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Influence of Pipe Diameter and Material on Water Hammer in Piped Systems

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Abstract

A sudden change in the pipeline's velocity results in a transient flow known as a "water hammer" in pipes. This phenomenon can cause negative and positive pressure in the pipeline and is often dangerous where the pipe can burst if the pressure is high enough. Therefore, it is necessary to study the variables affecting the water hammer to have a clear understanding of the controlling conditions of the water hammer, which could save the system from failures. This paper investigates the effects of pipe material and diameter on water hammer pressure. Three different pipe materials were examined (Steel, Concrete, and Polyvinyl chloride (PVC)) with different inner diameters (250, 350, and 500 mm). Numerical modeling and analysis are conducted to obtain the minimum and maximum pressure envelopes across the system of pipes. The numerical results obtained from the transient solver show that the normalized piezometric pressure calculated in different statuses directly changes with the change of the pipe material and diameter. The water hammer pressure has reduced significantly in pipe materials with less elastic modulus and larger diameter for the same operating condition.

Keywords: Piped system, Water hammer, Serge pressure, Pipe material, Pipeline simulation.

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1. INTRODUCTION

Water is essential for developing nations and establishing stable communities [1, 2]. The transit of water through the pipe systems is associated with many phenomena [3]. Abrupt Variations in the water distribution system's flow rate of hydroelectric and water systems produce hydraulic transients or water hammers, resulting in pressure and flow changes. The preservation of hydraulic transients in water pipe systems within safe limits is critical to the safety, effective operation, and extended service life of hydroelectric power systems [4]. Effective design of pressure piping systems requires adequate containment of water hammers associated with rapid and accelerated internal fluid pressure changes occurring within the piping system [5]. when there is an unexpected halt to the flow, either when following the rules or in an emergency, Rising and descending water hammer waves are two distinct types of waves. This respectively involves an increase or decrease in the amplitude of the wave. These hammer waves can seriously impair the performance of piping transfer or distribution systems and potentially harm the system components. In more extreme circumstances, these strong waves can lead to more serious accidents such as pipeline damage, elbow disconnection as well as operators' deaths [6]. Physically, this last incident is sparked by the appearance of vacuum pockets dispersed over the piping system, as a result of a local decrease in the fluid's pressure down to its pressure value. Then, [7, 8].

It is better to avoid a significant water hammer. But in most plumbing systems, this is not always feasible; therefore, the undesirable onset conditions should be lessened through the modification of the system's functional design. In this view, hydraulic designers consider a diversity of design criteria to eliminate or reduce the damage effects of water hammers[9]. Uncontrolled transient events can severely impact both a facility's civil and mechanical infrastructure [10]. Due to fluctuations in demand, power and water companies find it difficult to reduce water hammers in their water pipe systems [11]. Therefore, problems such as broken pipes and leaks are common in water distribution networks. In water distribution systems. The causes of transient events can be returned to the operation of valves, pumps shutdown, and accepting or rejecting turbine load [12]. Studying the phenomenon of water hammers has important scientific and practical purposes. Engineers, researchers, and water utilities are all interested in comprehending the influential transactions in nature, formation, and characteristics of water hammers [13, 14]. The maintenance of the pressure system demonstrates the considerable number of failures brought on by transit flows into the water supply system [15]. In addition, damage from the water hammer is often very expensive [16]. The major factors utilized to compute the phenomenon's key parameters, including maximum pressure, time, pipe material, wave oscillation, etc., are numerous models and formulae [17]. The hydraulic changes analysis is required for choosing valve types, pipe diameter, pipe material, pipe pressure, and the specs for surge arresters [18, 19].

The water hammer phenomenon was first described by Joukowsky with equations that predicted the expected pressure surge and wave travel time [20]. The earliest analytical and graphical solutions for the basic unsteady flow equations describing the water hammer were developed. It was proposed the explicit method of characteristics (MOC) as a method to solve water hammer equations, which was later improved, and several other models have been proposed for stability [4, 21, 22]. For more than a century have been the focus of both theoretical inquiry and considerable practical attention to closed-line hydraulic transients. A complete description of unsteady fluid flow is straightforward concerning the pipelines in one-dimensional analysis, but an interesting problem arises in fluid dynamics. For instance, there is currently a lack of knowledge on the structure and magnitude response of turbulence to transient waves in pipes as well as the loss of flow velocities in pipes as a result of hydrodynamic instabilities. However, Such knowledge is crucial for simulating water quality and energy dispersion through pipe transient water flux [23, 24].

A simplified method for calculating hydraulic transients is presented along with techniques for increasing the calculation time interval. Concentration and interpolation methods are contrasted with a mixture of implicit and characteristic methods [25]. Joukowsky proposed the standard water hammer theory in 1898, which is proposed to calculate the size and speed of pressure waves in water pipes [20]. According to this theory, pressure waves will continue to move without changing their attitude. Some of the facilitations in Joukowsky’s theory could not be used when considering water shock waves. The wide range of practical issues that justify water hammer modeling increases the importance of carefully formulating the underlying water hammer equations and critically analyzing their assumptions [5].

Numerical models are often used to study fluid transients because it is difficult, if not impossible, to obtain analytical solutions to the nonlinear equations governing transient fluids. Effective numerical models allow hydraulic engineers to construe hydraulic transients, and to proactively identify and assess different options for reducing any potential excessive pressures in the piping system. To simulate hydraulic transients for sophisticated piping network design and research projects, many software applications are available. No matter whether such software is readily available, hydraulic engineers must understand hydraulic transients and be able to evaluate the output of simulations with good engineering judgment. With the appearance of computers, there was great progress in resolving transients in developing numerical methods The problem has evolved greatly from very limited graphics processing up to digital processing of complex cases [13].

The present work aims to examine the attitude of transitory waves in pipelines with different pipe materials under water-hammer phenomena. Also, the paper is studying water hummer characteristics by changing the pipe material or diameter. A configuration considered for three different models is defined by varying levels of stiffness. Results have been discussed for the tested models. The pressure, wave time, and wave movement along the pipe length were analyzed in the suggested system. The conclusions and importance of pipe materials and their diameter impacts on water hammers have been illustrated.

2. GOVERNING EQUATIONS FOR WATER HAMMER

Water hammer analysis using Bentley HAMMER V8I is an efficient and trustworthy tool for determining the required surge protection. V8I can be used to analyze accurately and efficiently in a large-distance water pipeline system. It is the most widely used and trusted hydraulic modeling software on market today. Engineers may study intricate systems for pumps and pipelines as it changes between two stable states using the powerful yet simple-to-use application HAMMER. Only a few seconds to minutes are spent during hydraulic transients, yet they can seriously harm a system or make it difficult to operate. Bentley HAMMER aids engineers in better comprehending their piping and pumping networks, enabling them to create surge-control systems that are both reliable and cost-effective. This software can be used for steady-state analysis and transient analysis that happened due to water hammer. The wave equation in one dimension was used to demonstrate the observable effects of the water hammer. The formula for Joukowsky's equation is [26]:

$$\Delta P = \rho a \Delta V \qquad (1)$$

where ΔP is water hammer-related pressure increase (N/m^2), ρ is liquid density (kg/m^3), a is impulse wave velocity (m/s), and ΔV is the change in liquid velocity (m/s). The equation could be expressed as the following:

$$\Delta H = a\Delta V / g \qquad (2)$$

where ΔH is the hydraulic hammer pressure increment in terms of water column (m) and g is the acceleration due to gravity (m/s^2).

The pressure wave celerity, a, depends on the specific gravity and elastic modulus of the liquid, the pipe diameter, thickness of the pipe wall, the distance between supporting points, and the modulus of elasticity of pipe material. The following relationship is used for calculating the pressure wave celerity [27]:

$$a = \sqrt{\frac{1}{\frac{\rho}{k}+\frac{DC1}{Ee}}} \qquad (3)$$

where pipe diameter (D), the wall thickness of the pipe (e), pipe material elasticity modulus (E), liquid elasticity module of (K), and constant (C1).

3. METHODOLOGY

The effect of pipe materials and their diameters on the water hammer phenomenon was investigated. The current study was carried out with the help of the well-known surge programme Bentley HAMMER V8i. Bentley HAMMER V8i is a flexible programme that can simulate any kind of surge protection system. For more than 30 years, hundreds of engineers around the world have used it to design intricate transmission mains, small branching networks, and huge distribution networks. Environmental Hydraulics Group produced the technologies used to construct the Bentley HAMMER V8i. [28].

The model layout is set up as in Fig.1 to analyze the parameters that affect the water hammer phenomenon. The tested parameters would be the material of the pipe and the diameter of the pipe. It is required to use a pipeline to transfer water between two reservoirs. The elevation difference between the water surface upstream reservoir and the downstream reservoir is 15.0 m. The distance between the two reservoirs is about 5.0 km. the proposed pipe materials and diameters are shown in Table 1. The head losses, h_L can be defined by Hazen - William equation [29]:

$$h_L = 10.67 \left(\frac{Q}{C}\right)^{1.85} \frac{L}{D^{4.87}} \qquad (4)$$

where pipe length (L), C is Hazen – William coefficient, D is diameter of the pipe, and Q is the flow rate.

The power of the pump can be calculated as in equation 5 where Pump efficiency $\eta = 0.7$, required discharge Q equals to $0.196\ m^3/sec$, Pump head $H = h_L + \Delta Z$ m where h_L is the head losses, ΔZ is the elevation difference.

$$P\ (power) = \frac{\rho g Q H}{\eta\, 1000} KW \qquad (5)$$

where P is the pump power, ρ is the liquid density, and g is the gravity acceleration.

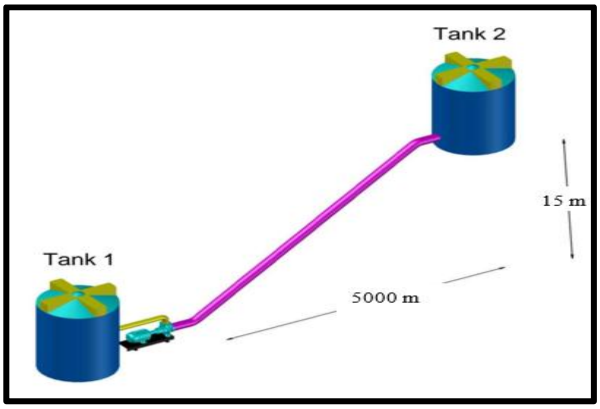

Fig. 1. Schematic diagram of pipeline system

TABLE 1. Study cases of water hammer at different pipe materials and diameters

	Diameter of pipe (mm)	Hazen Williams Coefficient C	a (m / s) The velocity of pressure wave
Case.1 (Steel)	**500**	**120 - 140**	**Up to 1485 (m / s)**
	350		
	250		
Case.2 (PVC)	**500**	**140 - 150**	**320 to 680 (m / s)**
	350		
	250		
Case.3 (Concrete)	**500**	**140 - 150**	**200 to 450 (m / s)**
	350		
	250		

4. RESULTS AND ANALYSIS

The water hammer effect was investigated using nine models: three models each of steel pipe in three different diameters, concrete pipe in three different diameters, and PVC pipe in three different diameters. When a pump is activated by raising pressure at the discharge side of the pump, a pressure wave (which raises pressure) is positively delivered down the pipeline toward the downstream tank. However, when the pump is abruptly halted, a frequent transient takes place in which the pressure at the pump's discharge side rapidly drops, and A wave of decreased pressure known as a negative pressure wave begins to move toward the upstream tank. The pressure may fall below atmospheric pressure to vapor pressure when the negative pressure wave hits the high point in the pipe. At this pressure, the liquid begins to evaporate as the gas inside it slowly releases, and this process continues until the pressure wave retrieves, the pressure values generated by the water hammer are discussed below.

4.1 Effect of Pipe Material

Three different pipe materials, steel, concrete, and PVC were considered at the same pipe diameter of 500mm for water hammer analysis. The results of water hammer pressure generated at the pump and that generated along the pipeline are given in Figure 2 and Figure 3, respectively. From the figures, A piped line based on plastic pipe material offers a significant attenuation influence of the pressure-head increase and decrease, together with an elongation influence of the duration of pressure-wave pulses. Furthermore, the pressure alleviation and periodic elongation effects are more proclaimed when using a plastic pipe material compared with concrete or metallic material. The hydraulic behavior of plastic pipes under transients differs from that of concrete and metallic pipes, it is more complex due to the viscoelasticity of the pipe walls. Plastic materials are much less strong than concrete or metallic materials, resulting in lower wave velocities and impedances. Viscoelasticity introduces frequency-dependent effects on wave velocities and damping. Elastic materials have a lower transient formation rate compared to rigid materials. In contrast, plastic pipes significantly reduce the pressure caused by water hammers due to their low characteristic resistance and quick damping as compared to metallic and concrete pipes. The formation of hydraulic transients in the pipeline system is strongly influenced by the pipeline material, where the elastic nature of the pipe walls and the ability of the fluid to compress comply with the water hammer pressure changes and eliminate these severe alterations in pressure to a degree. On the other hand, harder material pipe walls with high rigidity could not endure the water hammer pressure changes. Finally, it can be deduced that viscoelastic pipes effectively suppress water hammer pressure due to low characteristic impedance and rapid damping compared to rigid material pipes wall.

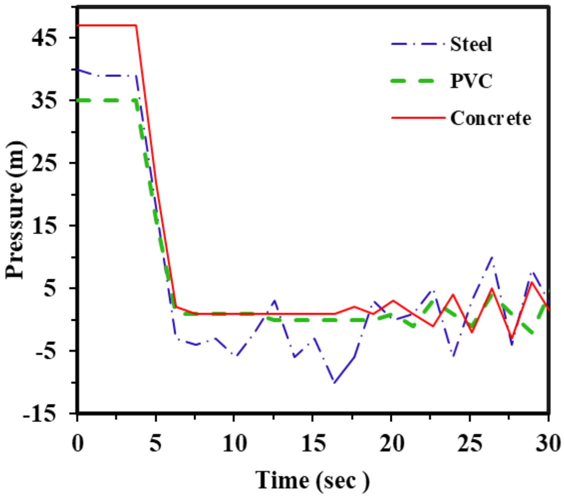

Figure. 2. Water hummer pressure at the pump for different pipe materials.

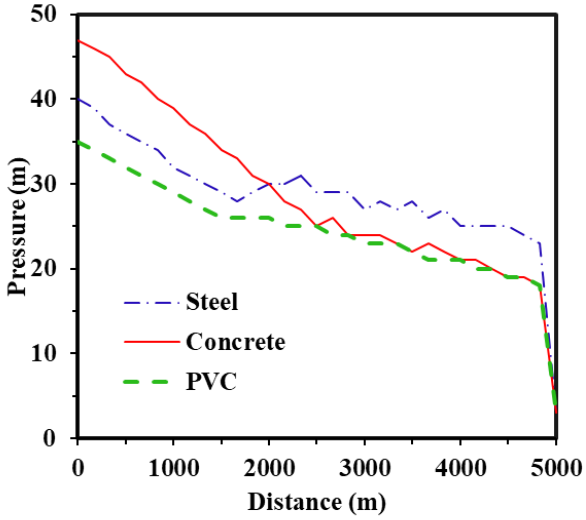

Figure. 3. Water hummer pressure along the pipeline for different pipe materials.

4.2 Effect of Pipe Diameter

Three different pipe diameters were evaluated for three different pipe materials as detailed in the preceding table. 1. Figure 4 to Figure 6 display the findings for wave speed and amplitude pressure.

Fig. 4a. shows the generated water hammer pressure at the pump in the case of changing the diameter of the steel pipe. It is clear that the increase in inner pipe diameter is associated with pressure reduction at the pump. Also, it could see that a distinct variation in pressure wave amplitude is a function of pipe diameter. It could notice that the bigger pipe diameter corresponds to the lower wave amplitude (blue curve). Fig. 4b. illustrates the generated water hammer pressure along the pipeline as a result of changing the diameter of the steel pipe. The higher water hammer pressure head was 160 m within a pipe diameter of 250mm. This pressure decreases to 40 m using a pipe diameter of 500mm. It is clear that the lower wave amplitude is correlated with a larger pipe diameter. This could return to the ability of big volumes of water in a wider diameter to dampen each other, and result in lower wave amplitude.

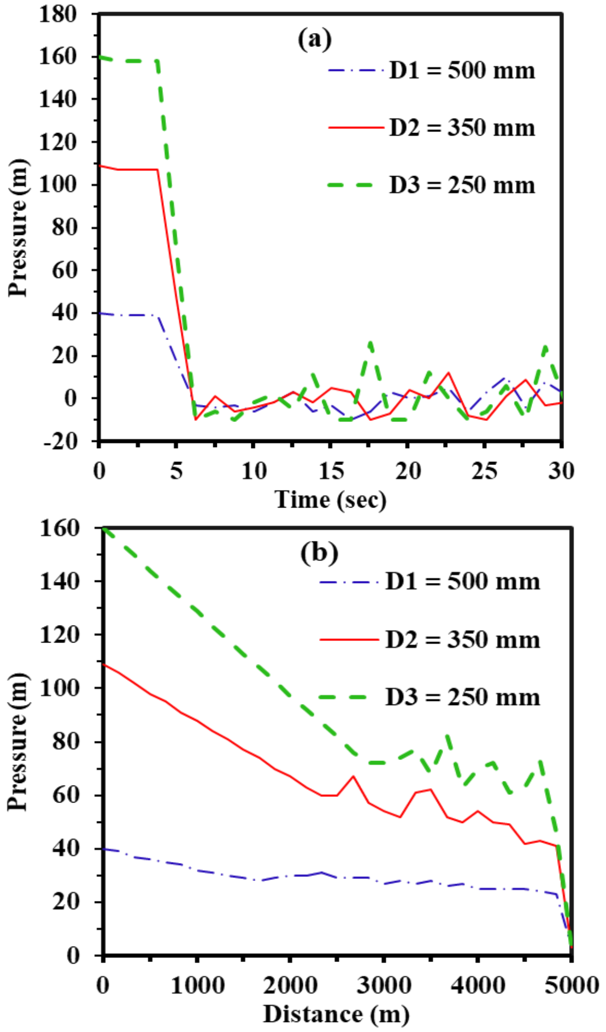

Figure. 4. Water hummer pressure (a) at the pump and (b) along the pipeline for different diameters of steel pipe.

The same trends have been shown in Figures 5 and 6. However, the water hammer pressure at the pump has been decreased to 128 and 112 for concrete and PVC, respectively. This could return to the elasticity of the pipe materials. Harder materials mean higher transient wave formation and lead to higher hammer pressure.

According to the above discussion, it can be seen that changing the diameter for different pipe materials affects both the magnitude of the pressure fluctuation as well as the rate of energy dissipation. When increasing pipe diameter, the pressure fluctuations decrease and lead to a decrease in the water velocity and compressive wave velocity, which sequentially reduces the water-hammer impact. However, the increment in diameter leads to an increase in the pipe cost. A proper design must consider the benefits of the bigger diameter and should optimize the design based on these trade-offs.

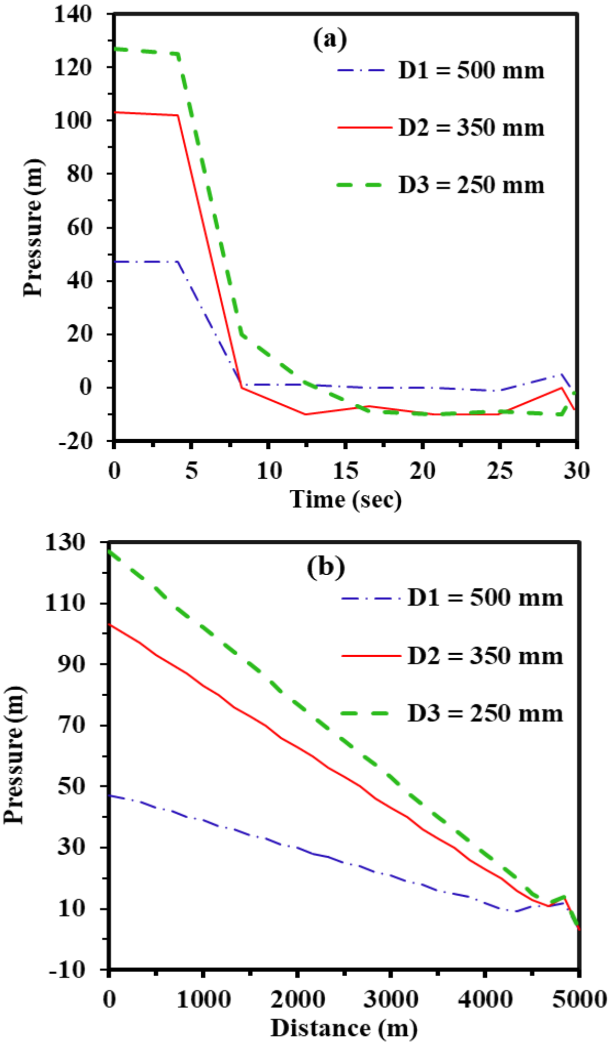

Figure. 5. Water hummer pressure (a) at the pump and (b) along the pipeline for different diameters of concrete pipe

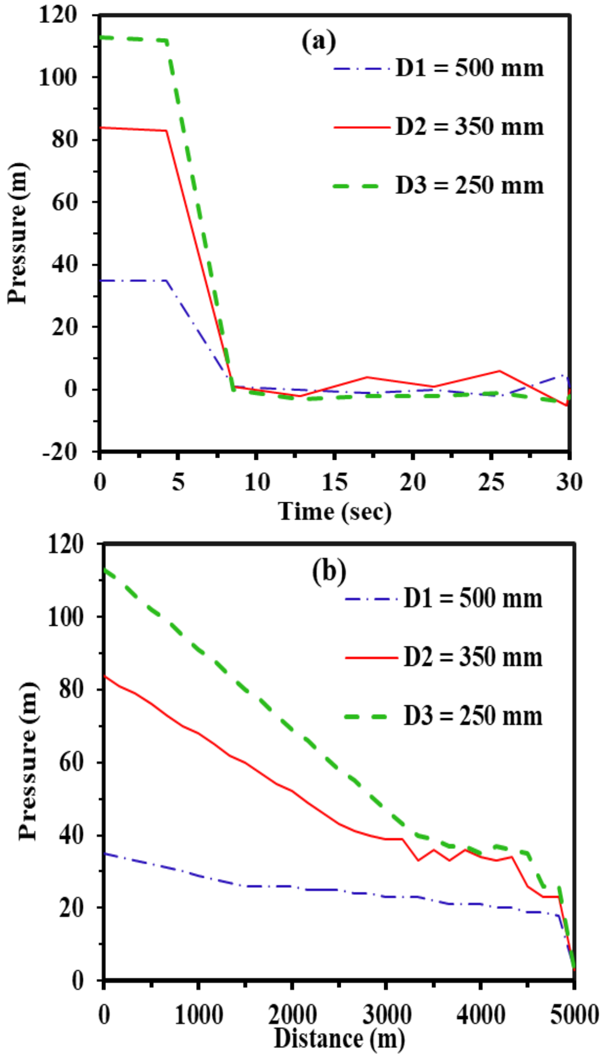

Figure. 6. Water hummer pressure (a) at the pump and (b) along the pipeline for different diameters of PVC pipe

Figure 7. illustrates the effect of pipe diameter on the maximum water hammer pressure for steel, concrete, and PVC. Three different equations have been derived to find the relations between the water hammer pressure and the diameter for the tested systems. It has been found that the logarithmic relations introduce the best fit in all three material pipe types with R-squared values (R2)of 0.9894, 0.9417, and 0.9248 for steel, concrete, and PVC, respectively.

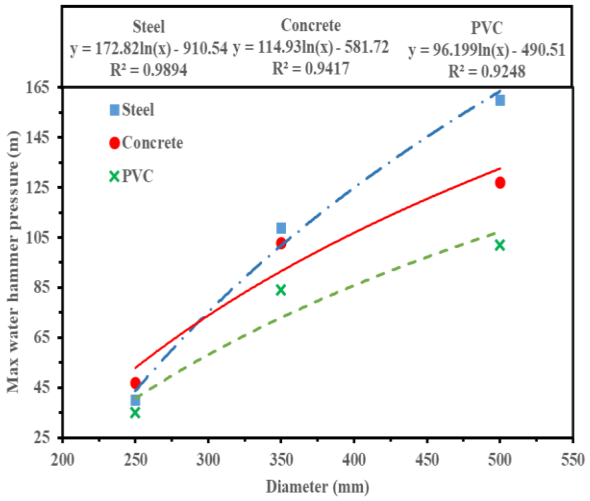

Figure. 7. Water hummer pressure at the pump for different diameters of PVC pipe

5. CONCLUSIONS

A water hammer model was set up to search the effect of pipeline diameter and material on water hammer pressure. Models' results show that the pressure generated due to the water hammer in plastic pipes is less than that of concrete and steel pipes. The results suggest that using a plastic pipeline in the pumping water distribution system has a significant head damping effect, combined with a period widening effect of pressure wave oscillations in transient scenarios caused by pump failure. Moreover, compared with concrete and metal pipe materials, the pressure damping, and time elongation effects are more declared when using plastic pipe materials. Another crucial factor that affects the water hammer is the inside diameter of the pipeline. Increasing diameter is associated with pressure fluctuations decrease, and this leads to a decrease the speed of compressive waves, flow rate, and impact from water hammer. For the tested systems, three distinct equations have been developed to determine the relationships between the inner diameter and the water hammer pressure. In all three types of material pipes, logarithmic relationships provide the best fit, with R^2 of 0.9894, 0.9417, and 0.9248 for steel, concrete, and PVC, respectively.

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تأثير قطر ومادة المواسيرعلى المطرقة المائية في أنظمة المواسير

الملخص العربي:

المطرقة المائية هي تدفق عابر في المواسير ناتج عن تغير سريع في السرعة عبر خط المواسير. يمكن أن تسبب هذه الظاهرة ضغطًا سلبيًا وإيجابيًا في خط المواسير وغالبًا ما تكون خطيرة حيث يمكن أن تنفجر الماسورة إذا كان الضغط مرتفعًا بدرجة كافية. لذلك ، من الضروري دراسة المتغيرات التي تؤثر على المطرقة المائية للحصول على فهم واضح لظروف التحكم في المطرقة المائية ، والتي يمكن أن تنقذ النظام من الأعطال. يتناول هذا البحث تأثيرات مادة المواسير وقطرها للتنبؤ على ضغط المطرقة المائية. تم فحص ثلاث مواد مختلفة من المواسير(الصلب والخرسانة والبولي فينيل كلوريد) وبأقطار داخلية مختلفة (250 ، 350 ، 500 مم). تم إجراء النمذجة والتحليل العددي للحصول على الضغط الأقصى والأدنى عبر نظام المواسير. أظهرت النتائج العددية التي تم الحصول عليها من المحلل العابر أن الضغط البيزومتري الطبيعي المحسوب في حالات مختلفة يتغير بشكل مباشر مع تغيير مادة الأنبوب وقطر الأنبوب حيث انخفض ضغط المطرقة المائية بشكل كبير في مواد المواسير ذات معامل مرونة أقل وقطر أكبر لنفس ظروف التشغيل.