

Water Hammer in Residential Buildings with Elevated Storage Tanks

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Abstract

Water hammer in residential buildings that depend on elevated water storage tanks for their water supply is investigated. Experiments were carried out using three different residential buildings. Water hammer was created by instantly opening/closing a control ball valve. Pressure spikes in such low pressure plumbing networks were found to be as much as three times the maximum normal pressure. As this transient pressure was high and could cause failures in plumbing fittings and fixtures, three different water hammer arrestors for residential and commercial applications were tested to suppress the pressure spikes resulting from water hammer. The small residential arrestors were found to be ineffective. On the other hand, the large (commercial) arrestors reduced the pressure spikes significantly. However, it is probably impractical to use these large arrestors for residential applications as they are expensive, and other means of water hammer suppression should be implemented to reduce water hammer effects.

Keywords: Water hammer, Plumbing networks, Arrestors.

Introduction

General

In areas where drinking water is scarce, and when population growth outpaces expansion of the water supply, it becomes difficult to maintain enough supply of water at enough pressure in drinking water networks. In a situation like this, water is pumped to different areas using some sort of a fixed rotating shift scheme. This is the case in most major cities in Saudi Arabia. Thus, in residential units (mostly villas over two floors) an appropriately sized underground water storage tank receives water from the network during pumping periods. The water is then pumped up to an elevated storage tank (usually 9–12 m above ground level) from which water is supplied to the house by gravity.

With less than 12 m of water pressure head, the pressure in such plumbing networks is low compared to houses with plumbing networks receiving water directly from municipality networks (the pressure head is usually more than 25 m of water in these networks). The problem then is that as these low pressure plumbing networks are installed and tested with the expectation of such low pressure, unaccounted for pressure increases or pressure spikes, such as those caused by transient events, can cause failure in the network. Therefore, transients may shorten the lifetime of low pressure networks and increase the number of maintenance calls. It is well known by owners of houses that depend on elevated storage tanks for their water supply that subjecting their plumbing networks directly to the municipality network pressure can easily cause immediate failure and leaks in the plumbing pipes and fixtures. In these houses, plumbing pipes are installed by digging out channels in the brick walls, then the pipes are laid in the channels and permanently cemented over. This method of installation makes it difficult to detect a leak at an early stage, the cost of repairs is high, and damage to the building may result.

Water Hammer

Sudden opening or closure of a tap can cause pressure spikes in the plumbing network. This phenomenon is called water hammer, and it can cause rupture and leaks in the pipes and fittings. Water hammer creates pressure waves that travel upstream and downstream of the closed/opened tap at nearly the speed of sound. The speed of the pressure wave for a completely rigid pipeline is given by

$$c = \left(\frac{k}{\rho} \right)^{1/2} \quad (1)$$

where c is the speed of the pressure wave, k is the modulus of elasticity for a liquid, and ρ is the density of the liquid.

The pressure head change due to water hammer is given by the following equation:

$$\Delta H = -\frac{c \Delta V}{g} \quad (2)$$

where ΔH is the change in the pressure head, ΔV is the change in fluid velocity, and g is the gravitational acceleration constant.

Eq. (1) applies to a completely rigid pipe. However, to account for pipeline restraint conditions, a more detailed equation for the speed of a pressure wave is given by (Wylie and Streeter, 1993):

$$c = \frac{\sqrt{k/\rho}}{\sqrt{1 + [(K/E)(D/e)]c_1}} \quad (3)$$

where E is the modulus of elasticity for the pipe material, D is the pipe diameter, e is the thickness of the pipe wall, and c_1 is a dimensionless parameter that describes the effect of the pipe constraint condition on the wave speed.

Thus, a sudden valve closure causes a positive pressure wave that travels upstream of the valve at a speed of c , and a sudden valve opening causes a negative pressure wave (pressure drop) to travel upstream of the valve at a speed of c . Positive pressure waves are added to the pressure already in the pipe and negative waves are subtracted from the pipe pressure to obtain pressure levels following the transient event. Special devices can be used to reduce the effect of water hammer in residential buildings. These devices include water hammer arrestors and air chambers, which absorb pressure surges caused by transient events such as sudden valve closure/opening.

Literature Review

There is not much literature on the subject of water hammer in low pressure networks. However, the water hammer problem in general has been discussed in the literature, and some of the most relevant studies are discussed here. Water hammer can be evaluated using either experimentation or theoretical simulation. Szymkiewicz and Mitosek (2005) compared a theoretical water hammer solution using a modified finite element method with the experimental results for a simple pipe system. Gibson and Levitt (1991) used a computer simulation of liquid flow in pipes. The simulation was found to agree with published water hammer data for a simple pipe system consisting of a large air-pressurized inlet reservoir of water at room temperature connected to an outlet reservoir at atmospheric pressure through a suitable copper pipe. Pressure history was measured just upstream of a downstream ball valve.

A considerable number of residential buildings use plastic pipes within the plumbing network. Water hammer in such networks can be analyzed in the same manner as those with metal pipes except that the pressure wave speed (c) in plastic pipes is lower. Mitosek and Roszkowski (1998) discussed the problems of unsteady flow in plastics pipes. They analyzed pressure wave velocities, cavitations and the influence of de-aeration on the increase in pressure as the pipe filled with water. Experiments were conducted on the commonly used plastic pipes: un-plasticised polyvinyl chloride, medium density polyethylene and high density polyethylene. It was found that the measured wave velocities in polyethylene pipes were much higher than expected from Zukovski's formula. Medium and high density polyethylene pipes displayed a higher resistance to sudden changes in water stream pressure. The increased rigidity did allow higher maximum pressure but it may also be a source of local cavitation during large decreases in pressure. Tests showed that the variation in pressure due to water hammer has a wave nature. Characteristic pressure changes with time of water hammer were established.

Some studies have dealt with water hammer in pipes with diameter changes. Logar (1991) studied water hammer resulting from a shutoff valve in a high head plant. It was observed that the initial water hammer pressure rise in a

pipe was followed by a further extreme pressure rise of double the magnitude upon rapid closure of a small flow. The amplification was found to be due to partial reflections at the diameter steps and total reflections at the reservoir at the upstream end of the pipe. Suggestions were offered for water hammer reduction.

Water hammer modelling is very sensitive to pipe friction. Pezzinga (2000) evaluated resistances in unsteady flow by means of a one-dimensional unsteady friction model. The model was applied to the case of water hammer in a single gravity pipeline and in a single pumped pipeline. The model output was compared to the experimental results for a zinc-plated steel pipe. It was found that the model does not predict the exact shape of the oscillation but it gives the minimums and maximums of the pressure head oscillation with good precision, if the correct values of the parameters are used in the model.

Water hammer control devices can be used to reduce the effect of water hammer. Some studies have discussed water hammer simulation in the presence of such devices. Jvarsheishvili and Namgaladze (1991) dealt with the water hammer problem in a main pipeline equipped with a safety device against high pressure. The concept was described by a differential equation of an unsteady pressure flow in pipes with a constant diameter, taking the rate of flow through the safety device into account and using the Dirac delta function and Heaviside unit function. A Fourier and sine-transformation was used to achieve the solution, in the form of an infinite and rapidly converging series. They considered cases with two or more safety valves installed in a pipeline or a slide-gate closing according to a certain law. The authors concluded that their method of calculation was advantageous, due to the shorter computer time required for the procedure than for numerical solutions of origin equations.

The studies listed above, although they deal with some aspects of water hammer, do not deal with water hammer in plumbing networks of residential buildings. In fact no study on water hammer in such low pressure systems is available in the literature today. The effects and consequences of water hammer could be much more costly than might be thought, resulting in major economic losses. Plumbing networks in such buildings are designed and installed with the expectation that the operating pressure is very low. However, water hammer could result in much higher pressures than expected. With such pressure spikes, premature failure of corrosion/erosion induced weak points in pipes and/or fittings can occur. Undetected small cracks that discharge water during high pressure spikes can lead to major damage to the building before they are detected and repaired. Thus, the objective of this study is to investigate water hammer in residential buildings with elevated storage tanks and to evaluate some of the commercially available water hammer arrestors.

Experimental Setup

Three residential buildings were used to carry out the experimental work. Since the plumbing network on the ground floor is supposed to experience more violent transient events than the first floor, a typical washbasin was chosen on the ground floor and a pressure sensor was installed just upstream of the

washbasin tap. Washbasin taps are mostly ball valves, as is the case in this experiment. The water hammer arrestor used in this experiment was installed opposite the pressure sensor just upstream of the control valve.

The pressure transducer used was a Validyne (DP15) variable reluctance differential pressure transducer. A Validyne sine wave carrier demodulator (CD15) was used to provide a DC output signal for dynamics as well as steady-state measurements. The data was logged into a PC using a high speed USB data logger from DataTranslation (Model DT9836). It acquires pressure data from the pressure sensor/transmitter at a pre-chosen sampling rate of 1000 readings/s. The data was stored in an Excel file for later analysis.

Experimental Plan

Water hammer in this experimental work was created by closing/opening the valve manually but as quickly as possible. Experimental runs were performed for each location as follows:

- Transient event #1 (TE_1) started with a fully closed valve, then the valve was fully opened as quickly as possible (by hand) and kept open until the transient effect vanished then the valve was fully closed again.
- Transient event #2 (TE_2) started with steady-state full flow conditions with the valve in the fully open position, then it was closed as quickly as possible (by hand).
- Pressure histories were recorded for both transient events and stored in Excel files for later analysis.

In this experimental work, TE_1 and TE_2 were considered for four different conditions:

1. Without using any water hammer arrestor.
2. With the use of a small water hammer arrestor.
3. With the use of a medium water hammer arrestor.
4. With the use of a large water hammer arrestor.

Discussion of the Results

Figures 1 and 2 show two typical runs for transient event #1 (TE_1) and Figure 3 shows a typical run for transient event #2 (TE_2). Figures 1 and 2 show two runs for the same flow conditions, and illustrate the good repeatability achieved for the experiments. The important points for both transient events are labelled in Figures 2 and 3, and this labelling system is used in the following paragraphs when the transient-induced pressure spikes are discussed.

Figure 2 shows a typical TE_1 starting with a steady pressure head of 9.25 m. After sudden valve opening at $t = 1.96$ s, the pressure head drops to 1.62 m. The sudden valve closure at $t = 3.99$ s caused a pressure head spike of 32.11 m. Then pressure head oscillation took place for sometime before vanishing due to friction. Figure 3 shows a typical TE_2 , which is similar to the second phase of TE_1 except that when performing TE_1 , the flow conditions were

held very much steady before valve closure, while in TE₂ the valve closure was done after a preset time interval after valve opening without paying attention to the flow to reach absolute steady-state conditions. The resulting pressure history of TE₂ after valve closure confirms that of TE₁. Figures 4–6 show the water hammer results for buildings A, B and C, respectively. The points labelled *a*, *b*, *c*, *d*, *e* and *f* are part TE₁ and those labelled *g*, *h*, *i* and *j* are part TE₂ (see Figures 2 and 3 for illustration of where these points are located in the course of the transient event). The two transient events were performed separately, but the results are combined in Figures 4–6 for convenience. The pressure at point *a* is the steady-state pressure before the transient occurrence and was measured when the valve was closed. That means it is the static head and is the maximum possible steady-state pressure head

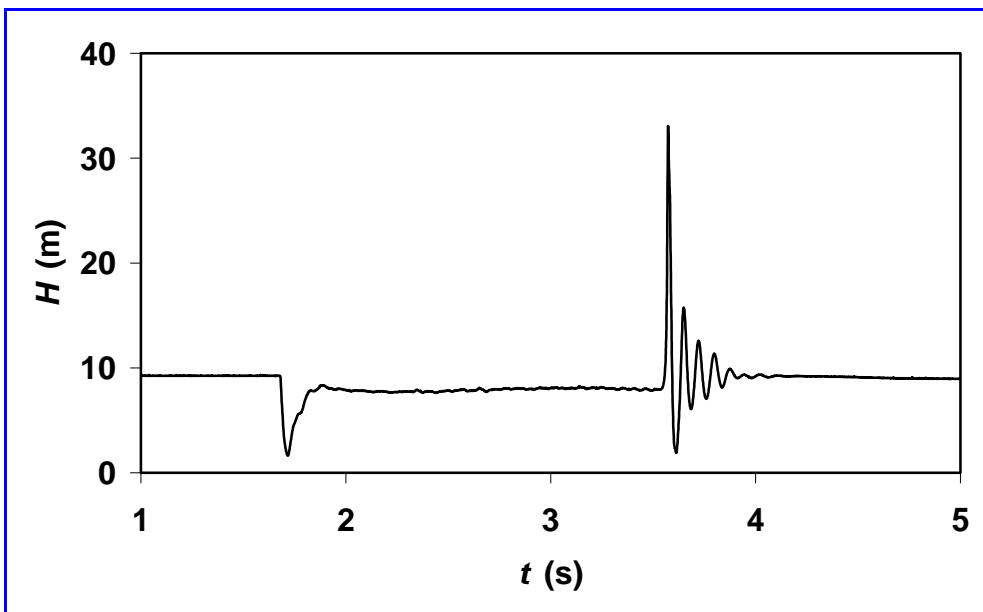


Figure 1: Example run for transient event #1 (TE₁) for residential building A without no arrestor

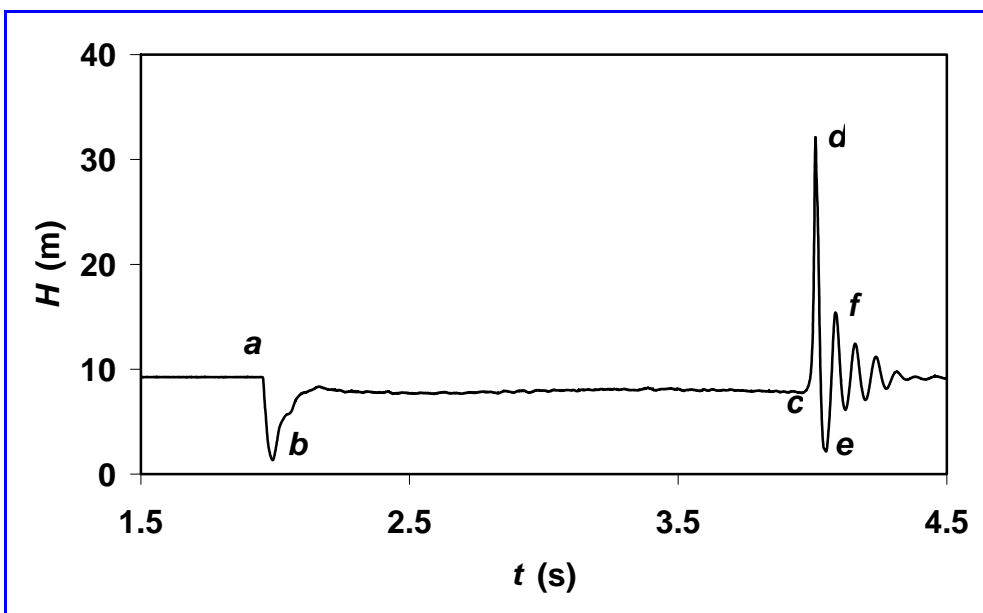


Figure 2: Another run for transient event #1 (TE₁) for residential building A without no arrestor

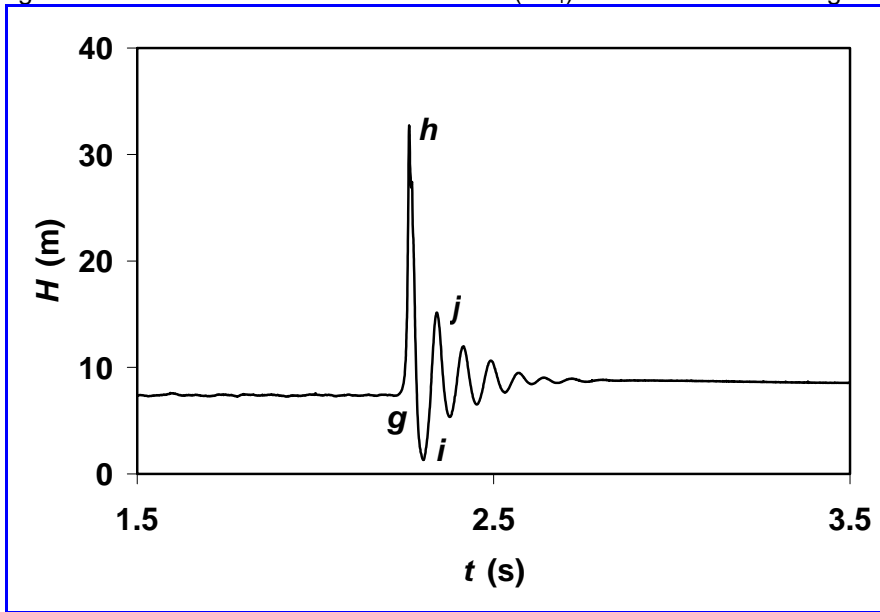


Figure 3: Example run for transient event #2 (TE₂) for residential building A without no arrestor

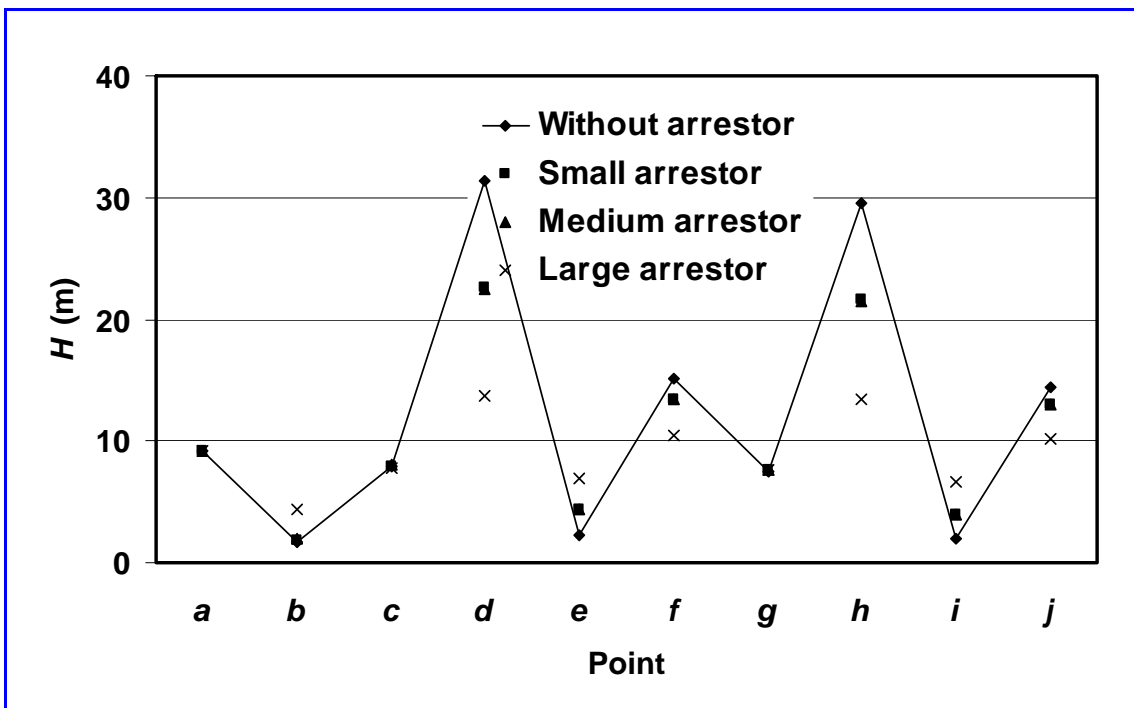


Figure 4: Pressure head values at some key points along the pressure head history for residential building A

In Figures 4–6, the pressure head results are presented for four cases: (1) without the use of arrestor, (2) with the use of a small arrestor, (3) with the use of a medium arrestor, and (4) with the use of a large arrestor. Three different runs were considered for each case and the average values were taken. It is evident from these figures that the maximum pressure head is at point *d* (which belongs to TE₁). When no arrestor was used, the value of the pressure head spike was 31.4 m, 27.6 m and 23.5 m for buildings A, B and C,

respectively. This means that the pressure head spike for the first two buildings is about three times the steady-state pressure head. These values of pressure head spikes may exceed the pressure head when a residential booster pump is used to pump water directly from the underground storage tank to the plumbing network. Repeated occurrence of such spikes would speed up the failure of any weak parts of the pipes and/or fittings. For instance, when corrosion occurs in a metallic fitting, a crack may develop at some point in time but pressure spikes could result in premature failure of such weak points as repeated stress would work with the corrosion to cause cracks and leaks. Figures 4–6 show that the small and medium arrestors did not reduce the pressure head spikes consistently for the three buildings. Thus it can be concluded that the small and medium arrestors are ineffective in dealing with water hammer for low pressure applications in residential buildings.

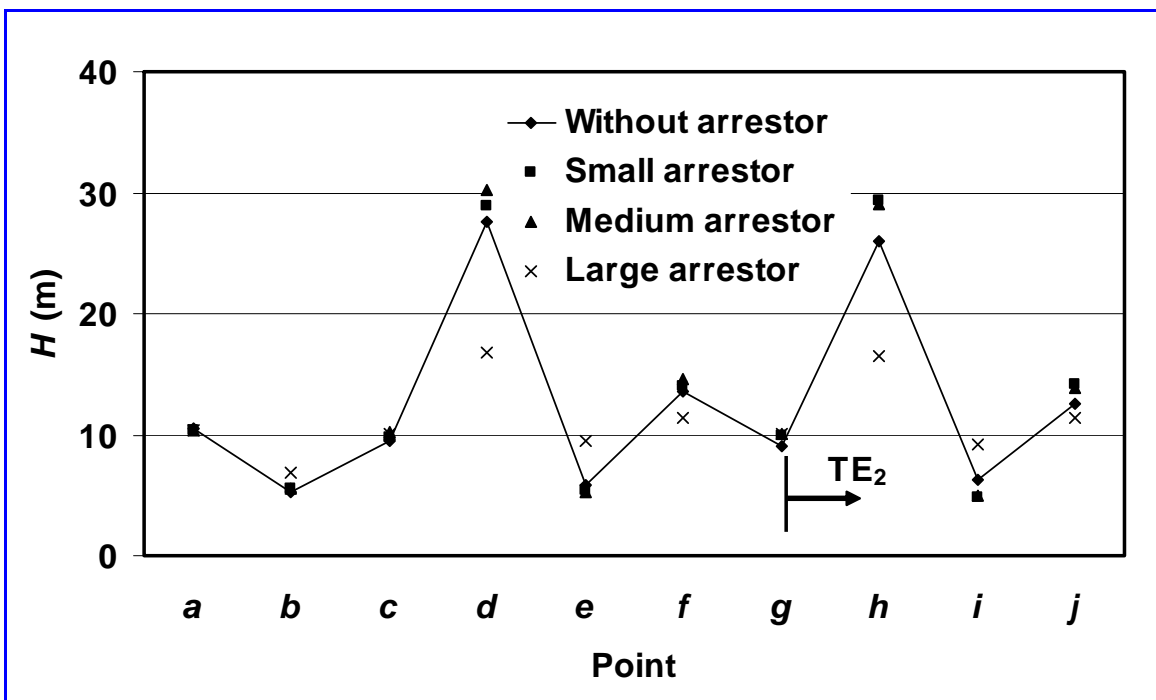


Figure 5: Pressure head values at some key points along the pressure head history for residential building B

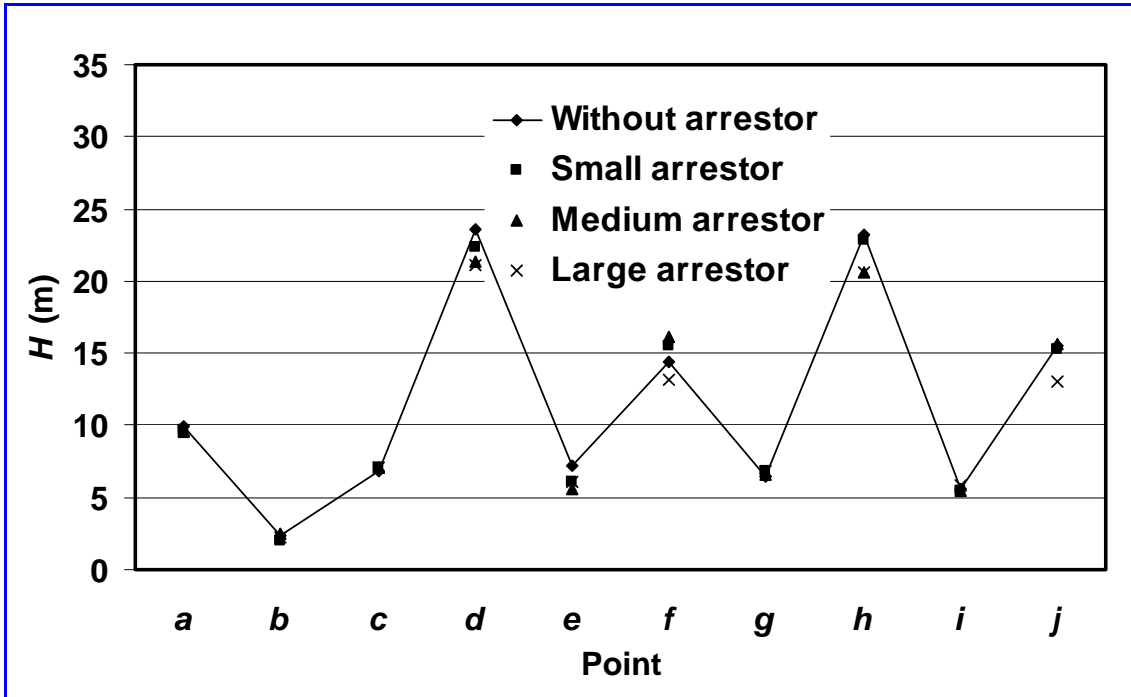


Figure 6: Pressure head values at some key points along the pressure head history for residential building C

On the other hand, when a large arrestor was used, the pressure heads at point *d* were 13.8 m, 16.8 m and 21.1 m for buildings A, B and C, respectively. When compared to the corresponding values when no arrestor was used (i.e., 31.4 m, 27.6 m and 23.5, respectively) the pressure spikes were reduced by 56.1%, 39.1% and 10.2% for buildings A, B and C, respectively. At point *h*, the pressure head values were 29.5 m, 26.0 m and 23.2 m for buildings A, B and C, respectively, when no arrestors was used. The large arrestor reduced the pressure spikes at this point by 54.3%, 36.4% and 11.3%, respectively, for the three buildings. It is evident that the ability of the water hammer arrestor to reduce pressure head spikes resulting from water hammer is a function of the magnitude of the pressure spike. The higher the magnitude the more the arrestor is capable of suppressing pressure head spike. This is true for small and large water hammer arrestors, and is the reason that the water hammer arrestors were least effective in building C. Water hammer arrestors are designed to be effective when used in a pressure head range of more than 30 m, which is the case in water distribution networks. However, when used in low pressure systems, such as buildings with an elevated storage tank, they become less effective.

When a control valve is suddenly opened, it causes a wave of pressure drop (negative wave) to occur. This pressure wave travels upstream of the valve and is reflected by the nearest boundary or a change in pipe direction or diameter. A negative pressure wave also occurs when a sharp positive wave hits the upstream boundary and is reflected back to the pipe system as a negative wave (see Figures 2 and 3). Point *b* in Figure 2 shows a negative pressure wave resulting from a valve opening. Point *e* in Figure 2 and point *i* in Figure 3 show a negative pressure wave resulting from a positive pressure

wave being reflected back by the boundary. The drop in pressure head from the valve opening is obtained by subtracting the pressure head at point *b* from that at point *a*. Thus, the drop in pressure head was 7.4 m, 5.3 m and 7.6 m for buildings A, B and C, respectively.

As Figures 4–6 show, the small and medium water hammer arrestors were not effective in reducing these pressure drops (negative pressure waves). However, the large arrestor did reduce these pressure drops at points *b*, *e* and *i*. The best way to measure the effectiveness of a water hammer arrestor in reducing a negative pressure wave is to compute how closely the arrestor maintains the negative pressure spike near the normal steady-state pressure level. For instance, at point *b* in building A, the pressure head without an arrestor was 1.72 m and when the large arrestor was used this value increased to 4.37 m. The difference between the two is divided by the steady-state pressure head at *a* (9.13 m) and multiplied by 100 to give 29.0%. The other values for buildings B and C are 15.1% and –1.6%, respectively. Performing the same computation for point *e* gives 51.8%, 35.7% and –12.3%, respectively. The results for point *i* are 51.9%, 27.7% and 2.4% for the three buildings, respectively. It is clear that the large arrestor protected the system against sudden low pressure. When comparing the results for the three buildings, and as concluded for positive pressure waves, it is clear that the effect of the water hammer arrestors was more pronounced when there was a high drop in the pressure head. This is the reason that the arrestors gave the best performance in building A and the worst performance in building C. Protection against low pressure spikes could be important if there are instruments or devices that require a minimum level of pressure to operate. Interruption of the inlet pressure to these devices could result in device shut-off. One example of such instruments is a residential reverse osmosis system that operates with a booster pump.

Conclusions

Water hammer in residential buildings that depend on an elevated storage tank for their water supply was studied. The maximum pressure head resulting from water hammer was evaluated for three different residential buildings. It was found that the transient pressure head could be as high as three times the normal pressure in these buildings. This can cause problems and premature failure in plumbing networks originally designed to operate at a low steady-state pressure. Water hammer arrestors were used to eliminate pressure spikes resulting from transient events. The small and medium arrestors designated for residential applications did not reduce water hammer as they were designed for higher pressure systems. Large commercial arrestors reduced water hammer significantly for positive and negative pressure waves. However, large commercial systems are very expensive compared to small residential arrestors. Nevertheless, it is recommended that water hammer problems should be eliminated in residential buildings with low pressure systems to avoid premature failure of plumbing pipes and fittings as the transient pressure may reach levels that cannot be ignored.

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