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Hydraulic Transient Analysis in Fluid Pipeline: A Review

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ABSTRACT
Hydraulic transient is an important phenomenon in the pipeline transportation system that have adverse and catastrophic effects on the most susceptible pipeline components such as valve, pumps, pipes as well as the environment. The major causes of hydraulic transients are sudden or abrupt valve closure or pump failures as a result of power outage. The major challenges of transient analysis techniques are to optimally achieve a balance between accuracy of results obtained from the analysis and simplicity of the adopted techniques in analyzing both complex and simple pipeline networks. In order to attain this fit many researchers have proposed, developed and used different models and algorithms to this regards. This paper surveys various transient analysis techniques, model and algorithm for protection of pipeline network system with a view of achieving optimal trade-off between transient analysis techniques used and the type of fluid flow pipeline analyzed. Performance and limitations of some of the previous works are identified. Finally, future investigations on petroleum and its products were recommended.

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INTRODUCTION

According to Jung & Karney, (2016) virtually all fluid transporting mediums will experience transient effects because almost all fluid flows will be altered, either gradually or suddenly. Pipeline networks systems are used for transferring natural gas, oils and other types of fluids (Pasupathy et al, 2013). Routine pipeline operational activities such as starting or stopping of pumps as well as opening or closing of valves constitute pipeline operational management activities (Itissam, 2014). Abnormalities in the operation and management schedules can lead to hydraulic transient (HT), which in turn leads to catastrophic damages or failure of the pipeline system as well as loss of transported products (Dalgıç, 2017). The study of HT analysis play an important role in the identification, quantification as well as prevention of severe and catastrophic failures in fluid flow and transportation systems (Wood, 2014).

Change in status of any of the flow control device (such as sudden valve closure or pump failure) will lead to the development of HT in the pipeline network system (Puntorieri et al., 2017; Kodura, 2016; Abuiziah et al., 2013b, Abuiziah et al., 2014, Nerella & Rathnam, 2015). HT analysis techniques are designed to investigate the causes of HT, reveal the extent of damage to be caused by the HT as well recommend possible solutions (Wood et al., 2005). It is impossible to totally eliminate pressure surge but its effects can be minimised or put under controlled (Subani & Amin, 2015). HT analysis will help to put in place safer and acceptable operational guidelines. Conducting transient analysis in a pipeline system is often more important conducting steady state condition analysis in a pipeline (Nerella & Rathnam, 2015). There are quite large number researches conducted on hydraulic transients occurring in closed conduits (Ali et al, 2010; Elbashir et al., 2007; Malppan & Sumam, 2015; Mohammed & Gad, 2012; Simão et al., 2015; Noorbehesht & Ghaseminejad, 2013). During the ancient times, fluid flows are studied and base on the context of cultural technologies, but with the scientific and mathematical advancement, a branch of engineering known as hydraulic engineering was developed from the knowledge of fluid flow.

Background

The study of HT in closed conduits has been a subject of research for many centuries (Achouyab, 2013). Researchers have proposed various methods for solving transient state problems under different conditions and assumptions. Joukowsky (1847–1921) and Kries (1853–1928) are the earliest researchers that studied HT problems (Salmanzadeh, 2013). These two researchers have contributed immensely towards the development of hydraulic Engineering.

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Walters (2018) opined that water hammer is predominantly considered by industries as a niche specialty; as a result of this, the study of water hammer or hydraulic transient were often handled by specialized and experienced consultants. Wood et al., (2005) reported that the fundamental and best existing equation in the field of transient flow theory was derived by Joukowsky. Allievi also derived from the first principles a theory for HT and this equation is treated as the first quantitative assessment to obtain pressure rise during a transient event as follows (Rathnayaka et al., 2013).

$$\Delta P = \pm \rho \ \ \Delta V \qquad \text{or} \qquad \Delta H \pm = \frac{a \Delta V}{g} \tag{1}$$

where *ΔH* is the head due to pressure surge (m), *g* is gravitational force (m/s^2), *a* is the wave velocity (m/s) and *Δ*V is the change in velocity (m/s) while ρ is the fluid density.

Flow Governing Equations

fluid flow in closed conduits under pressure is mathematically described by a pair of continuity (2) and motion (3) equations (Urbanowicz, 2017):

$$\frac{\partial}{\partial} + \rho c^2 \frac{\partial}{\partial} = 0 \tag{2}$$

$$\frac{\partial}{\partial} + \rho \frac{\partial}{\partial} + \rho \qquad + \frac{2}{R} \tau_W = 0 \tag{3}$$

where p is pressure, t is time, ρ is the mass density, c is the speed of pressure wave propagation, v is the flow velocity, x is the axis coordinate, g is the acceleration due to gravity, γ is the pipe tilt, R is the inner radius of the pipe and τ_w is the pipe wall shear stress.

HT analysis methods range from analytical methods to numerical solutions (Elbashir et al., 2007). According to larock, (2000) these methods are further divided into either elastic or rigid column method. Elastic method is a method of transient analysis that involves solving partial differential equations. Elastic method also involves evaluating the acoustic pressure wave. Also rapid changes in velocity and pressure, as well as the elasticity of the pipe and the fluid's compressibility are all considered and included in the analysis. While a rigid column method is a method of pressure surge analysis that involves solving simple ordinary differential equations mathematically or numerically. In this method, the elasticity of the pipe and the compressibility of the fluid are ignored in the analysis and whole of the fluid's column is assumed to move as a rigid body (Abuiziah et al., 2013a). In both cases, quasi-linear hyperbolic partial differential equations are used in the analysis of unstable fluid flow in pipelines (Liu et al., 2014). Also there are other ways of solving the sets of the differential equations for the analysis of hydraulic transient in a pipeline (Behbahani-Najed et al., 2010). Some of these ways are the arithmetic mean method (Abuiziah et al., 2014), Graphical method (Salmanzadeh, 2013), analytical (Lebele-alawa & Oparadike, experimental, (2015), experimental (Simão et al., (2014), Method of characteristics (MOC) (Carlsson, 2016), Finite difference methods (FDM) (Kim, 2008), Wave plan method (Bettaieb, 2015; Svindland, 2005). The most widely accepted and used ones are the method of characteristics (MOC) and wave characteristics method (WCM) (Malppan & Sumam, 2015). The main distinction between the two methods is the way pressure waves are traced between pipe boundaries. The MOC uses a numerical to traces a disturbance in a grid on characteristics, whereas WCM uses wave propagation method to trace the disturbance. These two outstanding methods are well documented in pressure transient (Ramalingam et al., 2009, Liu et al., 2014)) and have been implemented in various computer programs for pipe system transient analysis.

METHODS OF TRANSIENT ANALYSIS

Method of Characteristics (MOC)

Abuiziah et al, (2013a) carried out study on hydraulic transient in water pipeline network and how to prevent the phenomenon. The authors developed a numerical model based on method of characteristics to simulate and study transient behaviour in a pressurized pipeline systems transporting water. In the study, the model developed was applied to a simple water pipeline network having a surge control device connected to a reservoir. The results of the study showed that the minimum and maximum pressure heads at steady state conditions 30 m 43.13 m respectively while the minimum and maximum envelopes of pressure for the whole length of 1 Km are -4.9 m and 100.31 respectively.

Henclik, (2015) proposed a numerical approach to develop a standard model of water hammer with fluid-structure interaction. The scheme was formulated and transformed into a differential equation of motion and solved effectively using coupling matrix and the new mark method. The algorithms are implemented in a computer code using MOC, and the numerical results were

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compared with the records obtained from experiments from the laboratory. The study revealed that the concept of using "history parameters" allows one to effectively design water hammer analysis algorithm.

Ha et al., (2017) investigated water hammer due to valve closure in a water distribution network as well as the influence of pressure surge at defects on pipelines. Academic software known as HAMMER was used to simulate water distribution pipeline network and the magnitude of defects as a result of the pressure transient were calculated using SINTAP. Water distribution network having a length of 23639.84 m, 55 nodes and 78 pipes having a capacity of 1849 m^3/day operating at 30-60m pressure head was used for the study. The result of the study showed that the pipe walls in the pipeline with corrosion defect cannot withstand the pressure surge of 2.5Mpa generated by the closure of valve in the pipeline.

In a research conducted and reported by Garg & Arun, (2018) an analysis and simulation of hydraulic transients for a simple reservoir, pipeline and valve arrangement were carried out and the magnitude of water hammer pressure at various locations on a hydro power plant pipeline was investigated using MOC in MATLAB environment. The results from the simulations showed that the pressure head is at its peak at the valve, an increment of around 47 % from the static head, the magnitude of the pressure head at the valve is about 285 m. The study found that the magnitude of the pressure transient was at its highest peak at the valve when the valve suddenly closed but it continues to decrease along the valve to the reservoir.

Jiang *et al.,* (2018) conducted a research on pressure transient of water with cavitations in water distribution pipelines. A hydraulic transient model for water pipelines was constructed to analyze the dynamic characteristics of cavitations volume and the magnitude of transient pressures developed at both upstream and downstream ends of a valve in a water pipeline. FDM and MOC methods were used for the study. Comparison of results obtained through FDM and MOC showed that a volume of maximum vaporous cavity of 3.955×10^{-6} m^3 that lasted for 0.59 seconds was recorded using FDM while a vaporous cavity of 1.305×10^{-5} m^3 that lasted for a duration of about 0.61 s was recorded using the MOC.

Wave Characteristics Methods

Ramalingam et al., (2009) uses MOC and approaches WCM to develop computer programs to predict and analyzed oil-hammer in a crude oil pipeline. The effect of pipe friction as well as exciter behaviour was studied based on conventional reservoir-pipeline-valve layout. In this study, two scenarios having a flow rate of 19006.2 m^3/s were used, a scenario having a pipeline with length L = 6583.7 m with 8 cases and another with a pipeline having a length of L = 1097.3 m with 8 cases for R<1 and another scenario with pipeline having a length of 6583.7 m with 6 cases for R>1 and R<2 are considered. The research revealed that the results from wave planning method were closer to the accurate solution. Wave planning method has a maximum percentage error of 4.5 % for R<1 and 16% when R>1. While MOC has a maximum percentage error of 46.8% and 23.4% for R<1 and 89.5% and 69.2% when R>1.

Rigid column and full elastic methods were used by Abuiziah et al., (2014) to study transient phenomena in fluid transporting pipeline network. Flow governing equations were solve by using the fourth order Runge-Kutta numerical method for rigid column and MOC method were used to solve the equations in the full elastic method. This study revealed that rigid column method reduces its calculations complexity by effectively avoiding the interpolation error that occurs in the characteristics method and this method sometimes provides approximately the same simulation results as the full elastic method.

Akpan et al., (2015) studied unsteady flow conditions caused by abrupt change in flow velocity fluids in pipelines. WANDA Transient simulation software was used to carry out the modelling, simulation and analysis of pressure surge in two different pipeline systems for different flow conditions. The result of the simulation of air behaviour in air vessel used as protection device of the pipeline system analysis is in agreement with the numerical analysis obtained through rigid column analysis. However the effect of the initial air volume in the air vessel on the transient behaviour of the flow in the pipeline, were not presented in Graze's work and as such there are no data to compare them with.

In the year 2017, Mazij & Bergant used a flow passage set to study water hammer analysis in a hydro power station. The set up comprises of an inlet scroll case and outlet conduits. A rigid column

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method was adopted to conduct water analysis for an abrupt shut down of the system. Both the measured and the computed values of the scroll case pressure head is approximately 35 m, also the measured and computed rotational speed rise of the system is recorded as 36.5% and 35% respectively the authors reported that the pressure head and the speed rise are all within acceptable limits. A large discrepancy was recorded between the values of the negative axial hydraulic thrust and this is due to the fact that measuring hydraulic quantities at smaller wicket gate openings at high turbine speed

Analytical Method

Lebele-alawa & Oparadike, (2015) studied the role of valve operations in triggering pressure surge in a pipeline system. Pressure surge analysis was carried out on a crude oil flow station to investigate the effects of changes in pressure and flow rates in the pipeline. The pipeline system used for the study has a flow rate capacity of 0.0557 m^3/s with an initial pressure of 25 bar and an installed relief valve with closure time of 1.5 seconds. The initial fluid flow velocity in the system is 1.12 m/s but upon the system shut down in 1.5 seconds, the flow velocity rises to 53.7 m/s as a result of increase in pressure from 21 bar to 37.23 bar. When the valve closure time was increased to 2.5 second, then the velocity decreases to 25.1 m/s. This study revealed that decrease in valve closure rate will also lead to a corresponding decrease in pressure as well as flow velocity.

Rezaei, et al, (2015) investigates the failure conditions due to dynamic hydraulic in pipelines by analysing historical pipe failure records. Historical pipe burst records for a period of 10-year (2003-2013) from a water supply network in UK was used for the review and analyses. The record shows there were about 78,000 failures recorded over the period. The result of the analysis showed that increase in internal diameter of the pipes will leads to the reduction in burst failure rate per length in the pipeline. Also the revealed that lower tensile strength and brittleness of cast iron are the reasons behind the higher rate of failures. Starczewska et al., (2016) studies the occurrence of pressure transients in water distribution pipeline networks. Pressure transient behaviour was characterized in the complex water distribution pipeline by occurrence and differences. Histogram analysis method was used for the analysis of the rate of change of pressure for visual inspection of the data. The study revealed that pipeline network with a pumped source are equal or even higher in activity as shown in industrial district metered areas and also gravity fed domestic district metered areas showed little or no transient activity. However, the method adopted for the analysis takes care of only water

Duan, (2017) developed an analytical model with the aim of detecting leakages in pipelines. The developed model is a one dimensional water hammer model based on transfer matrix. Transient frequency responses are derived via linear transfer matrix method for single branch and loop connections used in this study. The developed model and its application were validated through numerical tests for both the single branched and looped pipelines. The results obtained from the developed model demonstrated applicability and accuracy in leakage detection and identifications. However, the study showed that it is more easy and accurate to locate leakages than to identify the size of the leakage using the developed model. Li et al, (2018) carried out a research on the analysis of pressure transient in vented horizontal pipe due to rapid filling. An analytical model for approximate solutions was developed to study the maximum pressure as well as the characteristics of pressure oscillations as a result of insignificant or no air released. ANSYS Fluent was used in details air–water interactions. According to the modelling results obtained from the study showed that the position of the venting orifice determines the magnitude of residual air in the system.

Experimental Method

Gjetvaj & Tadić, (2014) conducted a study on the impact of pressure rise in pipeline caused by water hammer on air vessel protected pipelines system. Pressure transient between a pumping station with a capacity of 100 l/s and a reservoir was measured and analysed numerically. The reservoir is 3355 m away from the pump station. The pipeline network is made of ductile iron and a PVC pipe having diameters of 500 mm and 400 mm respectively with a non-return valve and an air vessel with a diameter 2000 mm installed. The wave propagation velocity c = 1000 m/s. while the initial velocity of the water is 0.51 m/s. Since the mass density of water is 1000 kg/m^3, the pipeline contains water having a volume of 658 m^3, mass of 658.000 kg, a momentum of 335.600 kg·m/s, and a kinetic energy of 85.570 J.

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Zhang, (2016) conducted a research on pressure transient due to pump shut-down and the simultaneous closure of a Spherical valve in a pipeline system of a hydropower plant. Experimental and Computational methods were adopted by the authors in carrying out the study in this research work. The analysis of the data were carried out using Microsoft excel program. For the simplification of the complex computational procedure for transient flow analysis, the spherical valve and the characteristic of the pump were worked out. The study found that propagation of the pressure transients leads to the occurrence of wave reflection and wave transmission. Despite the fact that the study revealed that the wave tracking method is good and highly accurate in analyzing hydraulic transients, this study only take care of Pelton turbine system of hydro energy system.

Belloufi et al., (2017) used experimental method to investigate transient conditions of air in heat exchanger. The experiment was conducted in the University of Biskra using a of 53.16 m long and 110 mm diameter PVC pipe buried at 3 m depth. Also a one-dimensional numerical model was formulated using the finite differences. At inlet air temperature of 48.87°, a Thermal efficiency and temperature drop of 18.06 °C and 78.96 % respectively were recorded. The results of theoretical predictions were validated with the experimental results and it showed that they are in good agreement with a relative error of 7.46%. Bergant et al., (2017) investigates the effects of vaporous cavitations caused by the closures of valves at both upstream and downstream ends of a pipeline. Experimental and numerical methods were adopted for the investigation. The investigation revealed that multiple valve closure significantly increased the severity of column separation caused oscillations in the pipeline system. The investigation showed that initial fluid flow velocity was 2.19 m/s, the valve closure time is 20 mins, and it is less than the wave reflection time of 2L/a. A head pressure rise was induced at the valve. A negative pressure makes the pressure head to drop to vapour head in many positions in the pipeline.

Twyman, (2018) investigated water hammer a pipeline network due to valve closure. In the research, the effects of different types of valves such as butterfly, gate square gate circular, ball, needle and globe were modelled. The study revealed that the magnitude of pressures surge varies according to the type of valve used. The magnitude of pressures generated in a pipeline varies according to the type of valve used. Maximum pressure recorded by square gate and needle valves is about 21% more than the maximum pressure recorded by the ball, butterfly, circular gate, ball and globe valves, the first ones with a concave shape and the latter ones with a convex shape. Also needle and square gate valves recorded pressures that are 19% lower than the minimum pressures recorded by the circular gate, butterfly, globe and ball valves.

Wéber & Hős, (2018), improvised and designed a transient analysis method to study HT in the presence of air valve by means of experimental and numerical methods. Also ANSYS CFX was for the numerical analysis. The experimental study revealed that the presence of air valve has the effect of protecting the pipeline against significant vacuum but it also creates positive pressure peaks at the downstream of the valve. However, there were discrepancies in the results and the difference indicates that the numerical method was unable to catch the high positive pressure waves.

Other Numerical Methods

Maclean et al, (2018) studied and analysed gas flow in pipelines as transient non-isothermal. A commercial numerical CFD software known as ANSYS FLOTRAN was used for the simulation of the steady and transient flow in the gas pipeline. A set of gas distribution data was used to analyse the pressure transient in a gas pipeline network. The system has a diameter of 0.508 m, pressure at the inlet pressure of 15.3 M Pa and an initial volumetric flow rate of 5.30 MMm^3/D. Transient simulations were performed for four different scenarios at different gas temperature. The simulations are performed for scenarios with initial temperatures. The simulations results showed that there is decrease in pressure with increase pipe length.

Simão et al., (2015) conducted a research where experimental and numerical methods were used in the analyses of hydraulic transient and fluid-structure interaction. A one dimensional and three dimensional CFD based models were developed using finite element methods (FEM) for the prediction of fluid-structure interaction events. The experimental test was conducted with a pipe connected to the upstream with a head of 4 m, pressure transducers are installed at two points along the pipe system. An oscilloscope was connected to these pressure transducers for reading repetitive waveforms. A surge was generated by closing valves at 0.13sec. In 0.4 sec the pressure

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wave reaches the upstream boundary and reflects back. An overpressure was recorded after 0.93 s due to sudden closure of the valve. The study revealed that as the valve closes after 0.13 s, a transient event will be created (the pipe will reaches a maximum displacement of 3.14 m/s^2 in the x-axis as well as 2.2 m/s^2 in the y-axis making the structure to vibrates. The developed models did not take the effects of other flow control devices such as pumps and surge tanks into consideration.

Vataj & Berisha, (2018) developed a model for hydraulic transient regimes analysis using method of characteristics and Hardy Cross program in FORTRAN language. The developed model for was tested for stationary working regimes with fully open valves during the entire integration period. The results obtained from the developed model were compared with results that are currently literature for validation. The study revealed that installation of pressure vessel in pipeline system will reduce hydraulic shock effects. The author also recommends that proper attentions are to the given to correctly dimension hydraulic shocks.

Agostinho et al, (2018) carried out a research hydraulic transient in a water distribution systems. The research was carried out with the main objective of assessing the potential sensitiveness of pressure surges hydraulic transient indicators as well as finding how factors such as compressibility and inertia effects affects hydraulic transient. The study was conducted in Brazilian water distribution systems. The study revealed that the risk of the effects of pressure transient is not an isolate case in water distribution systems but is common and frequent to all fluid transporting pipelines. The study showed that the hydraulic transient analysis of the water distribution systems showed the inaccuracy and risk of skeletonizing model, as it may lead to under or overestimating of pressure transient.

Chaichan & Al-zubaidi, (2015) carried out a research on Hydraulic Transients in water pipelines as well as controlling the effects of hydraulic transient on water pipelines and pump systems. Surge 2012 transient analysis software (commercial software) was used to investigate the transient potentials in pipelines with and without any protection devices. The simulation result revealed that the worst case scenario would happen where all the running pumps get stopped at the same time when the system run without any transient/surge protection device. Rahul *et al*, (2015) presented a research paper on transient flow analysis in transverse corrugated pipes using CFD methods. Solid works software was used to model the pipe geometry and ANSYS FLUENT software was used as solver for CFD simulations of the pipeline system. The analysis showed that the flow pattern and the corrugation profile of the pipes lead to pressure drop in the corrugated pipe and also the approximation of the smooth wall was found to have better agreement with experimental values. However, the research did not consider the variation of vortex shedding frequency inside the.

From inception to date, many hydraulic analysis models were developed and widely used for design, fault detections, analysis, maintenance pipeline network systems as well as prediction of unforeseen pipeline failures. Further, the review revealed that HT analysis can be carried out by various numerical, experimental and analytical techniques using the flow governing equations. Also despite the fact that numerous researches were done on hydraulic transient on fluid pipelines conveying different types of fluid such as gas, water or oils but hydraulic transient analysis of petroleum pipeline conveying refined petroleum product such as PMS, DPK or AGO are not much was found in literature; the little available were not far-reaching enough, and mainly concentrated on water and crude oil, as such there is the need for the analysis of HT in pipeline networks transporting petroleum and its product because this type of pipeline transverse almost all parts.

CONCLUSION

This review focused on the analysis of hydraulic transient in closed conduits transporting fluids from one point to another. The review revealed that in the earlier stage of transient analysis, analytical and numerical techniques were used to solve hydraulic problems but with technological development methods like experimental, modelling and simulations were developed. Also the review found that despite the fact that numerous researches were done on hydraulic transient on fluid pipelines conveying different types of fluids but HT analysis of petroleum pipeline conveying refined petroleum product such as PMS, DPK or AGO as a result of valve or pump failure are scanty in the literature; the little available were not far-reaching enough, and mainly concentrated on water and crude oil, as such there is the need for analyzing the fluid flow activities in

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pipeline conveying fluid such as refined petroleum products.

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