REYNOLDS NUMBER DEPENDENCE ON THE EFFECT OF AXIAL STRESS ON UNSTEADY POLYVINYL CHLORIDE PIPELINE FLOW

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Abstract. This paper studies the Reynolds number dependence on the effect of axial stress on unsteady pipeline flow. The unsteadiness is caused by sudden and gradual closure of the valve situated at the downstream end of the pipe. The effect generated by the unsteadiness is controlled by varying the Reynolds number (Re). Measurements were taken at different part of the pipe for a full and half closure of the valve at various Reynolds numbers. The pressure head obtained increase as Reynolds number (Re) increases, measurement clearly shows that Reynolds number majorly control the response of the pressure head although other factors like pipe geometry and wave speed which is a function of material properties and working fluid also contribute. Reynolds number control the magnitude but the wavelength of oscillation is unaltered. For all values of Reynolds numbers considered in this study (3750, 4125, 4750, 5250, 6000) with Polyvinyl Chloride (PVC) material used as pipe, its variation caused pressure head to increase, decrease with time until another steady state is reached which make it constant after a particular time for the Reynolds number considered.

Keywords: Hydraulic transient, Control Valve, Flow velocity and Pressure head.

Introduction

Hydraulic transient in pipes have been a subject of both theoretical study and intense practical interest for more than hundred years, as a result of this, transient fluid flow pose interesting problems in fluid dynamic. Domestic and industrial application makes it interesting to the researchers. Hydraulic transient events are disturbances in the water caused during a change in state. The components of the disturbances are pressure and flow changes at a point that causes propagation of pressure waves throughout the distribution system. The pressure waves depend on the elasticity of the water and that of the pipe walls, as these wave propagate, they create transient pressure condition. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady state (Don, 2005).

Interfering with the flow of fluid in pipes has been the subject of numerous studies (Warsaw 2007; Kirshore 2007; Bryan and Duncan 1992). This has led to consideration of single and networks of pipe in order to study the effect of axial stress through the interference of valve at the downstream end of the pipe, although, numerical study has been mostly employed Re>4000, however, few records of experimental study at low Reynolds number exist. For example, Kazumi *et al* (2009) carried out a study on dynamic long pipe and they showed that with a pump acting as source of varying the Reynolds number and powered by a generator of electric power 2.5×10^5kw, it was reported that for Re=47,686.2, the pressure recorded was 1MPa in about 0.1 second. Also, Kirshore, (2007) carried out transient analysis in pipe networks, method of characteristic was used in the numerical simulation of a single long pipeline with reservoir upstream and valve downstream, with Reynolds number (Re=91,661.4), the pressure head rose from 120m to 232m within about 0.1second and are maintained for a longer duration. Similarly, Warsaw, (2007) uses hydraulic system with a Pump and controlled valve at the end of a steel pipe, the unsteadiness was caused by shifting the controlled valve directing the liquid flow, and pressure rise was measured from 1.85MPa to 9.65MPa in 0.1s. Moreover, numerical simulation of hydraulic pipe transient has been carried out employing method of characteristic and confirmed as the best method for the simulation (Gilberto, 2004 and Sharker, 2010).

Similar work was carried out by Yukio et al (2002) where upstream finite difference method was used with pipe length 54.37m and 6.29m reservoir elevation, the report shows that after the closure of the valve for velocities 0.10m/s and 0.11m/s, the negative pressure does not reach evaporation point and was considered as one-phase flow while at velocity 0.12m/s, the negative pressure head reached evaporation point and was considered as two-phase flow. Furthermore, Darmstadt (2004) used computational fluid dynamics to study dynamic interaction in hydraulic pipeline system, result of three methods were considered viz. concentrated parameter method, distribution parameter method and transfer matrix method. It was noted that the online coupled simulation is possible by the assignment of two parallel-working personal computers which respectively implement CFD calculation and the computation with the characteristic method. Mohammed et al (2005) also reviewed numerical simulation for 1D water hammer equation and noted that method of characteristic (MOC) is the most popular method, other techniques include wave plan, finite difference (FD) and finite volume. 2D mass and momentum equations together with the numerical solutions were also studied, while the boundary conditions were noted to include pumps, valves, nozzles, turbines, surge tanks, heat exchanger and condensers.

Axial stress effect has been studied hitherto mostly on large Reynolds number (Re>4000) turbulence flow, but this study looks at unsteadiness with various Reynolds number to see it effect. Masaji *et al* (2002) studied the effect of axial stress on unsteady pipeline flow on large Reynolds number. They showed that for a Reynolds number of Re=4450 and Re=6100 which are very high (turbulent flow), high pressure head were noticed after the sudden closure of the valve within a short period of time. The pressure head and time for each of the Reynolds number considered were different. The higher Reynolds number has the higher pressure head followed by the lower Reynolds number. This present study focuses primarily on the dependence of varying the Reynolds number (turbulent flow) as a control in studying the effect of sudden and gradual closure of valve at downstream end of the PVC pipe. This is necessary because PVC pipe is commonly used in today's building and reticulation system. It should be noted that PVC pipe is cheaper and not being corroded with time although it also have its own disadvantage.

Experimental detail and measurement method

Because of Reynolds number required for this present study, the height of water in the reservoir used in the Masaji et al 2002 was inadequate in order to vary the Reynolds number, also with the two high Reynolds number considered, it was not again appropriate to ascertain the dependency of Reynolds number in determining the effect of axial stress on unsteady fluid flow. Accordingly, measurement were made in the newly developed outline, driven by a free fall (gravitational acceleration) with the water level at the upstream was 4.37m relative to the valve at the downstream (fig. 1). Four polyvinyl chloride (PVC) pipes are connected to the reservoir of capacity 7.57m^3 (neglecting the pipe close to the reservoir) with dimensions L1=3.66m, L2=3.66m, L3=3.66m, L4=2.21m. The pipes has uniform internal diameter (D=0.025m) with L2 having height 2.06m relative to the valve at the downstream end, the wave speed, (a) used was 497.73m/s ($a = \frac{\sqrt{k/\ell}}{\sqrt{1 + \left(KD/eE\right)\left(1 - \mu^2\right)}}$, Bergant et al, 2006) where k is the bulk modulus of elasticity of the fluid, ℓ is the density of the fluid , D is the internal diameter of the pipe, e is the thickness of the pipe, E is the Young modulus of elasticity of material and μ is the Poisson's ratio of the material. Velocities were obtained by allowing a free flow initially $U_1 = (Q_1/A)$ where Q_1 is the flow rate of the velocity considered (m^3/s) and A is the area of the pipe used.

Five different Reynolds number ($\mathrm{Re} = \frac{uD}{\upsilon}$, where u is the velocity for a steady state, D is the internal diameter of the pipe and υ is the kinematic viscosity of the fluid) were considered (3750, 4125, 4750, 5250, 6000). Air valve (32mm internal diameter) situated at the downstream of the valve was used to generate the unsteadiness with measurement taken at different part of the pipe for various possibility of the Reynolds numbers considered. The repeatability of the experiment under these conditions was to ascertain the dependency of Reynolds number on the response of backward flow along stream-wise direction.

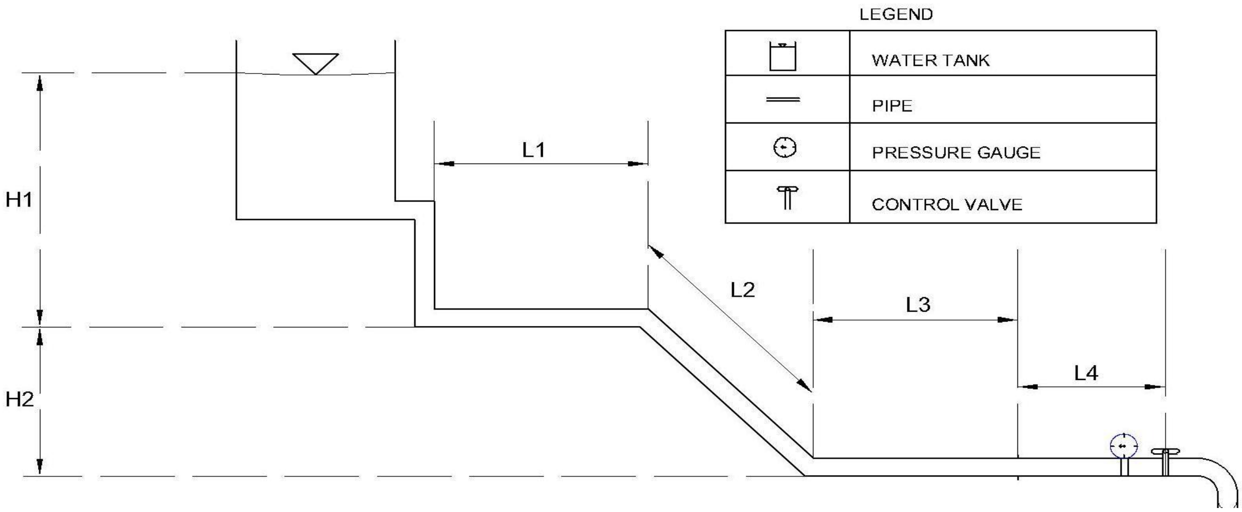

Fig. 1. Schematic Arrangement of the Experiment.

A Bourdon pressure gauge with a span of (0-2 bar) situated at various distance to the control valve and having an error of (±5%) was used to measure the pressure after sudden and gradual closure of the valve, pressure was converted to pressure head by means of ($P=\ell g(H-Z)$) where P is the pressure in N/m^2, ℓ is the fluid density, g is the gravitational acceleration, H is the pressure head in (m) and z is the point from which measurement were taken.

After the sudden closure of the valve at the downstream end of the pipe, measurement of pressure head were taken for each Reynolds number (Re) considered(3750, 4125, 4750, 5250, 6000), in order to attain some level of accuracy for pressure measurement, experiment was repeated for each Reynolds number for 5 times. Measurements were also taken after half closure of the valve for different Reynolds number and at the same time different part of the pipe carrying fluid. Measurements were made at 0.13m, 2.36m, and 6.17m relative to the valve location. In all the measurement, after every reading has been taken, the reservoir was re-filled to maintain constant water level as stated by Masaji et al. 2002. Using a propagation of error analysis, the uncertainty in the measurement of pressure head (H) was about $\pm 5\%$. This was estimated by measuring H 5 times at several locations relative to the valve position and at each location, the uncertainty was $\pm 5\%$ of the mean value.

Pressure Head

The measurement of pressure head provides means of determining the response of sudden or gradual closure of the valve. Measurement of pressure head along stream-wise direction for a fully closed valve with pressure gauge positioned at (0.13m, 2.36m, and 6.17m) from the valve are represented in Fig. 2, 3 & 4 respectively for various Reynolds number.

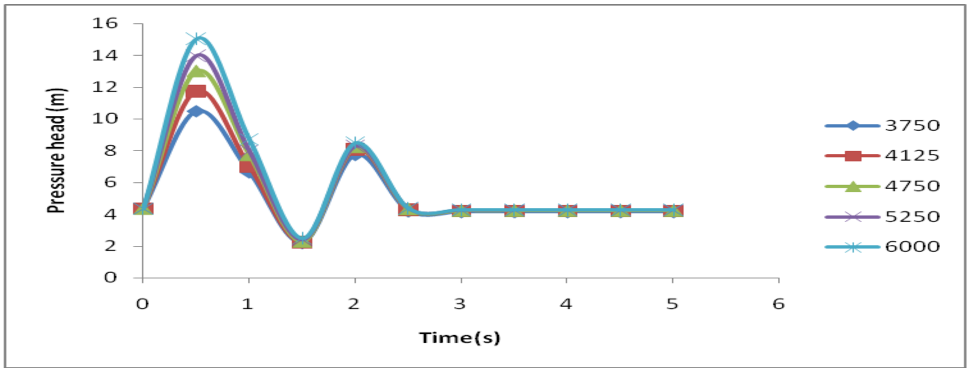

Fig. 2. Pressure Head (m) Against Time(s) for 0.13m from the Control Valve (fully closed).

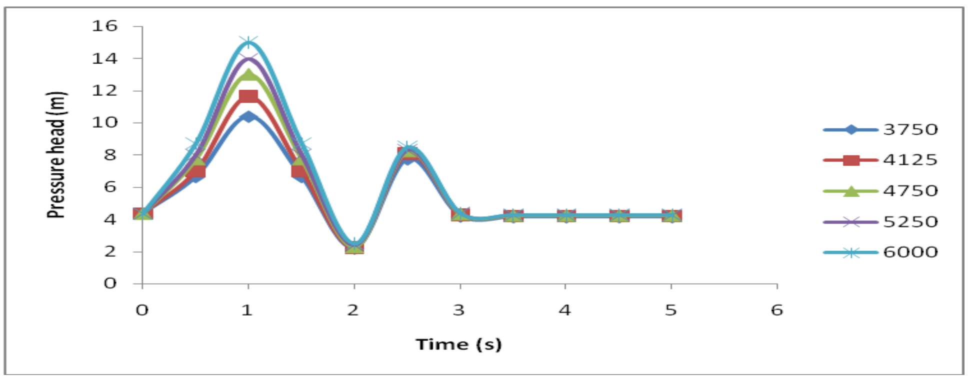

Fig. 3. Pressure Head (m) Against Time(s) for 2.36m from the Control Valve (Fully closed)

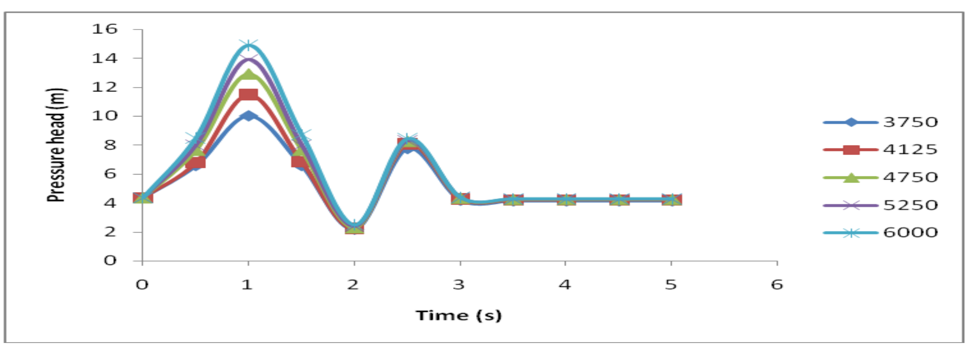

Fig. 4. Pressure Head (m) Against Time(s) for 6.17m from the Control Valve (Fully closed).

All distributions almost show the same behavior: Head (m) increase in a short time, decrease, increase again and then decrease to maintain a constant value. This value seems to be controlled by the Reynolds number applied; this is evident in fig. 2 with Reynolds number (Re=6000) having the highest value of head and follows in Figures 3 & 4 accordingly. It should be noted that while it takes 0.5second (regardless of the Reynolds number applied) for pressure head to reach maximum point when measurement was taken at 0.13m from the valve it takes 1seconds for reading taking at 2.36m and 6.17m from the valve respectively. The reason for this is not yet clear but might reflect the changes in the pipe orientation from L2 to L3 and this might possibly influence the flow structure and geometry. This is not surprising since back flow (reverse flow) depend strongly on pressure gradient. This reverse flow developed as a result of pressure build up in the entire region of the pipe. It is interesting to note that because of the material property of the PVC pipe, the pressure build up occur quickly as reflected in the distribution. This effect may cause sudden failure of PVC pipe in practice.

The present results would suggest that water hammer and pressure wave occur rapidly which translate to strong unsteadiness in PVC pipeline flows when the valve is closed suddenly. The different effect is the possibility of buckling of the system. The effect is stronger at high Reynolds number. It was seen that Reynolds number control the magnitude but the wavelength is unaltered as deduced in all the distributions.

The previous results show that Reynolds number alters the degree of unsteadiness as a result of sudden full closure of the pipe in a PVC pipe material. It is interesting to observe that the wavelength and the manner of alteration when the valve is half closed is similar to fully closed valve as showed in figures 5, 6 and 7.

Fig. 5, 6 & 7 shows measurement for a half closed valve for variation of Re (3750, 4125, 4750, 5250 and 6000) with pressure gauge positioned at different point on the pipe. i.e (0.13m, 2.36m, and 6.17m)

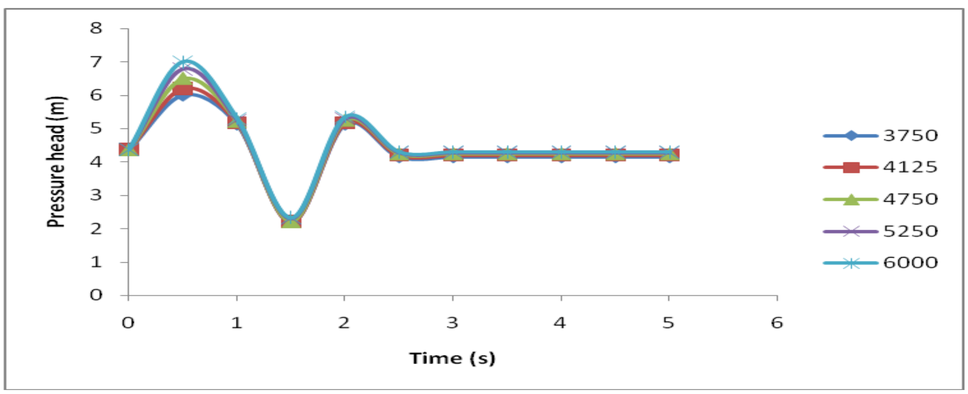

Fig. 5. Pressure Head (m) Against Time(s) for 0.13m from the Control Valve (Half closed).

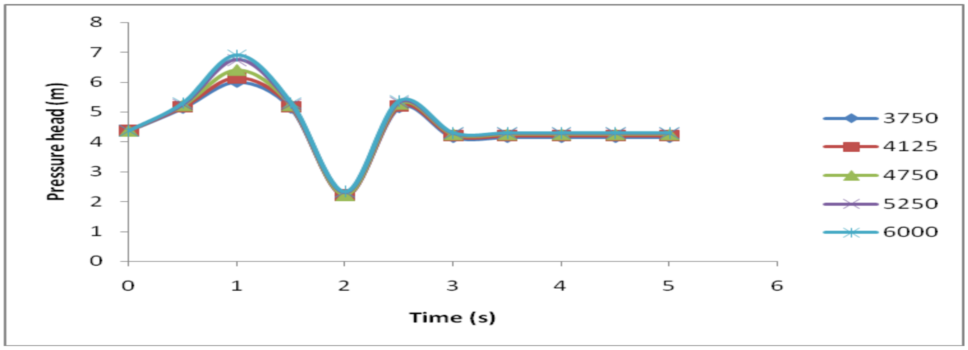

Fig. 6. Pressure Head (m) Against Time(s) for 2.36m from the Control Valve (Half closed).

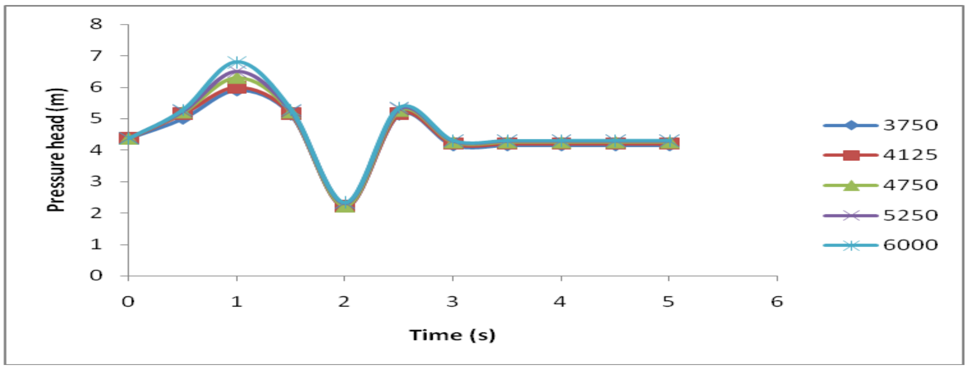

Fig. 7. Pressure Head (m) Against Time(s) for 6.17m from the Control Valve (Half closed).

It should be noted that irrespective of the Reynolds number and distance from the control valve, the minimum head occurs at about H=2m but the time it takes differ for the pressure gauge position at x=0.13m. For example, at x=0.13m, minimum head occur at t=1.5 second and t=2.0 second at 2.36m and 6.17m. The result would suggest that the closer to the control valve the faster it takes for the pressure wave to die out.

Similar explanation holds for the second peak value which occurs at the same head (h=5.13m) for t=2.0 second at x=0.13m and t=2.5 seconds at x=2.36m and 6.17m. This is not surprising since there is time lag for initial mean pressure head at x=0.13m and other locations. The overall observation would suggest that Reynolds numbers only alter the initial mean head.

It can clearly be shown that the distribution shows similar behavior as when the valve is fully closed only with the exception of reduced values of Head (m) due to slight disturbance caused by half closure of the valve. It can clearly be shown that due to high Reynolds number ($Re_{max=}6000$) employed, regardless of its value, the pressure head quickly returns to a constant value which suggest that Reynolds number majorly dictate the values of pressure head and its time which is in agreement with Masaji et al 2002.

Reynolds number effect

To further ascertain Reynolds number dependence, Figures 8 and 9 shows Re distribution of the maximum pressure head (Hmax) for various Reynolds number and locations both for fully closed valve and half closed valve.

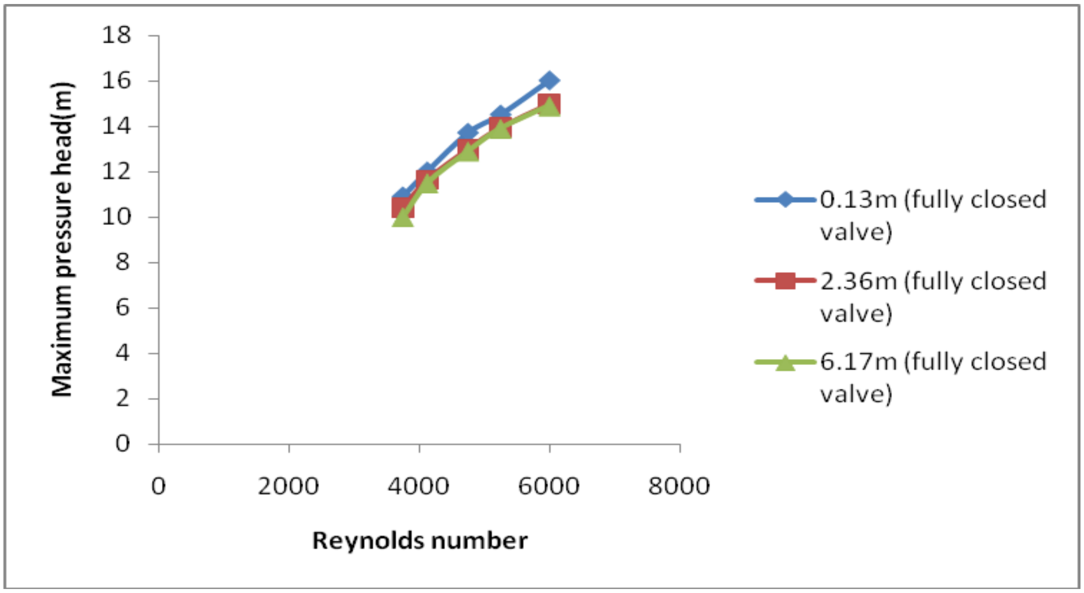

Fig. 8. Distribution of Maximum Head Against Reynolds Number for Fully Closed Valve

In both cases (fully closed and half-closed valve) and for all locations, Reynolds number control the magnitude of the pressure head. It is evident from the figures that the Reynolds number increase, the maximum pressure head increases.

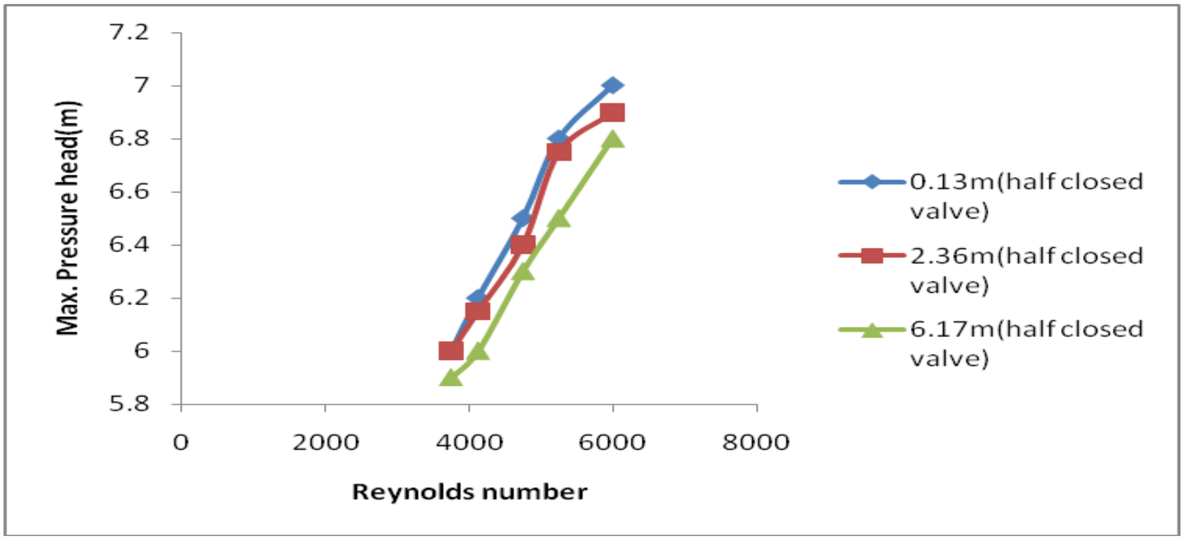

Fig. 9. Distribution of Maximum Head Against Reynolds Number for Half Closed Valve.

Bergant et al (2006) indicated the work of Joukowsky who argued that change in the initial velocity of the flow controls the change in head obtain in return ($\Delta H = \frac{a}{g}\Delta V$, where (a) is the wave speed, g= gravitational acceleration, H is the Head, V is the velocity). This is evident in figures 8 & 9 that the higher the Reynolds number, the higher the pressure head obtained because of the linear relationship between the pressure head and the velocity. According to Joukowsky, change in pressure head were 7.62m, 8.38m, 9.67m 10.67m and 12.19m for the present Reynolds number considered, whereas in the present experiment, the change in pressure head obtained when taking measurement at 0.13m for a fully closed valve were 6.53m, 7.63m, 9.33m, 10.13m and 11.63m. The difference in the variation may suggest possibility of the head losses which includes; minor losses due to obstruction (contraction, elbow and expansion) and friction which is a function of Reynolds number. It should be noted that with the use of PVC material as pipe, the effect of wave speed travelling upstream (Reservoir) and downstream (valve) as evident in the pressure head was quickly damped forming another steady state. It is therefore recommended that gradual closure of the valve will prevent buckling effect and failure in practise.

Conclusions

Pressure head measurement were carried out for various Reynolds number and streamwise locations for flow in a polyvinyl chloride pipe having valve at the downstream end and reservoir at the upstream with a view to determine the dependence of Reynolds number on unsteady pipeline flow. The results indicate that irrespective of the Reynolds number and locations, pressure head increase, decrease and later maintain a constant value transiently. For both cases of valve, it was observed that pressure head respond quickly closer to the valve than away from the valve with fully closed valve have the higher pressure head than the half closed valve.

Furthermore, Reynolds number controls the magnitude and oscillation of the maximum pressure head irrespective of the streamwise locations and the status of the valve.

Reference

Bryan, W. K. and Duncan, M. 1992. Efficient calculation of transient flow in simple pipe networks. Journal of hydraulic Engineering vol. 118. No 7: Pages 1014-1030.

Darmstadt, 2004. Numerical simulation of internal flow in hydraulic valves and dynamic interractions in hydraulic systems with CFD and simplified simulation methods. Ph.D Thesis. Institute of Turbomachinery and fluid power. Darmstadt University of Technology. Pages 1-149.

Don, J.W 2005. Waterhammer Analysis—Essential and Easy and Efficient. Journal of Enviromental Engineering vol. 131. No 8: Pages 1123-1130.

Gilberto, E. U. 2004. Hydraulic Pipe Transients by the Method of Characteristics. Journal of hydraulic Engineering. Pages1-12.

Bergant, A., Simpson, A.R. and Tigsseling, A.S. 2006. Water hammer with column separation: A historical review. Journal of fluid and structures Vol. 22: Pages 135-171.

Kazumi, I., Yukio, K., Akira, H., Kazuo, K. and Kota, S. 2009. Experimental study on dynamic pipe fracture in consideration of hydropower plant model. Journals of water science and Engineering Vol.2. No 4: Pages 60-68.

Kishore, S. 2007. Transient Analysis In Pipe Networks. M.Sc Thesis. Civil Engineering Dept. Faculty of Virginia Polytechnic Institute & State University. Pages 1-108.

Masaji, W., Yukio, K. and Hiroshi, S. 2002. A numerical study of effects of the axial Stress on unsteady liquid pipeline flows, IJMMS Vol.15: Pages 777–788.

Mohammed, S. G., Mingzhao, Duncan, A.M. and David, H. A. 2005. A Review of water hammer theory and practice. Applied Mechnics review Vol. 58: Pages 49-76.

Shaker, H. A. 2010. Numerical Modelling of Transient Flow In Long Oil Pipe Line System. Journal of Engineering and Technology Vol.28, No.16: Pages 5346-5364.

Warsaw, 2007. Simulation of transient flows in a hydraulic system with a long liquid line. Journal of theoretical and applied mechanics. Vol. 45, No 4: Pages 853-871.

Yukio, K., Masaji, W. and Tomonori, I. 1998. Phase Change Analysis in Waterhammer by Upstream Finite Difference Method, 3rd International Conference on Hydro-Science and Engineering, ICHE, CD-ROM, Cotbuss.