A Study on the Nature of Fluid Transients on Varying conduit parameters during Valve Closure

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***Abstract*- This work deals with the numerical modeling of the transient behavior of water pipe segments. A parametric study has been conducted using Fluid-Structural Interaction (FSI) in ANSYS™ 14.0, commercial flow analysis package. The method has been compared with the water hammer module for sudden valve closure in COMSOL™ Multiphysics 4.3. The results obtained from the study were validated with already published works. The study reveals how the pipe material stiffness, wall thickness, flow rate, water column length, type of supports, and time of closure of valve would influence the amplitude of peak pressure during water hammer and corresponding stress pattern induced in the material.**

Keywords- Water hammer; FSI simulation; peak pressure; peak stress.

I. INTRODUCTION

Fluid transients are otherwise known as Water Hammer. The Water hammer or hydraulic shock is the momentary increase in pressure inside a pipe caused by a sudden change of direction or velocity of the liquid flow in the pipe.

Change in the kinetic energy by changing the liquid velocity forces the pressure in the pipe to change. If the velocity of the liquid decreases (decrease in kinetic energy or dynamic head), the liquid pressure increases (increase in potential energy or static head). Thus water hammer occurs when a change in the fluid flow is imparted before the system can adjust itself acoustically. The high amplitude pressure energy developed inside is then transmitted along the pipeline as pressure waves travelling at sonic speeds.

Water hammer can be particularly dangerous because the increase in pressure can be severe enough to rupture a pipe or cause damage to the equipments in the pipeline system.

Water hammer does not occur due to valve closure only; anything which imparts a similar effect that is a sudden change in steady flow of fluid through conduit system can results in water hammer. The causes of water hammer can be,

- Sudden Valve closure
- Rapid pump startup
- Rapid pump shutdown
- Movement of air pockets in a pipe
- Water-column separation
- Change in slope in piping system etc.

Wylie and streeter [1] give detailed explanation on the nature of transient pressure waves in pipeline networks. The book is a classical tool for engineers and software developers working in this field to learn the nature of pressure waves during water hammer. Different numerical methods for solving out the problems involving fluid transients in pipeline networks with FORTRAN™ code are given. Domnic Bernard [2] developed a numerical simulation of water hammering effect takes place in an industrial penstock pipe. The result was comparable with the theoretical results. Tan Wee Choon [3] conducted an experiment on water hammering effect. Data acquisition system and accelerometer were used to monitor the pressure distribution and frequency of vibration in the pipe line. The study conducted for a PVC and Steel pipe at a working gauge pressure of 2.5Psi and 2.2Psi. The study concluded that the materials, length, diameter, working pressure etc of the pipe are some parameters which would certainly affect the wave speed and the pressure distribution characteristics in a pipe line. Also reveals that the fundamental equation based on Joukowsky's law fails to predict the peak pressure developed for low stiffness material at low flow rate condition.

Hyuk Jae Kwon [4] found that Darcy-Weisbach friction factor used in the numerical model Method Of Characteristics (MOC) is insufficient to accurately determine the pressure distribution during water hammer. It is reported that the head loss coefficient obtained from experiment was a very large value compared to that obtained through Darcy-Weisbach friction coefficient.

Augus Maryono [5] introduced a new method to monitor the pressure variation by using conventional manometers during water hammering effect. The transients are captured by using a video camera and slow motion playback to observe the manometer readings. The results are comparable with theoretical results. This method could be used only for highly scaled down lab setups.

S Meniconi *et al* [6] presents laboratory data and numerical modeling of the interaction of a surge wave with a partial blockage by a valve, a single pipe contraction or expansion and a series of pipe contraction/expansion in close proximity. The work gives an insight into the fact on how the Joukowsky's theorem and other numerical modeling concepts like Method of Characteristics (MOC) fail in solving pressure waves characteristics accurately during water hammer in varying conditions along the pipeline.

Robert A Leishear [7] used a Finite Element approach to simulate the water hammering effect in Steel and Aluminum pipes using ABAQUS™ analysis package. The analysis was used to model a moving shock wave due to sudden valve closure in a pipe, using a step pressure wave. It is noted that the maximum stress induced seem to be equal for both the materials when damping was neglected. It is reported that the median stress induced during dynamic pressure loading is equivalent to the stress induced during corresponding static pressure loading. Joukowsky's (1898) fundamental equation is still a widely used or accepted equation for approximate prediction of the peak pressure during water hammer due to sudden valve closure. This theorem is developed based on two main assumptions that (i) the pipe is assumed as rigid and (ii) friction effects are negligible during transients. It relates change in pressure with the change in velocity of the fluid flow.

$$\Delta p = \rho\, a\, \Delta v \qquad (1)$$

Where, a- speed of pressure wave through pipe

For the pipe assumed to be anchored with expansion joints throughout, speed of pressure wave is given by [1],

$$a = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1+\left[\left(\frac{K}{E}\right)\left(\frac{D}{t}\right)\right]}} \qquad (2)$$

Where, K – Bulk Modulus of water
ρ - Density of water
E – Young's modulus of pipe material
D – Inside Diameter of pipe
t – Wall thickness of pipe

Though a number of mathematical models are there to get the pressure distribution characteristics in a pipeline under transients, the method which uses the fundamental equations of fluid flow (the Equation of Motion and Equation of Continuity), the Method of Characteristics (MOC) is more popular along with graphical methods for specialized software applications developed for transient analysis. The pressure at any point in a pipe at any time during the transients can be solved out using this method.

Equation of Motion

$$g\frac{\partial H}{\partial x} + \frac{fV|V|}{2D} + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} = 0 \qquad (3)$$

Equation of Continuity

$$V\frac{\partial H}{\partial x} + \frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial V}{\partial x} = 0, \qquad (4)$$

The above are the two basic partial differential equations of fluid dynamics with head, H and velocity, V of the fluid varies with respect to time, t and position, x along the pipeline; and 'a' is the speed of pressure wave, g – acceleration due to gravity, D-inner diameter of pipe and 'f' is the Darcy's friction coefficient.

Hyuk Jae Kwon [4] has shown the insufficiency of using the Darcy's coefficient for solving transients. But in the case of larger diameter pipes the effect of friction is negligibly small.

S Meniconi *et al* [6] have already shown how it becomes difficult to accurately determine the transient pressure characteristics by MOC or by any other generally used methods to solve transients with the varying conditions along the pipeline.

Thus the Water hammer represents a complex hydraulic phenomenon with significant consequences on the proper functioning and safety of operation for pipe and conduit systems. The complexity and intricate physics of water hammer made it into the significant difficulties associated with finding a proper solution for understanding the mechanism of its occurrence. Consequently it finds difficult in proposing technically and economically viable design methods and devices that would help reduce and mitigate water hammer effects.

In this context this work is intended to explore in detail the mutual influence of fluid and structural properties in the transient response of water pipe segments. A numerical simulation of water hammer due to valve closure in a water pipe segment is done and a parametric study by creating fluid-structural interaction using ANSYS Workbench 14.0 to explore the effect of pipe material, wall thickness, flow rate, length of water column, time of closure of valve, type of supports (simply support and buried) etc., in the amplitude of peak pressure during water hammer are carried out.

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II. FSI SIMULATION IN ANSYS

ASTM A 1018 Steel pipe and ASTM D 1785 PVC pipe materials has been chosen throughout this study. Rectangular type brick element has been used for both the pipe and fluid bodies which gave good results [3]. Necessary inflations have been included towards the fluid-structural interface to improve the accuracy of the result by improving the mesh refinement. Sensitivity to time step has been checked. Time step of 0.02sec, 0.04sec and 0.002sec has been chosen for different models which shown good convergence. Being considered fluid here as an incompressible, usual method of choosing time step with courant number is not necessary. Grid dependency test shows less influence on the results. Only negligible influence was noted between fine and medium level meshing. Thus the computing time is saved from 11hrs to nearly 2hrs.

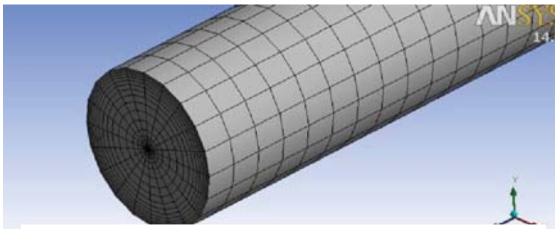

Figure 1: Fluid mesh.

- Pipe details:
  - Inner diameter, D = 0.5m
  - Wall thickness, t = 0.025m
  - Length of pipe, L = 5m
  - Material = Steel
  - Wall with friction is chosen with average roughness height 0.05mm [8]
- Fluid details:
  - Water at 25 Degree Centigrade.
  - Initial static head 14.66 bar
  - Calculated flow velocity = 2.429 m/s
- Valve details:
  - Valve operation is simulated with constant rate closure. In practical case it is possible with automated valves only.
  - Time of closure for sudden valve closure is chosen with the condition of sudden closure.
- Condition for sudden closure:
  - Time of closure, t < 2L/a
  - Where , L= length of pipe

  a = speed of pressure wave = 1344.87 m/s
  Time of closure chosen, t = 0.005 sec

Gate valve closure is simulated with the CFX Command Language (CCL); the basic expression is adapted [3].

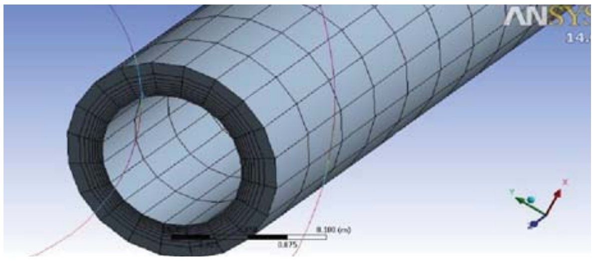

Figure 2: Pipe mesh

$$Q = V \times \pi D_p^{\,2} / 4 \times \rho_w$$

$$V = step(T - t/1[s]) \times (V_0 - V_0 t/T) \quad (5)$$

Where, Q – Discharge; V_0- Average initial flow velocity; T- Total time for valve closure; t- Time step.

III. RESULTS AND DISCUSSIONS

COMSOL Water Hammer module is developed based on the Joukowsky's law. The pipe there is considered as rigid and so the structural damping effect is absent in the pressure wave characteristics as we can see in the graph. The pressure wave plotted from ANSYS dies out much earlier than that plotted from COMSOL due to the structural damping effect. The result obtained from ANSYS is more realistic. The graphs in the study are plotted using ANSYS results.

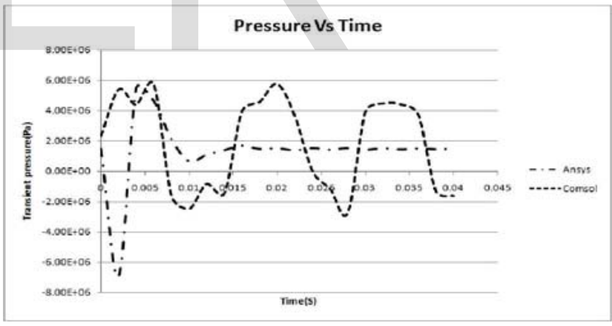

Figure 3: Comparison of simulation between COMSOL and ANSYS for sudden valve closure.

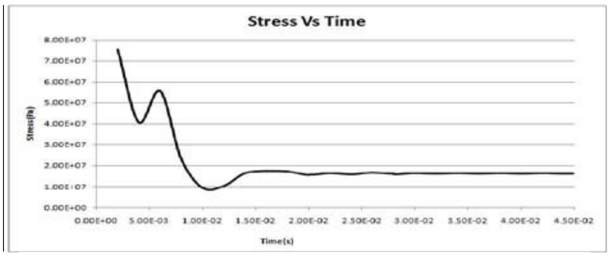

Figure 4: Stress Vs Time at peak pressure point (Near Valve)

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Maximum pressure and Maximum stress seems to be occurring at the same node near the valve position. Median dynamic stress induced due to dynamic pressure is observed as equal to the stress induced by an equivalent static pressure. This has been confirmed valid with Leishear [7].

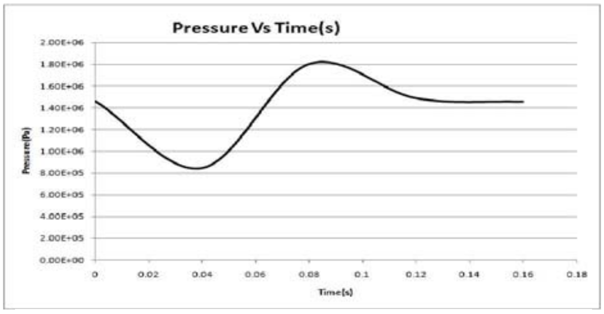

Figure 5: Pressure Vs Time at peak pressure point for slow closure (Closure time 2s)

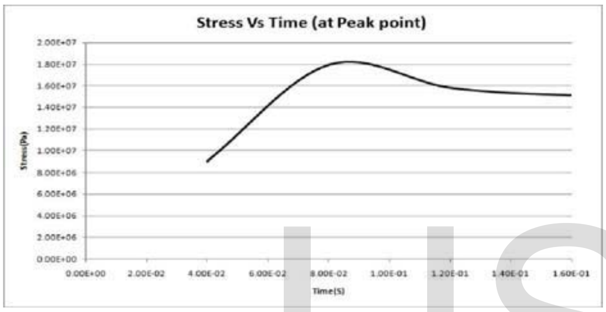

Figure 6: Stress Vs Time at peak pressure point for slow closure simulation

The shape of stress curve is seemed to be missing in the initial time period. This is because this simulation has been done with considering the steady state flow conditions as transient initialization and the fluid structural coupling started only at the beginning of transient simulation. This can be rectified by conducting an initial steady state simulation before the transient run.

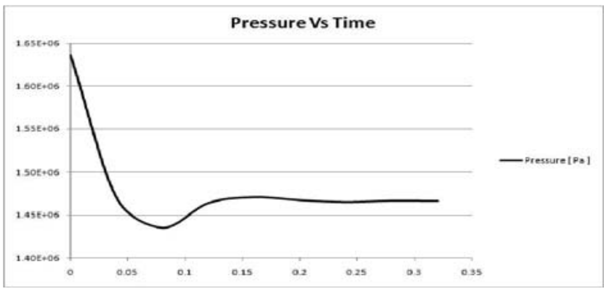

Figure 7: Pressure Vs Time at peak point for PVC pipe with same dimensions.

Condition of equivalency in dynamically induced stress and statically induced stress is found as invalid in the case of material with low stiffness. The Joukowsky's theorem seems to be invalid in predicting the maximum transient pressure developed at low flow rate case.

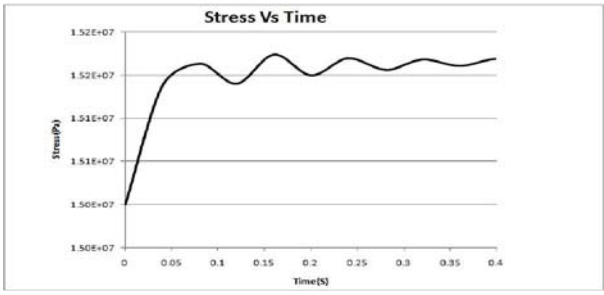

Figure 8: Stress Vs Time at peak point for PVC pipe

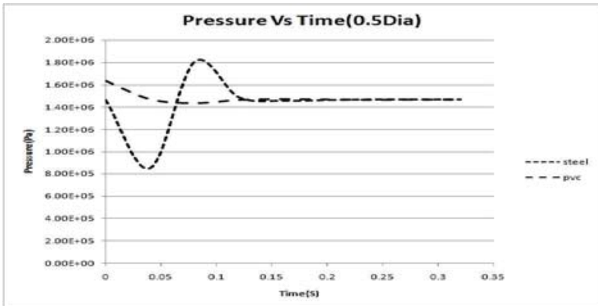

Fig 9: Comparison of pressure induced between Steel and PVC for 0.5m diameter pipe.

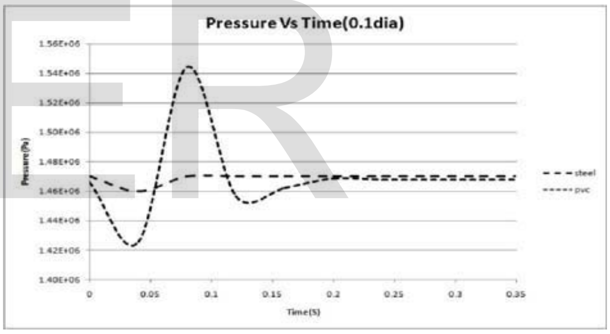

Fig 10: Comparison of pressure induced between PVC and Steel for reduced discharge of 0.1m diameter pipe.

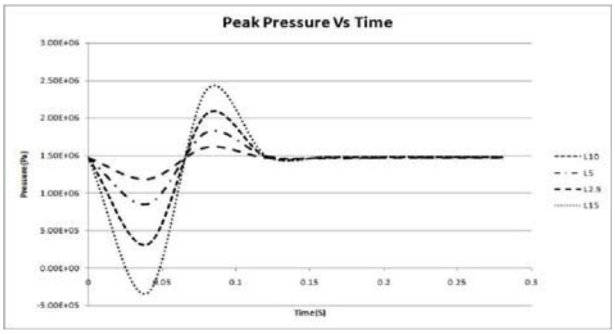

Figure 11: Study on influence of the length of water column (lengths are in meters)

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At low flow rate condition the pressure developed inside low stiffness material is more compared to that developed in the high stiffness material. This has been confirmed valid with the experiment of Tan Wee Choon [3]. Studies show that the head losses due to friction for larger diameter pipes are negligible over shorter spans. In the sensitivity analysis the frictional effect of pipe wall is not considered for the initialization of transient analysis (steady state flow details). Peak pressure variation with the length of water column has been observed in Tan Wee Choon's [3] experiment as well.

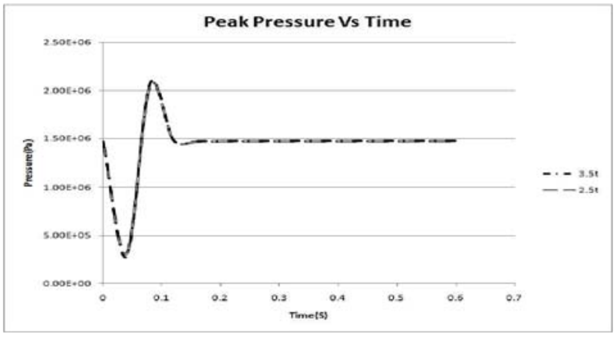

Figure 12: Study on influence of the wall thickness for steel-high stiffness material (Thickness in meters).

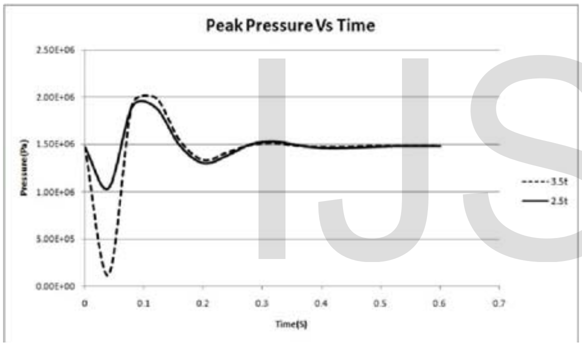

Figure 13: Study on influence of the wall thickness for PVC- low stiffness material (Thickness in meters).

The buried pipe is simulated as elastic supports [2, 8]
Density of high dense sand = 208.2 kg/m^3

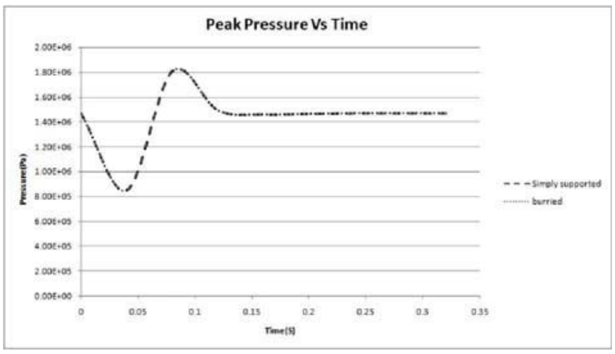

Figure 14: Study on influence of the type of supports

IV. CONCLUSIONS

1) The median dynamic stress induced during transient condition is found to be equal to the equivalent static stress during steady state condition and it has been confirmed with Leishear [7]. But this invention is found valid only for material with high stiffness value.
2) It is observed that the peak pressure seems to be increasing on increase in length of water column as observed in the experiment done by Tan Wee Choon [3].
3) For high stiffness materials and for the pipe with large diameters the numerical study over the 10m span pipe revealed that the type of supporting seems to be of negligible influence on the amplitude of peak pressure developed.
4) The wall thickness variation doesn't influence the peak pressure for high stiffness materials.
5) From the current study it has been confirmed that the peak pressure developed in large diameter pipes depend mainly on (for material with high stiffness value) flow rate, time of closure of valve, material stiffness value and length of water column.

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