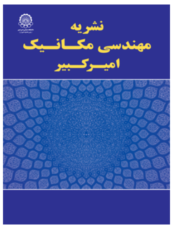


Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(7) (2021) 989-992
DOI: 10.22060/mej.2020.18624.6865

# Numerical simulation of water hammer in various fluids due to a fast valve closure

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**ABSTRACT:** The sudden changes of boundary conditions in the fluid transmission lines cause a transient flow, which is called water hammer. In this paper, the water hammer resulting from the fast closure of a valve in pipelines is simulated using numerical solution of continuity and Navier-Stokes equations. Simulation has been performed for a high-viscosity oil and for water. The initial flow regime for oil is laminar and for the water is turbulent. The obtained results are compared with the reported experimental data and a good agreement is observed. Velocity contours at different times show two regions with different behavior: the wall region and the pipe core region. In the wall region, the effects of fluid viscosity are dominant, the velocity gradients are sharper, and flow changes more rapidly. While the pipe core region is affected by fluid inertial forces. As the fluid viscosity decreases, the core region becomes more dominant. In addition, a parametric study has been conducted and the effect of different parameters on water hammer has been studied. The results show that by reducing the thickness or length of the pipe, or using a pipe with a lower elastic modulus, the water hammer effects can be significantly reduced. For example, by reducing the length of the pipe from 60 to 18 meters, the maximum pressure decreases by 11%.

**Review History:**

Received: Jun. 22, 2020
Revised: Oct. 10, 2020
Accepted: Nov. 14, 2020
Available Online: Nov. 26, 2020

**Keywords:**

Water hammer
Transient flow
Compressible flow
Numerical simulation
Pressure waves

## 1. INTRODUCTION

Water hammer is a transient hydraulic phenomenon that occurs when the fluid velocity is altered due to failure or handling of hydraulic devices (valves, turbines, etc.). The water hammer propagates as pressure wave along the pipeline and produces significant rise and drop of pressure. In order to prevent excessive pressure buildup in pipelines which cause pipeline damage, understanding the physics behind the water hammer phenomenon is very important. Most of the research on water hammer has been conducted either experimentally [1,2] or numerically using the method of characteristics (MOC) [3-4]. MOC is a one-dimensional (1D) method which ignores the effects of transient wall shear stress. However, water hammer is a complex fast transient flow which unsteady friction plays an important role. Therefore, traditional one dimensional MOC fails in the prediction of damping of wave fronts accurately. More precise prediction of the water hammer phenomena requires to employ full Navier–Stokes equations [5-7].

In the current paper, the 3D predictions of water hammer in a straight pipe resulting from fast valve closure are presented. Simulation is carried out using CFD based on unsteady Reynolds averaged Navier-Stokes (URANS) equations and without any change in the nature of the governing equations. In comparison with other studies, the water hammer in two fluids with two different Reynolds numbers is investigated and the effect of flow regime on the water hammer is discussed. In addition, 2D axisymmetric simulation results are compared with experimental data the accuracy of 2D simulations is presented. Moreover, the effects of pipe thickness, pipe material and pipe length on the water hammer are investigated and discussed.

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## 2. MODEL DESCRIPTION

A schematic diagram of the geometry considered for the water hammer simulations is depicted in Fig. 1. Operating conditions and geometrical parameters are chosen based on the experimental set-up [1]. The pressure variations in the middle (point $A$) and at the end (point $B$) of the pipe are measured. For compressible transient flows, the conservation laws of mass and momentum are given by:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_j)}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(-\rho\overline{u'_i u'_j}\right) \tag{2}$$

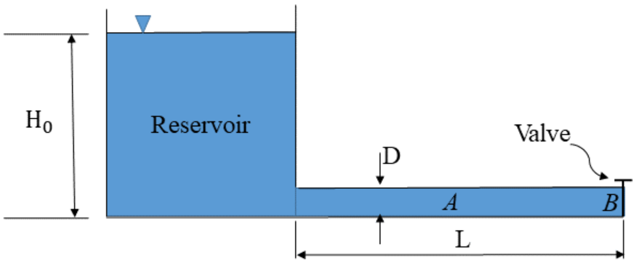


**Fig. 1. Schematic of the studied geometry**

For numerical simulations, first steady-state is simulated using the pressure inlet and the pressure outlet boundary conditions. When the solution converged, the downstream boundary is swift to wall boundary and the simulation continued with the unsteady scheme so that the water hammer phenomena is achieved. The numerical computation is carried out by solving the governing conservation equations along with the boundary conditions using general purpose finite volume based code, FLUENT. The grid independency for both 2D and 3D simulations is examined and insured. The time step of the transient solution is $10^{-4}$ s.

## 3. RESULTS AND DISCUSSION

Fig. 2 shows the pressure fluctuation at points *A* and *B* resulting from experiments and 2D and 3D simulations for oil flow. Time and pressure are depicted in the dimensionless forms. As clearly seen in Figure 2, the 3D simulation results are in excellent agreement with the experimental data of Holmboe et al. [1]. 2D and 3D results are almost the same in the first period. However, the difference between 2D simulation results and experimental data becomes more significant from the second period. Maximum relative error for 3D simulation is 11% and for 2D simulation is 18%.

Fig. 3 compares the experimental results with simulation predictions for water flow. 3D results and experimental data are very consistent and maximum relative error is 5%, while for the 2D simulation maximum relative error is 20%.

Comparing Figs. 2 and 3 shows that increasing the Reynolds number increases discrepancies between 2D and 3D simulation results. Therefore, water hammer simulation in turbulent flows requires 3D computations. In addition, Fig. 2 shows that the second pressure rise for oil flow is not as steep as the first pressure rise, which means that the wave propagation is affected by viscous dissipation effects. In the second pressure rise, pressure wave is losing the square-shape and is becoming more S-shape. Along with the comparison for water flow in Fig. 3, it becomes clear that wave damping in water flow is not as significant as oil flow and the amplitude and square shape is preserved for several cycles, indicating good reflection properties and small energy losses in the water flow.

In order to present a closer look at the characteristics of water hammer flow and analyze the transient flow dynamics, the velocity contours and streamlines obtained from 3D calculations for water flow are displayed in Fig. 4. It can be seen that at $t$=0 the velocity contour is similar to the fully-developed velocity profile. After valve closure at $t$=0, the generated pressure wave travels toward the constant head reservoir and reaches the reservoir at $t=T/4=0.026$ s. At $0<t<T/4$ the velocity contours show a reverse flow near the pipe wall. After that, the pressure wave is reflected and travels back as the head in the pipe equals to the reservoir level and arrives at the valve at $t=T/2$. For the times between $T/4<t<T/2$ the flow direction is becoming reversed from the valve toward the reservoirs. Then the pressure wave travels back

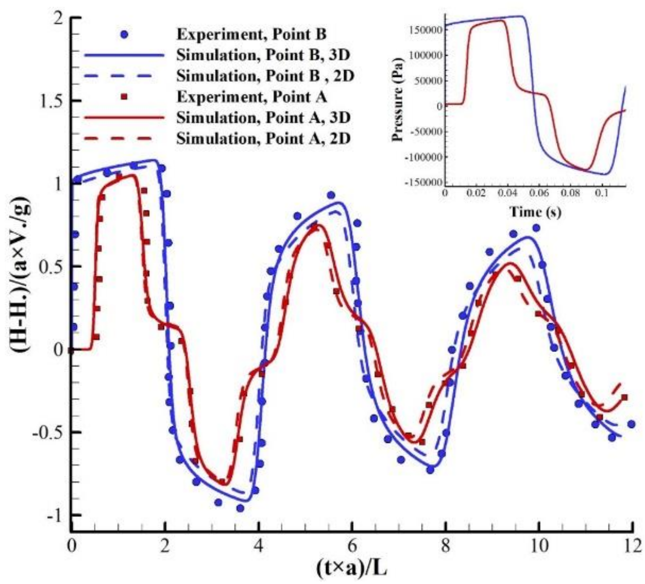


**Fig. 2. Comparison of experimental results with 2D and 3D simulation predictions at points *A* and *B* for oil flow**

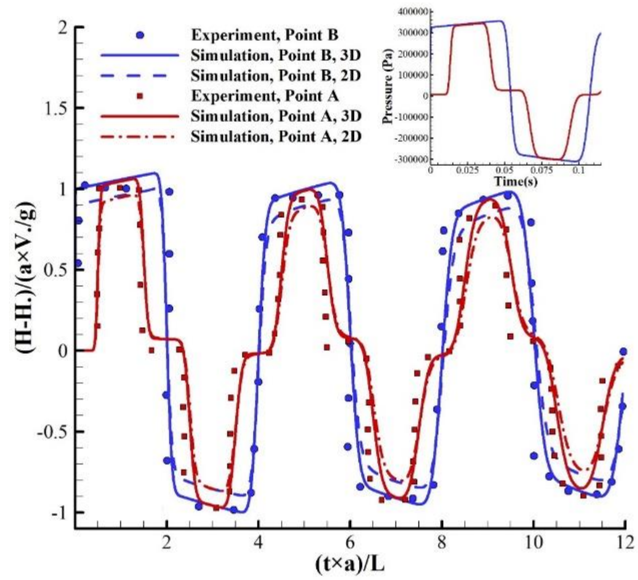


**Fig. 3. Comparison of experimental results with 2D and 3D simulation predictions at points *A* and *B* for water flow**

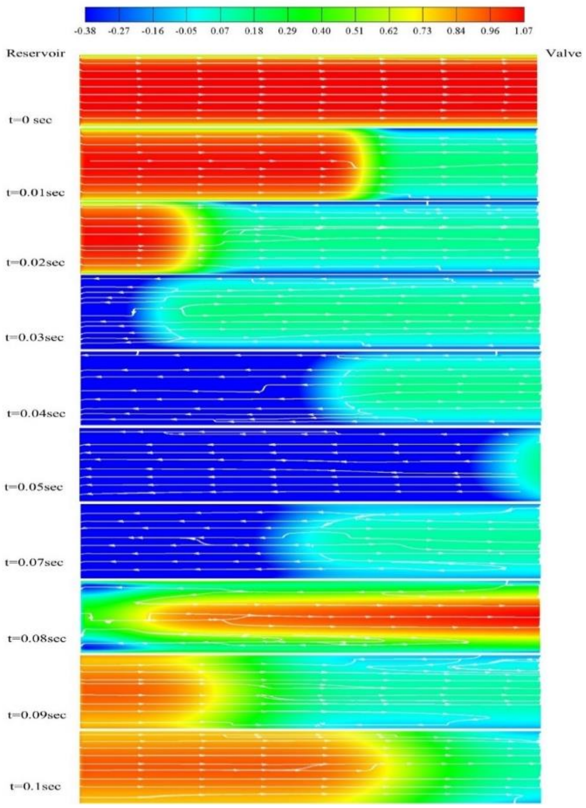


**Fig. 4. Axial velocity contours and streamlines from 0 s to 0.1 s in the middle section of the pipe for water flow**

to the reservoir, reaching the reservoir at $t=3T/4$ and again travels toward the valve and reaches the valve at $t=T=0.107$ s. During this time interval, the direction of the velocity vectors is again toward the valve.

## 4. CONCLUSIONS

This work reports on simulation of water hammer generated by the valve fast closure in two different fluids; a high-viscosity oil and water. The full Navier-Stokes equations are used to simulate water hammer phenomenon in the laminar and turbulent regimes using finite volume method. The flow is considered to be compressible and the effect of pipe elasticity is taken into account. The 3D simulation results for both fluids are found to be in good agreement with the reported experimental data in the literature. However, the accuracy of the 2D axisymmetric simulation results decreases by increasing the Reynolds number. Pressure variations over time in different sections of the pipe show that the maximum pressure is created at the valve location. The pressure rise in other parts of the pipe, due to the effects of transient wall shear stress and viscous dissipation, is reduced. Furthermore, the performed parametric study demonstrates that by using a pipe with a lower elastic modulus, and reducing the thickness or length of the pipe, the water hammer effects can be significantly reduced. By reducing the pipe thickness from 7 to 3 millimeters, the maximum pressure decreases by 5% and reducing the length of the pipe from 60 to 18 meters, decreases the maximum pressure by 11%.

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**HOW TO CITE THIS ARTICLE**

*R. Mohammadi, M. Aghaei, Numerical simulation of water hammer in various fluids due to a fast valve closure , Amirkabir J. Mech Eng., 53(7) (2021) 989-992.*

**DOI:** 10.22060/mej.2020.18624.6865