INVESTIGATION OF PRESSURE TRANSIENTS AND WAVE PROPAGATION EFFECTS IN A PRESSURIZED PETROLEUM PIPELINE USING WANDA TRANSIENT SOFTWARE

A.B. Muhammad*[1,2], A. Nasir[2], S.A. Ayo[2] and Bori Ige[2]

[1]Department of Mechanical Engineering, University of Maiduguri, P.M.B 1069 Maiduguri, Borno state, Nigeria

[2]Department of Mechanical Engineering, Federal University of Technology, Minna, Niger State Nigeria

*Corresponding author: abms4real@gmail.com; +2348033326217, +2348026077029

ABSTRACT

Pressure transients and effects of wave propagations due to instantaneous valve closure in a pipeline transporting premium motor spirit (PMS) were investigated using simulation approach in this paper. Pressure transient investigation and analysis are often more significant than the steady state analysis that hydraulic Engineers usually use in pipeline design because almost all pipelines experience pressure transient in their operations. Pressure transient analysis helps to understand the additional loads a pipeline can be subjected to as a result of instantaneous valve closures. In this paper, WANDA Transient 4.5.1210 commercial software was used for the analysis of the pressure transients due to instant valve closure in a petroleum pipeline. Three different instantaneous valve closure times of 4.5, 9 and 18 seconds were used in this investigation. It was observed in this research that rise in pressure is highest (1304 kPa) at node F (the node where the valve closure takes place) against the inlet pressure of 120 kPa and also there is drastic drop in pressure (-53.7 kPa) at node B (a node just upstream end of the pump). Also cavitations were observed at Node B due to the development of negative pressure as a result of the valve closure. The research recommends that surge tank should be installed at node F to stabilize the pressure surge and also air vessels are to be installed at node B to curtail damages due to cavitations.

Keywords: Transient, analysis, Pressure, Valve-closure, Pipeline and petrol

1 INTRODUCTION

Pipeline mode of transportation is one of the most efficient, effective, surest and safest means of transporting fluids such as petroleum and its products using pipeline networks [1, 2]. Pipelines are media needed for the transportation of hydrocarbons from reservoir, wellbore, refineries and other stations to the points of loading, storage or utilization [3]. Pipeline network system is made up of many components such as pipes and other flow control devices (pumps and valves) [4]. Transient pressures are commonly initiated in pipeline networks as a result of accidental or planned; manual or automatic sudden changes in valve settings, starting or stopping of pumps, sudden changes in reservoir levels, changes in demand and transmission conditions as well as sudden release of air from the pipeline via the relief valves during operations or at high elevations [5]. Change in status of the flow control devices simply means a state of flow in which fluid flow velocity and pressure vary rapidly due to sudden valve opening or closure and or pump failure [4, 6, 7] and these are caused by the actions of the pipeline operator, poorly selected pipeline components, mechanical failures as a result of poor maintenance culture or an external action. There are two categories of damage caused by pressure transient events, namely; catastrophic failure and fatigue like failure. Catastrophic failure is a type of failure caused by high magnitude transient waves generated as a result of valve closure or pump failure while a fatigue-like failures are normally caused as a result of prolong repeated impacts of smaller magnitude transient pressure over a long period [8]. In a fluid transporting pipeline network, if a valve is closed instantaneously, the momentum of the fluid will be shattered and high pressure wave will be built-up accordingly. This built-up high pressure wave will be transmitted down the pipe length with the velocity of the sound wave that may lead to knocking.

Transient analyses are conducted in pipelines networks in order to ascertain whether the networks are operating within maximum allowable operational pressure (MAOP) and as well meets the regulations and standards of pipeline operations as specified by American Petroleum Associations (API) American Society of Mechanical Engineers (ASME) and American Society of Testing Materials (ASTM) [9]. [7] stated that hydraulic transient analysis and evaluation are crucial in the design, operation and maintenance of existing and new pressurized pipeline networks. Conducting transient analysis in a pipeline system is often more important than conducting steady state condition analysis in a pipeline [7]. The aim of this research paper is investigation of pressure transient and the effects of wave propagation in a petroleum pipeline transporting premium motor spirit (PMS) also known as petrol or gasoline due to instantaneous valve closure using simulation approach.

Many researches were conducted on hydraulic transients in pipelines [10, 11, 12, 13, 14, 15] and host of others. There are numerous methods of HT analysis, ranging from analytical methods to numerical solutions [10]. According to [16] 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. 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 [17]. In both cases, quasi-linear hyperbolic partial differential equations are used in the analysis of unstable fluid flow in pipelines [18]. Some of the methods used in hydraulic transient analysis are arithmetic mean method [19], Graphical method [20], analytical [21], experimental [22], Method of characteristics (MOC) [23], Finite difference methods (FDM) [24], Wave plan method [25, 26]. According to a report by [13] the most widely accepted and used methods of hydraulic transient analysis are the method of characteristics (MOC) and wave characteristics method (WCM) and the main distinction between the two methods is the way pressure waves are traced between pipe boundaries. The MOC use numerical method to trace 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 the literature of pressure transient analysis [18, 27] and have been implemented in various computer programs for pipe system transient analysis. In this research work, a MOC based computational fluid dynamics simulation software called WANDA Transient 4.5.1210 was used for the analysis of hydraulic transient in a petroleum pipeline network.

2 MATERIALS AND METHODS

2.1 Materials

Materials used in this study includes Empirical formulae, WANDA Transient 4.5/1210 simulation software, upstream and downstream reservoirs, pipes, pump and valves (gate valve and non-return valves). WANDA Transient 4.5/1210 simulation software was used to analyse the pressure transient in the pipeline network. Equation (1) was used for calculating wave speed propagation for transient flow in the pipeline as reported by [7, 28].

$$a = \sqrt{\frac{\frac{k}{\rho}}{1+\left(\frac{k}{E}\right)\left(\frac{D}{e}\right)(C)}} \tag{1}$$

Where a is the wave speed, k is the bulk modulus of elasticity of the fluid, ρ is the mass density of the fluid, E is the Young's modulus of elasticity of the pipe material, e is the pipe wall thickness while C is movement restrain constant (full pipe restraint from axial movement, $C = 1-\mu^2$). According to [6] the bulk modulus of elasticity of a fluid is an important parameter in the analysis of wave speed of fluid and it can be obtained by using equation 2.

$$K = \frac{\Delta P}{\Delta \rho / \rho} \tag{2}$$

The head loss due to water hammer in the pipeline can be calculated using the Darcy-Welsbach relation presented as equation 3:

$$\mathrm{h_f} = \frac{\mathrm{fDLV^2}}{\mathrm{2gD}} \tag{3}$$

According to a report by [29] the instantaneous valve closure is characterized by valve closure time less than T and the value of T can be calculated by using equation

$$T = \frac{2L}{a} \tag{4}$$

Hydraulic transient behaviours in closed conduits can be analyzed by using equations of motion and continuity [30], the equation is shown as equation 5 as reported by [28].

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + \frac{fV|V|}{2D} = 0 \tag{5}$$

The term $V\partial V/\partial x$ in equation 5 is neglected in transient analysis as a result of low Mach-number and unsteady flows. [6] reported that equation 5 will reduce to equation 6

$$\frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + \frac{fV|V|}{2D} = 0 \tag{6}$$

Also according to [29] the continuity equation can be presented in equation 7.

$$\frac{1}{\rho}\frac{d\rho}{dt} + \frac{1}{A}\frac{dA}{dt} + \frac{\partial V}{\partial x} = 0 \tag{7}$$

If an elastic pipe is filled with a compressible fluid, equation 9 will reduce to relation presented in equation 8.

$$\frac{d\rho}{dt} + V\frac{\partial v}{dx} + \rho a^2\frac{\partial V}{\partial x} = 0 \tag{8}$$

The friction factor can be calculated by using the Colebrook-White equation as shown in equation 9 [31]

$$\frac{1}{\sqrt{\mathrm{f}}} = -2\log_{10}\left[\frac{\mu}{3.7D} + \frac{2.51}{Re\sqrt{\mathrm{f}}}\right] \tag{9}$$

2.2 Method of Data Collection

The pipeline and PMS parameters used in this analysis as presented in tables 1 and 2 were obtained from direct measurement, archives of the Nigeria National Petroleum Company (NNPC) and the literature [3, 32].

Table 1. Pipe parameters

Pipe	Pipe Material	Diameter (m)	Thickness (m)	Roughness (e/d) (mm)	E_y (N/m^2)
1	Carbon steel	0.3556	0.016	0.045	210×10^9

Table 2. Fluid parameters

Fluid	Density (m^3/kg)	Flow rate Q (m^3/s)	Inlet Pressure (kN/m^3)	μ (N/m^2)	E_y (N/m^2)	Cp (Kj/kg/K)	K (N/m^2)
PMS	720	0.297	120	6.4×10^{-7}	213.84	2.22	1.07×10^9

2.3 Pipeline Network Layout

A hypothetical petroleum pipeline network that consists of the followings, upstream and downstream reservoirs, pipes, pump and valves (gate valve and non-return valves) is adopted for this research work. The pipeline network is made up of are four carbon steel pipes (API 5L A25) of equal diameters of 0.3556m, thickness of 0.016m and surface roughness of 0.045mm. All the pipes are connected in series between the upstream reservoir (B1) and the downstream reservoir (B2). The upstream end of the first pipe, pipe 1 (P1) is connected to the upstream reservoir via node A while its downstream end is connected to the pump at node B, pipe P1 has a length of 1000m.Pipe 2 (P2) is the second pipe in the series, its upstream end is connected to the pump at node C and its downstream is connected to the check valve at node D, it has a length of 10000m. The third pipe in the series of the pipes is pipe 3 (P3), P3 is also connected the check valve at its upstream at node E while at the downstream is connected to the gate valve at node F; P3 also has a length of 10000 m. The last pipe in the series is pipe 4 (P4), it has a length of 1000m, the upstream end of P4 is connected to the gate valve at node G while its downstream end is connected to the downstream reservoir of the pipeline network at node H.

2.4 Procedures for Pipeline network simulations using WANDA Software

Step 1. Data collection: The first step in the simulation process is collection of relevant available informations that will be used in setting up the system. For the purpose of this research, petroleum pipeline network parameters such as the types, size and geometries of pipes, pumps and valves use in real pipeline networks were collected and were used as input data in the simulations. Step 2. Create the hydraulic model: The second step was the creation of the schematic diagram of the pipeline network system (hydraulic model) in the user interface. The hydraulic model was drawn using lines and other symbols representing various elements of the network from the palette of the software as well as connecting all the components together via nodes. Step 3. Specification of the pipeline system components: After the creation of the hydraulic model, the dimensions and other specifications of components such as the geometry, size and other fluid flow parameters were specified and are entered into the software via the property windows. Step 4. Calculate steady state: The next step in the simulation process was the steady state flow condition analysis under engineering mode. The steady state condition was calculated by the software during the first run of the simulation process and the results of the steady state were used as the initial conditions for the computation of the unsteady state. Step 5. Specify hydraulic actions: Next, the simulation mode was changed from engineering to transient mode using mode and option menu and then the hydraulic actions were specified. In the hydraulic actions, things such as valves closure time and the pump trip times were all specified in the property window. Step 6. Preparation and input of pump and valve characteristics tables: Characteristics tables for the pump and valves were prepared separately and inserted into the software via the property window. The input data specified in the pump table includes, pump head, discharge, speed and efficiency of the pump in relation to the other pump operation parameters. While for the valves, parameters such as valve size, valve type and flow rate through the valves were all specified. At this stage, all the physical properties and configuration of the pump and the valves were completely defined and specified. Step 7. Calculate transient: The next step is running the simulation and calculating the unsteady state flow condition under transient mode. The unsteady state (transient) conditions were calculated by the software during the second run of the simulation process. The results of the steady state flow conditions obtained in the first run were used as boundary conditions for the computation of the unsteady state. Step 8. Reporting results: At this step, the simulation results were retrieved from the output window. The results are obtained in tables and graphs form for further analysis

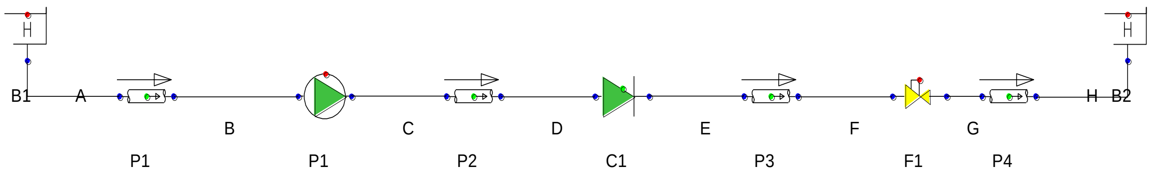

Figure 1. Pipeline Network System

Table 3 presents the parameters used in WANDA software for the analysis of the hydraulic transient in PMS while table 4 presents some physical constants used in the simulation. In this study, the valve closure times adopted are 4.95, 9 and 18 seconds which are less than wave propagation period of 36 seconds. The pressure of the fluid under normal operation conditions at nodes A, B, C, D, E, F, G and H are 98.14 kPa, 57 kPa, 820 kPa, 500 kPa, 500 kPa, 450 kPa, 205 kPa and 210.56 kPa respectively.

Table 3. Properties of Premium Motor Spirit (PMS)

Properties	PMS
Rheology type	Newtonian
Density	720.0 (kg/m^3)
Bulk modulus	1.070e9 (N/m^2)
Vapour pressure	48.00 (kPa.a)
Kinematic viscosity	0.001731 (m^2/s)
Acoustic wave speed	1160 (m/s)

3 RESULTS AND DICUSSION

Figure 2 shows the pressure head distribution before the advent of the valve closure in the pipeline network. Figure 2 further shows that the fluid possesses low pressure energy at nodes A and B while node C has the highest pressure head of 0.102 m due to the presence of pump at that node. After node. C, the pressure head starts to drop across nodes D, E and F. The graph indicates that the energy the fluid exerts on the pipeline is lowest at node B and highest at node C. The pressure head stabilises between nodes G and H at a pressure of 0.3 m.

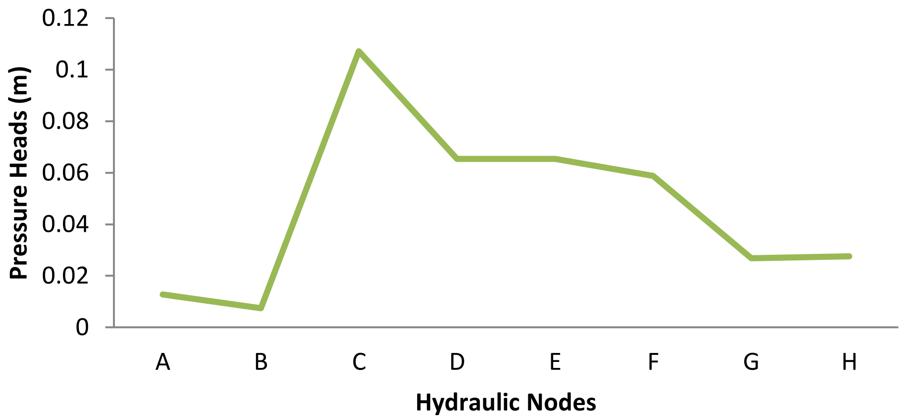

Figure 2. Pressure heads at various hydraulic nodes of the pipeline

3.1 Simulation results for valve closure time of 4.5 s, 9 s, and 18 s.

3.1.2 Simulation results of pressure transient due to instatenous vslve closure time of 4.5s in the pipes

Figure 3 present results of pressure transients due to instantaneous valve closure time of 4.5 s in the petroleum pipeline. The figure depicts that there is variation in pressure at the various hydraulic nodes of the pipeline due to the instantaneous valve closure. The pressure of the fluid fluctuates and oscillates between minimum and maximum pressures before stabilising as shown in figure 3. The pressure at node A fluctuates and oscillates between minimum pressure of 97.88 kPa and 98.34 kPa at times of 5.7 s and 56.7 s respectively. At node B, the pressure of the fluid drops to -53.7 kPa at a time of 3.9 s before rising to a maximum pressure of 292.2 kPa at a time of 0.1 s. The development of negative pressure at node B also leads to the formation of cavitations voids at the node as well as along pipe P1. At node C the pressure of the fluid fluctuates between a minimum pressure value of 271.5 kPa and a maximum pressure of 1099 kPa at times of 0.1 s and 36.3 s respectively. Nodes D and E have the same charactericsts, the pressures of the fluid at nodes D and E drops to a minimum pressure of 271.5 kPa at a time of 8.7 but later the pressure at these nodes rises to a maximum pressure of 1219 kPa at a time of 43.9 s. The figure also depicts that pressure of the fluid at node F fluctuates and oscillates between minimum pressures of 256.8 kPa at a time of 17.3 s and maximum pressures of 1320 kPa at a time of 53.5 s. The pressure of the fluid at node G fluctuates between minimum pressures of 57.3 kPa at 20.9 s and 418.7 kPa occurring at 19.5 s while at node H the pressure of the fluid has a little variation. The pressure fluctuates between a minimum pressure of 210.5 and maximum pressure of 210.6 at times of 20 S and 112.2 s respectively.

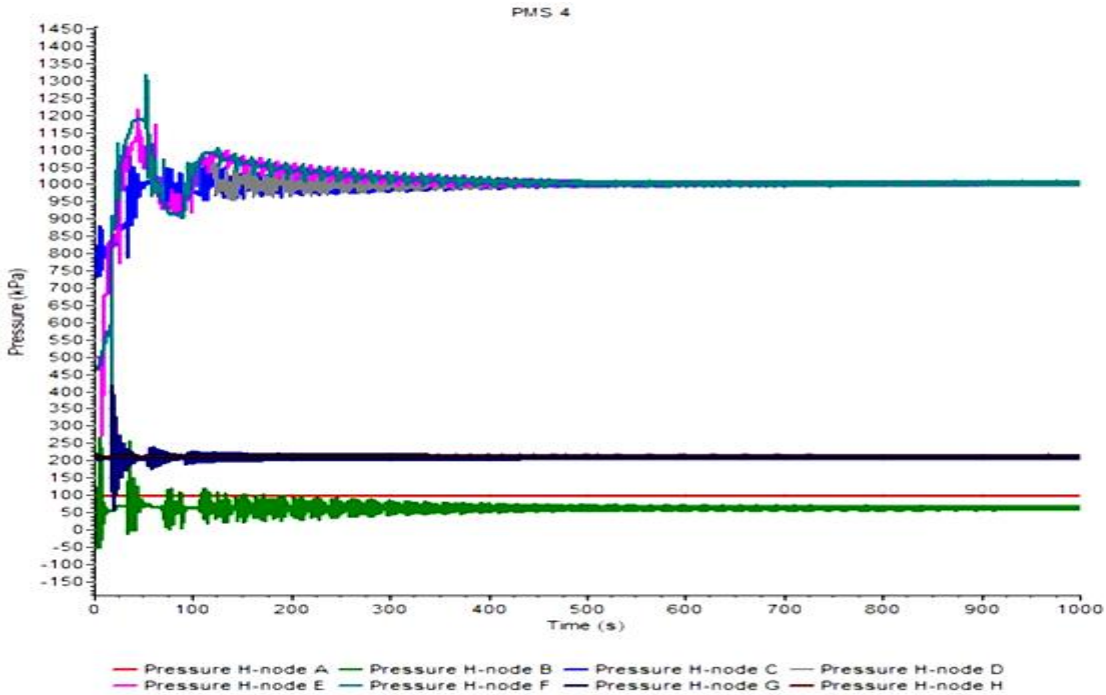

Figure 3. Pressure Transients at Hydraulic Nodes for a valve closure time of 4.5 s

3.1.2 Simulation results for PMS of valve closure time of 9 s

Figure 4 present results of pressure transients due to instantaneous valve closure time of 9 s in the pipeline network. The pressure of the fluid fluctuates and oscillates between minimum and maximum pressures before stabilising as shown in figure 4. The pressure at node A fluctuates and oscillates between minimum pressure of 97.88 kPa and 98.34 kPa at times of 5.7 s and 59.2 s respectively. At node B, the pressure of the fluid the pressure drops to -53.7 kPa at a time of 3.9 s before rising to a maximum pressure of 292.2 kPa at a time of 0.1 s. The development of negative pressure at node B also leads to the formation of cavitations voids at the node as well as along pipe P1. At node C the pressure of the fluid fluctuates between a minimum pressure value of 289.7 kPa and a maximum pressure of 1080 kPa at times of 0.1 s and 36.3 s respectively. Nodes D and E have the same pressure characteriscts, the pressures of the fluid at nodes D and E drops to a minimum pressure of 271.5 kPa at a time of 8.7 but later the pressure at these nodes rises to a maximum pressure of 1203 kPa at a time of 44.9 s. The figure also depicts that pressure of the fluid at node F fluctuates and oscillates between minimum pressures of 236.6 kPa at a time of 17.3 s and maximum pressures of 1316 kPa at a time of 53.5 s. The pressure of the fluid at node G fluctuates between minimum pressures of 52.45 kPa at 20.9 s and 435.7 kPa occurring at 19.5 s while at node H the pressure of the fluid has a little variation. The pressure fluctuates between a minimum pressure of 210.5 kPa and maximum pressure of 210.6 kPa at times of 20 s and 112.2 s respectively.

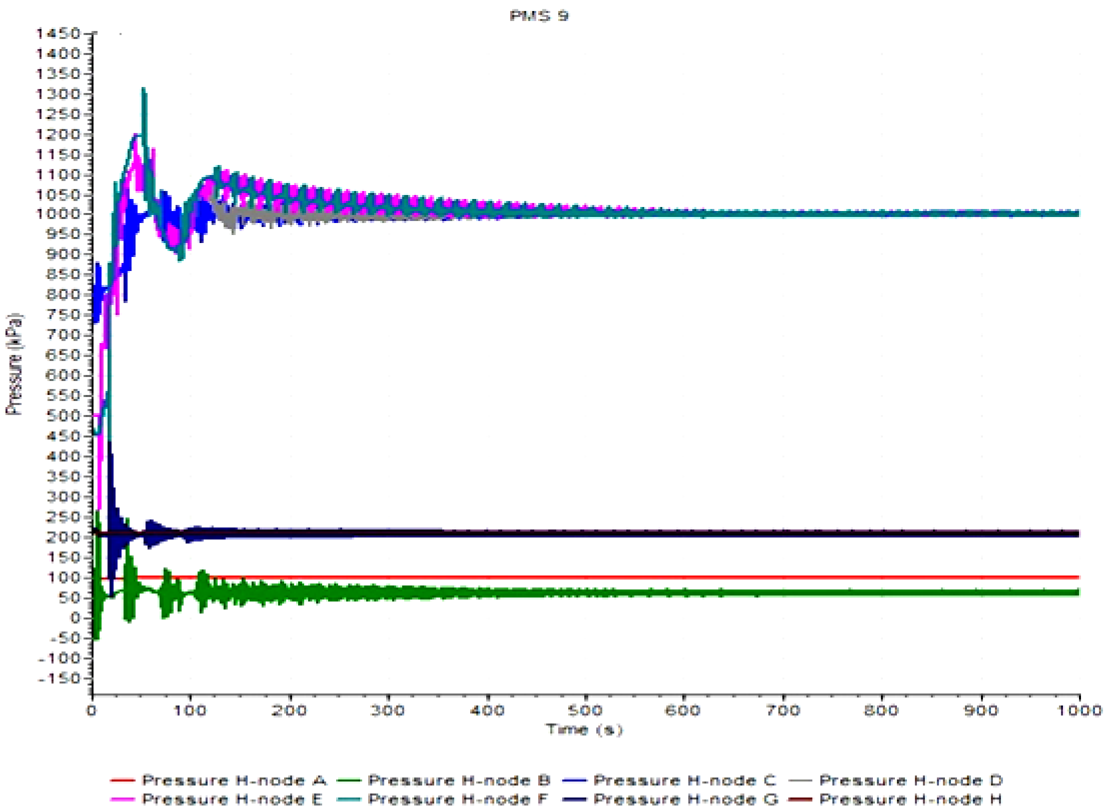

Figure 4. Pressure Transients at Hydraulic Nodes for a valve closure time of 9 s

3.1.3 Simulation results of pressure transient due to instatenous valve closure time of 8 s in the pipes network

Figure 5 present results of pressure transients due to instantaneous valve closure time of 18 s in the pipeline network. The figure depicts that there is variation in pressure in the various hydraulic nodes of the pipeline. The pressure of the fluid fluctuates and oscillates between minimum and maximum pressures before stabilising as shown in figure 5. The pressure at node A fluctuates and oscillates between minimum pressure of 97.88 kPa and 98.34 kPa at times of 5.7 s and 64.7 s respectively. At node B, the pressure of the fluid the pressure drops to -53.7 kPa at a time of 3.5 s before rising to a maximum pressure of 292.2 kPa at a time of 0.1 s. The development of negative pressure at node B also leads to the formation of cavitations voids at the node as well as along pipe P1. At node C the pressure of the fluid fluctuates between a minimum pressure value of 289 kPa and a maximum pressure of 1080 kPa at times of 0.1 s and 36.3 s respectively. Nodes D and E have the same pressure characteriscts, the pressures of the fluid at nodes D and E drops to a minimum pressure of 271.5 kPa at a time of 8.7 but later the pressure at these nodes rises to a maximum pressure of 1167 kPa at a time of 44.9 s. The figure also depicts that pressure of the fluid at node F fluctuates and oscillates between minimum pressures of 186.9 kPa at a time of 17.3 s and maximum pressures of 1304 kPa at a time of 53.5 s. The pressure of the fluid at node G fluctuates between minimum pressures of 49.74 kPa at 20.9 s and 473.8 kPa occurring at 19.1 s while at node H the pressure of the fluid has a little variation. The pressure fluctuates between a minimum pressure of 210.4 kPa and maximum pressure of 210.6 kPa at times of 20 s and 120.2 s respectively.

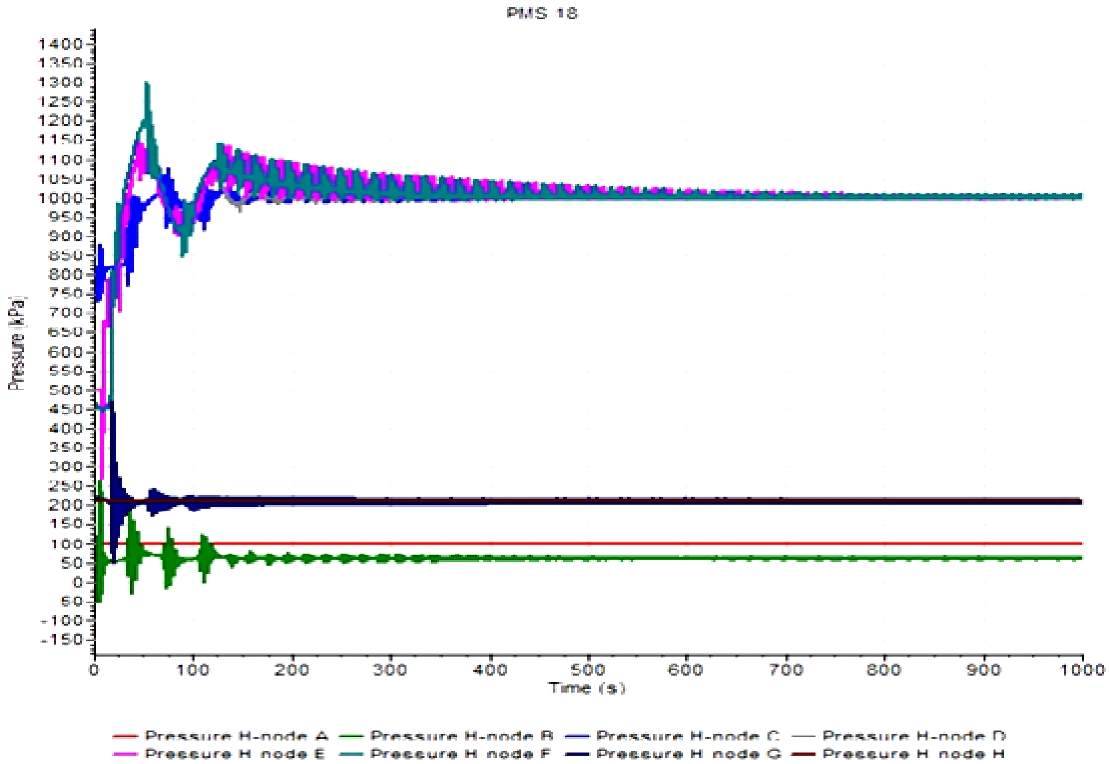

Figure 5. Pressure Transients at Hydraulic Nodes for a valve closure time of 18 s

3.3 Comparison of the High pressure transients in the pipeline network but different valve closure times

The comparison of the simulation results for the various valve closure times in the pipeline transporting the PMS is shown in figure 6. The graph depicts that pressure transients due to instantaneous closure of a gate valve in a petroleum pipeline transporting PMS reduces as the valve closure time increases. Therefore, in a pipeline network, it is better to have a longer valve closure time so as to reduce or eliminate the possibility of pressure transients, column separation or the formation of cavitations voids that may eventually lead to pipeline failure.

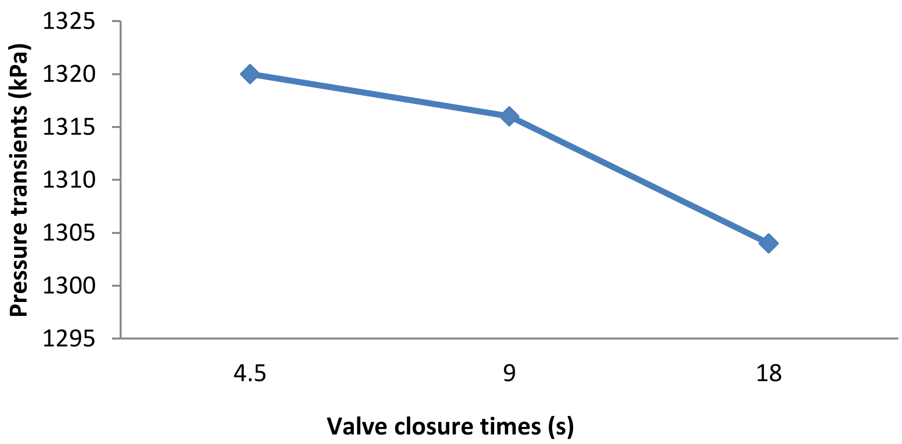

Figure 6. Comparison of pressure transient in the pipeline network at different valve closure times

4 CONCLUSION

The investigation of pressure transient due to instantaneous valve closure in a petroleum pipeline conveying premium motor spirit (PMS) also known as petrol or gasoline was carried out in this paper using simulation approach. A hypothetical petroleum pipeline network was adopted for the research work. The pipeline network under study consists of the followings, upstream and downstream reservoirs, pipes, pump and valves (gate valve and non-return valves). WANDA Transient 4.5.1210 simulation software was used to analyze the pressure transient in the pipeline network due to the instantaneous closure. It was observed in the study that pressure waves in the pipeline network oscillate between high and low pressure values as the result of the valve closure.

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