International Journal of
Emerging Research in Management &Technology
ISSN: 2278-9359 (Volume-4, Issue-6)

Research Article | **June 2015**

Water Hammering Effects in Pipe System and Dynamic Stress Prediction

Uday Naik
Department of Mechanical Engg
MIT, Kundapura, Karnataka, India

D Shreenivas Bhat
Department of Mechanical Engg
SDMCET, Dharwad, Karnataka, India

Abstract—

Water hammer is the one of the cause for the failure of the pipe. Water hammer is the sudden increase in the pressure in the pipe due to the sudden closure of the valve. In order to avoid the failure of the pipe due to hammering, careful study of water hammer and method to reduce the water hammer is essential. The pressure surge in the pipe is simulated and maximum pressure and stresses are determined using the Flownex , a simulation software. The influence of parameter is presented and results are compared with manual Calculations and available experimental data.

***Keywords**— Water hammering, CFD, Dynamic stress, Simulation, Analysis*

I. INTRODUCTION

Water hammer is a type of hydraulic transient that refers to rapid changes of pressure in a pipe system that can have devastating consequences, such as collapsing pipes and ruptured valves. It is therefore important to understand the phenomena that contribute to transient formation and be able to accurately calculate and analyze changes as well as maximum and minimum pressures occurring in a pipe system. Water Hammer occurs in a pumping system when valves are closed or opened suddenly or in the case of sudden failure of pumps. Determination of maximum water hammer is considered one of the most important technical and economical items of which engineers and designers of pumping stations and conveyance pipelines should take care.

Hammer Software is a recent application used to simulate water hammer. The present study focuses on determining significance of each input parameter of the application relative to the maximum amount of water hammer estimated by the software. The study determines estimated maximum water hammer variations due to variations of input parameters including water temperature, pipe type, thickness and diameter, electromotor rpm and power, and moment of inertia of electromotor and pump. There are various factors are responsible for the failure of the pipe network. The important are manufacture defects, temperature, internal stress, head loss, soil movement, water hammer etc.

This paper concentrated on the water hammer for its causes and predict maximum surge pressure in pipe network which can be considered for the future pipe design. The Computational Fluid Mechanics (CFD) analysis is the main tool for the analysis of the transient flow. The numerical analysis is very complex in the transient flow condition. It will give the accurate results for prediction pressure surge and stress in the pipe material for the given condition. These results are the basis for the safe and accurate design. The CFD simulation software called Flownex is used for the simulate the pressure variation in the pipe with respect to the time for steady flow, transient flow with gradual and sudden valve closure.

The maximum pressure, in the pipes and bends are determined for steady flow, gradual valve closure and sudden valve closure by manually and from the software simulation. The parameter affecting the water hammers are demonstrated.

The network is designed for different pressure and velocities using the Flownex designer to design the required length and diameter. Then water hammer effects are studied for these network. Finally, the simulated results discussed and are compared with the manual calculations.

II. MECHANICS OF WATER HAMMERING

Consider a long pipe AB connected at one end of to the tank contained water at a height of H from the centre of the pipe. At the other end of the pipe, a valve to regulate the flow of water is provided. When the valve is completely open, the water is flowing with velocity V in the pipe as shown in fig.1.

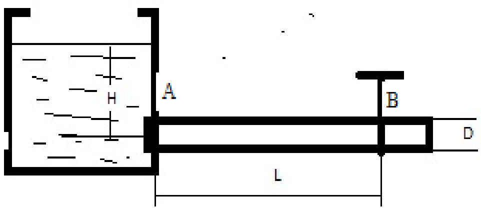


Fig.1 Pipe attached to tank with valve

If now valve is suddenly closed, momentum of water will be destroyed and consequently a wave of high pressure will be setup. This wave high pressure will transmitted along the pipe with the velocity of the sound wave and may create the noise called knocking. Also this wave of higher pressure has effect of hammering action on walls of the pipe and hence it is known as water hammer.

The pressure rise due to water hammer depends on

1. Velocity of flow of water in the pipe
2. The length of pipe
3. Time taken to close the valve
4. Elastic properties of the material

The following cases of water hammer pipes will be considered

- Gradual closure of valve
- Sudden closure of valve

A. Gradual closure of valve

Consider water is flowing through the pipe AB shown in fig. and the valve provided at the end of the pipe is closed gradually. Let A- Area of cross section of pipe AB

L – Length of pipe AB
V- Velocity of flow of water through pipe
t- Time in sec required to close the valve
p- Intensity of pressure wave produced
ρ- Density of water

Mass of water in the pipe AB =density *Volume of water
= ρ*A*L

The valve is closed gradually in the time_t‘ seconds and hence water is brought from initial velocity V to zero velocity in time _t‘ seconds.

Retardation of water =change of velocity / time
= (V- 0) / t

Retardation force= mass * retardation
= ρAL* V/t .... (1)

If _P‘ is the intensity of pressure wave produced due to the closure of valve, the force due to the pressure wave=P* area of pipe
=P*A .... (2)

Equating the two forces
ρAL * V/t =P*A
P= ρVL / t .... (3)

Pressure head , H= P / ρ*g
= ρVL / ρgt
Or H= LV / gt ....(4)

Note: 1. The valve is closure is said to be gradual,
if ‘ t > 2L / C’
Where t- time in sec. and C- Velocity of pressure wave
2. The valve closure is said to be sudden if ‘ t < 2L/ C ’

B. Sudden closure of valve

Equation- 4 gives the relation between increase in pressure due to the water hammer in the pipe and time required to close the valve. If t=0, the increase in the pressure will be infinite . but from the experiment, it is observed that the increase in the pressure due to the water hammer is finite, even for a rapid closure of valve. Thus the equation -4 is valid only for i) incompressible fluids and ii)when the pipe is rigid.

But when a wave of high pressure is created, the liquids gets compressed to some extent and also pipe material gets stretched. For the sudden closure of the valve ,the value of ‘t‘ is very small and hence the wave of high pressure is created.

Consider a pipe AB in which water is flowing as shown in fig.1

Let the pipe is rigid and valve fitted at the end B, is closed suddenly

Let A- Area of cross section of pipe AB
L – Length of pipe AB
V- Velocity of flow of water through pipe
P- Intensity of pressure wave produced
K- Bulk modulus of water

When the valve is closed suddenly, the kinetic energy of the flowing water is converted into strain energy of water, if the effect of friction is neglected and the pipe wall is assumed perfectly rigid.

Loss of KE = ½ * mass of water in pipe * V^2 =½ ρALV^2

Gain in strain energy = ½ (P^2 / K) * volume =½ (P^2 / K)* AL

Equating loss of kinetic energy to gain of strain energy.

$\frac{1}{2} \rho ALV^2 = \frac{1}{2} (P^2 / K) * AL$

$P^2 = \frac{1}{2} \rho ALV^2 * 2K / AL = \rho KV^2$

$P = V (\rho K)^{1/2}$

$= V \rho (K / \rho)^{1/2}$

$= V \rho C \qquad [\because (K / \rho)^{1/2} = C)]$

$= \rho VC \qquad$ Where C- velocity of pressure wave

C. Causes for Water Hammer

Hydraulic transient events are disturbances in the water caused during a change in state, typically from one steady or equilibrium condition to another. The principle 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 travel with the velocity of sound ~acoustic or sonic speed!, which depends on the elasticity of the water and that of the pipe walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady state to another without large fluctuations in pressure or flow.

In general, any disturbance in the water generated during change in mean flowconditions will initiate a sequence of transient pressures ~waves! in the water distribution system. Disturbances will normally originate from changes or actions that affect hydraulic devices or boundary conditions.

Typical events that require transient considerations include:

- Pump startup or shutdown
- Valve opening or closing ~variation in cross-sectional flow area
- Changes in boundary pressures ~e.g., losing overhead storage tank, adjustments in the water level at reservoirs, pressure changes in tanks, etc.
- Rapid changes in demand conditions ~e.g., hydrant flushing
- Changes in transmission conditions ~e.g., main break or line freezing
- Pipe filling or draining—air release from pipes and
- Check valve or regulator valve action.

III. ANALYTICAL CALCULATION

The magnitude of water hammer can be determined manually with the help of physical formulae . To study flow results, transient flow results for gradual and sudden closure can be calculated with the physical formulae. In this project main objective to determine the pressure in the pipe for steady, flow, transient flow with gradual and sudden closure of valve.

A. Input Parameters

TABLE 1 BOUNDARY INPUT PARAMETERS

Identifier	Pressure (kPa)	Temperature (°C)	Mass source (kg/s)
Boundary Condition - 1	1000	40	
Boundary Condition -2			-10

TABLE 2 NODES INPUT

Identifier	Elevation (m)
Node -1	4
Node -2	5
Node -3	5
Node -4	5
Node -5	31
Node -6	31
Node -7	31
Node -8	31

TABLE 3 PIPES INPUT

Identifier	Wall thickness (m)	Length (m)	Diameter (m)	material	Roughness from database (μm)
Pipe -1	0.005	10	0.075	Stainless steel	30
Pipe -2	0.005	10	0.075	Stainless steel	30
Pipe -3	0.005	10	0.075	Stainless steel	30

Pipe -4	0.005	10	0.075	Stainless steel	30
Pipe -5	0.005	10	0.075	Stainless steel	30
Pipe -6	0.005	100	0.075	Stainless steel	30
Pipe -7	0.005	1	0.075	Stainless steel	30

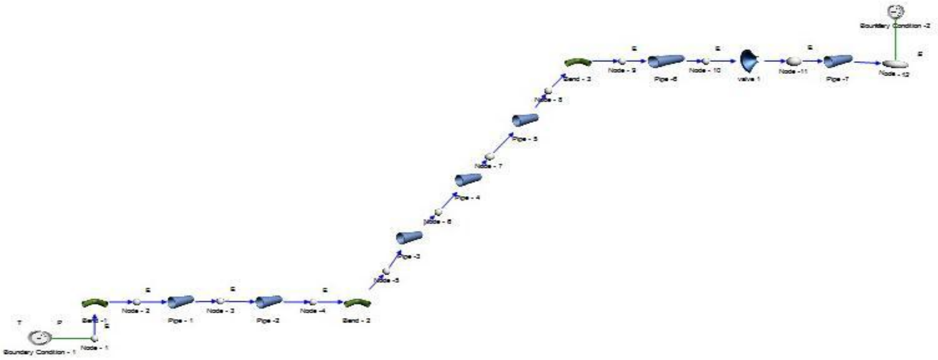


FIG.1 Simple Network

TABLE 4 VALVE INPUT

Identifier	Diameter (m)	Discharge coefficient
valve 1	0.075	1

TABLE 5 BENDS INPUT

Identifier	Diameter (m)	Bend angle (°)
Bend -1	0.075	90
Bend -2	0.075	90
Bend -3	0.075	120

B. Calculations

Mass flow, $\dot{m} = \rho*Q$
$= \rho*a*V$
$= \rho*(\pi/4)*d^2*V$
$10 = 1000 *(\pi/4) * 0.075^2 *V$
velocity , V=2.2635 m/s

1. Steady Flow

Reynolds Number , Re =V *D / υ (where υ-kinematic viscosity ,taken as $0.018*10^{-4}$ m^2/s)
$Re= 2.2635*0.075 / 0.018*10^{-4}$
=94312.5
As' Re' is above 4000 ,
Coefficient of friction $f= 0.079 / (Re)^{1/4}$
$= 0.079 / (94312.5)^{1/4}$
$= 4.508*10^{-3}$
Head loss due to friction in pipe-1, $hf1 = 4fLV^2 / 2gD$
$= 4*4.508*10^{-3}*10*2.2635^2 / 2*9.81*0.075$
= 0.6278 m
Similarly, Head loss due to friction in pipe-2,3,4,5
=0.6278 m
Head loss due to friction in pipe-6,
$hf6 = 4*4.508*10^{-3}*100*2.2635^2 / 2*9.81*0.075$
= 6.278m
Head loss due to friction in pipe-7,
$h f7 = 4*4.508*10^{-3}*1*2.2635^2 / 2*9.81*0.075$
= 0.0628 m
Head loss while entering the pipe , $hi =0.5 *V^2 / 2g$
$= 0.5 * 2.2635^2 / 2*9.81$
= 0.1306 m
Head loss in bend-1 $hb1 = kV^2 / 2g$
$= 0.5*2.2635^2 / 2*9.81$
=0.1306 m
[Bend friction coefficient ‗k' taken as 0.5 for 90° and 0.33 for 120°]

Head loss in bend-2,3 hb2 = hb3 = $0.33*2.2635^2 / 2*9.81$
= 0.0869 m

Total head loss = (hf1+ hf2+hf3+ hf4+ hf5+ hf6+ hf7)+ (hi+ hb1+ hb2+ hb3)= (5*0.6278 +6.278+0.0628) +(0.1306+0.1306+0.0869+0.0869)
=9.915 m

Applying Bernoulli‘s equation for node-1 and node-10

$P1 / \rho*g + V_1^2 / 2g + z1 = P2 / \rho*g + V_2^2 / 2g + z2 + losses$

$P1 - P2 = \rho*g (z2 - z1 + losses)$ [V1 =V2]$(1000- P2)*10^3 = 1000*9.81*(31- 4 + 9.915)$

P2 = 637.86 kPa (pipe-6 downstream node)

Maximum pressure in pipe -6, Psm = 1000-9.81*(31-4+9.915-6.278)= 700.4 kPa

Maximum circumferential stress fc = PD / 2t
= 700.4*0.075 / 2*0.005
= 5253 kN/m^2 or 5.253 N/ mm^2

Maximum longitudinal stress , fl = PD /4t
= 700.4*0.075 /2*0.005
= 2626.5 kN/m^2 or 2.6265 N/ mm^2

Ratio, 2L /C =2*150 / 1400=0.22 sec

If the Ratio (2L/C) < 0.22, it is sudden closure and If the Ratio (2L/C) > 0.22, it is gradual closure. In the calculation 0.20 sec taken for sudden closure and 50 sec taken for gradual closure.

2. Sudden Closure

Pressure due sudden closure of valve, Ps = ρ*V*C
= 1000*2.2635*1400
=3169 kPa

(where C=Velocity of pressure wave -- velocity of sound wave=1400 m/s)

Maximum circumferential stress fc = PD / 2t
= 3169*0.075 / 2*0.005
=23768 kN/ m^2 or 23.768 N/mm^2

Maximum longitudinal stress , fl = PD /4t
=3169*0.075 / 4*0.005
=11884 kN/ m^2 or 11.884 N/mm^2

3. Gradual Closure

Loss of head per unit length, i = hf /L
= 9.915/150= 0.0661m per m length

Hydraulic mean depth, m=D/4 = 0.075 /4= 0.01875m

Wkt , chezy‘s formula V=C* sqrt(m*i)
=1400*sqrt(0.01875*0.0661)=49.3 m/s

Increased in pressure due to gradual closure, Pi = ρVeL / t
= 1000* 49.3*150 / 50 = 147900Pa= 147.9 kPa

Maximum pressure in pipe-6 due to sudden closure= Psm+Pi = 700.4 + 147.9= 848.3 kPa

Maximum circumferential stress fc = PD / 2
= 848.3*0.075 / 2*0.005=6362 kN/ m^2 or 6.362N/mm^2

Maximum longitudinal stress, fl = PD /4t
=848.3*0.075 / 4*0.005
=3181 kN/ m^2 or 3.181 N/mm^2

IV. COMPUTATIONAL ANALYSIS

The basic pipe network consists of the input source which defined in the network by specifying the input boundary conditions. Similarly the target point can be specifying the outlet boundary conditions. The pressure and temperature or the mass flow rate can be represented on the boundary . The pipes are connected to each other represented by the nodes. The bends are used to get the required elevation. A valve is used that can be open and closed ,to provide flow or stop the flow to the outlet pipe.

A. Steady Flow Results

TABLE 6 BOUNDARY CONDITIONS RESULT

Identifier	**Pressure (kPa)**	**Temperature (°C)**	**Mass source (kg/s)**
Boundary Condition1	1000	40	10
Boundary Condition 2	639.20175	40.012972	-10

TABLE 7 PIPES RESULT

Identifier	Total volume flow (m^3/s)	maximum velocity (m/s)	Upstream Node Total Pressure (kPa)	Downstream Node Total Pressure (kPa)
Pipe -1	0.010074	2.280496	989.6073	983.4321
Pipe -2	0.010074	2.280503	983.4321	977.2568
Pipe -3	0.010074	2.280463	1025.158	1018.983
Pipe -4	0.010074	2.280471	1018.983	1012.808
Pipe -5	0.010074	2.280478	1012.808	1006.633
Pipe -6	0.010076	2.280850	704.1608	642.4004
Pipe -7	0.010076	2.280853	639.8193	639.20175

B. Transient Flow Result with Valve Closing

In the practical application valve can be open and closed frequently depend up on the demand at the target point. If the valve closure is gradual, the surge pressure (water hammer) is not so high. Hence the stress developed is not crossing the limit. When the valve is closed suddenly, then there is sudden increased back pressure which can vibrate the pipe and there can increase in the stress in pie system beyond the safe limit.

1. Gradual Closure

In this type the valve is closed slowly (more time taken to close the valve) with linearly from fully opened position to the closed position. Consider 50 sec is to be taken to close the valve with linearly.

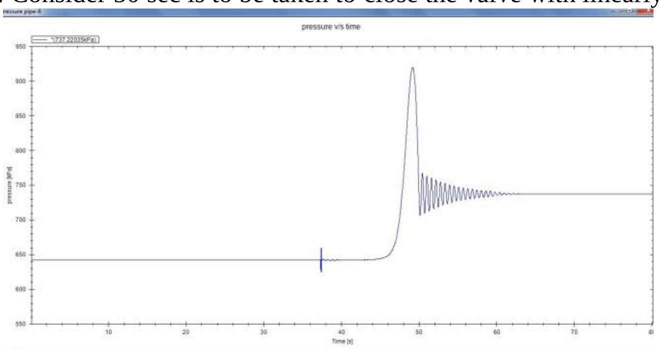
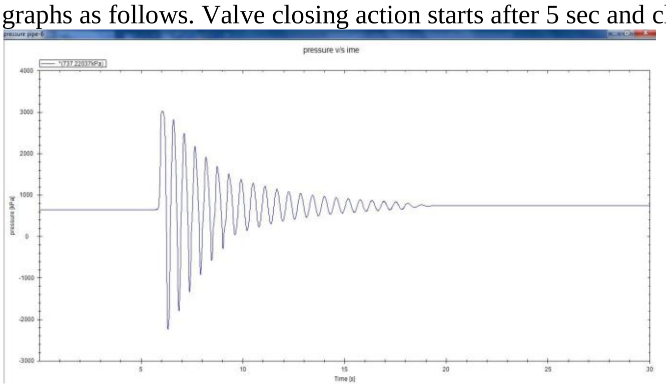


Fig.3 Pipe-6 pressure (gradual valve closure Nw-1)

Maximum circumferential stress=6915 kN/m^2
Maximum longitudinal stress =3457.5 kN/m^2

2. Sudden Closure

When the valve is closed suddenly, from the fully opened position to the closed position with linearly. Consider 0.2 sec is to be taken to close the valve. The transient results in the Flownex for the sudden closure of valve can be visualized through simulation graphs as follows. Valve closing action starts after 5 sec and closing duration is 1sec.



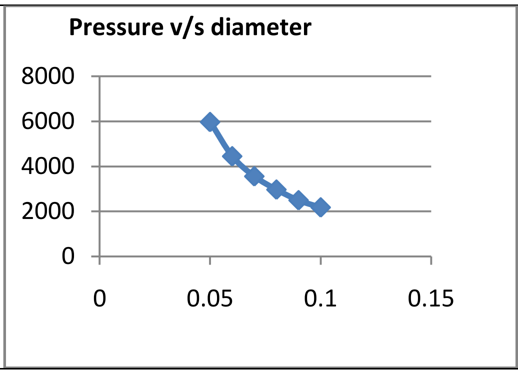
Max. pressure=3190 kPa
Fig.4 Pressure in pipe-6 v/s time(sudden closure Nw-1)
Maximum circumferential stress=23925 kN/m^2
Maximum longitudinal stress =11962.5 kN/m^2

C. Influence Of Parameters

For the above network (Nw-4) , the influence of change in the parameters such as diameter, pressure , velocity , length of pipe and time for valve closure on the water hammer are explained below.

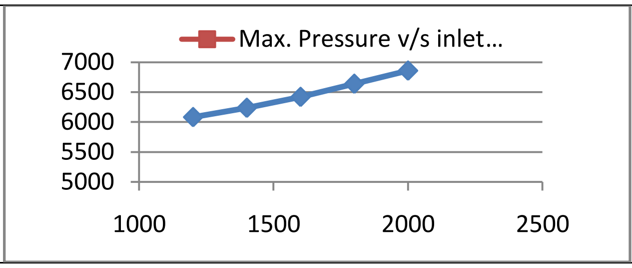
1. Pipe Diameter

Sl.No.	Pipe diameter (m)	Max. Pressure due sudden closure (kPa)
1	0.05	5970
2	0.06	4450
3	0.07	3560
4	0.08	2970
5	0.09	2497
6	0.10	2180



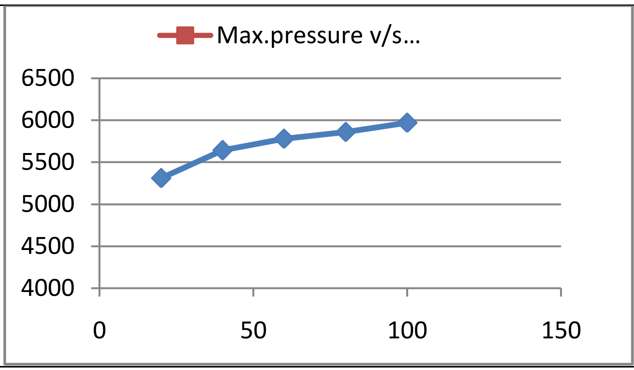
2. Inlet Pressure

Sl.No.	Inlet pressure (kPa)	Max. Pressure due sudden closure (kPa)
1	1200	6084
2	1400	6240
3	1600	6420
4	1800	6642
5	2000	6860



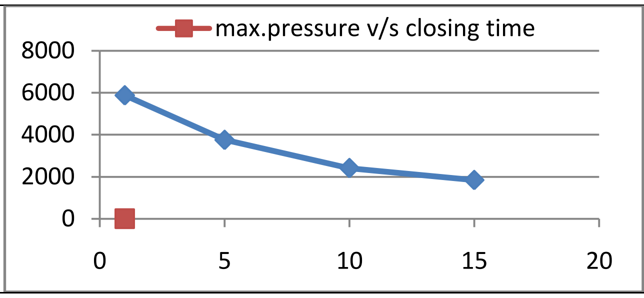
3. Length of Pipe

Sl.No.	Length of pipe-6 (m)	Max. Pressure due sudden closure (kPa)
1	20	5310
2	40	5640
3	60	5780
4	80	5860
5	100	5970



4. Valve Closing Time

Sl.No.	Closing time (sec)	Max. Pressure due sudden closure (kPa)
1	1	5870
2	5	3750
3	10	2410
4	15	1840



V. RESULT COMPARISIONS

A. Steady Flow Result

Inlet pressure =1000kPa ,temp=40° C, mass flow= 10kg/s

TABLE 8 COMPARISON OF STEADY FLOW RESULTS

Variable	Manual calculation	Software result
Pipe-6 upstream pressure (kPa)	700.4	704.16
Pipe-6 downstream pressure (kPa)	637.86	642.40

Avg. Velocity (m/s)	2.2635	2.2805
Max. stress in pipe-6 (N/mm^2)	5.253	5.281

B. Transient flow result

1. Gradual valve closure

TABLE 9 COMPARISON OF GRADUAL CLOSURE RESULTS

Variable	**Manual calculation**	**Software result**
Max. pressure in pipe-6 (kPa)	848.3	922
Max. Circumferential pressure(kPa)	6.362	6.915
Max. longitudinal pressure(kPa)	3.181	3.457

2. Sudden valve closure

TABLE 10. COMPARISON OF SUDDEN CLOSURE RESULTS

Variable	**Manual calculation**	**Software result**
Max. pressure in pipe-6 (kPa)	3169	3190
Max. Circumferential pressure(kPa)	23.768	23.925
Max. longitudinal pressure(kPa)	11.884	11.962

VI. CONCLUSION

The water hammering in the pipe due to the gradual closure and the sudden closure is studied and can be easily demonstrated by the software simulated graphs . The surge pressure due to the gradual closure and sudden closure of valve is simulated and compare with the manual calculations. It found satisfactory for various input pressures. The factors affect the water hammer are studied . It is cleared that the factors such as input pressure, time for valve closure, velocity of water, diameter of pipe, length of pipe and pipe materials mainly influences the water hammering. The introduction of the accumulator will reduce the water hammering slightly , but it is not possible eliminate the water hammering completely.

REFERENCES

[1] Bryan W. Karney and Duncan Mclnnis ―*Transient analysis of water distribution System*‖1990
[2] Jun-Shin Lee, Bong-Ki Kim, Wook-Ryun Lee and Ki-Yong Oh ―*Analysis of water hammer in pipelines by partial fraction expansion of transfer function in frequency domain*‖ 2010
[3] D Himr and V Habán ‖ *Simulation of low pressure water hammer*‖2010
[4] Abdulrahman Al-Khomairi ―*Surge Pressure Suppression in Pipelines Using Air-Filled Balls*‖ 2010
[5] Jim Wilcox and Trey Walters, *Evaluating dynamic loading in piping system caused by water hammer* 2012
[6] Dominic Bernard ―*Numeric Modelling of Water Hammer Effects in Penstocks*‖ 2013
[7] A. Simonen ―*Pressure Vessel and Piping Systems: Reliability, Risk and Safety Assessment*‖2007
[8] Paul F. Boulos, MWH soft inc. USA ‖*Shock and Water Hammer Loading*‖2007
[9] Don J. Wood‖ *Water Hammer Analysis—Essential and Easy*‖ 2005
[11] Andreas Dudlik and Sri Budi Handajani Schönfeld ― *The prevention of water hammer and cavitaional Hammer in Pipeline System*‖2006
[11] Shawn Batterton‖Water Hammer: *An Analysis of Plumbing Systems,Intrsion, and Pump Operation*‖ 2006
[12] A.S. Tijsseling and A.G.T.J. Heinsbroek ―*of bend motion on water hammer pressures and pipe stresses*‖2005

ABOUT AUTHOR

Mr. Uday Naik, Assistatnt Professor in Mechanical Engineering Department of Moodlakatte Institute of Technology Kundapura, completed Bachelor of Engineering under Visvesvaraya Technological University, Belgaum- Karnataka in SJM Institute of Technology, Chitradurga in 2003 and M.Tech. degree under Visvesvaraya Technological University,Belgaum- Karnataka, in SDM college of Engineering and Technology, Dharwad in 2013.

Mr. D Shreenivas Bhat ,Professor in Mechanical Engineering Department of SDM college of Engineering and Technology, Dharwad, completed Bachelor of Engineering under Karnataka University in SDM College of Engineering & Technology- Dharwad in 1984 and M.Tech. degree under Mangalore Univeristy in KREC -Suratkal in 1987 and Pursuing Ph. D from VTU – Belgaum.

