the latter ones have already been being used extensively, and the latter ones have also been come into the wide use in large-scale apartment complex.(6,7)

Experimental studies on the water hammer phenomena in simple water supply pipe systems and the effects of the water hammer alleviation devices in Korea include works done by Lee et al.(8) and Han and Kim.(9) One of numerical works for their design and performance improvements was done by Kang et al.(10) However, these works on the air chambers are primarily aimed at large-capacity water supply systems such as the city water supply. The air chambers employed for those systems are of large volume exceeding a couple of m^3, thus the characteristics of the large-volume air chambers may not be useful to understand the behavior of those of small-volume air chambers for building construction applications where their volumes are usually less than a few hundred of cm^3.

It is anticipated that the water hammer arresters will be used more dominantly than the air chambers as the water hammer reduction gadgets in the building construction industry in the near future. However, the use of the air chambers will last for a while due to the convenience of their fabrication and installation.

In this study, which is a continuation of the previous work,(11) the transient pressure in a simple water supply pipe system was numerically investigated by varying parameters such as the valve closure time, the wave speed and the static pressure. Then, the effects of the polytropic exponent, the air chamber volume, the diameter and shape of orifice, etc were also numerically investigated to characterize the small-volume air chambers.

2. Numerical analysis

A commercial code Flowmaster2 (version 5.2), which employs the method of characteristics, was applied for the analysis of one-dimensional pipe system. In order to validate the numerical calculation, the simulation results were compared with the previously reported experimental ones.(8) Figure 2 shows a typical simple water supply system consisting of constant temperature reservoir (1), surge tank (3), compressor (9), air tank (10), header (4), test section, closure valve (6) and collection reservoir (7). The test section is defined as from the outlet of the header to the center of closure valve. It is 18 m long and made out of a copper pipe (KSD 5301 L type, inner diameter of 19.94 mm, thickness of 1.14 mm). A normal close type solenoid valve was used to close the flow quickly, leading the water hammer, and a pressure sensor (5) was installed at 0.5

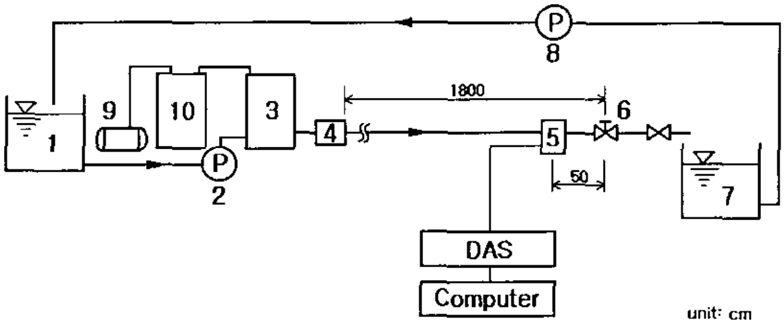


Fig. 2 Schematic diagram for water hammer experimental apparatus.(8)

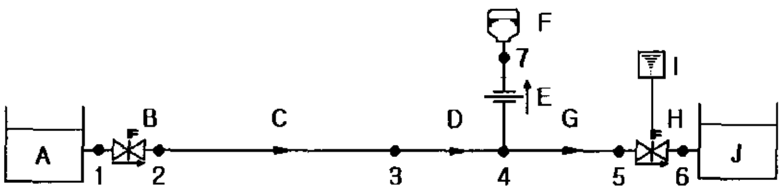


Fig. 3 Flowmaster2 network for simulating the water hammer of Fig. 2.

m upstream of the closure valve. More detailed description of experimental apparatus can be found in Ref. 8.

A Flowmaster2 network used in this study for simulating the water hammer is shown in Fig. 3. Some components such as constant temperature reservoir, compressor, air tank and header, which are less important for this study, were excluded. After the verification was done, the air chamber with orifice on it was added.

Table 1 Components of two water supply systems

Symbol	Component	
	Present Study	Ref. 8
A	Pressurized Reservoir	Pressurized Tank
B	Gate Valve	Valve
C	Horizontal Pipe I	Test Section
D	Horizontal Pipe II	Test Section (cont'd)
E	Orifice	-
F	Air Chamber	-
G	Horizontal Pipe III	Test Section (cont'd)
H	Gate Valve	Solenoid Valve
I	Controller	Computer System
J	Reservoir	Reservoir

Table 1 compares the components in Fig. 3 and parts of components in Fig. 2 that are directly related in this study.

In order to simulate the water hammer, the constant pressure in the pipe system is maintained by controlling the static pressure of the reservoir. The solenoid valve, which is unavailable in the commercial code, could be simulated as a combination of a gate valve and controller which are standard components in the code. In experiment, the pressure was measured at 0.5 m upstream of the solenoid valve, while in numerical simulation the air chamber and the pressure sensor are installed at 1 m (Node 3) and 0.5 m (Node 4) upstream of the solenoid valve, respectively. Therefore, the test section could be divided into three parts.

Overall, Flowmaster2 network in Fig. 3 contains ten calculation components and seven nodes. For a numerical result without the air chamber, which is done for the verification purpose, the air chamber is excluded and the pressure at Node 3 is observed and compared with the experimental data. On the other hand, the numerical experiment with the air chamber, the pressure at Node 3 is monitored, if otherwise specified. In computation, the time step of computation is determined by considering the wave speed and the length of test section, under a condition that the commercial code requires, and turns out to be 0.415 ms. The code is installed in a Pentium Ⅱ PC running at 300 MHz. The time required for computation of each case was less than 10 s and the iteration number of every time step calculation is less than ten for most of runs in the study.

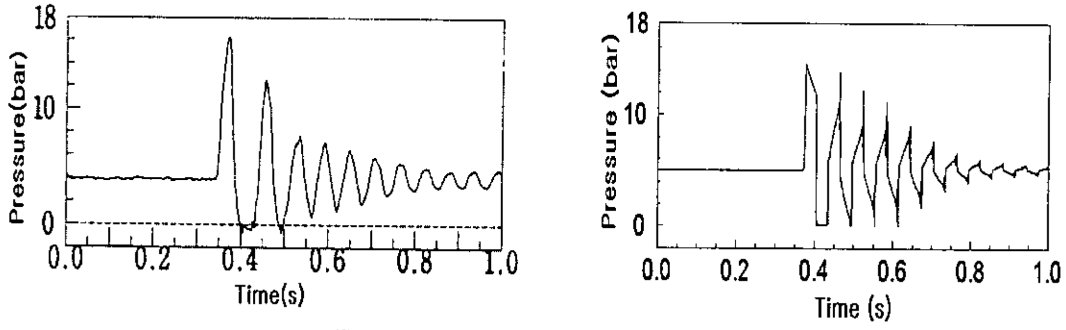
3. Results and discussion

When the 20℃ water flowing at the velocity of 0.8 m/s and the pressure of 4 bar stops quickly, the resulting transient pressure is shown in Fig. 4 (a). Here, $t=0$ s means arbitrary time at which pressure measurement begins. The valve is closed at the moment when the time elapses about 0.35 s. When the valve closure time is defined as the time interval between the time at which the valve begins to closes and the moment at which the peak pressure reaches, it was estimated to be approximately 26 ms. The wave speed was also determined to be about 1204 m/s. In order to simulate this experimental results, the orifice (E) and the air chamber (F) module in Fig. 3 is excluded and then the absolute pressure of upstream reservoir (A) and downstream reservoir (J) are maintained to be 4.997 and 4.910 bar, respectively, with the gate valves (B and H) fully open. With this flow balancing, the simulation conditions are maintained the same as the experimental ones. After 0.35 s, the gate valve (H) is closed within 25 ms by utilizing its corresponding controller (H). In this period of time, the simulated transient pressure is shown in Fig. 4 (b). Both the experimental and the simulated results agree very well, in terms of the period of the pressure waves. Keeping in mind that the numerical results show in terms of the absolute pressure, the amplitudes of both results are also quite comparable. Therefore, it is verified that the commercial code with the given conditions could be used to predict the transient pressure.

First of all, a numerical study was conducted by varying the valve closure time, the wave speed and the static pressure to investigate the characteristics of the water hammer in the simple water supply pipe system.

3.1 Effect of the valve closure time

The test procedure[(3)] of a water hammer arrester recommends that the valve closure time should be less than 30 ms. Also, the closure time of a quick valve which used in the building construction industry is a few ten milliseconds. Thus, the valve closure time in simulation is varied as 25, 50, 100, 200 and 400 ms



(a) Experiment[(8)]

(b) Simulation in this study

Fig. 4 Water hammer pressure caused by quick valve closure.

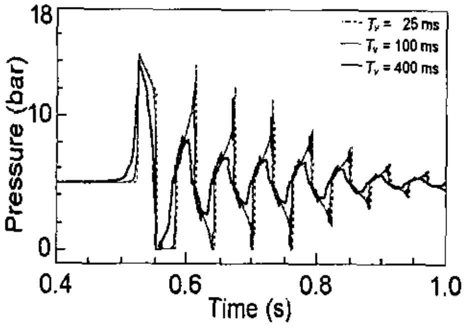


Fig. 5 Effect of the valve closure time on the water hammer pressure for $a=1204$ m/s and $p_s=5$ bar.

with the wave speed of 1024 m/s and the static pressure of 5 bar. For the convenience of simulation, it is assumed that the valve ends closing at 0.525 s. For example, in case of the valve closure time of 25 ms, the valve remains fully open until 0.500 s and begins to close at 0.500 s and completes the closing motion at 0.525 s. It is also assumed that the valve can be re-open slightly due to rebounding of its stem. This effect is incorporated to every case in simulation. The effect of the closure time on the water hammer pressure is shown in Fig. 5 for three cases of 25, 100, 400 ms out of the five for better comparison.

The effect of the valve closure time can be easily observed with the result of the 400 ms case having the longest closure time. During the closure time, that is from 0.125 s to 0.525 s, the valve closes linearly with its opening of 100% to 0%, respectively, but the pressure at the monitoring point is not affected much for most of the time interval and begins increasing sharply with the opening of 7%, or after 0.5 s or so. It is found that the amplitude of the pressure wave decreases and its wave form becomes more smooth as the valve closure time is increased. It is also found that the period of the pressure wave is not affected much by the valve closure time. For better comparison of the effect of the valve closure time on the amplitude of the pressure waves,

Table 2 Variation of maximum water hammer pressures as a function of the valve closure time

T_v (ms)	$p_{\max}$ (bar)		
	1st Pres. Wave	2nd Pres. Wave	3rd Pres. Wave
25	14.68	13.76	12.17
50	14.67	13.10	11.94
100	14.64	12.48	11.33
200	14.50	11.75	9.08
400	14.05	8.51	7.30

Table 2 summarizes the maximum values of the first three peaks as a function of the valve closure time. As shown in the table, the peak pressures decrease as the valve closure time in the range investigated is increased.

3.2 Effect of the wave speed

The speed of wave propagation in a pipe system is determined by the bulk modulus of fluid, the density of fluid, the Young's modulus of elasticity of the pipe material, the diameter of the pipe, the thickness of the pipe wall and constraint factor.(12) The theoretical value of the wave speed, based on the conditions set in this study, is estimated to be approximately 1291 m/s, but it is affected by the constraint

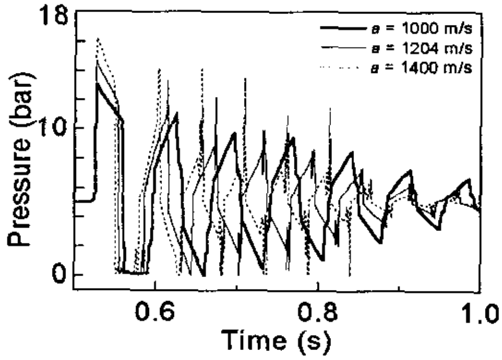


Fig. 6 Effect of the wave speed on the water hammer pressure for $T_v=25$ ms and $p_s=5$ bar.

factor which is not known. Thus, we vary it as 1000, 1100, 1204, 1300 and 1400 m/s to see the effect of the wave speed. Here, the value of 1204 m/s was calculated in the experiment.(8) Figure 6 indicates the transient pressure with the wave speed of 1000, 1024 and 1400 m/s under the conditions of the valve close time of 25 ms and the static pressure of 5 bar. It shows that the initial amplitude of the pressure wave increases but its period decreases as the wave speed is increased.

3.3 Effect of the static pressure

The static pressure of the pipe system of a large high-rise building is getting high, being in proportion to its longer vertical pipe lines. In that case, the static pressure of it is controlled through zoning to minimize the pressure difference of each level, but its precise control is not easy. To simulate this situation, the static pressure is varied as 2, 3, 4, 5 and 6 bar in numerical experiment while other conditions remain constant; that is, the valve closure time of 25 ms and the wave speed of 1204 m/s. Figure 7 shows the simulated results with the static pressures of 2, 4 and 6 bar. As shown in the figure, the amplitude of the first pressure wave increases roughly by the initial pressure increment and the period becomes shorter as the static pressure is increased.

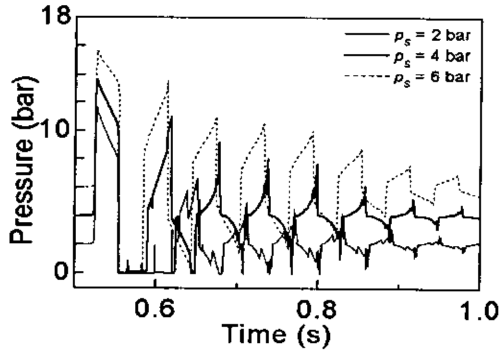


Fig. 7 Effect of the static pressure on the water hammer pressure for $T_v=25$ ms and $a=1204$ m/s.

So far, the characteristics of the water hammer in simple water supply pipe system are investigated with the parameters such as the valve closure time, the wave speed and the static pressure. Now, the transient pressure with an air chamber in the system as a water hammer reducing device is characterized. The effects of some parameters of the air chamber including the polytropic exponent, the air chamber volume and the diameter and shape of orifice attached, which are we believe dominant on its characteristics, are investigated. In order to investigate the effects of those parameters, 21 air chambers which have different specifications (see Table 3) are tested. The inner diameter of the air chamber is adopted to be the same as that of the test line, and its length which consequently determines its volume is varied from 300 mm to 1440 mm of five dif-

Table 3 Dimensions of air chambers tested

Case	L (mm)	V (cm^3)	H_w (mm)	Orifice		
				Type	d_0 (mm)	L_0 (mm)
1	300	93.7	60.6	Sharp-edged	5.98	-
2				ditto	8.97	-
3				ditto	11.96	-
4				ditto	16.62	-
5				Long-edged	5.98	5.00
6				ditto	8.97	5.00
7				ditto	11.96	5.00
8				ditto	16.62	5.00
9	500	156.1	101.0	Sharp-edged	11.96	-
10	800	249.8	161.7	ditto	11.96	-
11	1200	374.7	242.5	ditto	11.96	-
12	1440	449.7	291.0	ditto	5.98	-
13				ditto	8.97	-
14				ditto	11.96	-
15				ditto	16.62	-
16				Long-edged	5.98	5.00
17				ditto	8.97	5.00
18				ditto	11.96	5.00
19				ditto	11.96	10.00
20				ditto	11.96	19.94
21				ditto	16.62	5.00

ferent values. The former number is the length of the air chamber which is generally used in domestic building construction industry and the latter one is recommended by PDI specification.[3] The initial water level in Table 3, calculated by using the Boyle-Charles' law, means that the water level in the air chamber determined by the pressure difference between the initial pressure in pipe line and the atmospheric pressure. The shape of an orifice which is installed at inlet of the air chamber is of either sharp-edged or long-edged type. Orifice diameter of both types is varied as 5.98, 8.97, 11.96 and 16.62 mm and further orifice length of the latter type as 5.00, 10.00, and 19.94 mm. Other parameters in numerical experiment keep constant as follows; the water temperature of 20℃, the flow velocity of 0.8 m/s, the valve closure time of 25 ms, the wave speed of 1204 m/s and the static pressure of 5 bar.

3.4 Effect of the polytropic exponent

Air in the air chamber is undergone either expansion or compression in polytropic process.[10] The polytropic exponent of the air is unity in isothermal process and 1.4 in adiabatic one. The difference between the water hammer pressure and the static pressure with various polytropic exponents are shown in Fig. 8. Case 14 air chamber which is 1440 mm long and 11.96 mm in orifice diameter is tested with several different polytropic exponents. It is observed that the period of the pressure wave increases and its amplitude decreases as the polytropic exponents is decreased. The reason is that when the water flows back to the pipe system from the air chamber, the air undergoing in isothermal process gets more compressed than that in adiabatic process, and thus the water in the former process flows more to the system and the rate of the pressure drop is lower.[10] In this study, the polytropic exponent of 1.2, which is generally taken for similar applications, is adopted.

3.5 Effect of the volume of air chamber

The effect of the volume of the air chamber is tested with five different lengths of air chambers in the range between 300 mm and 1440 mm. Before addressing the issue, it may be worthwhile looking at the effect of the air chamber on the water hammer reduction, and thus the transient pressures with and without an air chamber (Case 14) are compared, as shown in Fig. 9. The amplitude of the water hammer pressure with the air chamber noticeably decreases but its period becomes a lot longer. Figure 10 shows the variation of the

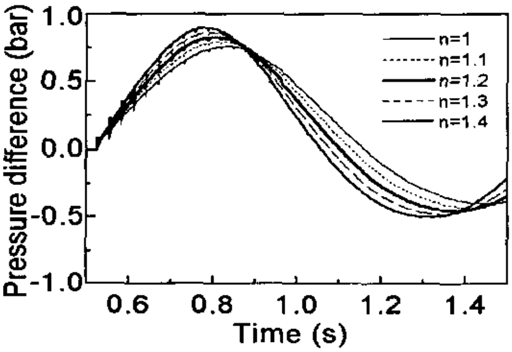


Fig. 8 Effect of the polytropic exponent on the water hammer pressure with an air chamber of Case 14.

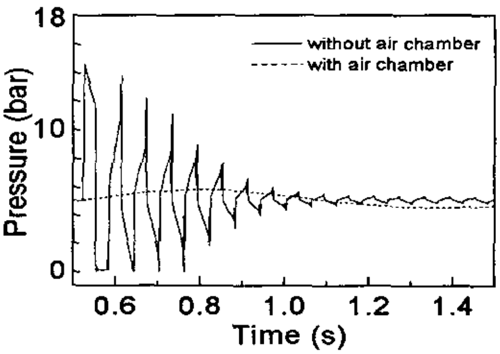


Fig. 9 Comparison of the water hammer pressures with and without an air chamber of Case 14.

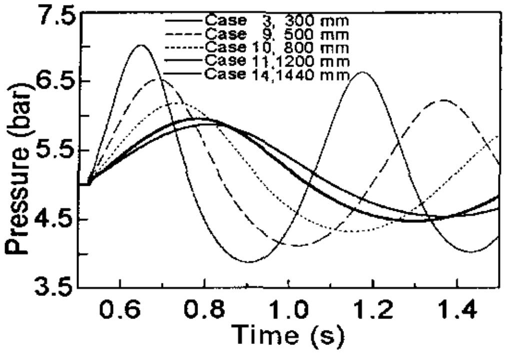


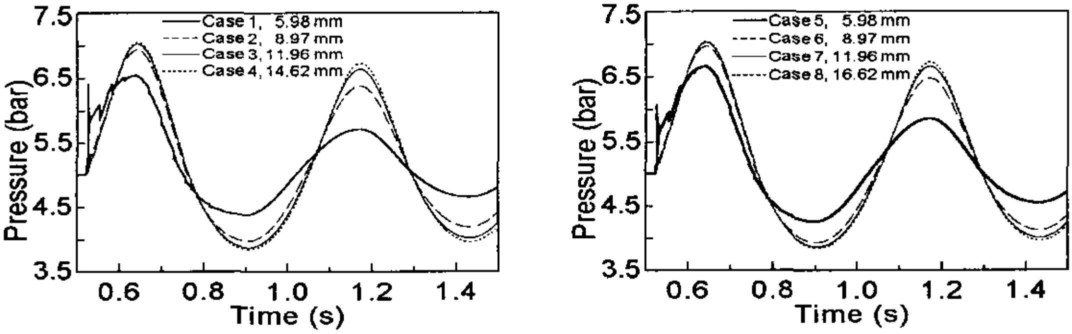
Fig. 10 Effect of the air chamber volume on the water hammer pressure with an 11.96 mm in diameter sharp-edged orifice.

water hammer pressure as a function of the volume of the air chamber whose orifice diameter is all 11.96 mm. As shown in the figure, the reduction in the water hammer pressure is more effective and the period of the pressure wave gets longer as the volume of the air chamber is increased. This is because that as the volume of the air chamber is increased, the rate of the pressure change of the air chamber decreases and the flow rate of the water between the air chamber and the pipe line increases.

3.6 Effect of the diameter and shape of orifice

An orifice installed in front of an air chamber determines the maximum and minimum pressure in the air chamber, and thus it is an important design factor when an air chamber with larger-volume is optimally designed.(10) For a small-volume air chamber which is frequently used in building construction industry, however, the orifice is not usually installed for the sake of itself, but the connector, which results in the change in the cross-sectional area, acts as an orifice. Therefore, the effects of the diameter and shape of the orifice should be scrutinized. Cases with different diameters and shapes of orifices are listed in Table 3. Flow coefficient of orifice of each case is taken from the data base in the commercial code.

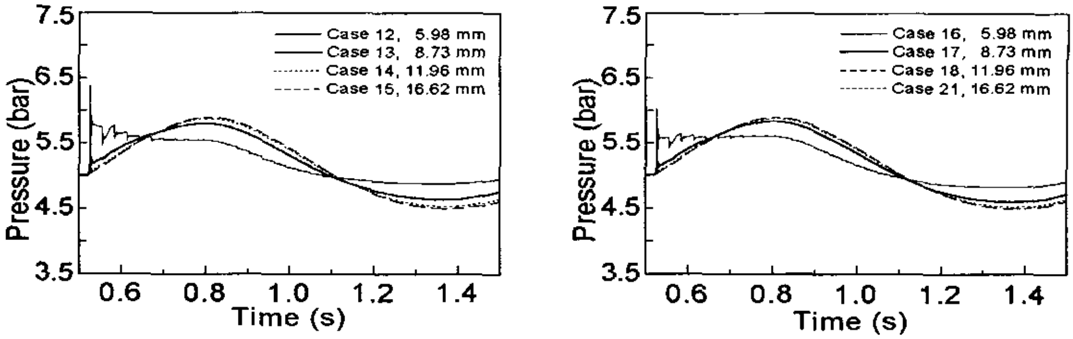
Figure 11 (a) shows the variation of the water hammer pressure as a function of the orifice diameter when a 300 mm long air chamber with a shape-edged orifice is employed. It is observed that as the orifice diameter is decreased, the amplitude of the pressure wave decreases and thus the water hammer pressure dampens more quickly, which is in good agreement with the previously reported.(10) For Case 1 having the smallest diameter orifice among the tested, the sudden uprising of the pressure is observed right after the valve closure, even though its magnitude is much less than that of the case without an air chamber (see Fig. 9). This could be caused by the relatively large flow resistance when the water flows into the



(a) Sharp-edged

(b) 5 mm long-edged

Fig. 11 Effect of the diameter of orifice on the water hammer pressure with 300 mm long air chamber.



(a) Sharp-edged (b) 5 mm long-edged

Fig. 12 Effect of the diameter of orifice on the water hammer pressure with 1440 mm long air chamber.

air chamber.

Figure 11 (b) shows the test results of long-edged orifices with orifice length of 5 mm instead of sharp-edged ones under the same conditions. The results are quite similar to those of the latter. In the same way, the effect of the orifice diameter was tested for 1440 mm long air chambers having either sharp-edged or long-edged orifice and their results are shown in Fig. 12 (a) and 12 (b), respectively. The results show very similar trends to those of 300 mm long air chambers except the reduction in the amplitude and the increase in the period of the pressure wave.

In order to see the effect of the orifice shape, 1400 mm long air chambers with four different orifice shapes, that is, sharp-edged, 5.00, 10.00 and 19.94 mm long, were tested, and their variations in the water hammer pressure are shown in Fig. 13 and Table 4. As shown in the figure, their amplitude of the pressure waves are slightly different to each other and their periods appear no noticeable change among them. Table 4 summarizes the maximum and the minimum values of the first peak pressure waves for the four cases to show the subtle trend with the orifice shape. It is observed that *the pressure amplitude with the sharp-edged* one is the smallest and that the amplitude gets larger a little bit as the orifice length of long-edged orifice is increased.

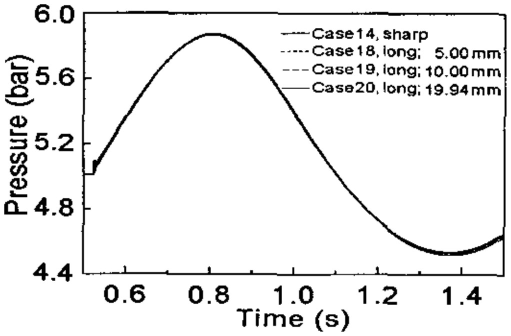


Fig. 13 Effect of the shape of orifice on the water hammer pressure.

Table 4 Variation of the first water hammer pressure wave with different shapes of orifices

Orifice Shape	$p_{\max}$ (bar)	$p_{\min}$ (bar)
Sharp-edged	5.870	4.539
Long-edged, $L_0 = 5.00$ mm	5.875	4.531
Long-edged, $L_0 = 10.00$ mm	5.878	4.526
Long-edged, $L_0 = 19.94$ mm	5.880	4.523

4. Conclusions

A numerical study has been conducted to characterize the transient pressure in a simple water supply pipe system with a small-volume air chamber by utilizing a commercial code. For the simple pipe system, the effects of the valve closure time, the wave speed and the static pressure were scrutinized while for the system with the air chamber, the effects of the polytropic exponent, the air chamber volume, the diameter and shape of orifice were numerically tested. Other parameters which can affect the water hammer such as the water temperature and the flow velocity were kept constant as 20℃, 8 m/s, respectively.

With the increase of the valve closure time, the amplitude of the pressure wave decreases and its shape gets more smooth, but its period is not affected much. As the wave speed is increased, the initial amplitude of the pressure wave increases, but its period decreases. The amplitude of the first peak pressure wave is increased by the amount of the static pressure increment, and its period slightly decreases with the increase of the static pressure.

Reduction characteristics of the water hammer pressure with an air chamber can be summarized as follows. As the polytropic exponent is decreased, the amplitude of the pressure wave gets lower, but its period increases. With the increase of the air chamber volume, the water hammer pressure reduces more effectively and its period becomes longer. In the range investigated, as the orifice diameter is decreased, the amplitude decreases, but its period appears not influenced, thus the water hammer pressure decays faster.

For the effect of the orifice shape, the sharp-edged orifice seems to be more effective than the long-edged one. When the length of the long-edged orifices is increased, the amplitude slightly increases.

A recommendation to building construction industry would be that the length of the air chamber, which is currently installed with the fixed length of 300 mm, should be adjusted, depending on the static pressure at the location where it is installed. The reason is that the static pressure at each level of a building is different and the volume or the length of the air chamber should be large enough to meet the allowable limit of the water hammer pressure.

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