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Exploring water hammer behavior using Comsol software

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ABSTRACT: *The water hammer phenomenon can have significant effects on the performance and safety of piping systems. In order to investigate this phenomenon, a comprehensive model of a pipeline system with reservoir and valve is developed. The COMSOL software is selected as the simulation tool for analysis. The study aims to understand the impact of water hammer, including pressure surges and pipe vibrations, on the system's behavior. Various parameters such as flow rate, valve closure time, and pipe material are considered in the simulations to evaluate their influence on the water hammer effect. The results obtained from the COMSOL analysis provide valuable insights into the behavior of the system under different operating conditions, facilitating the design and optimization of piping systems to mitigate the adverse effects of water hammer.*

KEYWORDS: *Water hammer, Piping system, Operating condition, pipe vibration.*

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I. INTRODUCTION

Water hammer is a liquid shock wave that occurs when flow is abruptly started or stopped. It is influenced by factors such as initial system pressure, fluid density, speed of sound in the fluid, elasticity of the fluid and pipe, fluid velocity changes, pipe diameter and thickness, and valve operating time. One study [1] was conducted to investigate the water hammer phenomenon in slurries using both experimental and numerical methods. The researchers developed a comprehensive experimental setup to replicate the water hammer effect in a slurry pipeline and analyzed the transient behavior of pressure surges and pipe vibrations. They also used computational fluid dynamics (CFD) simulations to gain a deeper understanding of the underlying mechanisms. Another study [2] specifically focused on the transient flow behavior of a hydrogen-natural gas mixture during water hammer events. The researchers examined the impact of different closing valve laws on the flow characteristics and analyzed pressure surges, flow velocities, and pipe vibrations to understand the effects of water hammer in the mixture. The findings from this study contribute to our understanding of transient flow phenomena in hydrogen-natural gas systems and provide valuable insights for the design and optimization of related infrastructure. Another aspect explored in [3] is the effect of valve closure time on water hammer occurrence and behavior. Through analysis, the researchers investigated the relationship between valve closure time and pressure surges in the pipeline system, emphasizing the importance of proper valve closure timing to mitigate the associated risks. Advancements in multiple-valve water hammer control techniques are discussed in [4]. The study explores various methods and strategies for mitigating water hammer effects using multiple valves, highlighting the effectiveness and benefits of employing such systems. In [5], the paper investigates water hammer phenomena in a pipe network caused by the rapid closure of a valve. The study analyzes the transient behavior of fluid flow and pressure surges resulting from the fast valve closure, providing insights into the impact of valve closure speed on water hammer effects in pipe networks. The design and analysis of water hammer effects in a network of pipelines are the main focus of [6]. The study examines the transient behavior of fluid flow and pressure surges resulting from rapid changes in flow velocity, offering insights into the factors influencing water hammer and proposing design considerations to mitigate its effects in pipeline networks. Experimental and numerical investigations on water hammer analysis in a pipeline are presented in [7]. The study considers the combined configuration of two different materials to understand the effects of material properties on water hammer behavior. It provides insights into the design and analysis of pipelines with different material combinations. Lastly, [8] concentrates on water hammer analysis in the main pipeline for the Taq-Taq Dam irrigation project in Iraq. The study aims to assess the potential water hammer phenomenon and its effects on the pipeline system, utilizing experimental and numerical analyses to evaluate the transient behavior and propose appropriate mitigation measures for the project.

The aim of this paper is to investigate the water hammer phenomenon in a model of a pipeline system with a reservoir and valves. The software Comsol is chosen as the tool for constructing the pipeline and simulating the system's output values. The study aims to provide valuable information for the design and optimization of pipeline systems, with the ultimate goal of mitigating the risks associated with water hammer events.

II. MATERIALS AND METHODS

2.1. Model of system with reservoir and valve

To simulate and evaluate the water hammer phenomenon, a model of a pipeline system with a reservoir and valves was constructed as shown in Figure 1.

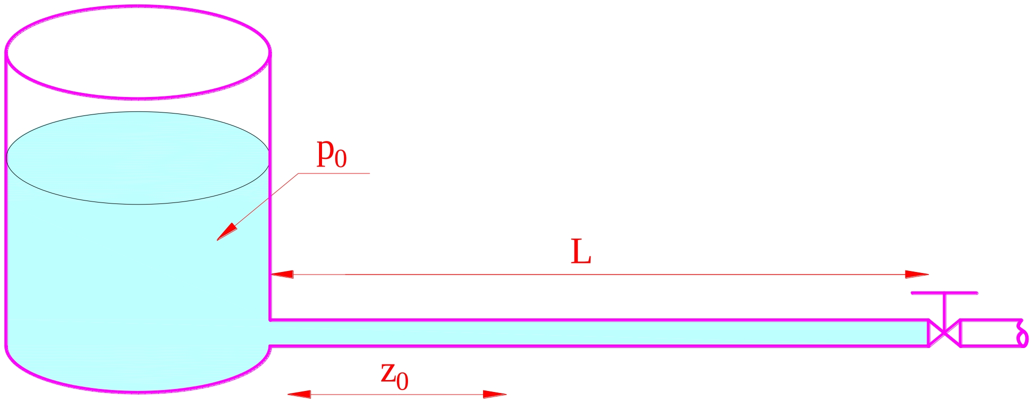

Fig 1. Model of system with reservoir and valve

2.2. Governing equations

The investigations into the water hammer phenomenon have a long history, as previously mentioned. In 1898, Joukowsky attempted to determine the maximum pressure change resulting from rapid water hammer, as expressed in the first equation (Wylie et al., 1993).

$$\Delta p = \Delta \upsilon . \rho . a \qquad 1$$

where: Δ υ = water velocity change, ρ = liquid density, *a* = wave propagation celerity.

Joukowsky's formula describes both positive water hammer (maximum pressure increase) and negative water hammer (minimum pressure decrease). A sudden gate closure causes a significant pressure increase, while negative pressure occurs when water accelerates suddenly (e.g., pump starting or gate opening). Engineers can use Joukowsky's equation to estimate maximum pressure changes. The wave celerity can be calculated using the equation provided (Wylie et al., 1993).

$$a = \frac{2.L}{T_R} \qquad 2$$

where: L = pipeline length, TR = return time of the reflected wave

In rapid water hammer scenarios, the closure time (TC) of the gate should ideally be shorter than the reflected wave's return time. Increasing the closure time helps reduce the magnitude of extreme pressure changes. When there is a linear change in liquid velocity and the total pressure increase is within 220% of the steady conditions prior to water hammer, Michaud's formula (Mitosek, 2008) is used to estimate the pressure increase.

$$\Delta p = \frac{2.\rho.\upsilon_0.L}{T_C} \qquad 3$$

where: υ_0 = velocity of steady flow before the beginning of the water hammer phenomenon, T_C = gate closure time.

Wood and Jones were the next researchers who tried to describe the influence of the gate on the transient flow. The α is used to describe the influence of the initial conditions according to the equation (Wood and Jones 1973):

$$\alpha = \frac{g.h_0}{\Delta\upsilon.a'} \qquad 4$$

where: $h0$ = the head drop across the valve under the initial steady flow conditions, which can be measured just before the water hammer phenomenon occurs, a = wave propagation celerity, $\Delta\,\upsilon$ – water velocity change.

The maximum pressure change is determined by the α parameter, which can be obtained from a chart using the dimensionless valve closure time. The formula described by Wood and Jones (1973) is used to calculate the dimensionless valve closure time.

$$t_C = \frac{T_C}{\frac{2.L'}{a}} \qquad 5$$

where: t_C = dimensionless valve closure time.

The unknown maximum transient pressure change is related to the dimensionless maximum transient pressure change, which can be obtained from the chart mentioned by Wood and Jones (1973).

$$\Delta p_m = \frac{\Delta p_{\max}}{\Delta\upsilon.\rho.a'} \qquad 6$$

where: Δp_m = dimensionless maximum transient pressure change, $\Delta p_{\max}$ = maximum transient pressure head.

III. RESULTS AND DISCUSSION

The model consists of a reservoir connected to a pipe of length L = 20 m with an inner radius R = 400 mm. The pipe is made of steel with Young's modulus E = 210 GPa and wall thickness w = 8 mm. At a distance z_0 = 11.15 m from the reservoir there is a pressure sensor measurement point. The reservoir acts as a constant pressure source with p0 = 1 atm. As an initial condition, the valve is open and water is flowing steadily at a flow rate of Q_0 = 0.55 m^3/s. At time t = 0 s the valve is closed instantaneously, thereby initiating the water hammer. Simulation results are shown in the figure below:

At time t = 0.22 s, Figure 2 displays the longitudinal pressure of the pipe. The pressure distribution graph reveals that the pipeline's maximum pressure, reaching a value of 4.65×10^5, occurs at a pipe section located 7m away.

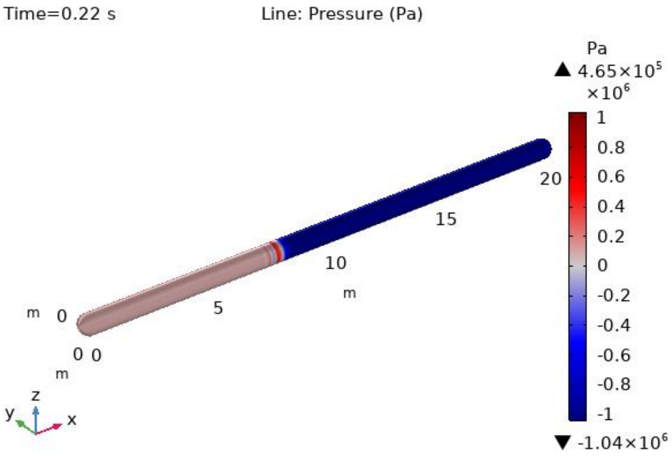

Fig 2. The pressure along the pipe at time t = 0.22 s

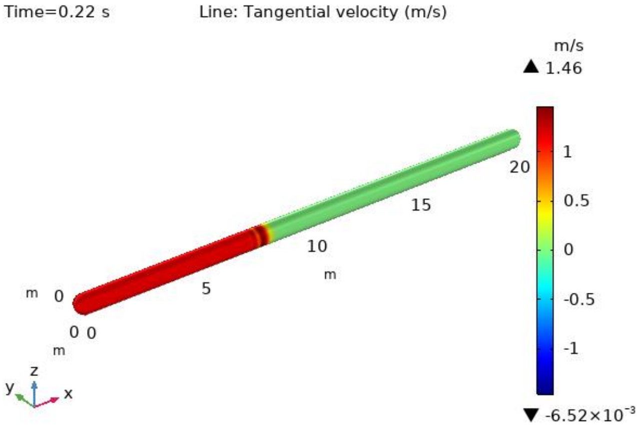

Fig 3. The velocity along the pipe at time t = 0.22 s

Likewise, at time t = 0.22 s, Figure3 depicts the velocity along the tube. The maximum velocity value, which is 1.46 m/s^2, occurs in the pipe section ranging from 0 to 7m in length.

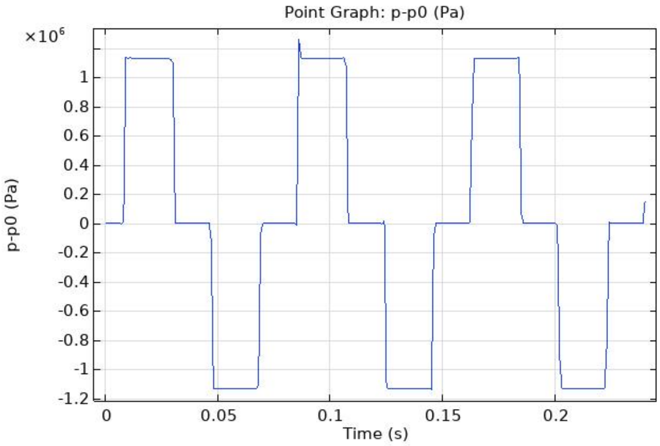

Fig 4. Excess pressure history measured at the pressure sensor

The excess pressure history, p −p0, as measured at the pressure sensor located at z0 is shown in Figure 4. Notice the numerically-induced high-frequency oscillations around the discontinuities in the pressure (the abrupt changes)

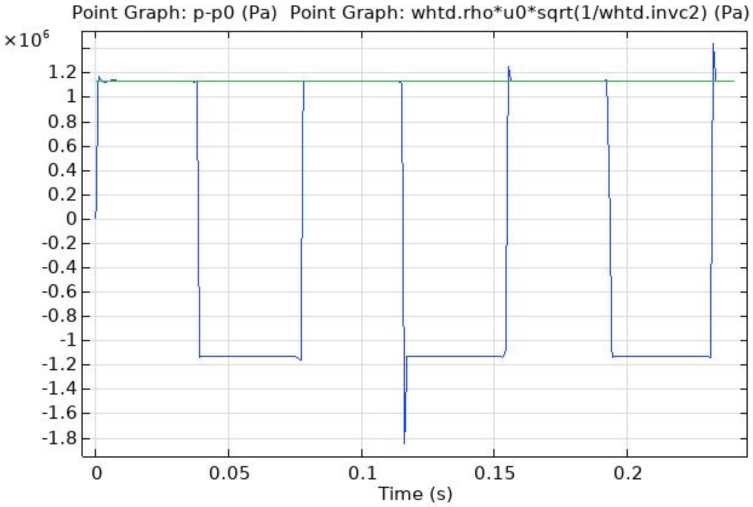

Fig 5. Excess pressure at the valve (blue line) and predicted water hammer amplitude (green line).

In Figure 5, the blue line represents the excess pressure at the valve, which corresponds to the amplitude of the water hammer. The observed amplitude of the excess pressure aligns perfectly with the theoretical prediction for positive oscillations. This alignment is expected since Joukowsky's theory is based on the assumption of a lossless sudden closure of a valve.

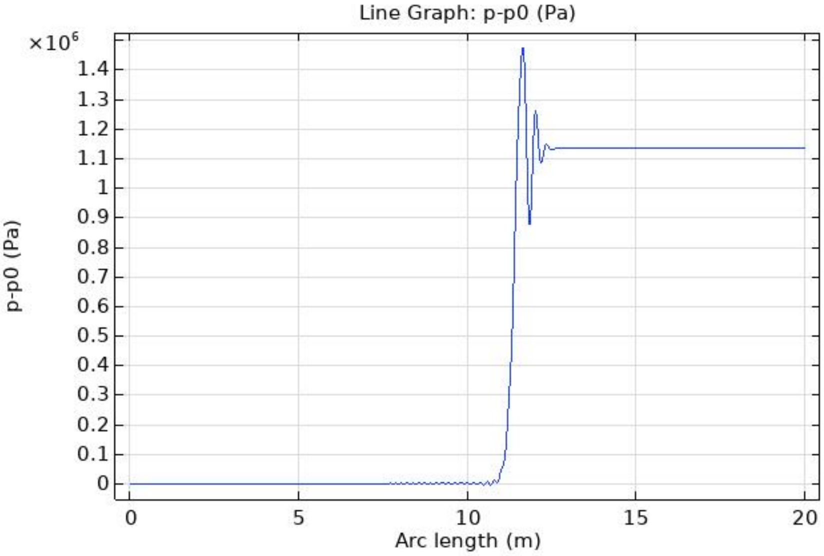

Fig 6. Excess pressure distribution along the pipe for t = 0.22 s.

Figure 6 depicts the pressure distribution along the pipe at time t = 0.22 s. The pressure wave exhibits a significant amplitude along the majority of the pipe, particularly between 11m and 13m, before stabilizing.

IV. CONCLUSION

This study successfully constructed a model of a system with a tank and valve using the Comsol software. The longitudinal pressure of the pipe at time t = 0.22 s was examined, revealing a maximum pressure of 4.65 × 10^5 at a pipe section located 7m away, as shown in Figure 1. Furthermore, Figure 3 presented the velocity distribution along the tube at the same time, with a maximum velocity of 1.46 m/s^2 observed in the pipe section ranging from 0 to 7m. Additionally, the pressure wave exhibited a significant amplitude along the majority of the pipe, particularly between 11m and 13m, before reaching a stabilized state. These findings provide valuable insights into the behavior of the system under consideration and contribute to a better understanding of water hammer phenomena.

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