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# Design and Analysis of Water Hammer Effect in a Network of Pipelines

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***Abstract-There will be a chance for the destruction of the system due to transient if it is not provided with adequate protection devices. Generally, transient takes place when parameters involving in conventional flow are distorted with respect to the time. Rapid closing of valve in a pipe network will be resulting into hydraulic transient known as water hammer occurs due to sudden change in pressure and velocity of flow with respect to time. Due to impulsive action, pressure surges are induced in the system travel along the pipe network with the rapid fluid acceleration leading to the dramatic effects like pipe line failure, damage to the system etc. Considering the importance of hydraulic transient analysis, we design a system capable of verifying pipe network containing fluid flow.This paper demonstrates design of different pipe structures in pipe line network and analysis of various parameters like excess pressure distribution, velocity variations and water hammer amplitude with respect to time using COMSOL Multiphysics v 4.3. The magnitude of water transient in pipe line network at different pressure points has been discussed in detail.***

***Keywords- COMSOL, Pressure distribution, Velocity variation, Water Hammer.***

## I. INTRODUCTION

The key to the conservation of water is good water measurement practices. As fluid will be running in water distribution system, system flow control is dependent based on the requirement for opening or closing of valves, and starting and stopping of pumps. When these operations are performed very quickly, they convert the kinetic energy carried by the fluid into strain energy in pipe walls, causing hydraulic transient [1] phenomena to come into existence in the water distribution system i.e., a pulse wave of abnormal pressure is generated which travels through the pipe network. Pressure surges that are formed or fluid transients in pipelines are referred to as Water hammer. This oscillatory form of unsteady flow generated by sudden changes results in system damage or failure if the transients are not minimized. So now the steady state flow conditions are altered by this effect [2] resulting in the disturbance to the initial flow conditions of the system. Where the system will tend to obtain a static flow rate by introduction of new steady state condition. The intensity of water hammer effects will depend upon the rate of change in the velocity or momentum. Conventional water hammer analyses provide information under operational conditions on two unknown parameters i.e., pressure and velocity within a pipe system. Generally effects such as unsteady friction, acoustic radiation to the surroundings or fluid structure interaction are not taken into account in the standard theory of water hammer, but were considered in general approach [3]. But mechanisms acting all along the entire pipe section such as axial stresses in the pipe and at specific points in the pipe system such as unrestrained valves will fall under fluid structure interaction extension theory for conventional water hammer method.

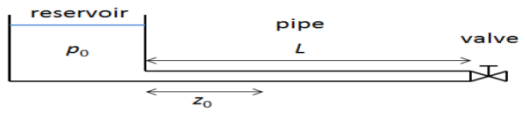


Figure 1. Pipe connected to control valve at the end with water inlet from reservoir.

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In the past three decades, since a large number of water hammer events occurred in the light-water- reactor power plants [4], a number of comprehensive studies on the phenomena associated with water hammer events have been performed. Generally water hammer can occur in any thermal-hydraulic systems and it is extremely dangerous for the thermal-hydraulic system since, if the pressure induced exceeds the pressure range of a pipe given by the manufacturer, it can lead to the failure of the pipeline integrity. Water hammers occurring at power plants are due to rapid valve operation [5], void induced operation, and condensation induced water hammer [6]. In existing Nuclear Power Plants water hammers can occur in case of an inflow of sub-cooled water into pipes or other parts of the equipment, which are filled with steam or steam-water mixture [7].

The water hammer theory has been proposed to account for a number of effects in biofluids under mechanical stress, as in the case of the origin of Korotkoff sounds during blood pressure measurement [8, 9] , or the development of a fluid-filled cavity within the spinal cord [10]. In the voice production system, the human vocal folds act as a valve [11 which induces pressure waves at a specific 'point' in the airways (the glottis), through successive compressing and decompressing actions (the glottis opens and closes repeatedly). Ishizaka was probably the first to advocate in 1976 the application of the water hammer theory, when discussing the input acoustic impedance looking into the trachea [12]. More recently, the water hammer theory was invoked in the context of tracheal wall motion detection [13]. Generally Water utilities, Industrial Pipeline Systems, Hydropower plants, chemical industries, Food, pharmaceutical industries face this water transient problem.

The present work reports the design of different pipe channels and analysis of the pressure distribution and velocity variation produced all along the pipe flow network when subjected to one pressure measuring point. Various parameters like inlet input pressure, wall thickness and measurement point are changed for analysis.

## II. USE OF COMSOL MULTIPHYSICS

The software package selected to model and simulate the pipe flow module was COMSOL Multiphysics Version 4.3. It is a powerful interactive environment for modelling and Multiphysics were selected because there was previous experience and expertise regarding its use as well as confidence in its capabilities. A finite element method based commercial software package, COMSOL Multiphysics, is used to produce a model and study the flow of liquid in different channels. This software provides the flexibility for selecting the required module using the model library, which consists of COMSOL Multiphysics, MEMS module, micro fluidics module etc. Using tools like parameterized geometry, interactive meshing, and custom solver sequences, you can quickly adapt to the ebbs and flows of your requirements, particle tracing module along with the live links for the MATLAB. At present this software can solve almost problems in multi physics systems and it creates the real world of multi physics systems without varying there material properties. The operation of this software is easier to understand and easier to implement in various aspects for designers, in the form of finite element analysis system.

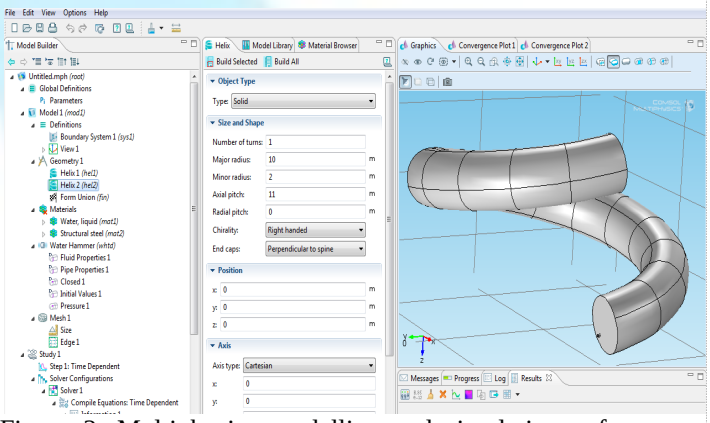


Figure 2. Multiphysics modelling and simulation software-COMSOL

In this model as the valve is assumed to close instantaneously the generated water hammer pulse has a step function like shape. To correctly solve this problem requires a well posed numerics. The length of the pipe is meshed with N elements giving a mesh size dx = L/N. For the transient solver to be well behaved requires that changes in a time step dt are made on lengths less than the mesh size. This gives the CFL number condition

**CFL= 0.2= c.dt/dx** ⟶ **(1)**

Meaning that changes during the time dt maximally move 20 % of the mesh length dx. Thus increasing the mesh resolution also requires decreasing the time stepping. This advanced version of software helps in designing the required geometry using free hand and the model can be analysed form multiple angles as it provides the rotation flexibility while working with it.

## III. THEORITICAL BACKGROUND

Water hammer theory dates to 19th century, where several authors have contributed their work in analyzing this effect. Among them, Joukowsky [14] conducted a systematic study of the water distribution system in Moscow and derived a formula that bears his name, that relates to pressure changes, Δp, to velocity changes, Δv, according to the equation

$$\Delta P = \rho c \Delta U \longrightarrow (2)$$

Where ρ is the fluid mass density and c is the speed of sound. This relation is commonly known as the "Joukowsky equation", but it is sometimes referred to as either the "Joukowsky-Frizell" or the "Allievi" equation.

For a compressible fluid in an elastic tube, c depends on the bulk elastic modulus of the fluid K on the elastic modulus of the pipe E, on the inner radius of the pipe D, and on its wall thickness. The water hammer equations are some version of the compressible fluid flow equations. The choice of the version is problem-dependent: basic water hammer neglects friction and damping mechanisms, classic water hammer takes into account fluid wall friction, extended water hammer allows for pipe motion and dynamic Fluid Structure Interaction [15, 16].

In water hammer at static condition pressure wave is a disturbance that propagates energy and momentum from one point to another through a medium without significant displacement of the particles of that medium. A transient pressure wave, subject's system piping and other facilities to oscillating at high pressures and low pressures. This cyclic loads and pressures can have a number of adverse effects on the hydraulic system. Hydraulic transients can cause hydraulic equipment's in a pipe network to fail if the transient pressures are excessively high. If the pressures are excessively higher than the pressure ratings of the pipeline, failure through pipe or joint rupture, or bend or elbow movement may occur. Conversely, excessive low pressures (negative pressures) can result in buckling, implosion and leakage at pipe joints during sub atmospheric phases. Low pressure transients are normally experienced on the down streamside of a closing valve. But when the valve is closed energy losses are introduced in the system and are normally prescribed by means of an empirical law in terms of a loss coefficient. This coefficient, ordinarily determined under steady flow conditions, is known as the valve discharge coefficient, especially when the pipeline is terminated by the valve. It enables to quantify the flow response in terms of the valve action through a relationship between the flow rate and pressure for each opening position of the valve. The discharge coefficient provides the critical piece of missing information for the water hammer analysis. Because the existing relationship between pressure and flow rate is often a quadratic law type, the empirical coefficient is defined in terms of the squared flow rate. When water distribution system comprising a short length of pipes (i.e., <2,000 ft. {600m}) will usually be less vulnerable to problems with hydraulic transient. This is because wave reflections e.g., at

tanks, reservoirs, junctions tend to limit further changes in pressure and counteract the initial transient effects. An important consideration is dead ends, which may be caused by closure of check valves that lock pressure waves into the system in cumulative fashion. Wave reflections will be both positive and negative pressures; as a result the effect of dead ends must be carefully evaluated in transient analysis.

These pressure surges provide the most effective and viable means of identifying weak spots, predicting potentially negative effects of hydraulic transient under a number of worst case scenarios, and evaluating how they may possibly be avoided and controlled. The basic pressure surge modeling is based on the numerical conservation of mass and linear momentum equations. For this Arbitary Lagrangian Elurian(LE)[17] numerical solution helps in providing the exact analytical solution. On the other hand when poorly calibrated hydraulic network models results in poor prediction of pressure surges thus leading to more hydraulic transients. In more complex systems especially, the cumulative effect of several types of devices which influence water hammer may have an adverse effect. However, even in simple cases, for example in pumping water into a reservoir, manipulations very unfavorable with regard to water hammer may take place. For example, after the failure of the pump, the operator may start it again. Much depends on the instant of this starting. If it is done at a time when the entire water hammer effect has died down, it is an operation for which the system must have been designed.

## IV. DESIGN PROCEDURE

The design and analysis of the hydraulic transient in a pipe flow includes geometry, defining the parameters for the required geometry, providing mesh & inputs. The 3D model is constructed in the drawing mode of COMSOL Multiphysics. In this, a pipe of length L = 20 m is constructed assuming that one end is connected to a reservoir, where a valve is placed at the other end. The pipe with inner radius of 398.5mm, the thickness of the wall about 8 mm and Young's modulus of 210GPa was designed. In order to verify pressure distribution, a pressure sensor measurement point at a distance of $z_0$= 11.15 m from the reservoir was arranged and flow has been sent into pipe with an initial flow rate of $Q_0$= 0.5 $m^3$/sec.

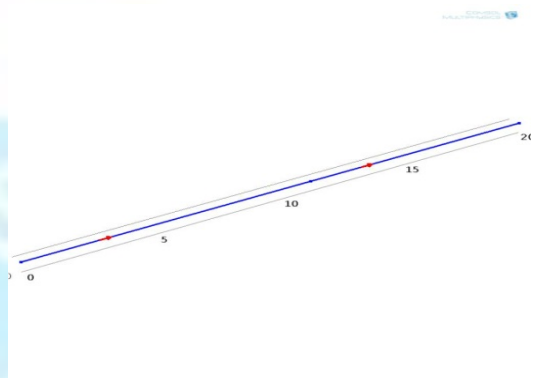


Figure 3. Single pipe line with closing vale at the output

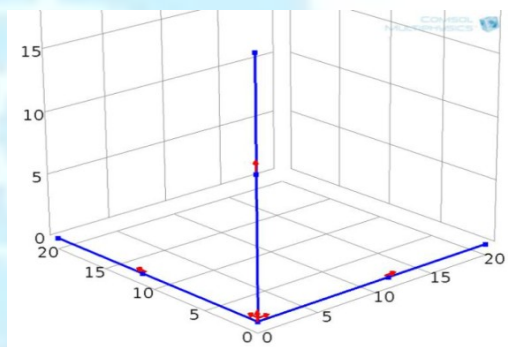


Figure 4. Three pipe line intersection in a network.

After designing the geometry for a flow channel in a pipe, materials are to be selected from the material browser. Water, liquid and structural steel are selected from the built in section of material browser. Edges are selected for water flow and steel pipe model sections. Now pipe properties are defined one by one by first selecting the round shape from the shape list of pipe shape. Initially the reservoir acts as a constant source for pressure producing $p_0$ which is equal to 1 atm. As the fluid is allowed to flow from the reservoir tank into the pipe model, the fluid enters the left boundary of the pipe first and leaves the right boundary of the pipe with the valve in open

condition. As the valve is open water is flowing at a steady flow rate, so at time t = o seconds the valve on the right hand side is closed instantaneously creating disturbance in the normal flow rate leading to a change in discharge at the valve. As a result of the compressibility of the water and the elastic behaviour of the pipe a sharp pressure pulse is generated travelling upstream of the valve. The water hammer wave speed c is given by the expression

$$1/c^2 = 1/c_s^2 + \rho\beta_A \longrightarrow (3)$$

Where $c_s$ is the isentropic speed of sound in the bulk fluid and is 1481 m/s while the second terms represents the component due to the pipe flexibility. The water density is ρ and $\beta_A$ the pipe cross sectional compressibility. Resulting in an effective wave speed of 1037 m/s. The instantaneous closure of the valve will results in a water hammer pulse of amplitude P given by Joukowsky's fundamental equation [18]

$$P = \rho c u_o \longrightarrow (4)$$

Where $u_0$ is the average fluid velocity before valve was closed. Exact solution can only be obtained based on the verification of the pipe system and valve point [19]. Study was extended for different pipe line intersection models based on the reference model [20]. To design a three axis pipe line intersection, from geometry more primitives, three polygons are chosen where first polygon coordinates corresponds to x in (1 z0 L), while y & z remain in (0 0 0). For second polygon y coordinates are (1 z0 L) and the remaining are left for (0 0 0), in a similar way z coordinates are (1 z0 L), and the resulting geometry is depicted in figure 4.

## V. RESULTS AND DISCUSSION

Using this Multiphysics modelling and simulation COMSOL software three different kinds of studies were carried out i.e., Study 1 is the time dependent is based on the fluid flow and its corresponding interaction with the pipe which results in pressure distribution along the pipe line along with the velocity variation. Where the Study 2 is not only based on the excess pressure measurement point but also valve point. On the other hand Study 3 corresponds to the pressure profile in the pipe line with respect to different times As it is a time dependent study, the ranges of the times are edited in the study setting section from range (0, 0.005, and 0.75) to range(0, 1e-3, 0.24). Now from study 1 right click and select show default solver. Then expand the solver window and click the time stepping section in which the maximum step check box is marked and in the associated edit field type dt. Now right click study 1 to compute the results. So pressure along pipe line at t=0.24s is obtained along with the velocity variation. Results are analysed by transforming the pipe line shapes to different geometry's. From the analysis of results, it allow us to conclude that when more pipes lines are inter connected there is more chance for water transient to tack place at an easy rate and cause damage to the system.

## VI. MESHING

Meshing can provide the information of required outputs anywhere on the proposed structure along with the input given. Numerical ripples are visible on the point graphs of excess pressure history at pressure sensor and water hammer amplitude. As the closure in the valve is instantaneous the pressure profile has a step like nature. This is difficult to resolve numerically. The ripples can be reduced by increasing the mesh resolution parameter **N**. So the number of mesh points (N) selected in this model is about 400. In this model meshing is done for the Edges of the pipe. Where the maximum element size of the parameter is defined for L/N m (L= 20 m & N= 400) and the minimum element size is 1[mm].

## VII. SIMULATION

In this study, the simulations are performed using the fundamental equation in water hammer theory that relates to pressure changes, Δp, to velocity changes, Δv, according to the equation (2). Simulation comprises of application of different input initial pressure at the inlet portion for different

pipe network sections. Pressure measurement points are changed along the pipe length L and computed for time interval from T=0 to T=0.24 seconds. Both the velocity and pressure are measured at the above time interval. Other parameters like water hammer amplitude, maximum and minimum pressure for two different geometry's; along with velocity variations are listed in table 1.

**Table** 1. Pressure distribution and velocity variation values for single pipe line & three pipe lines geometry.

| Parameters | Single pipe | Three pipes |
|---|---|---|
| **Min. Pressure at T=0.07s** | $-9.579*10^5$ Pa | $-1.577*10^5$ Pa |
| **Max. Pressure at T=0.07s** | $4.047*10^5$ Pa | $1.1617*10^6$ Pa |
| **Velocity Variation Range at T=0.23s** | $4.257*10^{-4}$ to 1.1632 m/s | 0.2672 to 1.2742 m/s |
| **Excess Pressure distribution along the pipe for t = 0.24 s.** | $1.35*10^6$ Pa | $-0.85*10^6$ Pa |

## VII. CONCLUSION

Flow channel is designed in a pipe network and its reaction with the valve when closed was analysed using COMSOL Multiphysics Version 4.3. Simulation for the proposed model is done by changing the initial flow rates along with the pipe networks to explore the variations in the properties of fluid like pressure distribution and velocity variation with respect to time. When inlet mean velocity is increased the magnitude of water hammer amplitude remains the same but the chances for the water transient is more which results in easy breakdown of pipe section. When multiple pipe line was connected the maximum pressure distribution and velocity variation were very less even though the water hammer amplitude remains the same when compared for different cases. Positive pressure difference exists when multiple pipes were connected where negative pressure difference exists for singe pipe line geometry, which states that network of pipe lines results in less water transient effect. This study can be extended by observing the changes in the flow by inclining the pipe line, by using T, L shaped piping geometries. Further extension was made for micro piping system by changing the dimensions of the geometry from meters to micro meters. This study helps in building micro piping network systems that are used in bio medical applications and Automobile industries.

## VIII. ACKNOWLEDGEMENTS

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FIGURES AND TABLES

CAPTION FOR FIGURES

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FIGURE 2. Multiphysics modelling and simulation software-COMSOL

FIGURE 3. Single pipe line with closing vale at the output.

FIGURE 4. Three pipe line intersection in a network.

FIGURE 5. Pressure distribution at T=0.07s for single pipe line geometry.

FIGURE 6. Pressure distribution at T=0.07s for three pipe line intersection geometry.

FIGURE 7. Velocity variation at T=0.23s for single pipe.

FIGURE 8. Velocity variation at T=0.23s for three pipe line intersection geometry.

FIGURE 9. Excess pressure history measured at the pressure sensor for single pipe line geometry.

FIGURE 10. Excess pressure history measured at the pressure sensor for three pipe line geometry.

FIGURE 11. Excess pressure at the valve (green line) & Predicted water hammer amplitude (Blue line) for single pipe line.

FIGURE 12. Excess pressure at the valve (green line) & Predicted water hammer amplitude (Blue line) for three pipe lines.

FIGURE 13. Excess pressure distribution along the pipe for t= 30 s for single pipeline geometry.

FIGURE 14. Excess pressure distribution along the pipe for t= 30 s for three pipeline geometry.

CAPTION FOR TABLE

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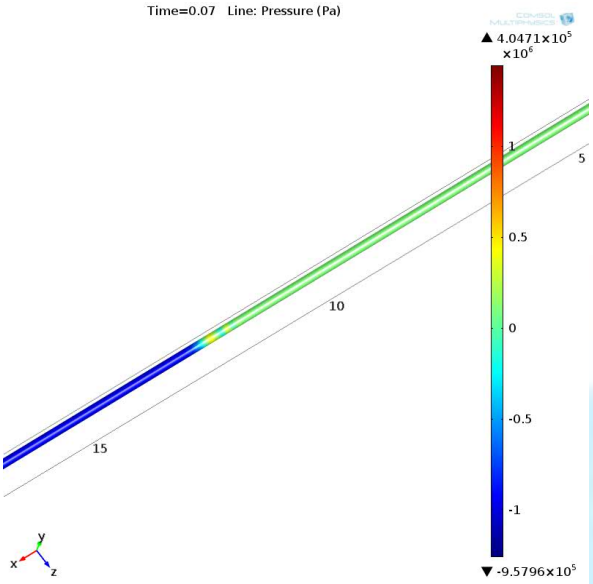



Figure 5: Pressure distribution at T=0.07s for single pipe line geometry.

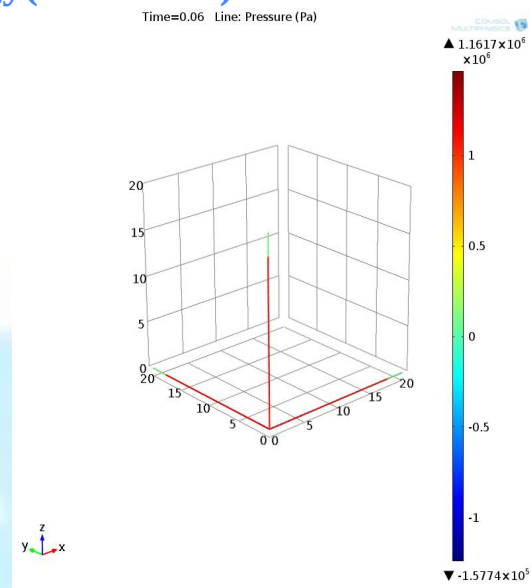



Figure 6: Pressure distribution at T=0.07s for three pipe line intersection geometry.

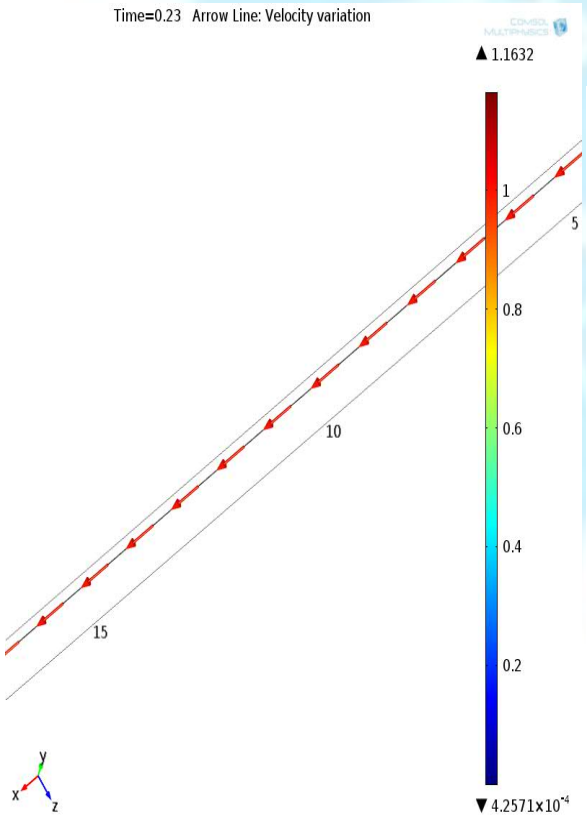
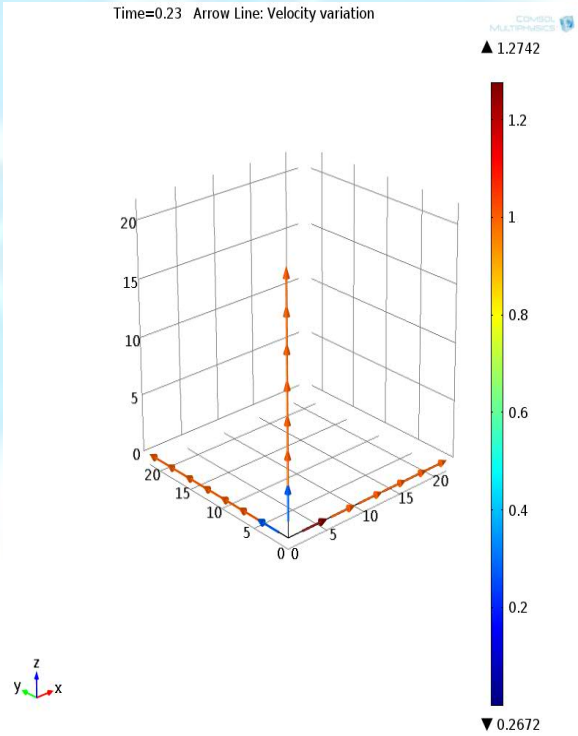



Figure 7: Velocity variation at T=0.23s for single pipe line geometry

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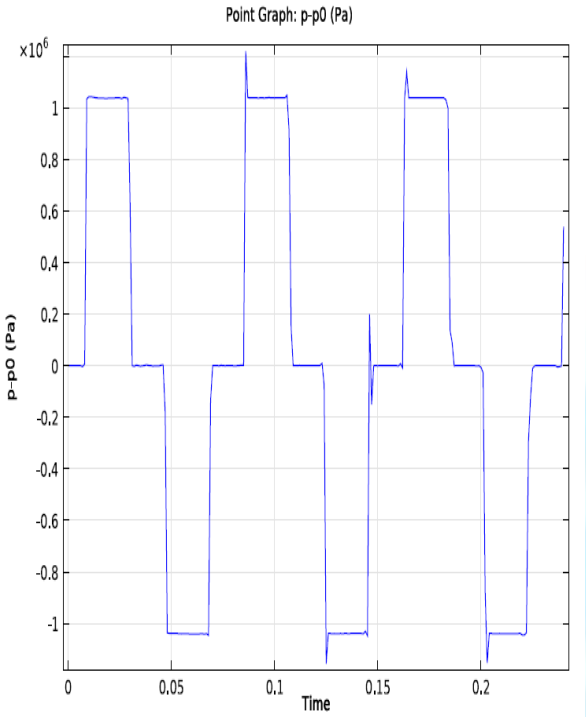


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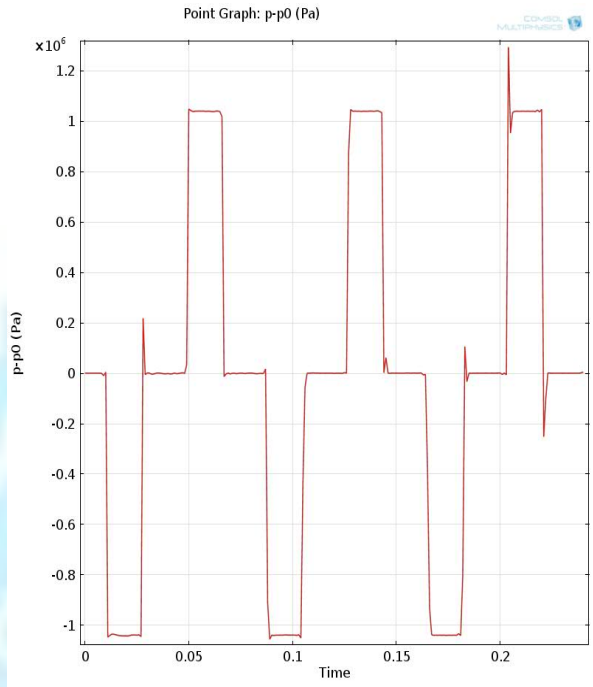
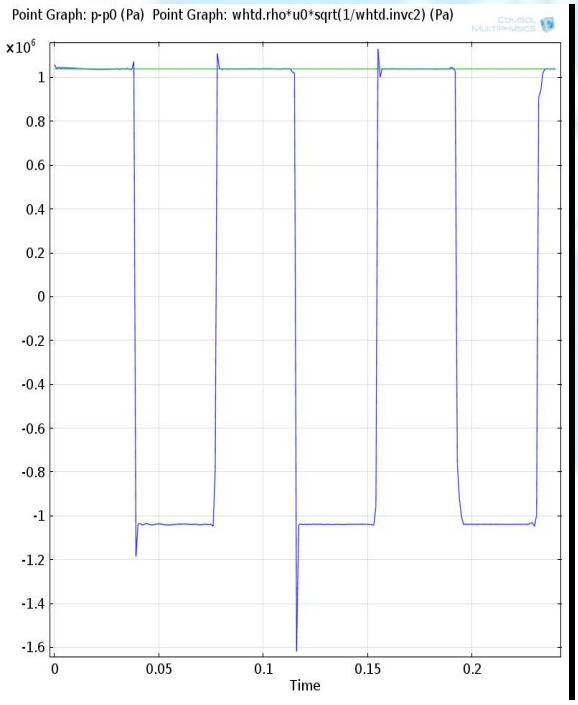



Figure 10. Excess pressure history measured at the pressure sensor for three pipe line geometry.

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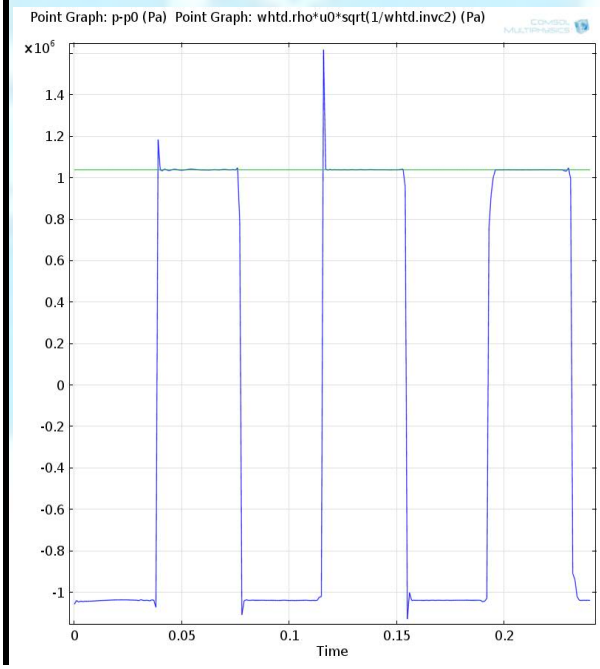


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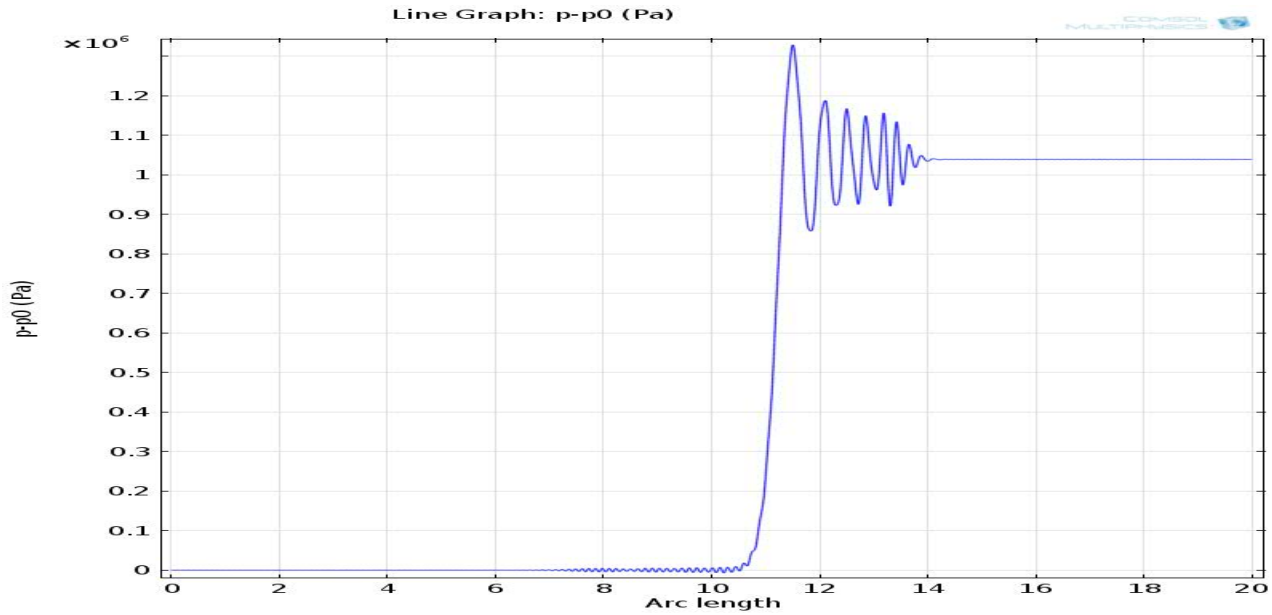



Figure 13. Excess pressure distribution along the pipe for t= 30 s for single pipeline geometry.

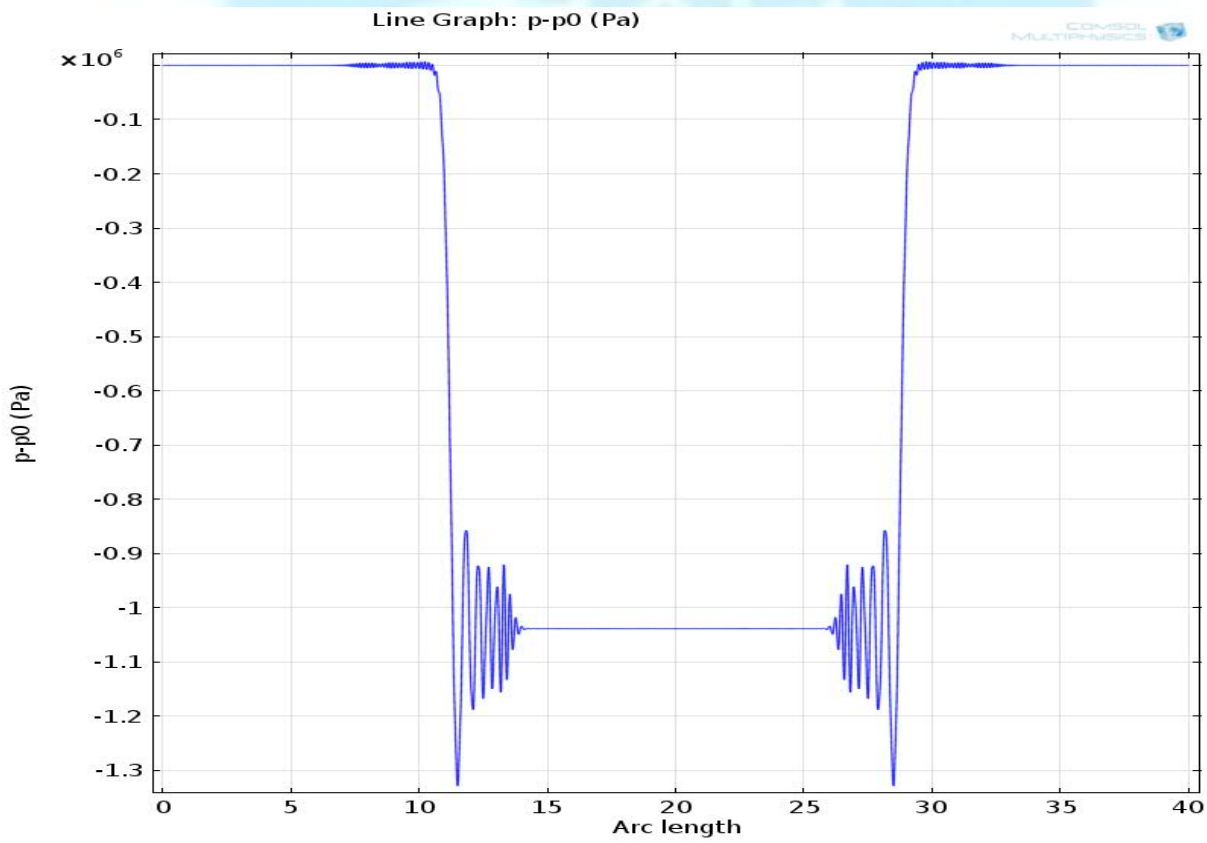
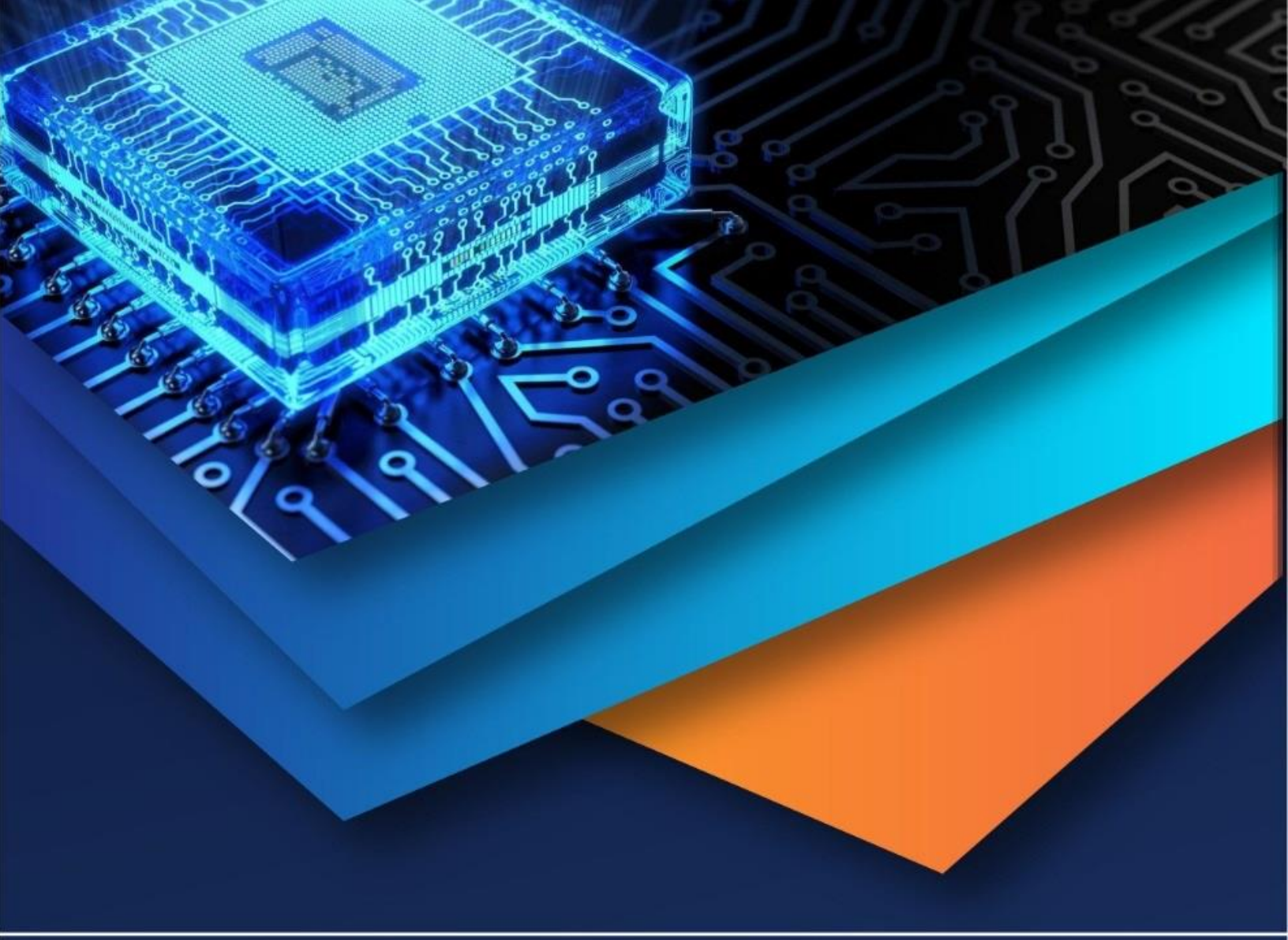



Figure 14. Excess pressure distribution along the pipe for t= 30 s for three pipe line intersection geometry.



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