MARMARA UNIVERSITY
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IN PURE AND APPLIED SCIENCES

ANALYSIS OF WATER HAMMER EFFECTS INSIDE PIPES USING ADVANCED CFD TECHNIQUES

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First of all, I hereby would like to reveal my deep gratitude to my advisor Ass. Prof. Dr. Emre Alpman, for his endless support and fruitful instructions in this study, for his patience, intelligence, diligence and deep knowledge. His directions and suggestions leaded me to find my way when I was stuck, and I was able to complete this study.

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BORULARDA SU DARBESİ ETKİLERİNİN İLERİ HESAPLAMALI AKIŞKANLAR DİNAMİĞİ TEKNİKLERİ İLE ANALİZİ

Su darbesi, sıvının hızı ve basıncındaki ani değişmelereden dolayı meydana gelen bir hidrolik olaydır. Bu hız ve basınç değişmelerinin bir kaç sebebi olabilir. Başlıca su darbesi nedenleri için ani vana kapanması, pompa güç ünitesinin bozulmasından dolayı pompanın su basamaması ve boru hattı üzerinde yer alan ekipmanların bozulması şeklinde öreneklendirilebilir. Su darbesi analizini günümüz ticari yazılımlarının dışında OpenFOAM gibi kullanıcıya açık kaynak kodlu yazılımlar aracılığıyla da yapılabilir.

Bu çalışmada, OpenFOAM içerisinde yer alan ve sıkıştırılabilir sıvılar için kullanılan bir zamana bağlı denklem çözücüsü olan sonicLiquidFoam aracılığıyla çeşitli boru hatlarında su darbesi analizi incelenecektir. Bunun için gerekli ağ yapısının oluşturulup, uygun sınır koşullarının belirlenmesi gereklidir. Gerekli ağ yapısının oluşturulmasında OpenFOAM içerisinde yer alan blockMesh özelliğinden yararlanılmıştır.

Sınır koşullarında, boru hattının bir ucunda sürekli sabit bir basınç etkisi yaratan rezervuar ve diğer ucunda ise su darbesi olayını gözlemleyebilmemiz için ani kapanabilen bir vananın bulunduğu kabul edilmiştir. Analizlerde, borunun çıkış kısmında yer alan vananın kapanma haraketini göstermek yerine vana kapanma hareketine karşılık gelen debi miktarları tanımlanmıştır. Bu sayede su darbesi analizinin OpenFOAM aracılığıyla yapılabilmesi ve elde edilen sonuçların deneysel veriler ile karşılaştırılabilmesi sağlanmıştır. Deneyde gözlenen su darbesinin neden olduğu maksimum basınç ile OpenFOAM üzerinde hesaplanan maksimum basınç değeri arasındaki fark yaklaşık olarak %4 mertebelerinde çıkmaktadır. Bu sonuç ise pozitif ve umut verici bir adım olarak yorumlanabilir.

ABSTRACT

ANALYSIS OF WATER HAMMER EFFECTS INSIDE PIPES USING ADVANCED CFD TECHNIQUES

Water hammer is a hydraulic phenomenon occured due to sudden changes in velocity and pressure of the fluid. There are few reasons for these changes in velocity and pressure. Sudden valve closure, pump failure due to power cut and malfunctioning any equipment along the pipeline could be main reasons for water hammer. As it is known that commercial softwares and programs can handle the analysis of water hammer, open source softwares such as OpenFOAM alternatively perform such analysis as well.

In this study, investigation of water hammer in different pipings will be done by means of sonicLiquidFoam which is a transient solver under OpenFOAM for compressible liquids. In order to do this analysis, creating mesh structures and determining appropriate boundary conditions are required. In meshing structure, blockMesh under OpenFOAM is utilized.

In boundary conditions, it is assumed that there is a reservoir and a valve on the pipeline since the reservoir is providing constant pressure for pipeline’s end and the valve is closing swiftly to be able to observe water hammer. Instead of making valve closing during the analysis, flow rates corresponding to the valve closing situation are defined accordingly. In this way, it can be illustrated that water hammer analysis is done by OpenFOAM and the results obtained from OpenFOAM are compared with experimental results. Difference between maximum pressure in OpenFOAM analysis and experiment is approximately 4%. This outcome can be interpreted as a positive and encouraging milestone.

SYMBOLS

$\mathbf{A}$: Cross-sectional area of pipe (m^2)

$\mathbf{C}$: Dimensionless coefficient depending on the type of pipe connection (-)

$\boldsymbol{C}$: Courant number (-)

$\mathbf{g}$: Gravitational acceleration (m/s^2)

$\boldsymbol{h_a}$: Over pressure (Pa)

$\boldsymbol{K}$: Elasticity of fluid (Pa)

$\boldsymbol{L}$: Pipe length (m)

$\boldsymbol{p_0}$: Reference pressure (Pa)

$\boldsymbol{Q}$: Flow rate (m^3/sec)

$\boldsymbol{T}$: Period of Time (sec)

$\boldsymbol{t_c}$: Time of valve closing (sec)

$\boldsymbol{v}$: Fluid velocity (m/s)

$\boldsymbol{a}$: Wave speed (m/s)

γ : Specific weight of fluid (N/m^3)

$\mathbf{\Delta H}$: Head pressure change (m)

$\mathbf{\Delta A}$: Pipe cross-sectional area change (m^2)

$\mathbf{\Delta s}$: Amount of pipe extension (m)

$\boldsymbol{\Delta t}$: Time step (sec)

$\mathbf{\Delta V}$: Increment of flow velocity (m/s)

$\mathbf{\Delta x}$: Spacing of the grid in the numerical model (m)

$\boldsymbol{\Delta}\forall/\forall$: Fractional volume change (-)

$\boldsymbol{\Delta\rho}$: Density change of the fluid under pressure (kg/m^3)

$\boldsymbol{\mu}$: Poisson's ratio of the pipe material

ρ : Mass density of fluid (kg/m^3)

$\boldsymbol{\rho_0}$: Reference density (kg/m^3)

$\boldsymbol{V_0}$: Initial velocity (m/s)

$\boldsymbol{\tau_w}$: Wall shear stress in N/m^2.

$\boldsymbol{\psi}$: Derivative of density acccording to pressure (m^3/s)

ABBREVIATIONS

CFD : Computational Fluid Dynamic

CV : Control Volume

DSI : Devlet Su İşleri (State Hydraulic Works)

PISO : Pressure Implicit with Splitting of Operators

SIMPLE : Semi-Implicit Method for Pressure-Linked Equations

1. INTRODUCTION

Conveying water to end points requires many efforts when it comes to safety and reliability. More than hundreds years in the world, people have been dealing with water transmissions by means of closed conduits [1]. Knowing such an important job to access safe and clean water without having any problems might be understood as a valuable endeavour. On that basis, water transmission system plays an integral role for those who are in need of water badly. In some countries, lack of water makes people focus on controlling water seamlessly to ensure they are handling water without waste and evaporation. To do so, people in such territories, where water is needed badly, prefer to use closed conduits in order to achieve water in an efficient way. Then, the closed conduits meaning that pipeline can be actually understood as a valuable and political system in their daily lives.

For water transmission by closed conduits, there had been many ways associated with conveying water from one point to another based on the physical conditions at places where people wanted to construct their transmission systems. Some of these ways are rectangular shaped pipeline, egg shaped pipeline, circular shaped pipeline which have been now widely preferred by many people. In Turkey, State Hydraulic Works (DSI) decided to replace nearly all open conduits by closed conduits together with pipelines since power of controlling water would pave the way for the country to achieve its targets such as increasing agricultural activities, incomes of local people by trading their products cultivated from their lands as a result of water being conveyed by those pipelines [2].

Water transmission by pipeline can be handled by pumped and gravity systems. Roughly speaking, pumped systems are used in irrigation, potable, circulating cooling water pipelines, and gravity systems are used in waste water and some of hydro power plants. In both systems, every types of water issues in relation to design, construction and operation shall be taken into account to have a sustainable pipeline system. For these reasons, hydraulics of pipelines must be carefully taken into account so that design of pipeline can be extended for the people who benefit from.

Hydraulics of the pipeline consist of many different topics and rely on nearly all components of the pipeline when it comes to radical and rapid changes in flow [3]. In general, components of pipeline can mainly be valves, reservoirs, pumps, small pipe branch networks, by-pass lines, tanks etc. These are altogether tremendously important when it comes to safe operation and long service life of the pipeline. Therefore, failure of one of them might be a huge and serious problem.

Flow inside pipeline can be classified as steady and transient condition.

Steady conditions meaning that no changes related to pressure and velocity, pipeline is stable and no disturbance is normally observed. Thanks to stable and constant parameters, no damages is expected from the pipeline. On that basis, flow characteristics inside pipeline is based on steady condition.

In transient conditions meaning that abrupt changes when it comes to pressure and velocity, pipeline is not stable anymore and flow inside pipeline will go through transients until the initial steady state is achieved. These transient pressures are superimposed on the steady state conditions which are present in the line when the transient occurs. Thus, total pressure is obtained by summing the steady state and transient pressure in the pipeline. Due to such sudden changes of flow parameters, the transient flow can result in severe failures and problems which are adversely effecting pipelines as a result. To witstand these over pressures, other saying is surge pressures, pipes are properly and accordingly designed against the severity of transient pressures [4]. The provision for a pipeline including fast closing valve scenario is taken into account in case of emergency conditions [5]. These cases require a short valve closure time and therefore the valve closure arrangement has high significance in terms of reducing the maximum pressure [6].

Historically, many scientists and engineers in the water industry were quite interested in water transmission problems to be able to point out problems and sort it out accordingly. One of those leading searchers and engineers, named as Lorenzo Allievi, investigated an explosion occurred in a hydro electrical power plant in 1902. As a result of his findings on this real incident, he has been known as the first person explaining the water hammer phenomenon.

Water hammer is a pressure spike resulting from various reasons such as sudden opening and closing valves, pump starts and stops, or water column separation which are altogether blocking the flow in pipelines. In another words, water hammer is named as pressure transients since steady state is no longer matter at this time. These transients due to above-mentioned general reasons can cause high pressure and low pressure along the pipeline depending on parameters which are completely described in detail later on. During these transients, water hammer, which can be main reason for problems about the mechanical integrity of a pipeline, is generated due to sudden momentum changes in the fluid and it can create formation of cavitation pockets of vapor at saturation pressure in the lines, which are rapidly collapsed as liquid flow rushes in to fill them [7]. To avoid any damages under these conditions, pipes are to be restrained adequately by a complete pipe installation and placing supports [8]. For example, Oigawa Hydropower station in 1950 in Japan and similarly Lapino Hydropower plant in 1997 in Poland were unfortunately faced with a flood of whole power house. It was investigated and found that water hammer initiated by sudden valve closure was main reason for the ruptures of the penstocks [9].

In the scope of this thesis, water hammer analysis by means of open source computational fluid dynamics software named as OpenFOAM is aimed. Transient analysis is hereby based on sudden closing of the valve located at outlet of pipeline by assuming reservoir enabling to have a constant pressure at inlet of pipeline. To observe water hammer phenomenon in different pipe configurations such as straight line, curved line, various diameters of pipelines and different scenearios are completed. To validate results of water hammer analysis by OpenFOAM, benchmark study is also verified successfully. For benchmark study, results from experimental and CFD numerical study are compared with OpenFOAM to have exhaustive information about capability of open source software for further studies.

1.1 Literature Review

In pipelines systems conveying water, sudden change in fluid velocity and pressure caused by some certain reasons such as abruptly closing and opening valves, and power failures for pump shut-down may result in water hammer. To be able to theoretically and practically understand water hammer phenomenon, unsteady and/or transient flow shall be examined clearly and various analysis might be performed to comprehend. In addition, there are numbers of common terms referring directly to water hammer, and these are generally named as Steady and Unsteady Flow, Transient Flow, Uniform and Non-uniform Flow, Column Separation and Pressure Surge.

In the past, fluid transient event for water hammer was quite hard to capture for many engineers and researchers. Due to the fact that, many researchers and scientist have significantly conducted bunch of studies for water hammer in closed conduits, which are still remaining important and referred by nearly all researchers dealing with further studies in relation to fluid transients. Thanks to such a great historical background, too many of fruitful studies are now available when it comes to fluid transients.

Water hammer theory actually describes the wave propagation occurred alongside the fully-liquid pipelines.[10]. The studies associated with fluid transient conducted to investigate the propagation of sound waves in air, the propagation of waves in shallow water, and the flow blood in arteries had been playing an integral roles for the sake of improving the transients' studies. The 17th and 18th centuries were periods for Newton and Lagrange to study the propagation of sound waves in air, but their theoretical findings were not complying with experimental results. Later on, a partial differential equation for wave propagation, which has paved the way for further studies, was developed by Euler. Monge developed and introduced the term method of characteristics which was well known about graphical method for integration of the partial differential equations. Laplace also studied for the theoretical and experimental findings about velocity of sound in air to explain the difference between the findings. According to non-complying results, Laplace reasoned that relationship derived by Newton and Lagrange were resulting from Boyle's law which was invalid when it comes to varying pressure. The pressure wave speed was initially investigated by Young in 1808. Following many tests by Marey to find the pressure wave speed in water and in mercury, he ended up with a theory which was the wave speed was independent of the amplitude of the pressure waves; it was proportional to the pipe's elasticity. Korteweg in 1878 determined the wave velocity as per the elasticity of both the pipe wall and the fluid whereas researchers had only considered one of the pipe wall and fluid at a time. When it comes to studies related to water hammer under principles of fluid transient, Michaud in 1878 was known the first one to study about it. He also contemplated the use of air chambers and protection devices used in reducing high pressure during water hammer problems [11]. Plus, some experiments, which were designed to construct a correlation between flow velocity in a pipe and the corresponding pressure rise, were unfortunately failed due to the fact that their pipeline were not long enough. In 1898, Frizell, consulting engineer for the Ogden hydroelectric development in Utah, investigated a pipeline used as penstock up to 9.45 km long within the scope of the hydroelectric power plant in order to have expressions about the velocity of water hammer waves and the pressure spike caused by abrupt changes on the flow [12]. He also delved into details for the effects of branch lines, wave reflections and successive waves. In following years, Joukowski published an important report, which has been paving the way for next generations, about some experiments in Moscow for the pipeline [13]. As a result of his studies and experimental results, he managed to develop an expression for the wave velocity. What he achieved were about correlation between flow velocity and pressure rise due to reduction of flow velocity by means of the conservation of energy and the continuity condition. To sum things up, he found a way to show that maximum closing time was $t_c \leq 2L/a$ and hereby t_c, L and a are representing time of valve closing, pipe length and wave speed respectively. Hence, this correlation is generally named as “Joukowski Equation”, but also sometimes called as “Allievi Equation” since Allievi was also significantly involved in achieving the water hammer phenomenon during his studies on above-mentioned investigations at Ogden hydroelectric developments.

Referring to first glimpse of water hammer phenomenon in closed conduits by Juokowsski and Allievi, many enthusiastic researchers and engineers were involved in developing and contributing theoretical approaches to existing theories. With these findings, current water hammer solutions are shaped depending on system parameters. From now on, further studies will be briefly summarized.

In 1938, Frank and Schüller [14] investigated and analyzed the oscillations in surge tank used in absorbing excessive pressure. According to their studies, they dealt with two different cases and these are constant flow and constant gate opening cases respectively. At constant flow case, it was about understanding of variation of discharge rates which were corresponding to the values of steady-state conditions. At second case named constant gate opening, it was about combination various gate valve positions and this case was considered under a full gate opening due to sudden hydraulic load at the time when the gate remaining constant. Based on these two cases, the oscillations are stable for the first case by taking frictional losses into account and the oscillations are stable for the second case. As a result, Frank calculated the maximum down surge for the case which was including sudden loads from turbine itself.

Parmakian in 1963 used graphical methods to analyze water hammer inside pipelines. The method has been utilized by many researchers for many years [15]. According to the theory he utilized, he did find various graphical solution schemes as per dimensional and non-dimensional parameters for flow velocity and pressure head in particular.

In 1987, Chaudhry studied about water hammer by considering pipe wall elasticity and compressibility of water in transient effects by applying continuity principle [16]. Within his researches and studies, he aimed at deriving suitable boundary conditions or equations for boundary conditions for accessories along the pipeline such as valves, sprinklers, surge tank and air relieve chambers since he considered conservation of mass for the control volume selected. He was also trying to investigate whether these boundary conditions would affect the transient flow inside pipelines. The water hammer equations can be actually solved by means of all methods which are suitable for hyperbolic equations. His method was based on method of characteristic, which is abbreviated as MOC, with results obtained by digital computer. The MOC is theoretically complex and it requires a lot of steps and calculations to find solution for a problem about typical transient pipe flow. It is apparently said that the more complexity on the pipe system, more number of required calculations. At the end, he concluded that validity of those boundary conditions were proved after comparison between the results taken from method of characteristic and the results taken from the graphical method. He also showed that pressure wave could be reduced and controlled by adding small pipe branches called as sprinklers.

Dealing with water hammer in pipe networks requires the engineers and researchers to focus on the solution to be found by utilizing theoretical and practical background of conventional facts. Meaning that engineering knowledge, boundary conditions, applicability of design rules, and software-based program's capabilities are surely regarded as considerations for the sake of achieving sustainable and reliable solutions. Not limited to such considerations, the engineers and researchers are supposed to handle such matters in an economical methods.

Various methods are now available and that is why software-based programs have been developed in every single day to obtain more accurate and precise results within a short period of time compared to preceding versions or competitor’s ones.

Within the scope of this study, computational fluid dynamics (CFD) via the open source CFD software OpenFOAM is utilized in order to analyze the water hammer inside the pipelines because of sudden valve closures. Pipeline system is designed within a blockMesh utility thanks to OpenFOAM itself. Equations are based on compressible flow in hydraulics. That is why codes related to method of characteristics is implemented as a set of boundary conditions to observe pressure fluctuations in the OpenFOAM open source CFD software. Investigation of accuracy and robustness are handled depending on the mesh size used in analysis. In studies of analysis, valve is considered to be gate valve causing transient flow. Validation of the results are carried out by using experimental data done in the past.

2. MATERIAL AND METHOD

The principals and numerical methods to handle water hammer analysis inside pipeline are presented under this chapter. Exhaustive information about transient flow and modeling the subject analysis in terms of numerical and computational mesh are found to be important since the results needed to be valid experimentally and theoretically require practical and conceptual acknowledgement as a result. Technical fundamental for water hammer is developed on the basis of conventional relationship of physics or fluid mechanics. As an introduction comment before succeeding sections, do not lose sight of the fact that while the principals for water hammer helps researchers and engineers apprehend the basic design steps associated with pipeline, it also requires special time step distance relationship in order to maintain a satisfactory level of accuracy [17]. Consequently, OpenFOAM provides the researchers and engineers with illustrative results for studying transients flows in pipelines, representing water hammer, and showing the ways of calculation types based on boundary conditions.

2.1. Transient Flow Inside Pipes

Transient analysis of piping system is more important than analyzing the steady state operating conditions that researchers and engineers normally use as the basis for system design. As much as the rate of flow is changed swiftly, transient pressures are becoming more and more considerable since such disturbances along pipeline would automatically result in pressure waves travelling of large magnitude [18]. Those transient pressures happening along pipeline itself are superimposed on other piping structure. In general, transients are caused by the normal variation in flow patters of pipelines that trigger pump operations and valve manipulations. Other transients are namely defined as incidental or emergency operations. Types of transient are classified as two versions which are quasi-steady flow being characterized by absence of inertial or elastic effects on the flow behaviour, and true transient flow being characterized by the fluid's elasticity and fluid's inertia.

The first type of transient namely quasi-steady flow can be briefly described that the main characteristic of this type of transient flow is the gradual variation of discharges and pressure with time. Therefore, the flow appears to be steady if it is investigated under short time interval. For a typical transient example about quasi-steady flow, draininig of a large tank and reservoirs can be referred.

The second type of transient namely true transient flow can be referred to rigid-column flow when inertial effects are significant however compressibility effects of pipe and fluid are comperatively minor or negligible. Another saying, true transient flows must include fluid inertia and better to include the elasticity or compressibility of the fluid and the conduit. On the other hand, true transient flow will be called as water hammer when it comes to taking into account for elasticity effects of pipe and fluids in addition to the inertial effects [19]. The difference between column flow and water hammer is generally categorized that column flow handles accurately the oscillation of the water level in surge tanks since inertial effects are considered whereas elastic or compressibility effects are relatively ignored, and water hammer handles precisely the oscillation of the water pressures resulting from sudden closure of a valve due to inclusion of the elasticity of both pipe and the liquid during the analysis itself.

2.2. Water Hammer Inside Pipes

Water hammer inside pipes is caused by sudden flow rate changes and transient pressures shall be carefully considered to have safe operation, less maintanence service and longer service life of pipelines. Those sudden changes in pressure and rate of flow cause shock waves which periodically oscillate along the pipeline. In case shock waves faces with an obstacles such as valve, sound can be heard as hammering the pipeline. Due to the fact that hammering sound during this event, the situation is called as water hammer in fluid transient. If the moving fluid mass is suddenly retarded or accelerated, the pressure will rise or fall accordingly. Water hammer is often caused by maneuvers such as closing or opening of gates or valves, start-up or shut-down of pumps, regulation of pumps or turbines etc. Depending on such reasons, water hammer can result in excessive pressure, vacuum, vibration etc. that might impact the pipeline stability. General factors, which can affect the water hammer pressure in a pipe system are given as;

- The velocity of the fluid in the pipe
- The rate of change of velocity (e.g. closing time of valve)
- The compressibility of the water
- The physical layout of the pipe system

Rapid closing of a valve in a pipe system which does not have air relief device will result in unacceptable water hammer pressure. Water hammer can be controlled by means of e.g.

- Regulation of maximum rate of closing/opening of valves.
- Programmed start-up and shut-down of pumps.
- Bypass at pumps and valves.
- Pressure relief valves.
- Surge tanks and chambers.

Water hammer effects must be completely evaluated for the pipe system to make sure stability of the pipeline is technically found to be okay. Exact water hammer calculations are complicated and usually performed using specialized computer programs which are mostly based on commercial software. Exact water hammer calculations do, however, require extensive understanding of the problem and laborious mathematical calculations. Within succeeding pages, the basic principles of water hammer theory are explained for fundamental and general understanding.

As a theoretical case, complete and instantaneous valve closure is assumed. The pressure which rises right after sudden valve closing is investigated.

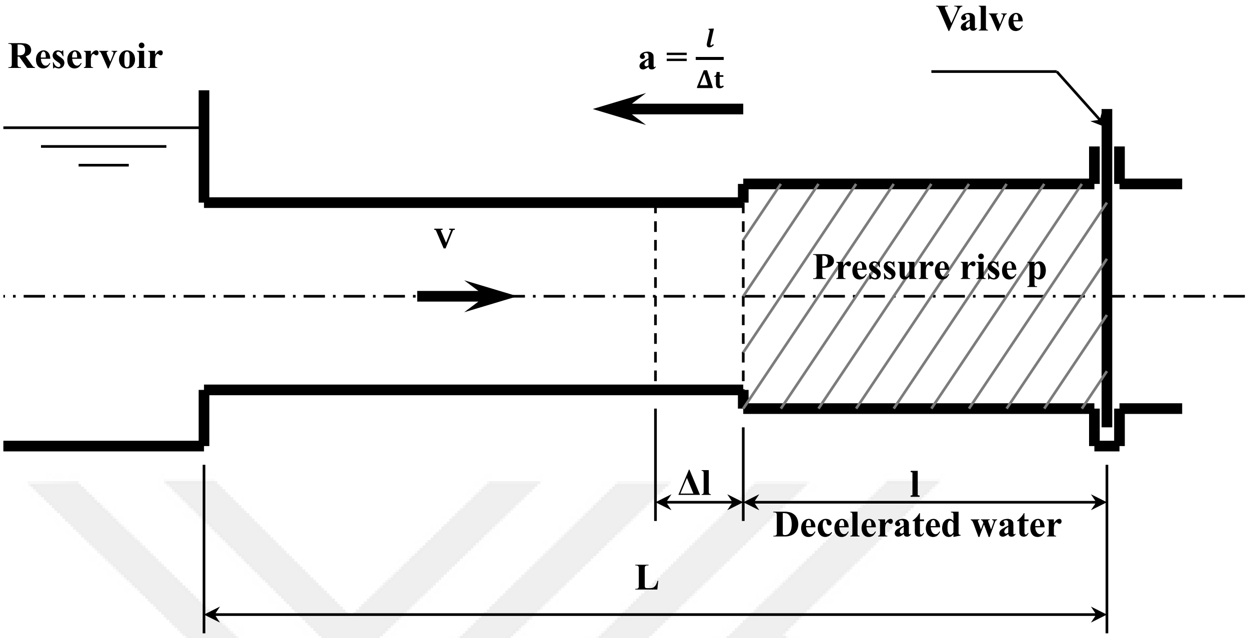


Figure 2.1. Pressure Rise in Pipeline Resulting From Sudden Valve Closing.

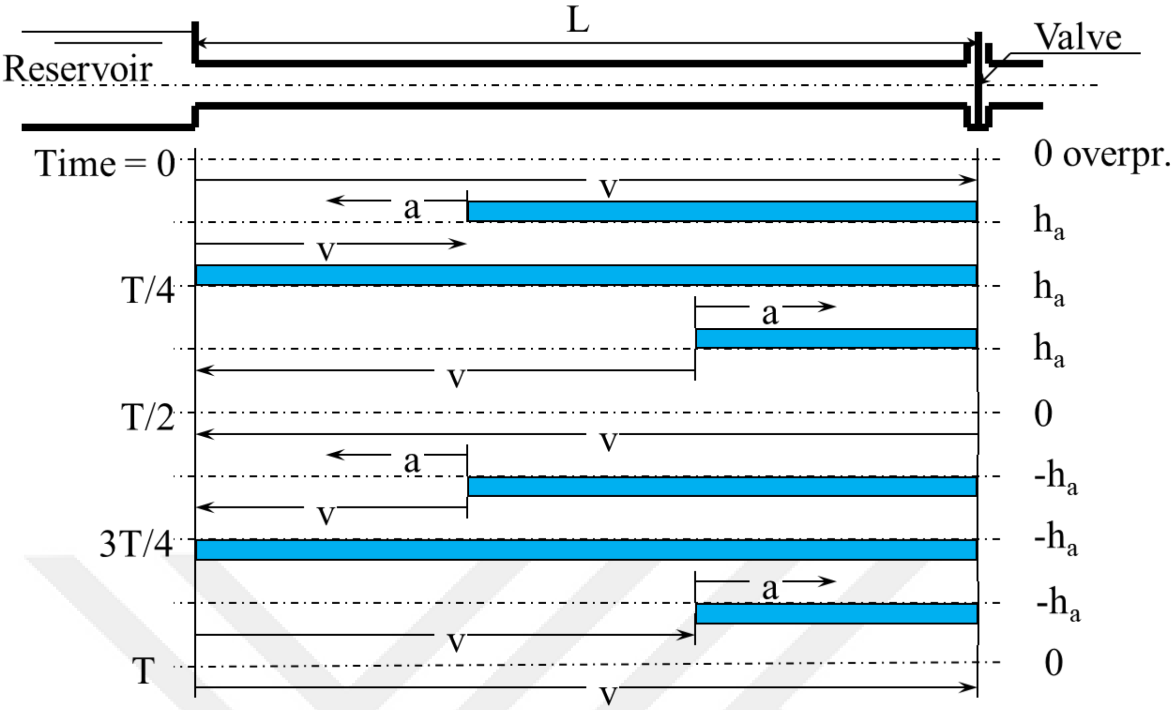
Obtaining extreme pressure heads in the pipe system requires utilizing the unsteady flow equations to be solved [19]. To be able to fully understand the fundamentals of water hammer, basic conventional correlations of physics or fluid mechanics are developed. Water hammer equations are applied to perform relevant calculations about the liquid unsteady flow inside pipeline [20].

2.2.1. Governing transient flow equations

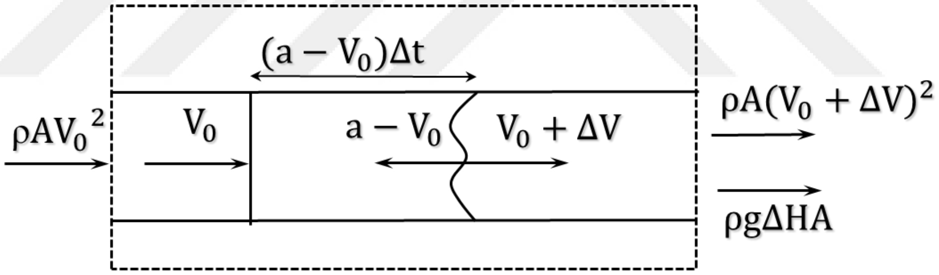
Water hammer equations are solved according to theories and methods under transient flow in the pipes. The momentum and continuity equations are solved numerically for the pressure and flow rates. The unsteady momentum equation is applied to a control volume shown as hatch area in Figure 2.1. The momentum and continuity equations are solved numerically for the pressures and flow rates.

As indicated in Figure 2.1, the interface between the overpressurized decelerated water column and the undisturbed flowing water, moves towards the reservoir at a rate of $a = \mathrm{l}/\Delta t$. This rate of movement of the pressure wave, a, has been given several different names in the literature such as pressure wave, surge wave celerity, speed of sound etc. Here we have mostly referred as “pressure wave”.

A steady state case in pipeline, water flow propagates in the right direction, Figure 2.2. At the beginning of instantaneous valve closure process, the flow velocity at the end of the pipeline swiftly increases [21]. At the time after closing, the pressure wave starts travelling all the way from the valve to the reservoir which is inlet. All the water column has come to a stop and has the overpressure, h_a. The water has no momentum any longer to maintain the overpressure and the pressure difference at the inlet reverses the water flow, starting at the inlet. The overpressure is relieved and the water is accelerated to have the same velocity as originally but in the opposite direction meaning that towards the valve. When the overpressure is relieved for all of the pipe and the water column is moving towards the reservoir at a velocity of $"-v"$. Due to the momentum of the water masses the water pressure falls at the valve to an underpressure of $"-h_a"$. After this half cycle, a negative pressure wave travels from the valve to the inlet and back again. Figure 2.2.(a) is created to show the complete water hammer transient cycle for better understanding about overpressure and pressure wave in a simple way. The water hammer (surge pressure) cycle will repeat itself but the pressure intensity will be reduced in time due to pipe friction. To sum things up, water will continue to flow into the valve until the kinetic energy of the water in the pipeline is increased. Pressure inside pipeline at place where the valve is located will continue to rise until the pressure is considerably greater than the pressure in the reservoir. A flow will begin to move in the opposite direction. Then, the period of this oscillation can be found.



a) Water Hammer Transient Cycle.



b) Control Volume.

Figure 2.2 General views on; a) water hammer transient cycle, b) control volume.

According to Newton’s second law to control volume of fluid, the momentum equation given by Equation 2.1 states for the control volume given in Figure 2.2.(b).

$$\gamma \Delta H A = \rho A(a - V_0)\Delta V + \rho A(V_0 + \Delta V)^2 - \rho A {V_0}^2 \qquad (2.1)$$

where,

γ : specific weight of fluid (N/m^3)

ΔH : head pressure change (m)

A : cross-sectional area of pipe (m^2)

ρ : mass density of fluid (kg/m^3)

a : wave speed (m/s)

V_0 : initial velocity (m/s)

ΔV : increment of flow velocity (m/s)

g : gravitational acceleration (m/s^2)

Accounting for all forces acting on the fluid within the control volume at a particular time must be specified in order to apply momentum equation whereas momentum which are in the direction of in and out of the control volume must also be evaluated accordingly. In Figure 2.2(b), the mass of fluid is represented by $\rho A(a - V_0)$, and the velocity change of this mass fluid per second is represeting the velocity change of the mass of fluid in one second is ΔV which is very small value therefore the term given by ΔV^2 can be neglected to be able to simplify the Equation 2.1.

$$\Delta H = -\frac{a\Delta V}{g}\left(1 + \frac{V_0}{a}\right) \approx -\frac{a\Delta V}{g} \tag{2.2}$$

As defined, ΔH stands for head pressure, sometimes called as piezometric head, and its negative sign refers to wave speed moving upstream while the positive sign in Equation 2.1 refers to wave speed moving downstream [22]. In practice, water hammer wave speed ranges between 100 m/s and 1400 m/s where as flow velocity of the fluid ranges from 1 m/s to 10 m/s [23]. For this reason, value of V_0/a is going to be very small. At the time when valve at downstream is closed, fluid veloctiy is surely going to be zero. Velocity change represented by ΔV will be equal to "$-V_0$" as a result of difference between fluid velocity, which is zero at fully valve closure, and initial velocity.

Theoretically, the time for valve closing should be shorther than the time of the reflected wave. The equation defined in Equation 2.2 is valid for the valve closing scenarios which are closing faster than the wave speed traveling from valve to reservoir and coming back to the valve location as a reflected wave. It is worthy mentioning that the equation is applied to the condition in which valve closing time, t_c, is shorter than wave speed travelling time which is found to be equal $2L/a$ where L represents the length of pipe.

As seen in Figure 2.1, pipe may be stretched by Δs due to suddenly closed valve depending on how the pipeline is restrained. Stretching of the pipe occurs in L/a seconds and it is assumed that velocity is to be $\Delta sa/L$. Therefore, ΔV corresponds to $\Delta sa/L - V_0$ and mass of fluid passes through the pipe is yielding $\rho AV_0L/a$ during the elapsed time of

L/a after the valve closure. This mass is stored within the pipe itself by stretching its cross-sectional area ΔA, and extension of the pipe Δs. Lastly, mass density of the liquid $\Delta\rho$ is increased as a result of compressible properties of the liquid. According to this situtation, equation can be pointed out by using continuity principle as given in Equation 2.3.

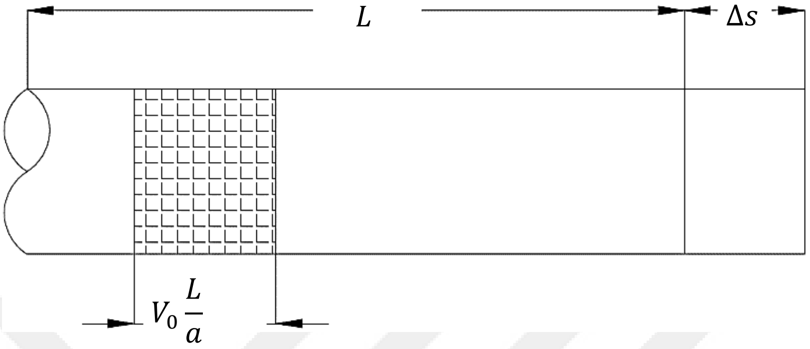


Figure 2.3 Conceptual Scheme of the Flow After Sudden Valve Closure.

where,

L	:	Length of the pipeline (m)
ΔA	:	Pipe cross-sectional area change (m^2)
Δs	:	Amount of pipe extension (m)
Δρ	:	Density change of the fluid under pressure (kg/m^3)

$$\rho A V_0 \frac{L}{a} = \rho L \Delta A + \rho A \Delta s + L A \Delta\rho \tag{2.3}$$

Following the solution of Equation 2.3 together with $\Delta V = \Delta s/L - V_0$, it is possible to eliminate V_0 and below equation is obtained.

$$-\frac{\Delta V}{a} = \frac{\Delta A}{A} + \frac{\Delta\rho}{\rho} \tag{2.4}$$

Combination of Equation 2.2 and 2.4 gives a new equation to be able to reduce wave speed equation.

$$a^2 = \frac{g\Delta H}{\frac{\Delta A}{A} + \frac{\Delta\rho}{\rho}} \tag{2.5}$$

In case of that the pipeline is restrained to be able to make Δs zero, Equation 2.5 would be rearranged with the bulk modulus of elasticity of the fluid, which is represented by K. As known, fluids occasionally depend on changes in relation to heat and temperature.

Meaning that the fluid usually expands provided that it is heated or depressiruzed, and the fluid usually contracts when it is cooled or pressurised. But the volume changes of different fluids are various. A fluid is going to contract when more pressure is applied and volume of the fluid will change because volume and pressure are inversely proportional. The negative sign in the definition of Equation 2.6 points out that K is a positive quantity at all [24]. It is worthy noting that mass of the fluid remains constant but its volume changes. In piping systems, small changes in liquids could cause water hammer and therefore Equation 2.6 provides how to calculate the bulk modulus of elasticity of fluid K.

$$K = \frac{\Delta\rho}{\frac{\Delta\rho}{\rho}} = -\frac{\Delta p}{\frac{\Delta\forall}{\forall}} \tag{2.6}$$

where the fractional volume change is represented by a term of $\Delta\forall/\forall$. The fractional volume change is substituted from Equation 2.5 as follows

$$a^2 = \frac{\frac{K}{\rho}}{1 + \frac{K}{A} + \frac{\Delta A}{\Delta\rho}} \tag{2.7}$$

Depending on the pipeline wall structure having a thick dimension, pressure rise due to water hammer may not create an important increase in cross-sectional area of the pipe. In such cases, pressure rise, which may not have pipe cross-sectional area increased, would be transferred to volume of the fluid to be compressed as a result of pressure. On that basis, wave speed inside the pipeline can be alternatively defined as per the types of the pipe materials – flexible pipes and thin walled pipes.

Equation 2.8 is valid for flexible pipes and Equation 2.9 is valid for thin walled pipes as follows

$$a \approx \sqrt{\frac{A}{\rho}\frac{\Delta\rho}{\Delta A}} \tag{2.8}$$

$$a = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1 + \left[\left(\frac{K}{E}\right)\left(\frac{D}{e}\right)\right] C_1}} \tag{2.9}$$

Where C defines a constant value and it refers to the pipe conditions. Meaning that C is a dimensionless coefficient depending on the type of connections along pipeline. In case of pipe is designed to anchor at its upstream end, formulation of $C = 1 - \mu/2$ is utilised in Equation 2.9. When it comes to pipe is completely anchored against axial movements, formulation of $C = 1 - \mu^2$ is used. If the pipe is designed to allow expansion throughout the pipeline, it is considered that $C = 1$. Meanwhile, μ represents Poisson's ratio of the pipe material [25].

2.2.2. Continuity and momentum equations

Trying to achieve hydraulic values inside pipelines such as velocity V, discharge flow rate Q, pressure P, or piezometric head H at a desired time would be significant during a transient event namely water hammer analysis. To obtain such values by means of continuity and momentum equations, derivation of the continuity equation and law of mass conservation are going to be applied accordingly. Momentum equation meaning that equation of motion is derived from a control volume of conical tube as shown in Figure 2.4. In equations for both momentum and continuity, x and t are independent variables whereas P and V are dependent ones.

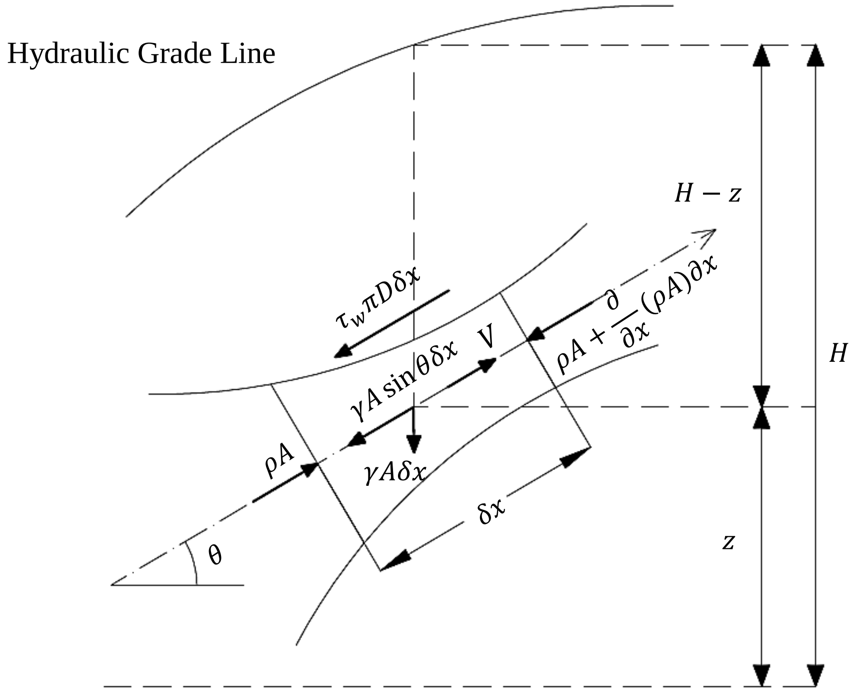


Figure 2.4 Momentum Equation in Pipeline.

As a result of summation of all forces exerting on the control volume (CV), it is obviously said that the summation is equal to summation of momentum in the control volume and momentum flux through the control surface-1 and the control surface-2. In Equation 2.10, sum of all forces along x direction is shown.

$$\Sigma F_x = PA - \left[PA + \frac{\partial}{\partial x}(PA)\delta x\right] - \tau_w \pi D \delta x - \rho g A \sin\theta\, \delta x \tag{2.10}$$

where τ_w represents wall shear stress in N/m^2.

The rate of change of linear momentum in the control volume is given as follows

$$\frac{\partial}{\partial t}\int_{C.V.} \rho V d\forall = \frac{\partial}{\partial t}(\rho V A)\delta x \tag{2.11}$$

The rate of linear momentum flux through the control surface is given as follows

$$\frac{\partial}{\partial x}(\rho V^2 A)\delta x \tag{2.12}$$

Rearranging the momentum equation gives

$$-\left(A\frac{\partial P}{\partial x} + \tau_w \pi D + \rho g A \sin\theta\right)\delta x = \frac{\partial}{\partial t}(\rho V A)\delta x + \frac{\partial}{\partial x}(\rho V^2 A)\delta x \tag{2.13}$$

To end up with a so called equation of motion, above equation is divided by δx and simplified by arranging the equation after it is divided by ρA.

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x} + g\sin\theta + \frac{4\tau_w}{\rho D} = 0 \tag{2.13}$$

As briefed previously, continuity equation is a derivation of the law of conservation of mass. In Figure 2.5, it is shown that the control volume, which is also used in momentum equation, is taken into account. Fluid inside the control volume is in a form of single phase being liquid and compressible, conduit walls are elastic. This equation states that the change of mass inside the control volume corresponds to the mass flux through the control surface sections.

Continuity equation is given by Equation 2.14.

$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \rho a^2\frac{\partial V}{\partial x} = 0 \tag{2.14}$$

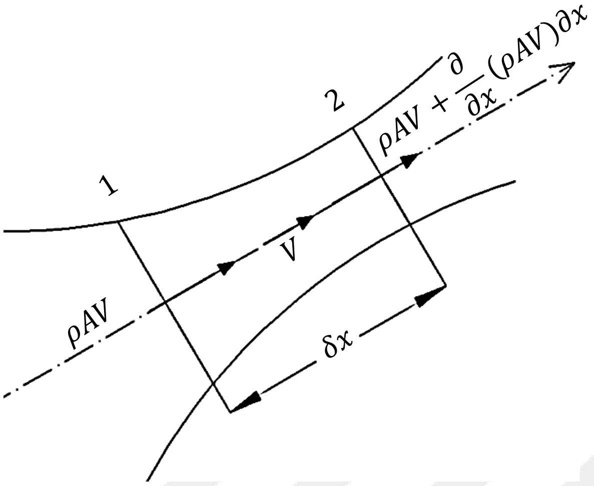


Figure 2.5 Continuity Equation in Pipeline.

2.3. Numerical Procedure and Computational Mesh

In this study, water hammer analysis is performed using computational fluid dynamics via the open source CFD software OpenFOAM. This chapter contains instructions on how OpenFOAM solves water hammer analysis inside the pipeline within its transient solver named as sonicLiquidFoam which is defined as transient solver for trans-sonic/supersonic, laminar flow of a compressible liquid [26]. Furthermore, meshing structures of the control volumes of the geometries are described in order to understand decomposing geometries.

2.3.1. SonicLiquidFoam

The sonicLiquidFoam is a solver handling the compressible flow of a liquid by assuming that the fluid obeys the rule for barotropic equation of state meaning that density of the fluid is a dependent of pressure only without taking temperature into account since the temperature is assumed to be constant [27]. The pressure and density are linearly correlated by the equation of state which is given by Equation 2.15.

$$\rho = \rho_0 + \psi(p - p_0) \tag{2.15}$$

where ψ stands for derivative of density according to pressure and it is accepted that it remains constant. Likewise, ρ_0 and and p_0 are referring to reference state and both of them are constant and these values are introduced as input through the file of thermodynamicProperties under OpenFOAM. The sonicLiquidFoam is working based on the principles of an algorithm namely PIMPLE which is a combination of SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) and PISO (Pressure Implicit with Splitting of Operators). The relevant flow chart of the PIMPLE algorithm over a time step can be reviewed in Figure 2.6.

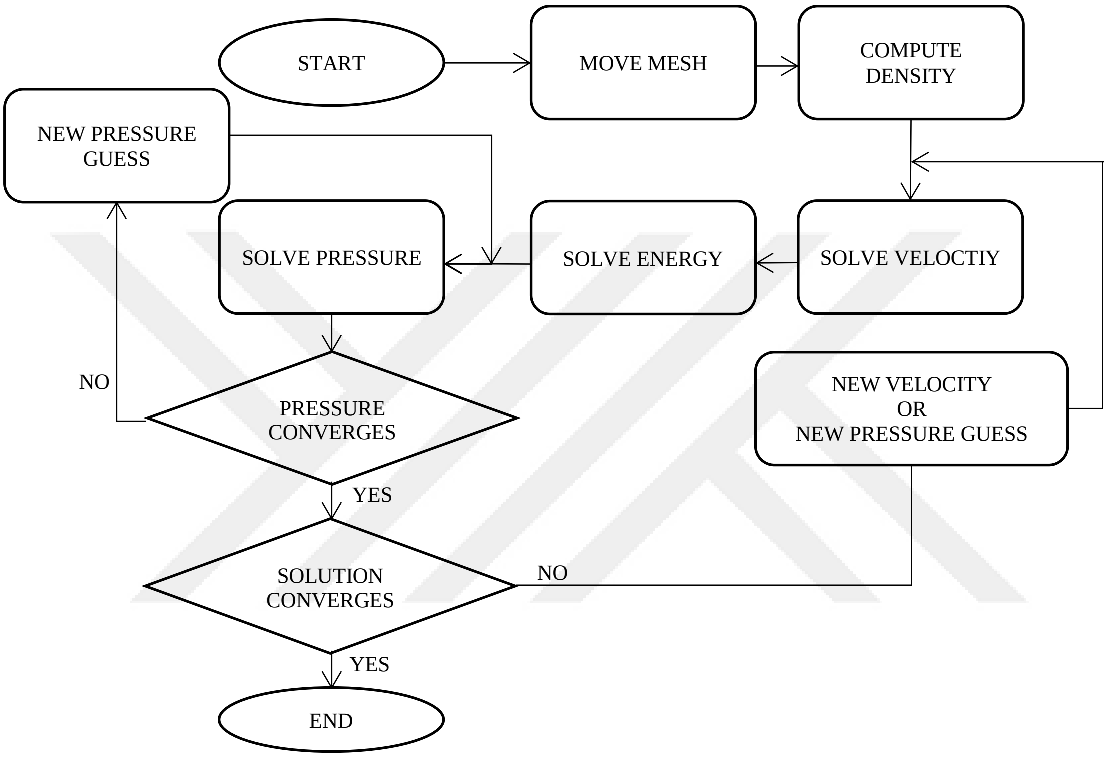


Figure 2.6 PIMPLE algorithm flowchart.

Within the capability of the program, which is handling transient matters thanks to sonicLiquidFoam, it benefits from PISO algorithm to forward in time in order to converge. Recall from the Courant number, it is a measurement of how much information proceeds within a computational grid cell in a period of time-step, computational grid cell and time-step are represented by Δx and Δt respectively. Water hammer analysis by means of OpenFOAM would require to utilize the solver which is valid for compressible fluids in transient problems since the solver is based on density based solver. Thus it would be important to know the fact that the Courant number has to be considered to achieve results smoothly and without facing a failed calculation due to the Courant number itself because the program does not allows user to continue the calculations with the Courant number as a value of 4 or above. The Courant number is generally limited to guarantee numerical stability of the solution [28]. In addition, the Courant number is dimensionless unit, and in order to maintain a Courant number less than 4, the time step must be reduced accordingly, and better results are only obtained provided that the Courant number is less than 1. The Courant number is shown how to calculate in Equation 2.16.

$$C \equiv \frac{u\Delta t}{\Delta x} \tag{2.16}$$

where,

C : Courant number (-)

Δt : Time-step (second)

Δx : Spacing of the grid in the numerical model (m)

Within succeeding sections, more details about how sonicLiquidFoam solves the problems are going to be presented and principal of solution steps are shown.

Computation requires time step to be identified and then the computation is initially started. Firstly continuity equation is sorted out according to Equation 2.17.

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho u_i}{\partial x_i} = 0 \tag{2.17}$$

Applying PIMPLE loop to solve very small time-steps during the cumputation – it is worthy mentioning that PIMPLE loop is an algorithm which is combination of PISO (Pressure Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms and those are iterative solvers. Then, solving for momentum equation is started as indicated in Equation 2.18.

$$\frac{\partial\rho u_i}{\partial t}\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) - \frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}\right) = \frac{\partial p}{\partial x_i} \tag{2.18}$$

Following solving equations for momentum, begin the pressure corrector loop as defined located at $FOAM_SOLVERS/compressible/sonicFoam/sonicLiquidFoam in Open-FOAM. In the case directory, correction for the pressure is applied as per the number of times specified in the nCorrectors criteria under system/fvSolution file. Repeating solving equations for momentum and trying the pressure corrector loop the number of times stated as nOuterCorrectors in the system/fvSolution up to the level in which the conditions identified in the residualControl are reached out. For Equation 2.15, the variation in density shall be linearized. Finally proceeding to the next time-step to look for possible convergence if any.

2.3.2. Computational Mesh

Better analysis results surely comes from the quality of mesh created when it comes to accurate and precise solutions from the analysis. Thanks to open source software, today it is also possible to create the relevant domains of the mesh shortly and comperatively less costly using such programs. For these reasons, mesh structures to be examined as per boundary conditions are here described in detail to provide exhaustive information about the analysis itself.

Within the study of analysis of water hammer, five different models have been created to be able to understand water hammer pressure inside different cases, thus the details of the cases can be seen in Table 2.1.

First case to be analyzed is about an experiment, which was handled in at the Instituto Superior Técnico of Lisbon in Portugal, and this experiment shows us a typical pipeline system comprising of one reservoir and valve in order to examine the effects of water hammer in case instantaneous valve closure [29]. Since the first analysis is an example of verification study for the experiment by Soares, the details associated with mesh structure, case itself, and geometrical dimensions are initially illustrated in Table 2.1.

Table 2.1 Case specification of tested models.

Name of Case	Diameter of Pipeline [mm]	Length of Pipeline [m]	Description
1	20	15.22	Straight pipeline having 20 mm in diameter and 15.22 m long in horizontal direction. Plus, reservoir and valve are available along the pipeline.
2	20	15.22	Curvilinear pipeline having 20 mm in diameter and 15.22 m long in equally horizontal and vertical directions. Plus, one 90° elbow, reservoir and valve are considered in analysis.

3	15 - 20	15.22	Pipeline comprises of header and branch diameters as 20 mm and 15 mm respectively. It is 15.22 m long. Plus, one t-junction, reservoir and valve are considerd in analysis. It is worthy noting that branch pipe is deemed to be surge tank.
4	22	37	Straight pipeline having 22 mm in diameter and 37 m long in horizontal direction. Plus, reservoir and valve are available along the pipeline. Mesh structure is comperatively less than fifth case.
5	22	37	Straight pipeline having 22 mm in diameter and 37 m long in horizontal direction. Plus, reservoir and valve are available along the pipeline.

Creating a case with geometry and mesh is an important subordinate step in CFD analysis for accurate and precise results. Meshing, however, might take considerable long time due to some reasons such as complexity of geometries (long pipe to decompose in a fine way), insufficient computer capacity etc. By using OpenFOAM, there is also another useful way to decompose the domain of the geometries into a set of one or more three dimensional hexahedral blocks thanks to blockMesh utility. Quality of meshes created for CFD analysis can also be checked via OpenFOAM itself by a command named as "checkMesh". Furthermore, details of the corresponding meshes can also be fully reviewed by using a command of "checkMesh – allTopology –allGeometry".

In Figure 2.6, geometry and mesh structure of the each case under this thesis study can be reviewed.

Table 2.2 Mesh data obtained by means of "checkMesh".

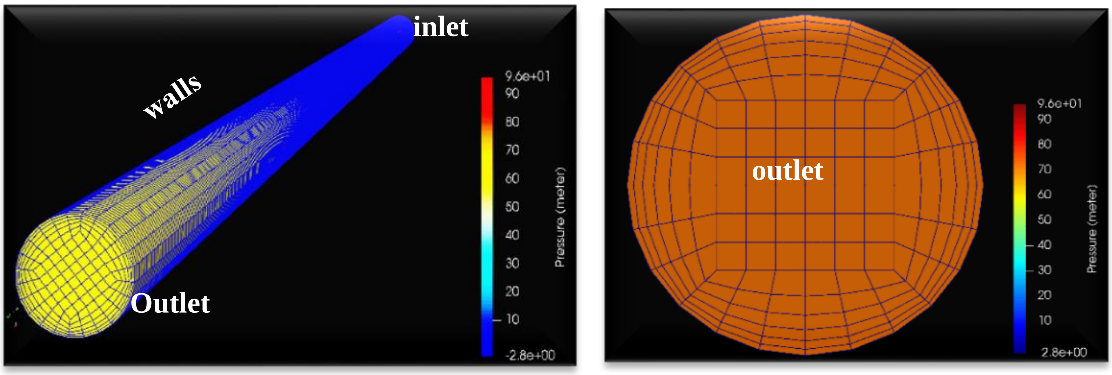
Description	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Points	96.693	242.484	102.028	50.887	149.745
Faces	276.180	710.969	296.847	146.720	437.520

Internal faces	263.820	696.031	288.467	141.280	426.480
Hexahedra cells	90.000	234.500	97.500	48.000	144.000
Boundary patches	3	3	4	3	3
Faces inlet	180	469	1.125	320	720
Face walls	12.000	14.000	6.131	4.800	9.600
Faces outlet	180	469	1.125	320	720
Max cell opennes	1,83E-16	9,09E-15	1,51E-16	6,38E-16	3,99E-16
Minimum face area	6,54E-07	7,34E-08	1,36E-09	3,79E-07	1,65E-07
Maximum face area	7,95E-05	6,89E-05	0,000199	0,000532	0,000266
Min volume	1,99E-08	2,13E-09	9,03E-10	9,35E-08	3,06E-08
Max volume	8,46E-08	8,03E-08	1,03E-07	4,78E-07	1,59E-07
Total volume	0,004727	0,004508	0,004798	0,013979	0,014029
Max non-orthogonality	18,25	23,58	78,70	22,79	29,20
Average non-orthogonality	4,32	4,62	6,54	4,68	5,18
Nb. severely non-orthogonal faces	-	-	-	-	-
Max skewness	1,26	2,13	4,87	1,18	1,17

According to Table 2.2, it is obviously seen that maximum non-orhogonalities of the geometries are generally more than 30°. It is worthy mentioning that maximum non-orthogonality is supposed to be less than 30° in order to end up with an orthogonal mesh structure and the boundary openness is not supposed to be larger than the value of 10^{-16} which is approximately equals to zero. On the contrary, average non-orthogonality for all cases is less than 30°.

2.3.3. Grid Generation and Boundary Conditions

In analysis, the cases are to have some certain grid depending on the geometry complexity and analysis method. In Figure 2.7, one of experiments for water hammer analysis, which is going to be used as verification study, is shown how meshing and geometry of pipeline looks like.



(a) (b)

Figure 2.7 Generated grid according to study of Soares et al. [28]; a) isometric view b) front view.

Visualization of mesh structures designed for analysis has been obtained from ParaView, which is quite useful when it comes to visual illustration of CFD studies.

To see mesh dependency, some additional analysis are completed by using a different experiment which was done by Bergant et al [30]. In these analysis, mesh structures for the pipes are 36, 48 and 144 thousands respectively. Their pressure oscillation plots are given in Figure 2.8 and it is literally said that nearly no deviation is found between the relevant graphs. To see experimental data used in analysis, Table 2.3 can be reviewed.

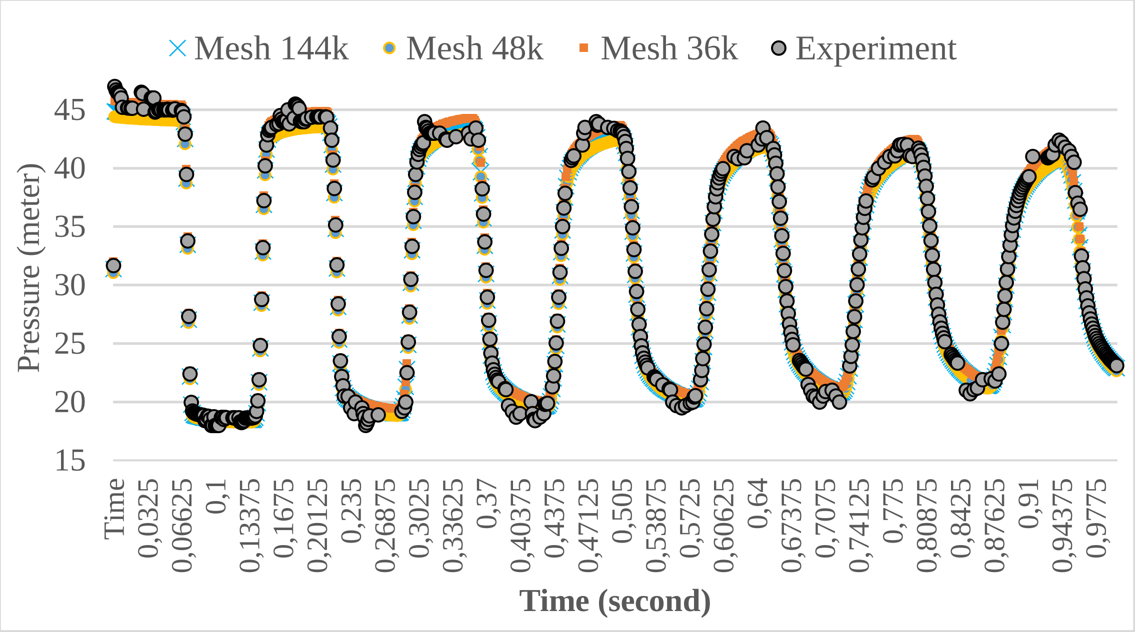


Figure 2.8 Mesh dependency check.

Table 2.3 Experimental information – Bergant et al.

Parameter	**Value**
Pipe Length (m)	37
Pipe Internal Diameter (mm)	22
Valve Closure Time (ms)	0.009
Initial Fluid Velocity (m/s)	0.1
Reservoir Head (m)	32

According to the test rig of experiments by Soares, two types of studies had been completed. These experiments are about low speed flow for fluid and high speed flow for fluid. In case low velocity profile inside the pipeline, water hammer can be analyzed in a single phase water hammer. Within this study to show experimental data and theooretical data are complying, lowest velocity causing a single phase water hammer will be taken into account in analysis. Table 2.4 shows the relevant experimental parameters used in this thesis [31].

Table 2.4 Experimental information - Soares.

Parameter	**Value**
Pipe Length (m)	15.22
Pipe Internal Diameter (mm)	20
Valve Closure Time (ms)	16.50
Initial Fluid Velocity (m/s)	0.423
Young Modulus (GPa)	120
Reservoir Head (m)	46

As the valve starts closing to create water hammer, it is surely that valve is going to be closed gradually and this physical valve closing is not being realised unless dynamic meshing is used. But, it is also possible to consider the relationship between velocity and mass flow rate at pipe’s outlet. By doing so, mass flow at outlet section of the pipe could be controlled accordingly. This is the main reason why massFlowRate command has been utilized to fulfill water hammer analysis. Boundary condition based on massFlowRate can be seen in Table 2.5 which showing time variable mass flow rates.

Table 2.5 Boundary condition.

massFlowRate	Value
type	flowRateOutletVelocity
massFlowRate table	{ ((0.000 0.14) (0.005 0.13) (0.010 0.12) (0.020 0.00)
rhouOutlet	1000;); }

2.3.4. Validation

Water hammer by means of OpenFOAM that used in this study, has not been experimentally investigated. In order to verify the study and cases used in OpenFOAM, experiment, which was done by Soares in 2015, was utilized in terms of geometry, pipe profile, and experimental results. Actually, Soares has performed two types of tests – first one is an experiment about water hammer based on low speed fluid velocity with no cavitation model, and second one is based on comperatively higher velocity and with cavitation model. On that basis, first experiment which was low speed and no cavitation model has been considerd in validation studies. In Figure 2.9, experimental study and CFD calculation is easily compared – this plot consists of pressure oscillations at outlet of the pipeline. Comparison graph was obtained from the OpenFOAM analysis based on Case Number 1 and its boundary conditions can be checked from Table 3.1.

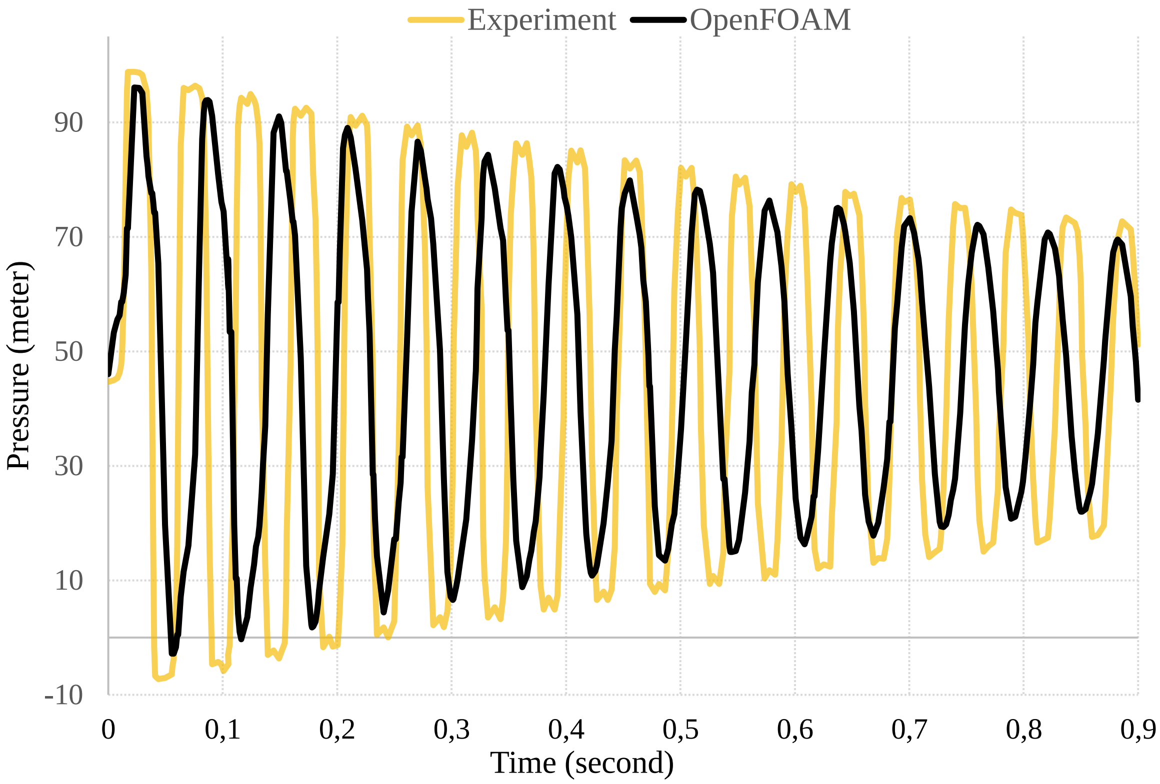


Figure 2.9 Comparison between experimental data and OpenFOAM results of Case 1# (Pressure at outlet with respect to time).

Based on the fact that the results from experiment and OpenFOAM calculations as seen above, it is ended up with a slight difference, but the profile drawn is more or less same just it downs a bit for OpenFOAM calculations. It is worthy noting that calculations catch the points where direction changes.

3. RESULTS

In this study, water hammer analysis using open source CFD software program was studied by observing pressure oscillations caused by sudden valve closures which were defined by the users/programmer to arrange the speed of the closing valve. Depending on the pipelines and size of the control volumes, the results of the corresponding cases were calculated and summarised. The CFD results of the cases together with calculation times are shown in Table 3.1.

Table 3.1 Results of the cases.

Description	Max. Pressure (meter)	Min. Pressure (meter)	Calculation Time (second)	Boundary Conditions
Case 1# Ø20mm L=15.22m Straight Pipe	96.09	-2.78	17.483	Pressure: Inlet→fixedValue Outlet→zeroGradient Velocity: Inlet→ zeroGradient Outlet→massFlowRate Valve Closing ($t_c = 0.02$ seconds)
Case 2# Ø20mm L=15.22m Pipe and one 90° Elbow	108.05	-.2.85	137.961	Pressure: Inlet→fixedValue Outlet→zeroGradient Velocity: Inlet→ zeroGradient Outlet→massFlowRate Valve Closing ($t_c = 0.02$ seconds)
Case 3# Ø20mm L=15.22m Pipe and one T-junction	94.28	-2.50	87.022	Pressure: Inlet→fixedValue Outlet→zeroGradient Velocity: Inlet→ zeroGradient Outlet→massFlowRate Valve Closing ($t_c = 0.02$ seconds)
Case 4# Ø22mm L=37m Straight Pipe	45.77	18.82	14.109	Pressure: Inlet→fixedValue Outlet→zeroGradient Velocity: Inlet→ zeroGradient Outlet→massFlowRate Valve Closing ($t_c = 0.009$ seconds)

Case 5# Ø22mm L=37m Straight Pipe	45.77	18.82	45.454	Pressure: Inlet→fixedValue Outlet→zeroGradient Velocity: Inlet→ zeroGradient Outlet→massFlowRate Valve Closing (t_c = 0.009 seconds)

At first case, straight pipe is created to observe water hammer by sudden closing $t_c = 0.02sec$ of a valve located at pipe outlet. The mesh structure of the geometry and pressure oscillation just after valve closing are shown as follows.

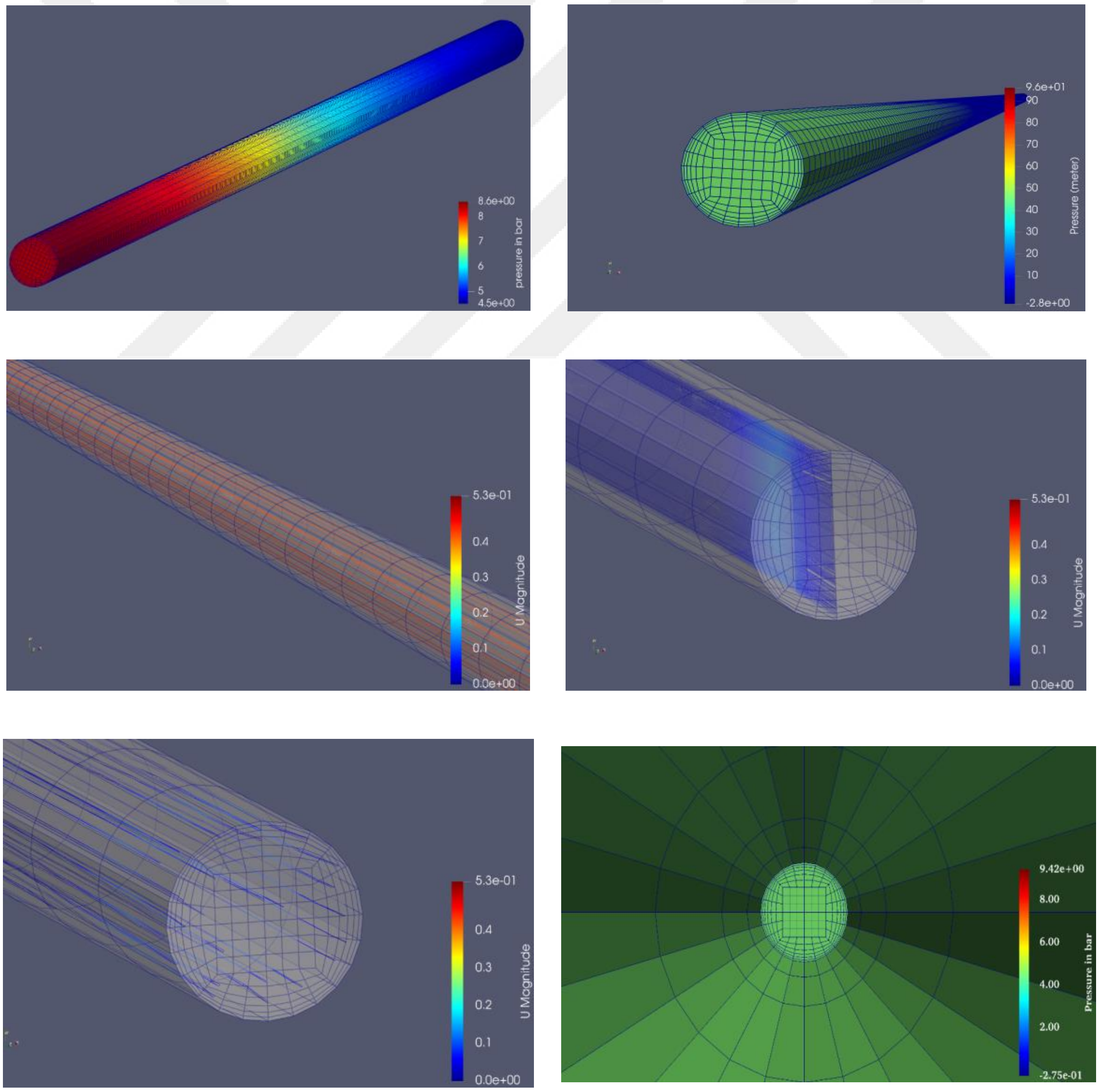
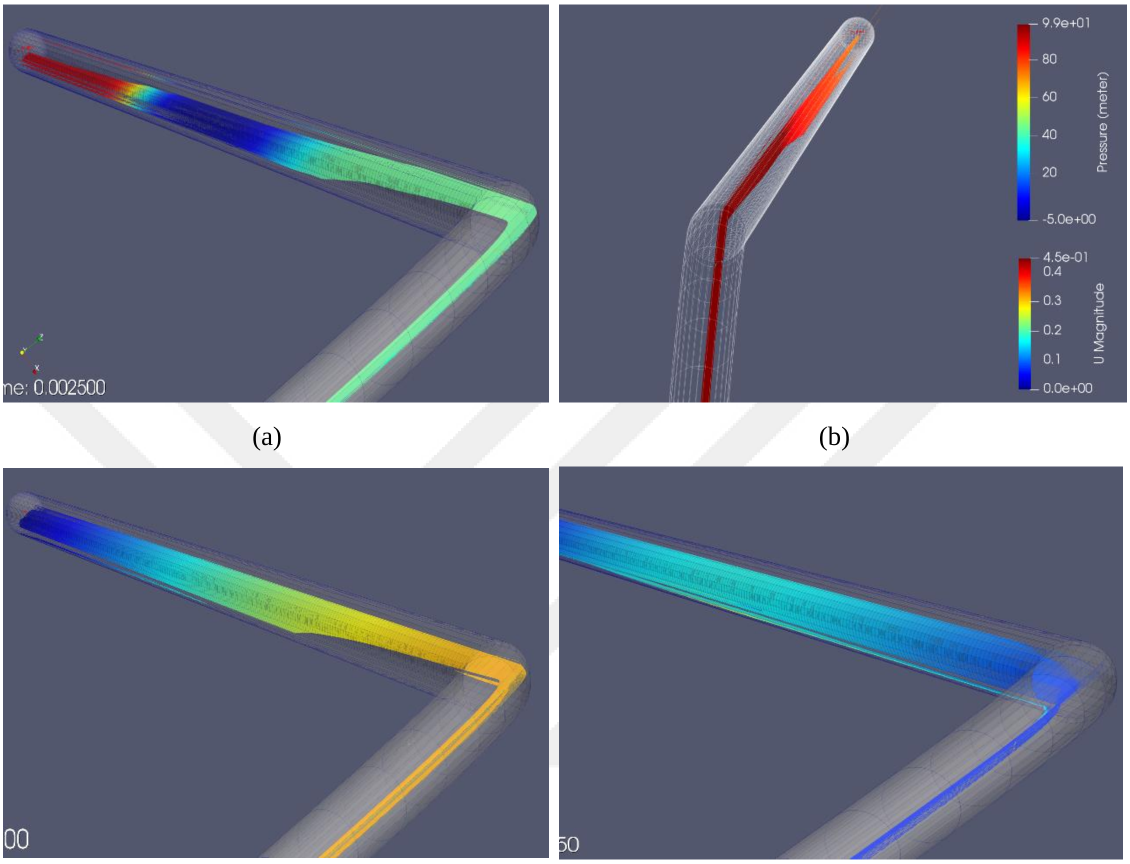


Figure 3.1 Mesh domain belonging to Case 1

At second case, one elbow having 90° angle is considered along the pipeline to see water hammer pressure magnitude and to observe wave speed reflections during the analysis. On that basis, Figure 3.2 is created to see streamlines along the pipeline.

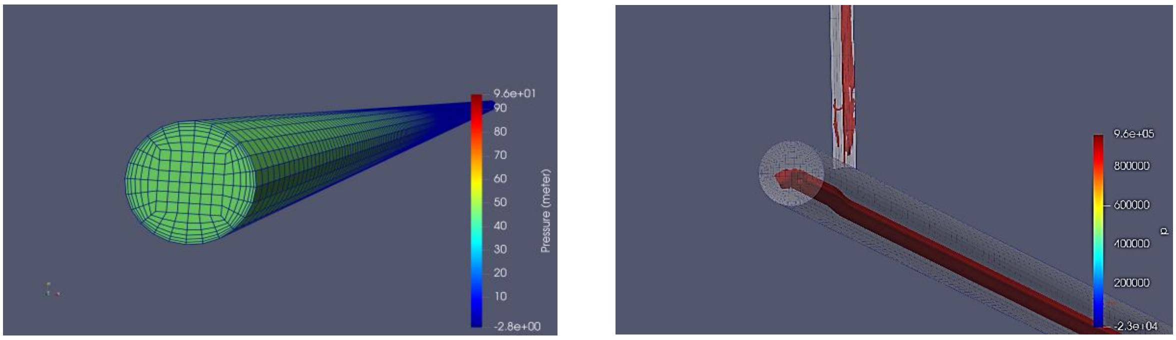


(a) (b)

(c) (d)

Figure 3.2 Streamlines that colored with velocity magnitude a) General layout b) Zoom in view nearby elbow c) Pressure and velocity ranges d) Another streamline view nearby elbow

At third case, one t-junction is contempleted to see water hammer effects in case there is a way for excessive pressure to relieve the pipeline. In this case, nozzle pipeline is attached to main pipe diameter to relieve excessive pressure due to water hammer by means of this nozzle itself as shown in Figure 3.3. According to Figure 3.4, it shows that pressure at outlet due to water hammer is alleviated thanks to nozzle existence since it has apparently taken certain amount of pressure as expected.



(a) (b)

Figure 3.3 First case (straight pipe) and third case (t-junction pipe)

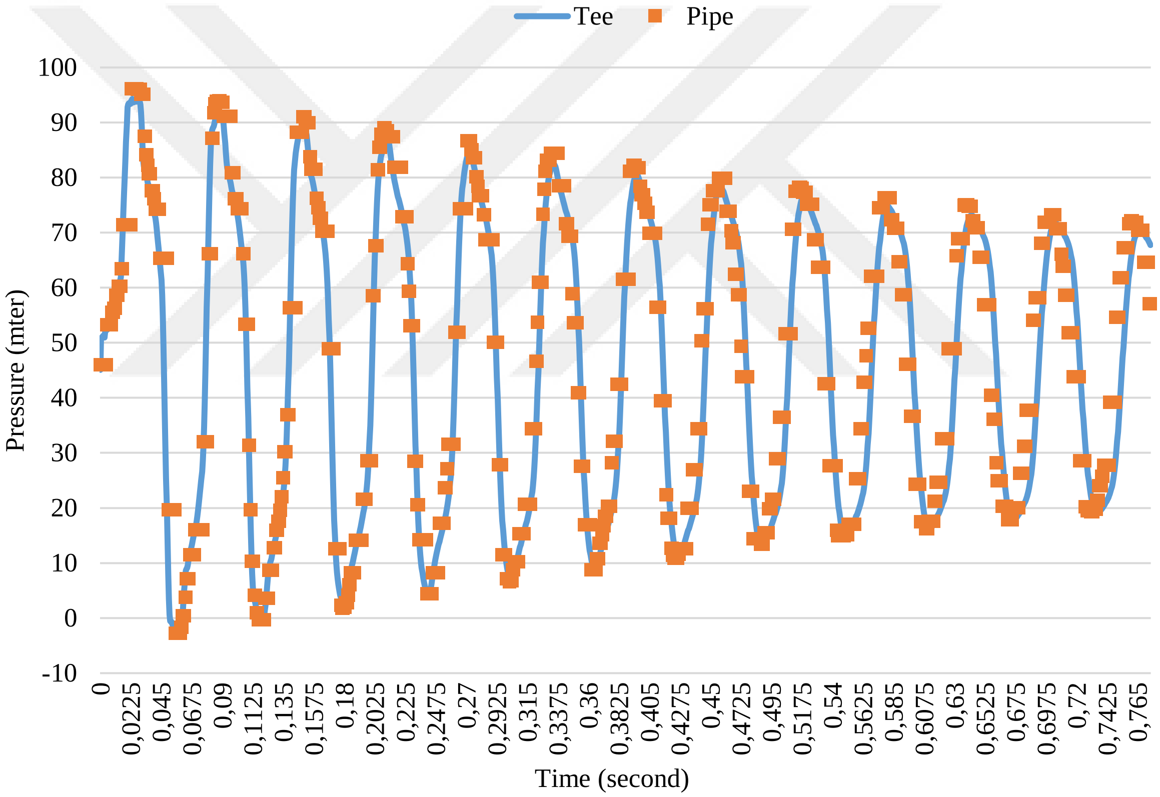


Figure 3.4 Comparison chart between Case 1# (straight pipe) and Case 3# (t-junction pipe)

4. CONCLUSION

In this study, water hammer inside pipeline numerically analyzed by using open source CFD software OpenFOAM and its subordinate utilities such as blockMesh.

As known, sonicLiquidFoam, which is a transient solver for compressible liquids, does not have turbulence but it is anyway useful to calculate water hammer analysis for the pipelines at which flows are in laminar version and cavitation effect is not considered. Furthermore, time varying flow rate at outlet of pipeline has been identified to be able to consider valve as moving since flow rate has been successfully introduced into the boundary conditions as if the valve was closing as much as the time of how the user has entered.

One of the cases performed under this study is about to check whether water hammer pressure could be alleviated by using pipe modification or not. On that basis nozzle attachment is placed at proximity to outlet of the pipeline where the valve is present. Thanks to close placing nearby valve, maximum pressure generated right after sudden valve closure has been managed to decrease from 96.09 meter in pressure to 94.28 meter in pressure as expected according to results written in Table 3.1. This means that pipeline routing could be alternatively designed and modified in order to have a pipeline deal with less water hammer. Last but not least, OpenFOAM is quite preferable method in terms of capacity since complex pipeline including elbow, tee etc. requires more mathematical operations to calculate maximum pressure inside the pipelines. Compared to other solutions methods such as MOC when it comes to analysis of water hammer for elbow, t-juntion pipe, OpenFOAM can be preferred in such cases due to the fact that it is more flexible in creating complex control volumes and less cost in solving the equations required for water hammer.

In conclusion, water hammer pressure in pipelines can be calculated using open source softwares and the results of such calculations can be verified with relevant experiments provided that the flow inside the pipeline is based on laminar and no cavitation.

4.1. Future Study

In this study, water hammer analysis is completed without any dynamic movement on the valve itself, two phase case and turbulence are not considered throughout the analysis since the software does not currently have such capability unless it is developed.

In addition to above-mentioned matters, it is possible to include pipe elasticity in case water hammer since the pipeline will be expanded at the time water hammer starts. Elasticity of the pipe and water hammer analysis can be modelled as coupling system to completely run the analysis for realistic water hammer casses. Also, it is possible to include pump geometry and pump characteristics during the water hammer analysis as a future study. By doing so, it will be great opportunity to model the system as the way the user can observe the pump situation in case of water hammer

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CURRICULUM VITAE

Current Occupation **Design Engineer at SUBOR GRP PIPE INDUSTRY**			
Candidate information	1. Name of candidate **ANIL ISTANBULLU** 	2. Contact Info Phone : +90549 796 4080 Email : anil.istanbullu@gmail.com Adress: Güllübalar Mah. Pendik / Istanbul, Turkey Linkedin : https://tr.linkedin.com/in/an%C4%B1l-istanbullu-95560660	3. Date of birth : 18.07.1992 Place of birth : Çorum, Turkey
	4. Educational Information B.S. Mechanical Engineering (English) at Marmara University, Istanbul in Turkey */ 2010 – 2015 /* *During my academic life I have taken many courses and some of them interests me most are Thermodynamics, Fluid Mechanics, Heat Transfer, Manufacturing Processes, Machine Design, Internal Combustion Engine, and Experimental Methods with sensors.*		
Present employment	5. Name of employer SUBOR BORU SANAYİ ve TİCARET A.Ş.		
	Address of employer Acıbadem Mahallesi Sokullu Sokak No:12 Kadıköy, Istanbul / Turkey		
	Telephone +90216 474 19 00		
	Fax +90216 474 19 14		
	Proposed Job title of candidate is Senior Mechanical Engineer		Experience duration: … >**4 Years**

From	*To*	*Company / Project / Position / Relevant technical and management*
2015	…	SUBOR BORU SANAYİ ve TİCARET A.Ş. Engineering Department – Mechanical Design Engineer for Glass Reinforced Polyester Pipes (GRP) Having a strong background in design, project management, product design, risk assessment and integrated quality and control documentation management as per ISO 9001, ISO 14001 and OHSAS 18001 norms. Overall Responsibilities: – Designing GRP pipes as per each project requirement and international standards. – Stress analysis by CAESAR II and Water Hammer Calculation by PIPENET in scope of projects.

		– Managing and monitoring risks associated with piping system interfaces and developed risk mitigations plans via documented schedule subtasks. Evaluation of subcontractor bids, comparisons with other subcontractors. – Establishing a single point of contact position and communicating the information and developing presentations regarding my design between client and client technical assistances (design team) to address the progress with deliverables. – Election of suitable chemical materials used in pipes production according to ASTM, Know-How and other international and local specifications. – Applying design rules and meeting system design specification requirements. – Verifying design, providing evidence that product meets its requirements via design verification plan. – Proceeding value management actions to obtain cost reduction for the pipes to be competitive and reliable. – Making benchmark of GRP pipe competitors in market when it comes to sales and market for nearly identical products. – Improvement and development of maintenance / installation methods. – Tracking-monitoring warranty status of the products in the field and take required actions to improve warranty indicators. – Drawing and 3D modeling release with fundamental knowledge of GD&T with AutoCAD. – Reporting the progress of projects with the management of my clients and counterparts in client's design team with weekly/monthly meetings via online meeting and/or regular on-site visits. – Liaising with representatives of clients, supporting the client activities in any bidding period when it comes to use of GRP pipes, and participating in proposing/modifying specifications complying with international standards and codes such as ASME, AWWA, EN and ISO. – Providing cost reduction methods and leading production team's activities within the various projects. – Getting involved in searching new possible markets with sales and marketing deparment in African Countries such as Kenya, Uganda and Rwanda and conducting technical seminars to inform attendants about deep knowledge about the products. *Note: Certified by DQS GmbH as an Internal Auditor.*
2014	2014	EKMEKÇİOĞULLARI GROUP Çorum in Turkey By the means of my internship, I could repeat my knowledge gained from school and realized what I will avail myself of them. In addition to this, I found a facility to develop my practical skill. This trainee program has led me to wide my acknowledgement about production with respect to order, sales service, transportation of goods, after-sales service, quality management and arranging draft commercial and technical e-mails for local and international clients/authorities/designers/suppliers. Follow-up components, assembly, packing and transporting of products. Duration: 30 work days in Summer Season
2013	2013	DİSAN HİDROLİK MAKİNA SANAYİ ve LTD. ŞTİ. Yenibosna, Istanbul in Turkey Investigations for assembly department at DİSAN HİDROLİK MAKİNA SANAYİ ve LTD. ŞTİ. Follow-up components, assembly, packing and transporting of products. Preparing 3D component drawings for company's products which are mainly conveying systems for recycling.

Computer and Software Skills	
OPENFOAM	Water hammer calculation inside the pipelines according to various pump and valve scenarios, plotting pipeline elevation summary graph, solutions preventing pipeline from water hammer.
CAESAR II	Stress and flexibility analysis based on loads such as soil, seismic, wind and occasional loads, determining optimum support type and their locations on pipeline
MATLAB	Able to plot complex equations such as differential equation including method of characteristics, preparing GUI interface for user-friendly purposes, calculations based on basic algorithm cases.
SOLIDWORKS	Preparing 2-D drawings for components, extruding as per required dimension, preparing report for static and/or stress analysis with respect to desired solution.
AUTOCAD	Preparing isometric and component drawings for pipeline, sectional drawings for support material used in pipeline system, 3-D model design such as (architectural, mechanical etc.).
CATIA	Analyzing of components under ordinary and/or extraordinary conditions, interpreting completed analysis with respect to results and reporting.
MS OFFICE	Good skills at Office, Excel and Power Point. (Executive summary, company presentation, method of statements for the clients/designers.)