Effect of Length to Diameter Ratio on Transient Flow Characteristics

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ABSTRACT

Hydraulic transient analysis is vital in the design of water pipeline systems for the selection of appropriate pipe materials and pressure classes as it leads to large fluctuations in pressure, known as water hammer. The different parameters that influence the water hammer characteristics are closure time, length of pipe, the diameter of pipe and pipe wall thickness. A clear understanding of the situations leading to water hammer is required to avoid system malfunction or breakdown. This paper numerically analyses how the length to diameter ratio of pipe affects the water hammer effect. Numerical modelling and analysis are carried out in ANSYS FLUENT solving the Navier-Stokes Equations. This study simulates the flow in elastic and viscoelastic pipes with varying length to diameter ratio. Change in L/D ratio affects the water hammer pressure based on the 2L/c criteria for closure time. If the closure condition changes from sudden to gradual, the water hammer pressure reduces significantly.

KEYWORDS

Transient flow, Computational Fluid Dynamics, Length to Diameter ratio

1. INTRODUCTION

Hydraulic transients arise in pressurized structures as a result of rapid variations. Velocity changes due to valve closures or pump operations cause pressure surges that propagate away from the source throughout the pipes [1]. The elastic nature of the pipe boundaries and the compressibility of the fluid prevent these sudden changes in pressure to a degree. These pressure changes during a transient period are regularly very massive and occur within seconds. If the induced maximum pressure exceeds the mechanical strength of the pipe material, different types of failure can occur such as bursting of pipe, damages to pipe connections and valves etc [2]. Similarly, if the minimal pressure drops beneath the vapour pressure of the fluid, it results cavitations and may be harmful to the pipeline system. Hence, hydraulic transient analysis is critical in the design of water pipe line structures for choice of pipe materials and pressure classes, and for specification of surge safety devices [3]. Analysis of water hammer allows choosing of an appropriate parameter of system like pipe material, thickness of wall, length to diameter ratio or flow velocity [4].

Provenzano and Gabriel [5] studied the affect of inner pipe-diameter on water hammer phenomenon. It was found that the pressure wave amplitude increases exponentially with decrease in pipe diameter. They concluded that the bigger conduit diameter and lesser rigid materials are good to make a safe pipe network. Jha et al. [6] analyzed the influence of geometrical changes in the flow path on the pressure waves generated due to sudden valve closure by solving Navier–Stokes equations in time, using ANSYS Fluent software. Attenuation of the pressure amplitude was found to be slower in the geometry used in the study compared with experimental results due to a more gradual change in cross-sectional area.

Stojkovski and Stojkovski [7] analyzed the impact of the pipe fabric over the water hammer effect and a numerical model is constructed to evaluate the pressure wave propagation for different pipe configurations and pipe materials, i.e. steel and plastic PVC pipe. They examined how the wave period and intensity is changed over the time. They determined that the time of deformation will cause delaying of the pressure wave throughout the system. The drift fluctuations are increased with the time, starting from low to excessive intensities, due to the fact that the pipe is deforming gradually through the time. Urbanowicz and Firkowski [8] analyzed that the individual and group impact of parameters representing flowing liquid (density, bulk modulus and kinematic viscosity) and pipe material (Young's Modulus, wall thickness, internal radius and Poisson's Ratio) influencing the water hammer happening within the metallic pipes. The present study aimed to analyse the influence of length to diameter ratio in the characteristics of transient flow through elastic and viscoelastic pipes.

2. METHODOLOGY

ANSYS Fluent is an industrial CFD software used for the study. The fluid flow modelling and analysis accomplished in ANSYS FLUENT, solving the Navier-Stokes Equations and the results from the study was validated with the results of the experiments conducted in Water flow lab in Fluid Control Research Institute, Palakkad [9]. For analyzing the influence of length to diameter ratio, simulate the transient flow in elastic pipes (Mild Steel)and viscoelastic pipes (UPVC and HDPE pipes) using CFD in ANSYS Fluent with L/D ratios 300, 400, 500 and 600 and compare the results of both elastic and viscoelastic pipes. Numerical simulation based on the finite volume method was performed to solve the continuity and momentum equation.

The continuity equation for a compressible fluid may be written as follows

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0 \qquad (1)$$

Here, ρ is the fluid density and U_i is the fluid velocity x_i direction.
The momentum equation is

$$\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial (\rho U_i U_j)}{\partial x_j} = \frac{\partial p}{\partial x_t} + \frac{\partial}{\partial x_j}\left[\mu\left[\frac{\partial U_i}{x_j} + \frac{\partial U_j}{\partial x_j} - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{tj}\right]\right] + \rho g_t + F_t \qquad (2)$$

The first term at the left hand side describes the variation of the fluid momentum in time; the second term describes the transport of the momentum in the flow. The first term on the right hand side describes the effect of gradients in the pressure p; the second term, the transport of momentum due to the molecular viscosity; the third term, the effect of gravity g; and in the last term, F_t lumps together all other forces acting on the fluid.

2.1 Experimental set up

To analyze the transient flow in viscoelastic pipelines, an experimental model was set up at the Fluid Control Research Institute, Palakkad. Fig.1 indicates schematic sketch of the experimental setup. UPVC pipe was taken for the study. The model consisted of a 30.13 m long pressure pipeline with water from an overhead tank with steady head of 17m. On the downstream end of the pipe, a control valve and a pressure actuated Quick Acting Valve was mounted to govern the flow rate and to simulate the sudden closure of the valve respectively. The valve closure was controlled using a pressure gauge connected to it. To make certain the specified flow rate through the pipe a digital flow meter was used. Pressure transducers were attached to the pipe at the outlet and at a distance of 20 m from the outlet of pipe for keeping a continuous record of pressure variations.

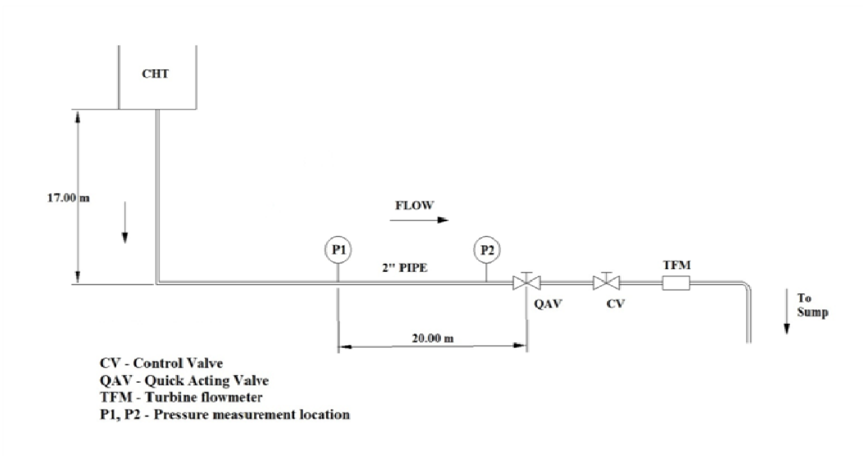

Figure.1 A Schematic sketch of the experimental setup

The properties of the materials used for testing were given in Table 1.

Table 1. Properties of pipes used in experiment

Parameter	**UPVC pipe**	**HDPE pipe**	**Mild Steel pipe**
Length, L (m)	30.13	30	30.3
Internal diameter, D (m)	0.0512	0.04707	0.0524
Density (kg/m^3)	1430	960	7850
Modulus of elasticity, E (GPa)	3	1.035	200
Pressure inlet (m)	17	17	17
Roughness height(m)	0.0000015	0.0000015	0.0008
Poisson's ratio(μ)	0.34	0.38	0.3

3. Results and analysis

3.1 Grid independence study

Grid independence study was accomplished to decide the optimum solution for the problem. Transient flow through UPVC pipe was simulated with distinctive mesh sizes as 5 mm, 10mm, 25mm, 50mm keeping all other conditions the same. Fluid flow in UPVC pipe was modelled with the details given in Table 1. Flow velocity is taken as 0.4m/s and valve closure time as 0.04s. Details of the grid study are given in Table 2. Figure 2 shows the comparison of pressure distribution for different mesh sizes.

Table 2. Details of the grid independence study

Mesh Size	5 mm	10 mm	25 mm	50 mm
No of Nodes	7,65,429	3,82,778	1,44,840	76,708
No of Elements	6,99,016	3,49,508	1,31,454	69,948
Element Quality	0.91738	0.55118	0.14186	0.036151
Aspect Ratio	1.5394	2.9317	7.1063	14.649
Orthogonal Quality	0.98352	0.98352	0.98352	0.98352
Skewness	0.14505	0.14505	0.14505	0.14505

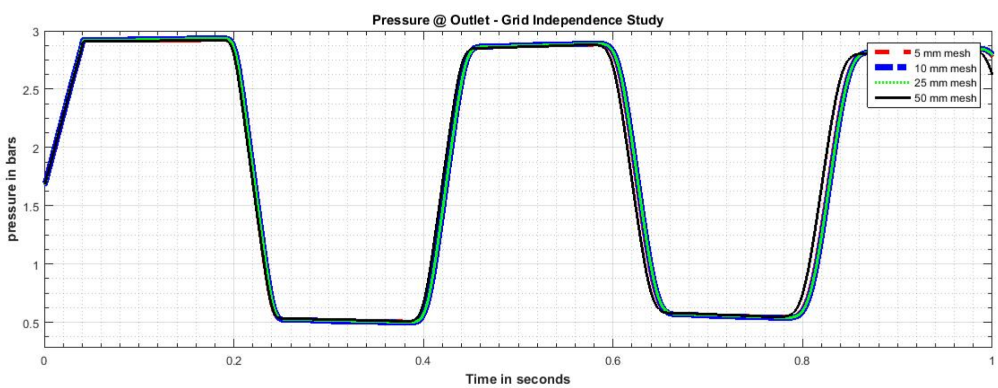

Figure 2. Grid independence study

From Fig.2 it can be seen that the pressure variation is almost same for all the grid sizes. The grid quality measures such as element quality, aspect ratio, skewness and orthogonal quality are within the appropriate range in all cases. But the element quality was considerably reduced for flow simulation with 25 mm and 50 mm mesh sizes. Simulation with more number of nodes and elements makes the analysis complex one. So we adopt 10 mm mesh size for further study.

3.2 Validation of transient analysis

For the numerical analysis of transient flow in UPVC pipe, fluid flow through pipe was simulated in pipe with diameter 51.2 mm and length 30.13 m. Boundary conditions provided at the inlet as pressure inlet - 170000 Pa and at the outlet as mass flow outlet- 0.8207 kg/s. Pressure variations had been monitored at outlet and 20 m from outlet. The result obtained after simulation was compared with the results of experiment carried out in FCRI Palakkad. Figure.3 shows the comparison of pressure distribution from numerical method and experimental study.

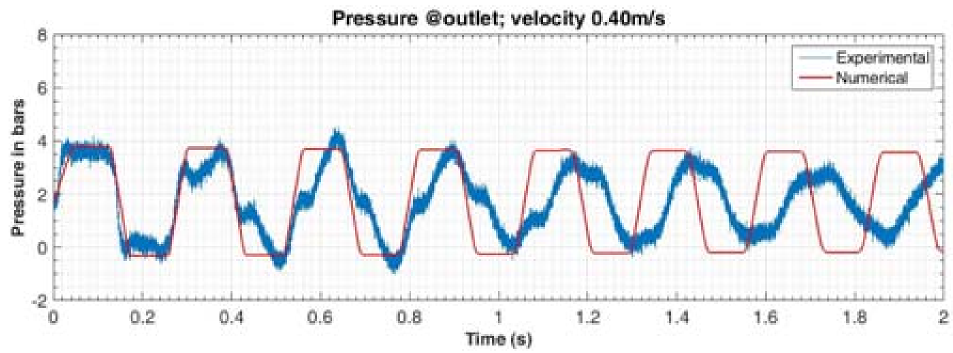

Figure 3. Pressure variation in UPVC pipe at outlet

The intensity of first peak of water hammer pressure is same in both experimental and numerical studies. This indicates the accuracy of the numerical model in predicting the water hammer pressure. But dampening of the curve is more in the experimental result than the result obtained by using the numerical evaluation.

To study the influence of length to diameter ratio during transient flow, a parametric study was conducted using the model.

3.3 Influence of length to diameter ratio of pipe

In order to estimate the relationship between pipe length and pressure wave amplitude and to quantify those, transient flow had been modelled for three different materials with four different pipe lengths. The materials selected are Mild Steel (elastic), UPVC and HDPE (viscoelastic). The pipe lengths selected for the study are 15m, 20m, 25m and 30m. Corresponding L/D ratios are 300, 400, 500 and 600 respectively. The simulation outcomes for Mild Steel, UPVC and HDPE pipes are given as a comparison graph in Figure.4, Figure.5 and Figure.6 respectively. The variation of pressure for different pipe lengths is shown in Table 3.

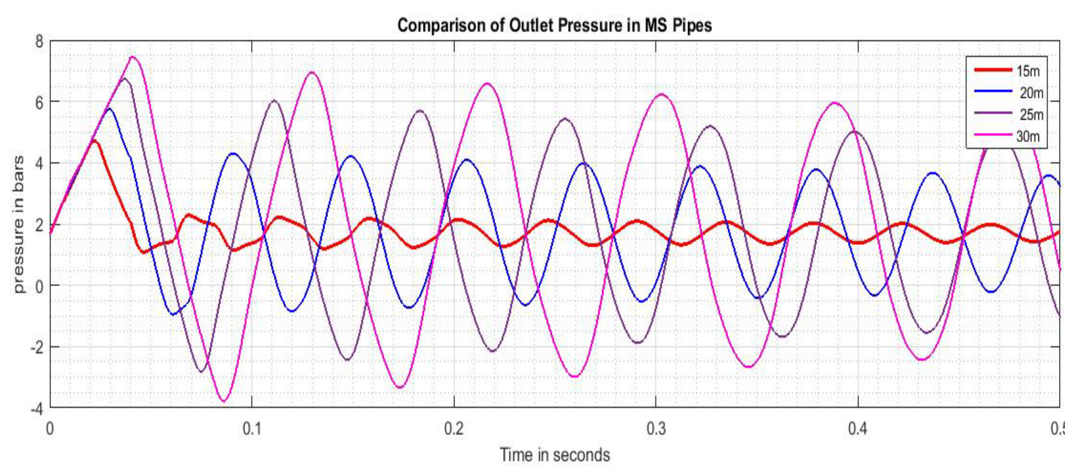

Figure 4. Pressure at outlet of mild steel pipe with various lengths - closure time 0.04s

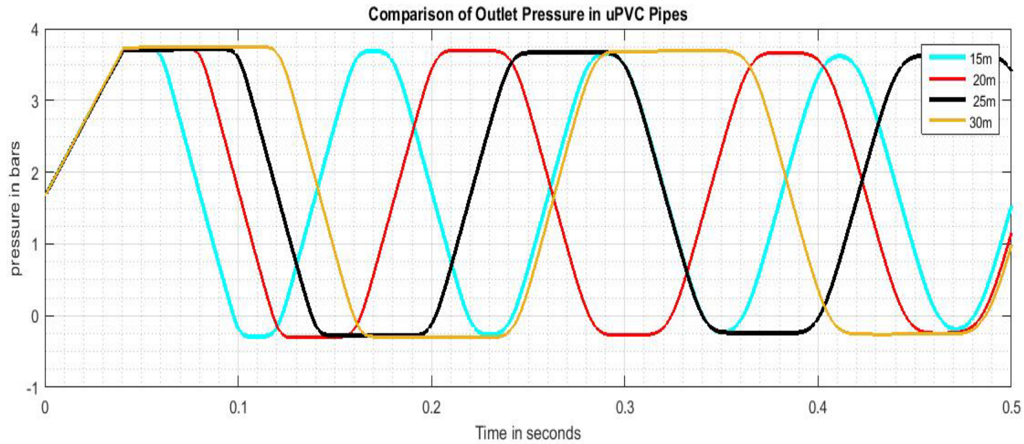

Figure 5. Pressure at outlet of UPVC pipe with various lengths- closure time 0.04s

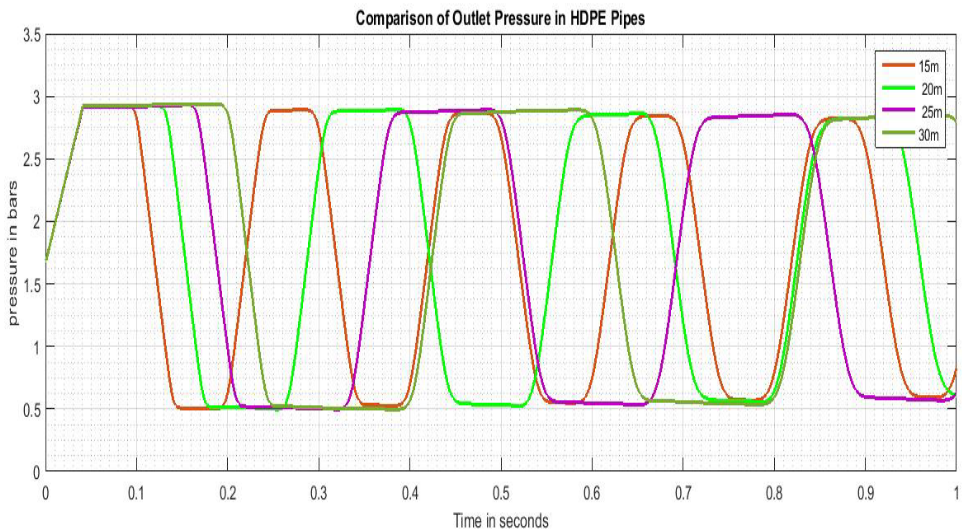

Figure 6. Pressure at outlet of HDPE pipe with various lengths - closure time 0.04s

Table 3**.** Pressure at outlet with various length to diameter ratios

Length of pipe	**L/D ratio**	**Mild Steel**		**UPVC**		**HDPE**	
		Pressure (10^5Pa)	**Time period (s)**	**Pressure (10^5Pa)**	**Time period (s)**	**Pressure (10^5Pa)**	**Time period (s)**
15 m	300	4.71	0.0466	3.71	0.1169	2.91	0.238
20 m	400	5.74	0.0611	3.72	0.1726	2.92	0.3327
25 m	500	6.72	0.0739	3.71	0.2076	2.92	0.4064
30 m	600	7.46	0.0893	3.72	0.2564	2.92	0.541

The study shows that, in Mild Steel pipe with four pipe lengths used in the numerical study, the water hammer pressure decreases and the pressure wave damps fast when length and L/D ratio decreases. But in the case of four pipe lengths selected for UPVC and HDPE pipes, magnitude of pressure peaks is unbiased of changes in L/D ratio, but time period of pressure wave reduces as the L/D ratio decreases. The authors investigated the reason behind this behaviour. The study ended up on the fact that the change in length of pipe will change the 2L/c criteria adopted for the classification of valve closure as sudden or gradual closure. For this study, the valve closure time taken as 0.04s uniformly. So, while the pipe length changes, valve closure condition change between sudden or gradual. These changes for all the three pipes are given in Table 4.

Table 4. Pipe length and valve closure type

Valve closure time taken: 0.04s	**Mild Steel**		**UPVC**		**HDPE**	
Length	2L/c (s)	valve closure condition	2L/c (s)	valve closure condition	2L/c (s)	valve closure condition
15	0.021	Gradual	0.06	Sudden	0.10	Sudden
20	0.028	Gradual	0.08	Sudden	0.13	Sudden
25	0.036	Gradual	0.10	Sudden	0.16	Sudden
30	0.043	Sudden	0.12	Sudden	0.20	Sudden

From the above table, it is observed that as the length changes, valve closure condition remains as sudden closure in all cases of UPVC and HDPE pipes. That is why pressure peaks are independent of change in length of UPVC and HDPE pipes. In the case of mild steel pipe, for the selected pipe lengths in the study, as the length of pipe decreases the valve closure condition changed from sudden to gradual based on the 2L/c criteria for closure time. So there is considerable variation in pressure peaks with change in length and L/D ratio. If the closure condition changes from sudden to gradual, the water hammer pressure reduces extensively. Hence, it can be concluded that if the valve closure condition changes with the change in pipe length, the corresponding change in pressure intensity and pressure wave period will be drastic. Otherwise the change will be only in the pressure wave period and pressure intensity remains unaltered.

4. CONCLUSION

In this study, transient flow analyses in elastic and viscoelastic pipes have been carried out by using the principles of Computational Fluid Dynamics (CFD) in ANSYS Fluent software. The created model was validated using the experimental results. The numerical investigation was carried out with four different pipe lengths, to study the influence of pipe length to diameter ratio. The study reveals the fact that the change in length of pipe will change the 2L/c criteria adopted for the classification of valve closure as sudden or gradual closure. As the valve closure condition remains as sudden closure in all cases of UPVC and HDPE pipes, the pressure peaks are independent of change in length of UPVC and HDPE pipes. In the case of mild steel pipe, the valve closure condition changed from sudden to gradual based on the 2L/c criteria for closure time. So there is considerable variation in pressure peaks with change in length and L/D ratio. Hence, it can be concluded that if the valve closure condition changes with the change in pipe length, the corresponding change in pressure intensity and pressure wave period will be drastic. Otherwise the change will be only in the pressure wave period and pressure intensity remains unaltered.

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