Dynamic Characteristics of Water Hammer Arresters for Building Service Applications

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ABSTRACT: Dynamic characteristics of water hammer arresters installed in a building water supply system have been investigated numerically by utilizing a commercial code that employs the method of characteristics. Some preliminary results with those arrester models produced in this study agree well with the previously reported. Then, the arrester models have been incorporated into a water supply pipe system of a 59 m^2 apartment unit constructed by a leading construction company, and their dynamic characteristics have been investigated, especially on the reduction in the water hammer pressure. It is found that the setting of the arresters in the pipe system, which is recommended by the company, may not be proper for reducing the pressure down below 1,082.0 kPa (10.0 kg_f/cm^2) when quick-closure valves in the pipe system are closed within 30 ms at the static pressure of 542.6 kPa (4.5 kg_f/cm^2). More arresters in the system may be required to meet pressure criteria stated on the related standards and codes.

1. Introduction

Either the quick-closure of valves or the startup and trip of pumps in a building water supply pipe system results in, what so called, the water hammer phenomena. Accompanied pressure waves with high amplitude may 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 the water.(1)

Typical gadgets used for reducing the water hammer pressure in the systems are water hammer arresters and air chambers. They utilize in principle the compressibility of the gas contained in themselves to absorb the excessive high pressure of the supply water. However, the gas, usually the air, in the former one directly contacts the water and is absorbed into the water, resulting in the collapse of the air volume while the latter one has either piston, membrane, or bellows between the air and water so that the gas, either the air or inert gas, can be preserved.

In developed foreign countries, the methods for designing the air chambers and for predicting their performances were well established. Also, related standards and codes(2-4) 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, which 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.(5)

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There are some experimental studies on the water hammer phenomena in simple water supply pipe systems[6] and on the effects of the water hammer alleviation devices.[7,8] A few numerical works, mainly focused on the reduction of the water hammer pressure with the air chambers, include works done by Kang et al.[9] and Hwang et al.[10] To the best of the author's knowledge, however, there is little work done on the effect of the water hammer arresters for building service applications in Korea.

In order to investigate the dynamic characteristics of the water hammer arresters for building service applications, the piston-type arrester models have been incorporated into the water supply pipe system of a 59 m^2 apartment unit and numerically tested in this study.

2. Numerical experiments

2.1 Model apartment and its water supply pipe system

A water supply pipe system of an apartment unit of 59 m^2 at the 6th floor of the 20 story apartment building constructed by a leading construction company[11] has been selected for this study. Fig. 1 indicates a schematic diagram of the water supply pipe system of the apartment unit. The water comes in through a 20 mm diameter copper pipe and goes out to eight branch pipes of 15 mm in diameter. Each branch line has either a faucet or a valve at its end, and each flow outlet is termed as follows for the convenience; kitchen faucet (KF), front balcony faucet (FBF), bowl low tank (BLT), wash bowl faucet (WBF), bath tub faucet (BTF), boiler water supply (BWS), washer faucet (WF), and rear balcony faucet (RBF).

Table 1 Design criteria of the water supply system of the model apartment unit

Item	Value / Description
Flow velocity	Less than 1.5 m/s
Flow resistance for pipes	Less than 20 mmAq/m
Fixture unit (FU)	3 FU
Inlet pipe nominal diameter	20 mm
Outlet pipe nominal diameter	15 mm
Pipe material	Copper

There are an ASSE (American Society of Sanitary Engineering) size A water hammer arrester in the WBF branch line and an ASSE size AA water hammer arrester in the BWS branch line, although not shown in the figure. There is another ASSE size A arrester in the hot water supply pipe system, but it is not included in this study. Some design criteria of the water supply pipe system of the model apartment unit specified in a specification of the company are listed in Table 1.

2.2 Water hammer arresters

Numerous water hammer arresters are now

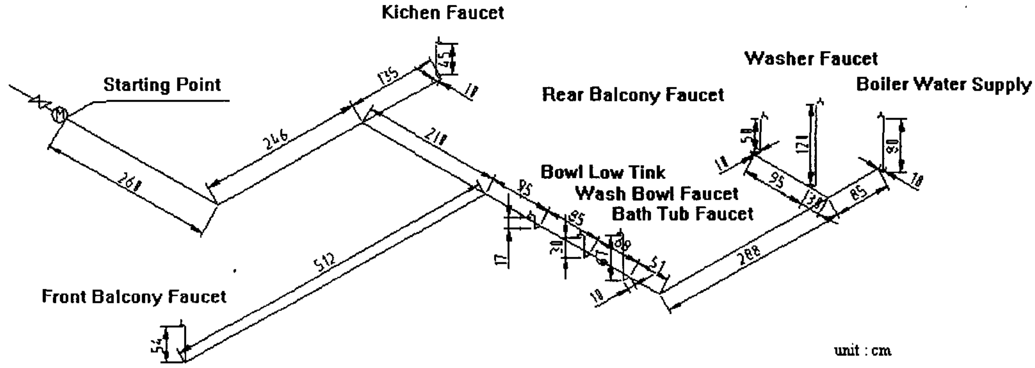


Fig. 1 Schematic diagram of water supply pipe system of a model apartment unit of 59 m^2.

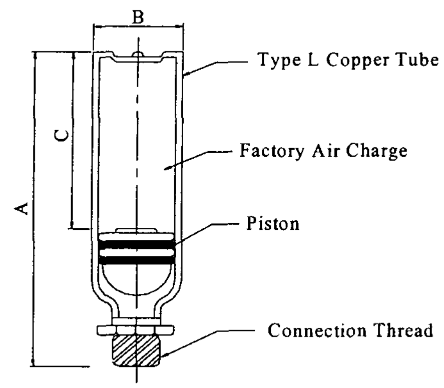


Fig. 2 Schematic diagram of a water hammer arrester.[12]

available in the market, and Sioux Chief products[12] which meet the related standards and codes[2-4] are chosen. A schematic diagram of a water hammer arrester of the company is shown in Fig. 2. It is basically made of an L-type copper pipe, and a compressed gas chamber (pressure: 493.6 kPa, 4.0 kgf/cm^2) and a piston in it. Several classes of the arresters are available, depending on the fixture unit (FU). Major specifications of the arresters used in this study are listed in Table 2. The height of the gas chamber, "C" in Fig. 2, is calculated as the volume of the chamber divided by its cross-sectional area, and the initial piston level is estimated by using the Boyle-Charles law with the pressure difference between the charged gas and the water.

Data in Table 2 have been provided as input parameters for numerical experiments. Maximum working temperature, number of cycles for endurance test, pressure for burst test, controlled surge pressure at design, and maximum working pressure of the arresters are 121.1℃ (250°F), 500,000 cycles, 20,106.0 kPa (204.0 kgf/cm^2, 2,900 psig), 1,140.8 kPa (10.6 kgf/cm^2, 150 psig), and 2,513.7 kPa (24.6 kgf/cm^2, 350 psig), respectively.[12]

2.3 Numerical analysis

Applying the laws of conservation of mass, of linear momentum, and of energy leads to the basic equations[13] for homogeneous, geometrically one-dimensional flow of the application being considered. The equations and associated static pressure boundary conditions are solved by using a commercial code Flowmaster2 (version 5.2)[14] which employs the method of characteristics for the analysis of the building water supply pipe system. The validation of the numerical experiments being conducted was already done when the reduction of water hammering in a simple water supply pipe system with an air chamber was investigated,[10] and thus a separate validation work for this research has not been performed. However, the results of this numerical experiments have been double-checked by referring to those previously reported[8,10] for confirming their general trend.

Figure 3 shows a Flowmaster2 network used in this study for simulating the transient flow in the building water supply pipe system shown in Fig. 1. It consists of 85 components and 74 nodes in total. Among them, component A is the pressure source for inlet boundary condition, and components O, X, AH, AR, BA, BO, BX, and CG are the pressure sources for outlet boundary conditions at the KF, FBF, BLT, WBF, BTF, BWS, WF, and RBF branch lines, respectively. Quick-closure valves denoted as M, V, AF, AP, AY, BM, BV, and CE have artificial controllers denoted as N, W, AG, AQ, AZ, BN, BW, and CF, respectively for mimi-

Table 2 Specifications[12] of the water hammer arresters used for numerical experiments

ASSE size	Dimensions (mm)			Air chamber volume (cm^3)	Initial piston level (mm)	FU
	A	B	C			
AA	120.7	22.2	73.7	23	1.7	1~4
A	165.1	34.9	101.2	82	2.8~7.1	4~11

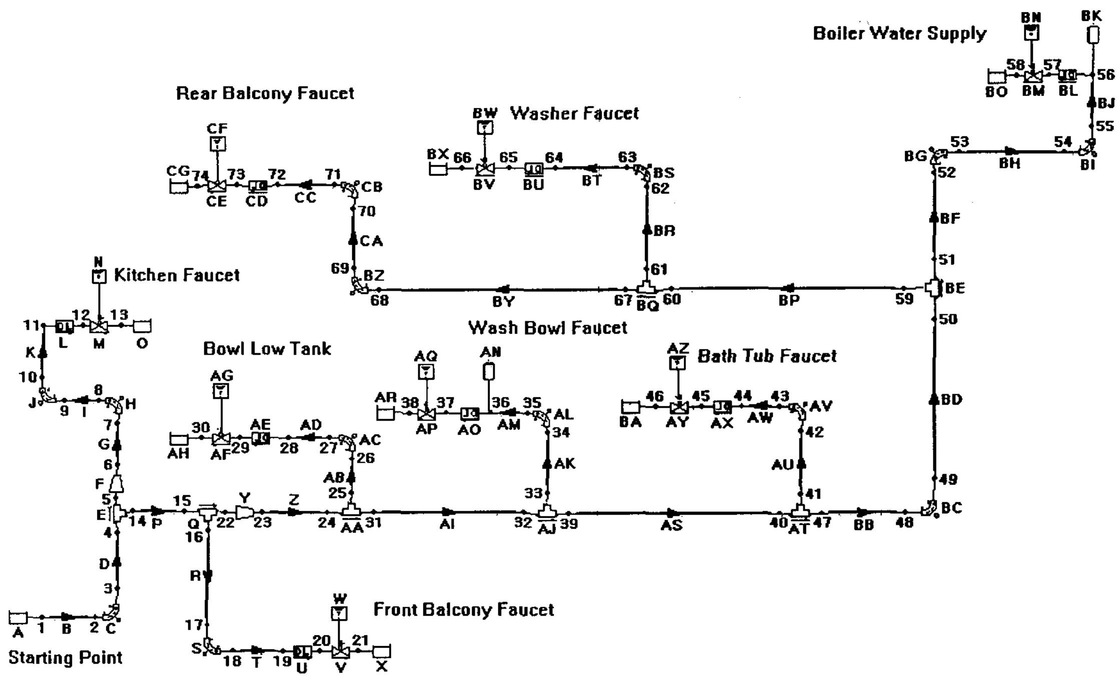


Fig. 3 Network for simulating the water hammer of Fig. 1.

cking the effect of their quick closure. Other components including pipes, tees, elbows, reducers, etc. in the pipe system shown in Fig. 1 are incorporated in the code network system by using the corresponding standard components of the commercial code.

Another artificial components are DL (discrete loss) components denoted as L, U, AE, AO, AX, BL, BU, and CD. They work as additional flow resistance source for flow balancing, which may be necessary since incorporating only real components in the pipe system may not yield actual flow conditions. Input parameters used for determining the values of the DL components include the water temperature, inlet pressure, outlet pressure and flow velocity at each branch line, and they are set to be 20℃, 542.6 kPa (4.5 kg_f/cm^2), 0 kPa, and 1.5 m/s. At this time, all the valves are fully open. During the flow balancing, the equivalent opening area of DL components are adjusted; and they turned out to be in the range of 0.0133~0.0135 cm^2 after the flow balancing is done.

Components AN and BK represent water hammer arresters; the former one for ASSE size A and the latter one for ASSE size AA (see Table 2 for their detailed specifications). One major assumption for this numerical study is related to the dynamic characteristics of the water hammer arrester. Since the commercial code does not have water hammer arrester model among its standard components, the component of bladder type air accumulator, which is believed to be the most similar one, is used alternatively. This one has an artificial membrane that separates the gas from the water, and can thus simulate the separation of the gas and water of the water hammer arresters considered. However, it may not simulate the effect of the friction between the wall of the gas chamber and the piston, which would lead to the slight error in the linear momentum equation. When the cases without the arresters are simulated, the arrester models have been disconnected from the network.

Process variables such as the pressure and flow velocity at each node of the network system shown in Fig. 3 have been calculated during the numerical experiments. However, those at nodes right before the quick-closure valves, that is, Nodes 11, 19, 28, 36, 44, 56, 64, and 72 have been monitored, since they can show the transient water hammer pressure very well.

The time step of computation has been determined in such a way that most of the pipes are considered to be elastic, not rigid, and it turned out to be 0.001 s when a condition that the code requires was met. The diameter, length, and material of the pipes and the wave speed as well have been provided for determining the time step. The code has been installed in a Pentium III PC running at 600 MHz. The time required for computation of each case was less than 60 s and the iteration number of every time step calculation was less than ten for most of runs in the study.

3. Results and discussion

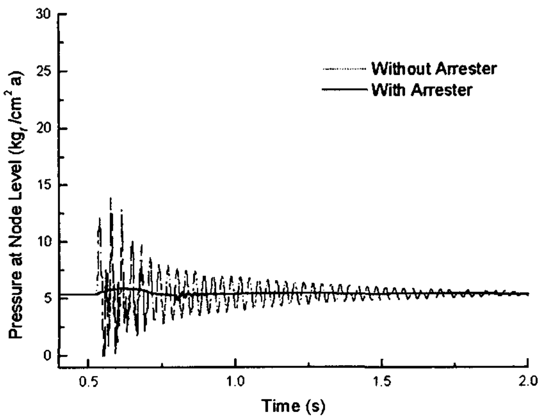
Since it is highly unlikely to open all of eight valves in the apartment unit being considered simultaneously, the characteristics of transient pressure has been investigated branch line by branch line. Among the eight valves at the end of the corresponding branch lines, KF, WBF, BTF, and WF were considered as quick-closure valves. The test procedure[3] of a water hammer arrester recommends that the valve closure time should be less than 0.03 s. Also, the closure time of a quick valve used in the building construction industries is known to be a few ten milliseconds. Thus, the valve closure time in simulation was set to be 0.03 s. For the convenience of simulation, it is assumed that the valve ends closing at 0.53 s, implying that the valve remains fully open by 0.50 s, begins to close at that moment, continues closing linearly with respect to the time, and ends the closing motion at 0.53 s.

The speed of sound in a pipe system is determined by the bulk modulus of the fluid, Young's modulus of elasticity of the pipe material, diameter of the pipe, thickness of the pipe wall and other constraint factor.[12] However, since the diameter of the pipes is either 20 mm or 15 mm and the constraint factor is not known, its value can not be calculated accurately and thus approximate value of 1,283 m/s has been used, instead. Also, it is assumed that the water temperature remains 20 ℃ and the polytropic exponent of the air in the compressed gas chamber is 1.2. Other input parameters including the cross-sectional area and height of the cylinder and the initial position level, as listed in Table 2, have also been provided.

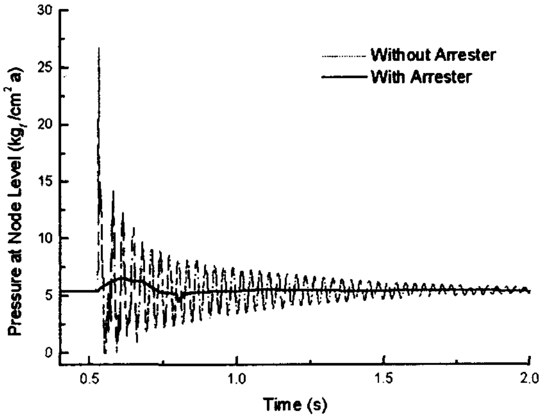
3.1 Characteristics of model water supply pipe system

Initially, the transient surge pressure at the model water supply pipe system without the water hammer arresters and its reduction with them have been investigated. Dotted curves in Fig. 4 indicate the transient water hammer pressure at the KF, WBF, BTF, and WF branch lines. Right after the valve is closed at 0.53 s, the pressure rises abruptly and reaches its maximum, and then reduces gradually to the static value at around 2 s.

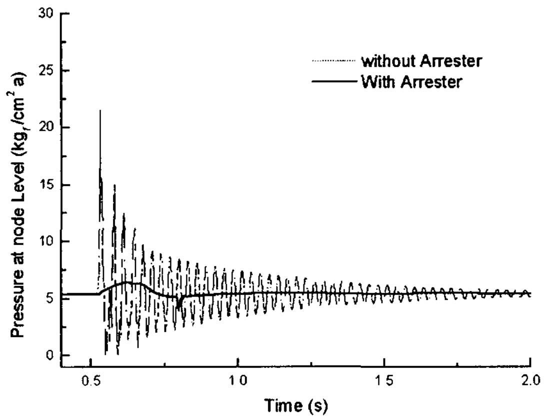
When the pressures at all the eight branch lines are compared, the one at the WBF branch line at which the quick closure of the valve occurs is the highest of 2,608.6 kPa (26.6 kg_f/cm^2), and the KF one shows the lowest of 1,196.4 kPa (12.2 kg_f/cm^2). As shown in Fig. 1, the KF is relatively far upsteam away from the WBF, thus the direction of the wave propagation is against the flow direction, resulting in more energy dissipation. in addition to the loss due to the distance. This is why the pressure at the KF is low. For the other branch lines, the pressure at the WF, BTF, BRF, BWS, FBF, and BLT branch lines is high in descending



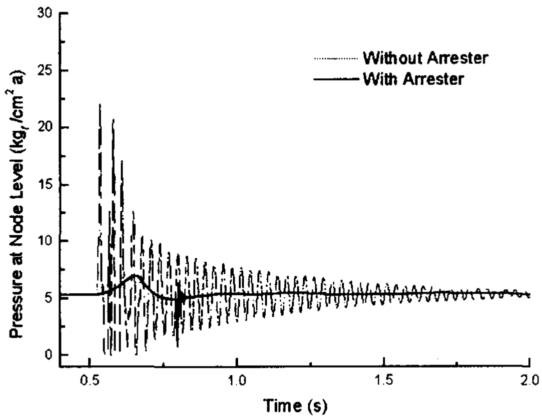
(a) at KF branch line



(b) at WBF branch line



(c) at BTF branch line



(d) at WF branch line

Fig. 4 Comparisons of the water hammer pressures with and without the arresters when WBF is quickly closed.

order, as shown in Table 3.

Next, the cases with the arresters have been simulated. According to the specification of the leading construction company, an ASSE size A water hammer arrester at the WBF branch line and an ASSE size AA water hammer arrester at the BWS branch line are installed. When WBF is quickly closed with the pipe network being considered, the transient pressures at the eight branch line are shown in Fig. 4 (solid curves) and their maximum are listed in Table 3. The spike pressures at all the branch lines are reduced in the ranges of 578.6~715.6 kPa (5.9~7.3 kg_f/cm^2), and the periods of the pressure waves get increased. Thus, the transient pressure can be maintained below 1082.0 kPa (10.0 kg_f/cm^2) when the faucet at WBF branch line at which a water hammer arrester is installed is quickly closed.

Next, the transient pressures at the end of the KF, BTF, and WF branch lines have been monitored when their corresponding valves were quickly closed. This result is also listed in Table 3. As we may expect, maximum transient pressure occurs at the branch line of quick-closure action, the second peak occurs at the neighboring branch line, and the weakest one is observed at the farthest branch line from

Table 3 Comparisons of the water hammer pressures with and without the arresters at each branch line

Valve quickly closed	Branch line	Water hammer pressure (kg_f/cm^2)		Valve quickly closed	Branch line	Water hammer pressure (kg_f/cm^2)	
		w/o arresters	w/ arresters			w/o arresters	w/ arresters
KF	KF	26.2	25.6	BTF	KF	12.6	6.1
	FBF	17.8	13.6		FBF	19.4	7.1
	BLT	11.5	7.8		BLT	17.2	7.1
	WBF	12.2	5.9		WBF	22.1	6.5
	BTF	12.5	6.1		BTF	33.1	17.4
	BWS	14.1	6.1		BWS	23.1	6.9
	WF	14.5	6.0		WF	25.5	7.8
	RBF	14.3	6.1		RBF	23.7	6.9
WBF	KF	12.2	5.9	WF	KF	14.9	5.7
	FBF	18.0	6.1		FBF	25.3	6.1
	BLT	17.8	6.3		BLT	18.3	6.1
	WBF	26.6	6.5		WBF	22.6	6.9
	BTF	21.5	6.4		BTF	25.7	8.0
	BWS	20.5	7.3		BWS	41.9	7.6
	WF	22.1	7.0		WF	46.2	21.8
	RBF	20.9	7.0		RBF	43.4	18.9

the quick-closure valve. It is worthy to mention that those maximum pressure exceed the allowable pressure of 1,082 kPa (10.0 kg_f/cm^2), and thus the pipe system needs to be improved.

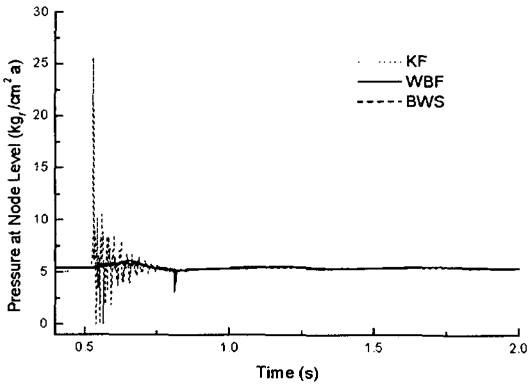
The transient pressures of all the cases of combination of the valves and branch lines have been investigated. Due to the limited space of this paper, only the results of the branch lines whose valves are closed – KF, BTF, and WF – and of branch lines at which the arresters are installed – WBF and BWS – are shown in Fig. 5.

Similarly, the transient pressure at the branch line of its valve quick closure is significantly high while that at the branch line having the arresters on it is reduced distinctively. Another interesting finding is that the magnitude of the transient pressure caused by a valve is affected by the relative location of the valve in the pipe network. The pressure spike caused by BTF that is in the middle of the two arresters is relatively low, compared to those of other two valve cases.

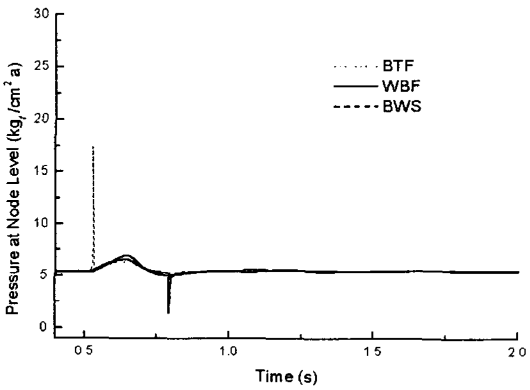
3.2 Effect of the installing location

In order to see the effect of the installing location of the arrester, the ASSE size A arrester that was at the WBF branch line in the model water supply pipe system has been relocated while the ASSE size AA arrester remained at the BWS line. Fig. 6 (a), (b), and (c) show the water hammer pressures at some branch lines after the size A arrester is moved to KF, BTF, and WF, respectively.

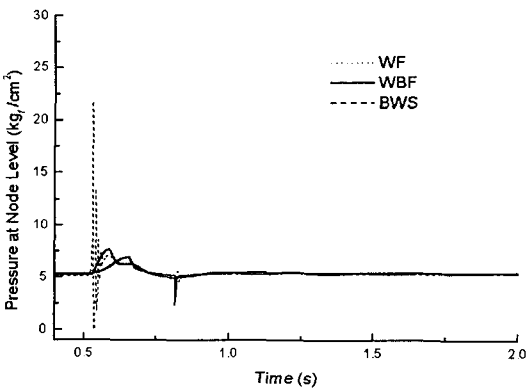
As shown in Fig. 6 (a), the spike pressures at the three branch lines are all below 1,082.0 kPa (10.0 kg_f/cm^2). The KF and BWS lines have arresters on them, and it is thus believed that the low spike pressure is caused by the arresters. However, the pressure at BTF line is low due to the distance from the location of quick closure valve, KF in this case, and thus the shape of the pressure wave is rather com-



(a) with KF quickly closed

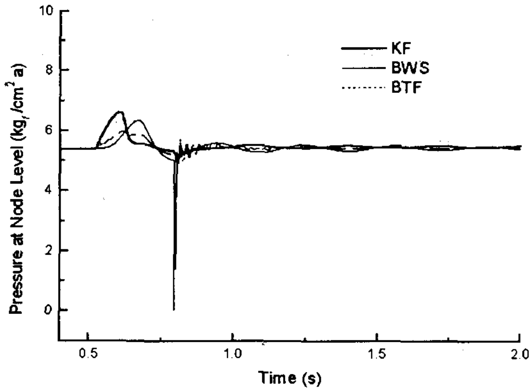


(b) with BTF quickly closed

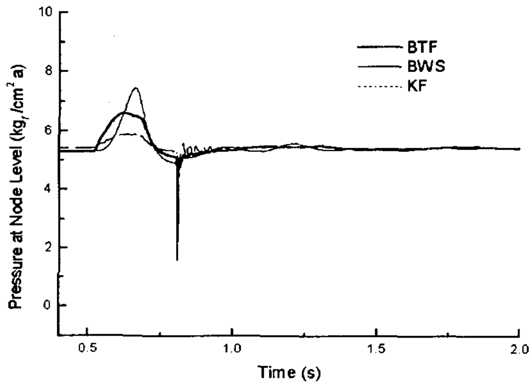


(c) with WF quickly closed

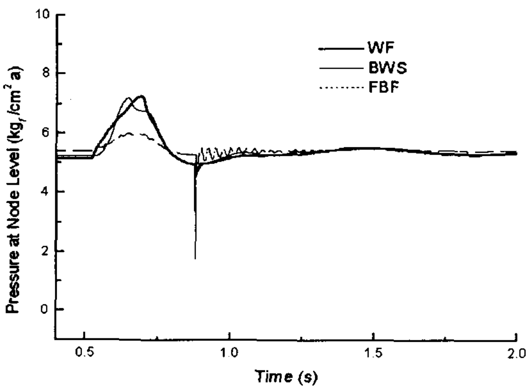
Fig. 5 Comparisons of the water hammer pressures of a branch line at which the quick valve closure occurs and of two branch lines (WBF and BWS) at which the arresters are installed.



(a) with KF quickly closed



(b) with BTF quickly closed



(c) with WF quickly closed

Fig. 6 Comparisons of the water hammer pressures of a branch line at which one arrester is installed and the quick valve closure occurs, of BWS branch line at which the other arrester is installed, and of an arbitrary branch line.

Table 4 Comparisons of the water hammer pressures when an ASSE size A water hammer arrester is relocated

Valve quickly closed	Branch line	Reduced water hammer pressure (kg_f/cm^2)
KF	KF	6.6
	FBF	6.0
	BLT	6.0
	WBF	6.0
	BTF	5.9
	BWS	6.3
	WF	6.1
	RBF	6.2
BTF	KF	5.9
	FBF	6.1
	BLT	6.3
	WBF	6.4
	BTF	6.6
	BWS	7.4
	WF	7.1
	RBF	7.1
WF	KF	5.8
	FBF	6.0
	BLT	6.2
	WBF	6.3
	BTF	6.4
	BWS	7.2
	WF	7.2
	RBF	7.0

plicated. Similar trends can be found in both Fig. 6 (b) and (c).

As seen in Table 4, the spike pressures at all branch lines during the above simulation are in the range of 568.8~725.7 kPa (5.8~7.4 kg_f/cm^2). These are very similar to the results of the original case, listed in Table 3. Thus, it is anticipated that the spike pressures at all the branch lines do not vary much, although the arrester is relocated as long as the quick-closure valve action occurs at that branch line at which the arrester is installed. It is thus recommended that the water hammer arresters should be installed at every branch line whose end terminal valve may be closed quickly to maintain the spike pressure at any point in the building water supply system below 1,082.0 kPa (10.0 kg_f/cm^2).

4. Conclusions

A numerical study has been conducted to characterize the transient pressure and its reduction with the arresters in a simple water supply pipe system. The pipe system is adapted from an apartment unit of 59 m^2 at the 6th floor of the 20 story apartment building constructed by a leading construction company. It consists of eight branch lines having 20 mm and 15 mm diameter copper pipes, KF, FBF, BLT, WBF, BTF, BWS, WF, RBF, and two water hammer arresters as well. The arresters are an ASSE size A installed at WBF branch line and an ASSE size AA installed at BWS branch line.

Input parameters for the numerical experiments include the water temperature of 20℃, the speed of wave propagation of 1,283 m/s, the polytropic exponent of the air in the compressed gas chamber of 1.2, the valve closure time of 0.03 s, and the static pressure of the incoming water of 542.6 kPa (4.5 kg_f/cm^2), etc.

Followings are findings from the numerical experiments:

(1) Quick-closure of valves in the model water supply pipe system before arresters being installed generates the transient pressure up to 2,569.4~4,530.8 kPa (26.2~46.2 kg_f/cm^2) at the branch lines that the valves are installed. After two arresters being installed, that is, an ASSE size A arrester at WBF branch line and an ASSE size AA arrester at BWS branch line, as specified in the corresponding specification of the company, the pressure values go down to below 1.082.0 kPa (10.0 kg_f/cm^2) at the branch lines. However, the transient pressures exceed the criteria when the valves at other branch lines are quickly closed.

(2) Although the ASSE size A arrester is relocated to other branch lines such as KF, BTF, and WF while the ASSE size AA arrester remains at the BWS line, the magnitudes of the spike pressures are unchanged.

(3) It is recommended that the water hammer arresters should be installed at every branch lines whose terminal valve may be closed quickly in order to maintain the spike pressure at any point in the building water supply system being considered below 1,082.0 kPa (10.0 kg_f/cm^2).

In order to provide the related building construction industries with more practical and useful data, more systematic research should be conducted. For example, more complex pipe systems that can be found in high-rise and large buildings need to be investigated, in addition to rather a simple water supply pipe system investigated in this study. Also, the pipe system made of new materials need to be studied.

Acknowledgement

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