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Hydraulic Transient Analysis of a Petroleum Pipeline Transporting Dual Purpose Kerosene Using Modelling and Simulation Approach

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ABSTRACT

Hydraulic transient analysis of a pipeline transporting dual purpose kerosene (DPK) was carried out in this research using simulation approach. Many petroleum pump stations and pipelines experience leakages and failures at their nodes due to changes in flow parameters that lead to hydraulic transient. Such types of unsteady situations are encountered frequently in pipelines where the valves are suddenly closed. WANDA Transient 4.5.1210 commercial software was used for the analysis of hydraulic transient. Variation in pressures and discharges with respect to time after the closure of a gate valve at the downstream of a pipeline were observed. It was observed in the study that pressure at node F rise significantly up to about 1354 kPa against the initial inlet pressure of 120 kPa due to the instantaneous valve closure and it was also observed that pressure at node B drops to a negative pressure of -101 kPa and hence the formation of cavitations at that node B and pipe P2. The analysis showed that the magnitude of the pressure surge decreases as the valve closure is increased. The research recommended that surge tanks should be installed at node F to stabilize the pressure surge and also air vessels are to be installed at nodes B to curtail damages due to cavitations.

1. INTRODUCTION

Pipeline mode of transportation is one of the most efficient, effective and safest means of transporting fluids such as petroleum and its products (Boye *et al.*, 2017). Pipeline network is made up of collection of many components such as pipes and other flow control devices (pumps and valves) (Mylapilli, 2015). And change in status of any of the flow control device will lead to the development of hydraulic transient in the pipeline network (Abuiziah *et al.*, 2014). 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 of valves and or pump failure (Gómez, 2018; Mylapilli, 2015; Nerella and Rathnam, 2015) 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 and by an external action. Hydraulic transient is also termed pressure surge, transient waves, fast transients, fluid transients, hydraulic hammer, oil hammer or water hammer (Duan, 2017; Naik and Shreenivas, 2015).

Hydraulic transient has devastating destructive and catastrophic consequences that include collapsing of pipelines and ruptured valves (Duan, 2017; Mylapilli, 2015). There are two categories of damages caused by pressure transient events; 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 fatigue-like failures are normally caused as a result of prolong repeated impacts of smaller magnitude transient pressure over a long period (Starczewska *et al.*, (2016).

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 leads to knocking. Transients analyses are conducted in pipelines networks in order to verify whether the networks are operating within acceptable operating limits and as well meets the regulations and standards (Rodriguez and Pavel, 2016). Nerella and Rathnam (2015) 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 (Nerella and Rathnam, 2015). The aim of this paper is conducting hydraulic transient analysis due to instantaneous closure of valve in a petroleum pipeline transporting Dual Purpose Kerosene (DPK) using modelling and simulation approach.

Large number of researches were conducted on hydraulic transients in pipelines (Ali *et al.*, 2010; Elbashir *et al.*, 2007; Malppan and Sumam, 2015; Mohammed and Gad, 2012; Simão *et al.*, 2015; Noorbehes and Ghaseminejad, 2013). Hydraulic transient 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. 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.*, 2013). In both cases, quasi-linear hyperbolic partial differential equations are used in the analysis of unstable fluid flow in pipelines (Liu *et al.*, 2014). Some of the methods used in hydraulic transient analysis are arithmetic mean method (Abuiziah *et al.*, 2014), graphical method (Salmanzadeh, 2013), analytical (Lebele-alawa and Oparadike, 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).

Malppan and Sumam (2015) reported that 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 (Ramalingam *et al.*, 2009; Liu *et al.*, 2014) and have been implemented in various computer programs for pipe system transient analysis. In this 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. WANDA is one of the most outstanding commercial simulation software that uses MOC for the analysis of fluid and heat flow in pipeline networks (Leruth and Pothof, 2012).

Muhammad *et al*. (2019) reported that 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 but 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.

2. MATERIALS AND METHODS

Method of Data Collection

The pipeline parameters presented in Table 1 were obtained from the literature as reported by (Oyedeko, (2015) while the DPK parameters presented Tables 2 were obtained from direct measurement, archives of the Nigeria National Petroleum Company (NNPC) and the literature (Oyedeko, 2015 and Chuka, 2016).

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)	M (N/m^2)	E_y(N/m^2)	Cp (Kj/kg/K)	K (N/m^2)
DPK	810	0.297	120	0.006	213.84	2.22	1.07×10^9

The basic water hammer equation is used to express the change in pressure head produced by the surge in the pipes, as shown in equation 1.

$$\Delta H = -\frac{a}{g}\Delta v \qquad (1)$$

The fundamental water hammer theory which describes the pressure amplitude was laid by Joukowsky and is presented in equation 2 (Carlsson 2016).

$$\Delta P = \pm\rho a\Delta V \text{ or } \Delta H \pm = \frac{a\Delta V}{g} \qquad (2)$$

where

a is the pressure (water hammer) wave speed (m/s)
ρ is the fluid density (kg/m^3)
g is acceleration caused by gravity (m/s^2)

Equation (3) was used for calculating wave speed propagation for transient flow in the pipeline as reported (Nerella and Rathnam, 2015; Yang *et al.*, 2017)

$$a = \sqrt{\frac{\frac{k}{\rho}}{1+\left(\frac{k}{E}\right)\left(\frac{D}{e}\right)(C)}} \qquad (3)$$

where

k is the bulk modulus of elasticity of the fluid (N/m^2)
ρ is the mass density of the fluid (kg/m^3)
E is the Young's modulus of elasticity of the pipe material
e is the pipe wall thickness (N/m^2)
C is movement restrain constant (full pipe restraint from axial movement, $C = 1-\mu^2$).

According to Gómez (2018), 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 4.

$$K = \frac{\Delta P}{\Delta\rho/\rho} \tag{4}$$

Where
Δp is change in pressure of the fluid under consideration (kPa)
ρ is the mass density of the fluid (kg/m^3)
$\Delta\rho$ change in mass density of the fluid respectively (kg/m^3)

The head loss due to water hammer in the pipeline can be calculated using the Darcy-Welsbach relation presented as equation 5:

$$\mathrm{h_f} = \frac{\mathrm{fDLV^2}}{\mathrm{2gD}} \tag{5}$$

Where
f is the friction factor,
D is the pipe diameter (m)
L is the length of the pipe (m)
V is the flow velocity (m/s)g is acceleration caused by gravity (m/s^2)

Pires et al. (2017) reported that instantaneous valve closure is characterized by valve closure time less than T and the value of T can be calculated by using equation (6)

$$T = \frac{2L}{a} \tag{6}$$

Where
T is the reflection time (s)
L is the length of the pipe (m)
a is the wave speed (m/s)

Hydraulic transient behaviours in closed conduits can be analyzed by using equations of motion and continuity (Carey, 2014), the equation is shown as equation 7 as reported by (Yang *et al.*,2017)

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + \frac{fV|V|}{2D} = 0 \tag{7}$$

where, *D* is the diameter of the pipe, *f* is the Darcy-Weisbach friction factor, *g* is the acceleration due to gravity, *p* is the fluid pressure in the pipe, *t* is time, *x* is the distance on the pipe axis, *V* is the mean flow velocity of the fluid, ρ is the mass density of the fluid and θ is the pipe's angle of inclination.

The term $V\partial V/\partial x$ in equation 7 is neglected in transient analysis as a result of low Mach-number and unsteady flows, therefore equation 7can be written as equation 8 (Gómez, 2018)

$$\frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + g\sin\theta + \frac{fV|V|}{2D} = 0 \tag{8}$$

Also according to Carey, (2014) the continuity equation can be presented in equation 9.

$$\frac{1}{\rho}\frac{d\rho}{dt} + \frac{1}{A}\frac{dA}{dt} + \frac{\partial V}{\partial x} = 0 \tag{9}$$

If an elastic pipe is filled with a compressible fluid, equation (9) will reduce to relation presented in equation (10).

$$\frac{d\rho}{dt} + V\frac{\partial v}{dx} + \rho a^2\frac{\partial V}{\partial x} = 0 \tag{10}$$

where
D is the diameter of the pipe (m)
f is the Darcy-Weisbach friction factor,
g is acceleration caused by gravity (m/s^2)
P is the fluid pressure in the pipe (kPa)
t is time (s)
x is the distance on the pipe axis (m)
V is the mean flow velocity of the fluid (m/s)
ρ is the mass density of the fluid (kg/m^3)
θ is the pipe's angle of inclination (°)

The friction factor can be calculated by using the Colebrook-White equation as shown in equation (11) (Wang *et al.*, 2011)

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{\mu}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right] \tag{11}$$

where
f is the friction factor
Re is the Reynolds number of the flow
D is the diameter of the fluid (m)
μ is the coefficient of viscosity

Pipeline Network Layout

A hypothetical petroleum pipeline network is adopted for this work. The pipeline network consists of the followings, upstream and downstream reservoirs, pipes, pump and valves (gate valve and non- return valves). Reservoir-pipe-pump-valve-valve-reservoir system was adopted for was adopted following Nerella and Rathnam (2015). Figure 1 depicts the model of the pipeline layout adopted. The pipeline network is made up of four carbon steel pipes 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 (P), it has a length of 1000 m, 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.

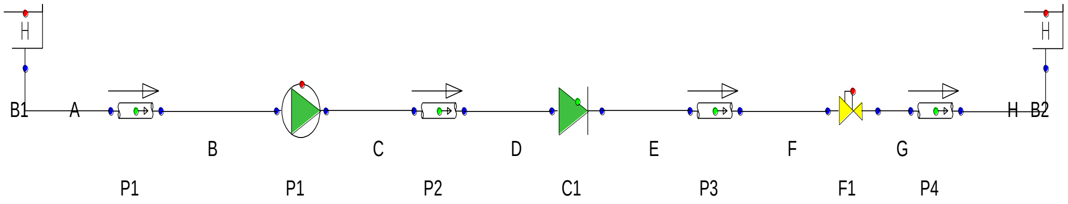

Fig. 1: Model of Pipeline Network Layout

Table 3 presents some of the parameters used in WANDA software for the analysis of the hydraulic transient in DPK while Table 4 presents some physical constants under which the simulation was conducted. In this study, the valve closure time adopted is 34 second which is less than wave propagation time (period) of 70.4 seconds.

Table 3: Properties of AGO

Liquid name	DPK
Rheology type	Newtonian
Density	810.0 kg/m^3
Bulk modulus	1.300×10^9 N/m^2
Vapour pressure	0.500 kPa.a
Kinematic viscosity	2.710e-5 m^2/s

Table 4: Physical Constant used in the simulations

Atmospheric pressure	101.4 (kPa.a)
Gravitational acceleration	9.810 (m/s2)
Ambient temperature	37.00 (°C)

3. RESULTS AND DICUSSION

Nerella and Rathnam (2015) reported that in transient analysis, it is a tradition to investigate only the maximum values of pressure head and flow rate. Evidently these two parameters can provide adequate information about other flow parameters which are mutually dependent.

Simulation Results

Figures 2 and 3 depict transient pressure and flow rate of DPK in pipe at node A of the pipeline due to instantaneous valve closure. The pressure at the node before valve closure is110.42 kPa with a 260 m^3/h but due to the closure of the valve at the downstream of the pipeline network, the pressure of the fluid fluctuates and oscillates between a minimum value of 110.06 kPa and a maximum pressure of 110.63 kPa at times of 4.8 s and 73.3 s respectively until reaches steady state pressure distribution at about 110.64 kPa. So also the flow rate oscillates between 415 m^3/h and 0 m^3/h.

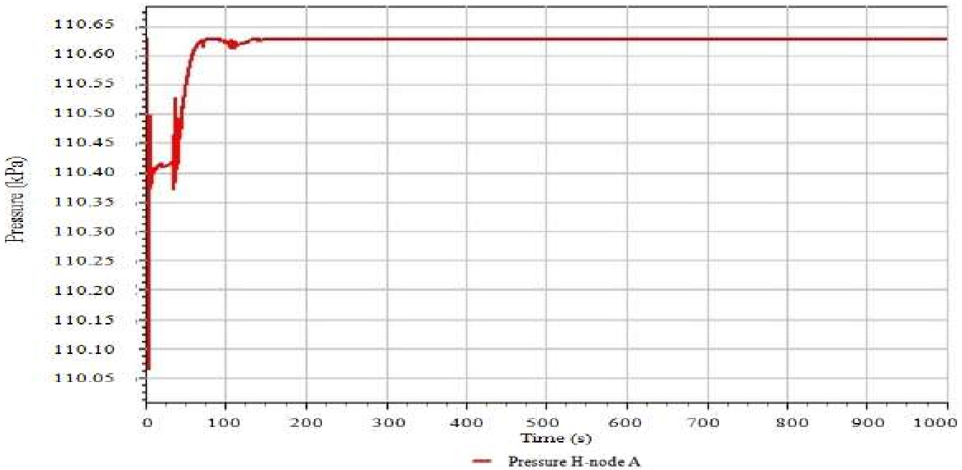

Fig. 2: Pressure due to valve closure at node A

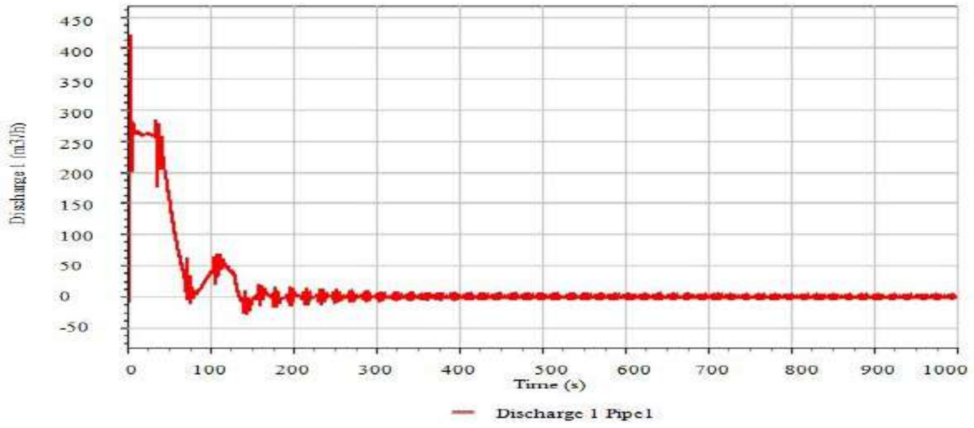

Fig. 3: Discharge at node A due to valve closure

Figures 4 and 5 presents pressure surge and discharge at node B due to valve closure, the figures depicts that DPK reaches the node with a pressure of 60 kPa and a flow rate of 265.5 m^3/h. But due to the valve closure the pressure oscillates between a maximum pressure of 367.3 kPa occurring at 5.6 s and a minimum pressure of -100.1 kPa occurring at a time of 3.5 s. So also the discharge also fluctuates between -18.79 m^3/h and 310.3 m^3/h at times of 5.6 s and 147 s respectively. The drop in pressure leads to the development of negative pressure at this node and hence the formation of cavitation of a magnitude of 0.003895 at 3.4 s at the node and long the length of pipeline as shown in Figure 6.

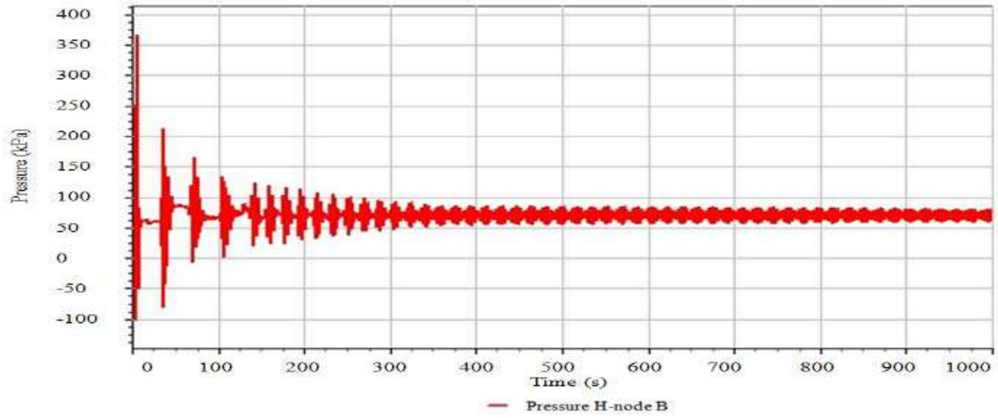

Fig. 4: Pressure due to valve closure at node B

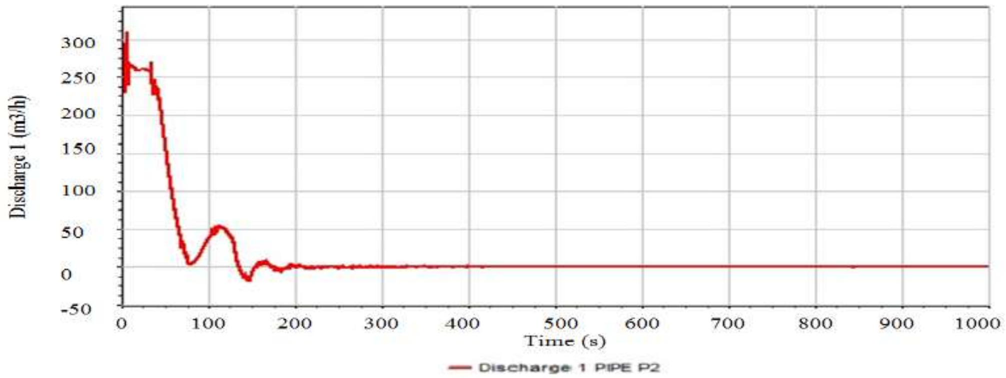

Fig. 5: Discharge at Node B Due To Valve Closure

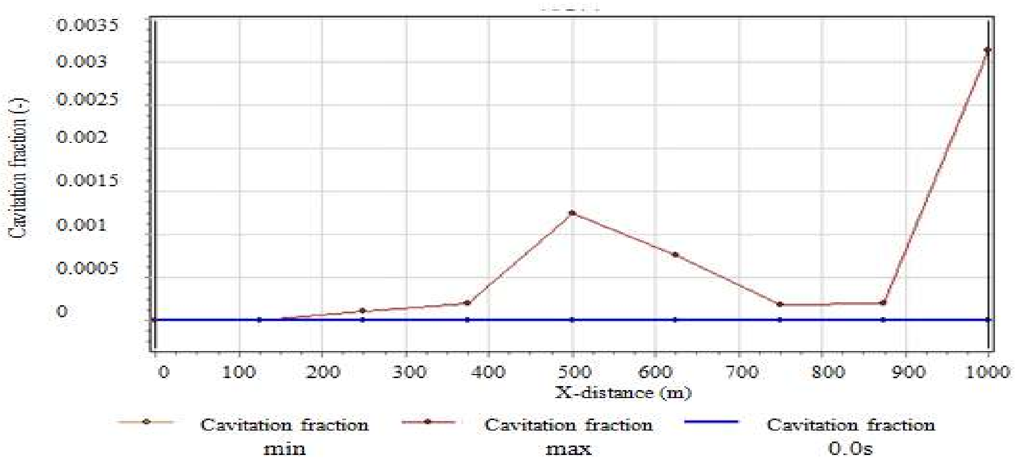

Fig. 6: Cavitations developed due to valve closure in the pipeline network

Figure 7 and 8 shows the nature of pressure and flow rate at node C before and after valve closure. Prior to the valve closure, the pressure and the discharge are 910 kPa and 265.5 m^3/h, but when the valve is closured, the pressure at the node drops to 331.1kPaat 0.1 s and at 71.1 s, the pressure rise to 1205 kPa. And also the discharge at the node oscillates between -18.79 m^3/h and 310.3 m^3/h at 5.6 s and 147.3 s respectively.

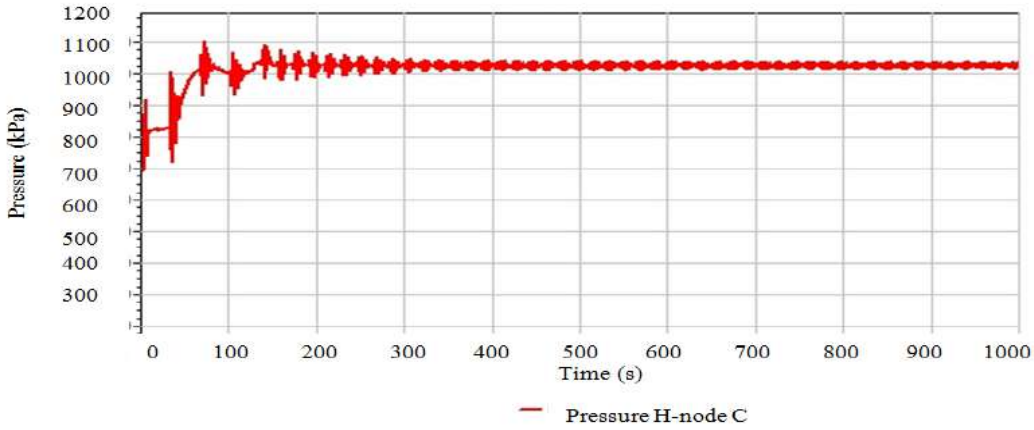

Fig. 7: Pressure at node C due to valve closure

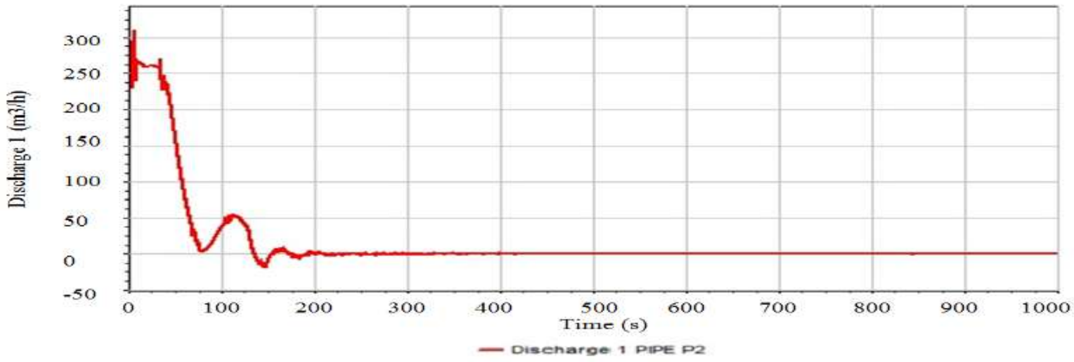

Fig. 8: Discharge at Node C Due To Valve Closure

Figures 9 and 10 depict pressure transient and discharge variations at node D. The pressure at the node prior to the valve closure is 540 kPa and the discharge is 160m^3/h but when the valve is closed, the pressure oscillates between a minimum pressure of 303.5 kPa at 8.5 s and a maximum of 1257 kPa at 60.5 s before stabilizing at 1200 kPa. And also the flow rate fluctuates between296.9m^3/h and 0 m^3/h at 14 s and 134.1 a respectively.

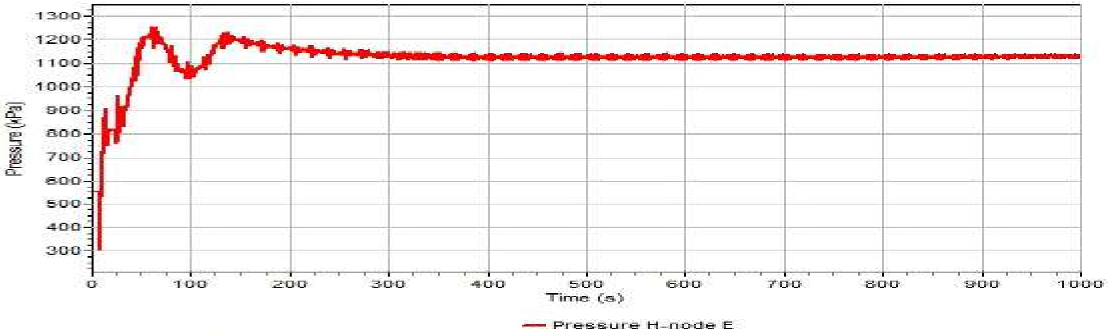

Fig. 9: Pressure at node D due to valve closure

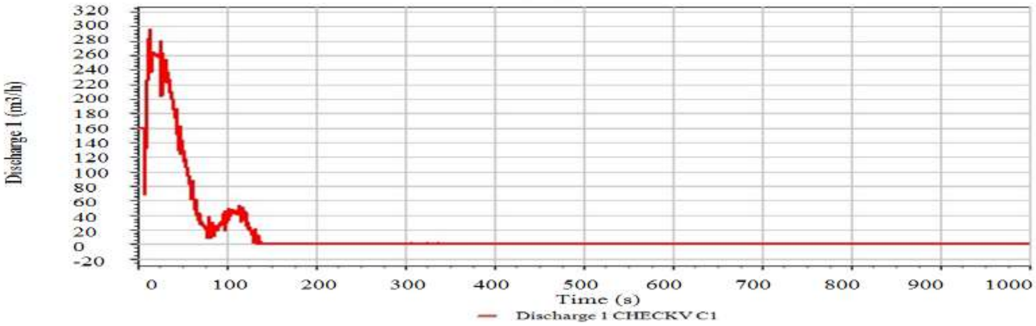

Fig. 10: Discharge at node D due to valve closure

Pressure and discharge variations experienced due to the valve closure at node E are presented in figures 11 and 12 respectively. Figure 10 depicts pressure surge at node E due to the instantaneous valve closure. The fluid reached the node with a pressure of 564 kPa prior to the valve closure but due to the valve closure, the pressure oscillates between a minimum pressure of 303.5 occurring at 8.5 s and a maximum pressure of 1257 kPa at 60.5 s. Figure 12 also shows that the discharge also oscillates between a minimum discharge of 0 m^3/h at 134.1 sand a maximum discharge of 296.9 m^3/h at 14 s respectively

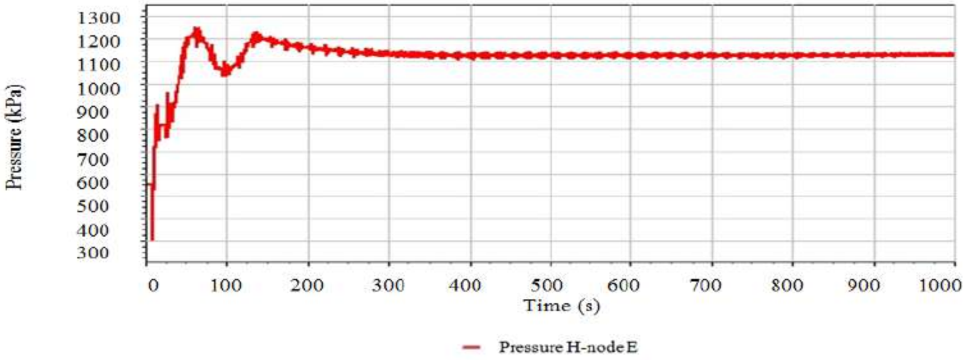

Fig. 11: Pressure at node E due to valve closure

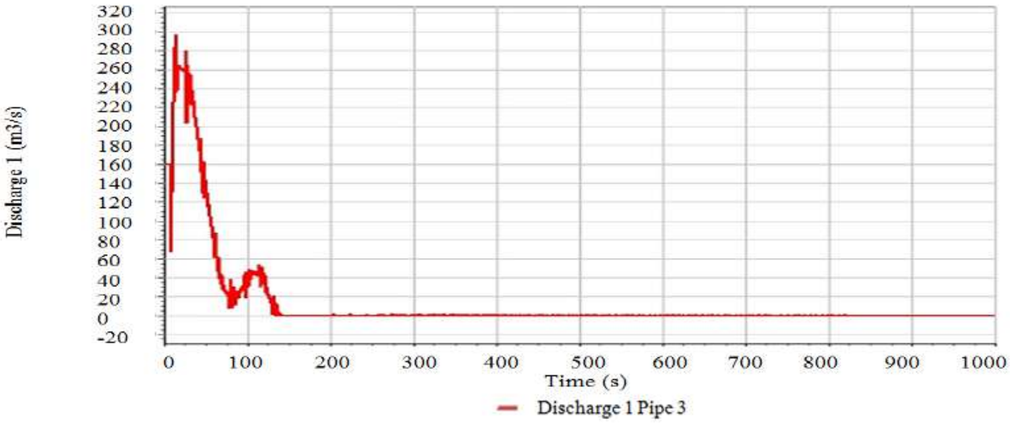

Fig. 12: Discharge at node E due to valve closure

Figures 13 and 14 shows hydraulic transient behaviour at node F of the pipeline network, the figure shows the pressure and discharge of DPK before the advent of the valve closure as around 490 kPa and 164 m^3/h. But when the valve is closured, the pressure and the discharge at the node oscillates between a minimum and maximum values of 176.8 kPa, 1354kPa, 0 m^3/h and 259.3m^3/h respectively. Node F experiences the highest rise in pressure because this is the node where the valve closure takes place.

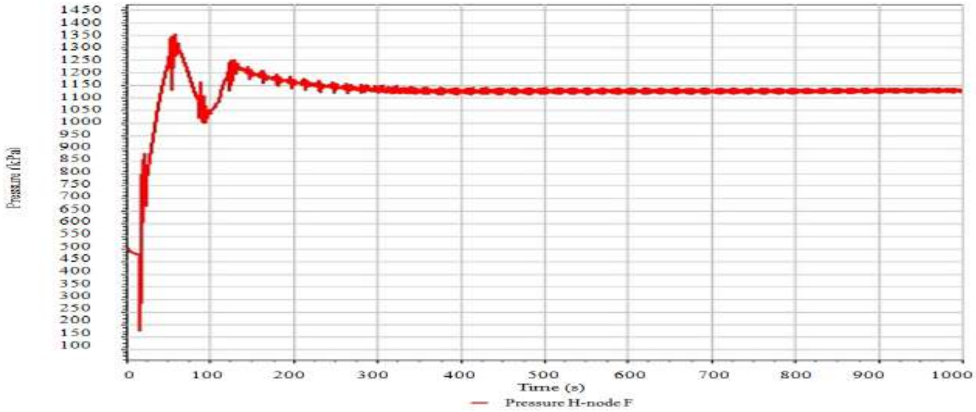

Fig. 13: Pressure at node F due to valve closure

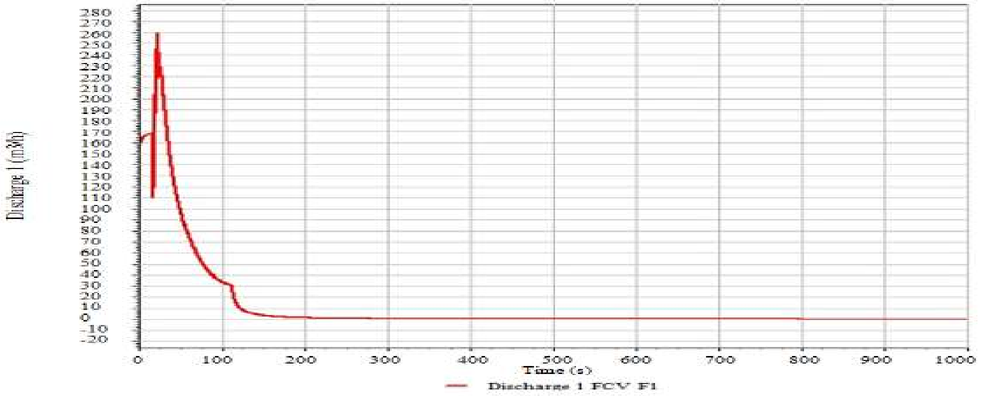

Fig. 14: Discharge at node F due to valve closure

Figures 15, 16, 17 and 18 shows pressure and discharge transients at nodes at downstream of the closed gate valve. Figures 15 and 16 depicts nature of pressure at a node immediately after the closed valve (node G). The pressure and discharge at node G before the valve closure are 245 kPa and 164 m^3/h, but after the valve closure, the pressure oscillates between a minimum pressure of 75.95 kPa at 16.9 s and a maximum pressure of 562.3 kPa and at 18.5 s. So also the discharge at node G fluctuates between a discharge of 259.3 m^3/h at 14 s and a minimum discharge of 0 m^3/h at a time of 814.4 s respectively.

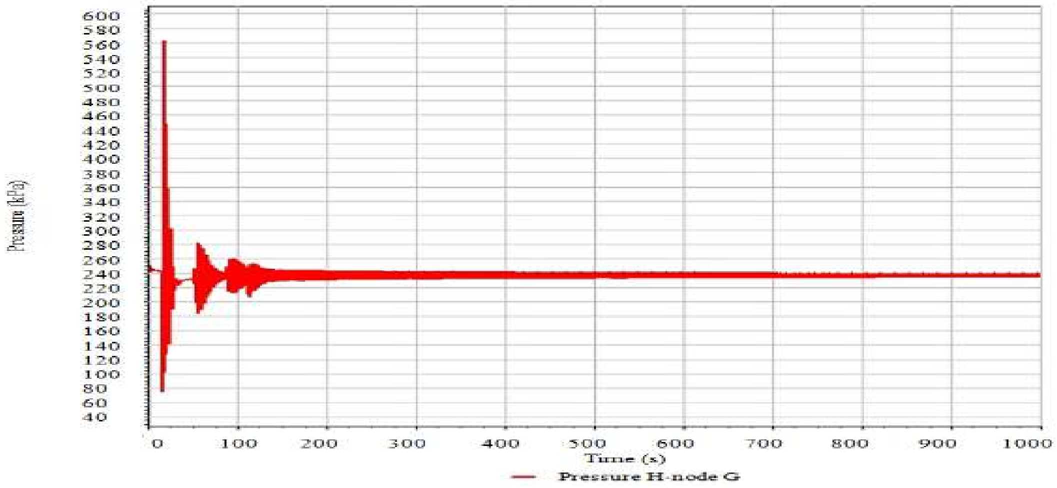

Fig. 15: Pressure at node G due to valve closure

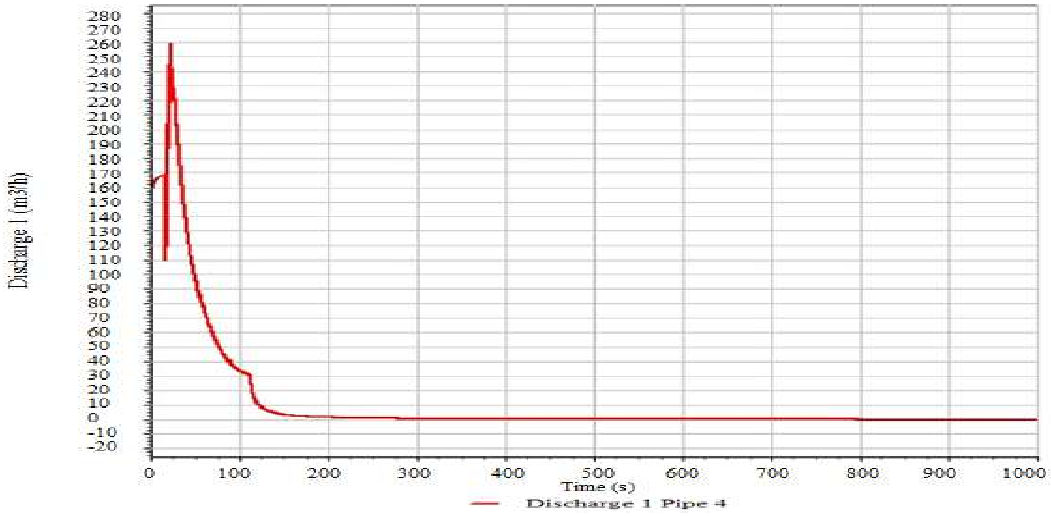

Fig. 16: Discharge at node G due to valve closure

Figures 17 and 18 depict pressure and discharge at node H. The change in pressure at node H is not much, the fluid reaches the node prior to the closure of valve with a pressure and discharge of 236.88 kPa and 164 m^3/h but when the valve was closed, the pressure oscillates between 235.7 kPa and 237 kPa 22.8 s and 152.5 s respectively while the discharge oscillates between 278 and -1.112 at times of 22.8 s and 328.5 s respectively

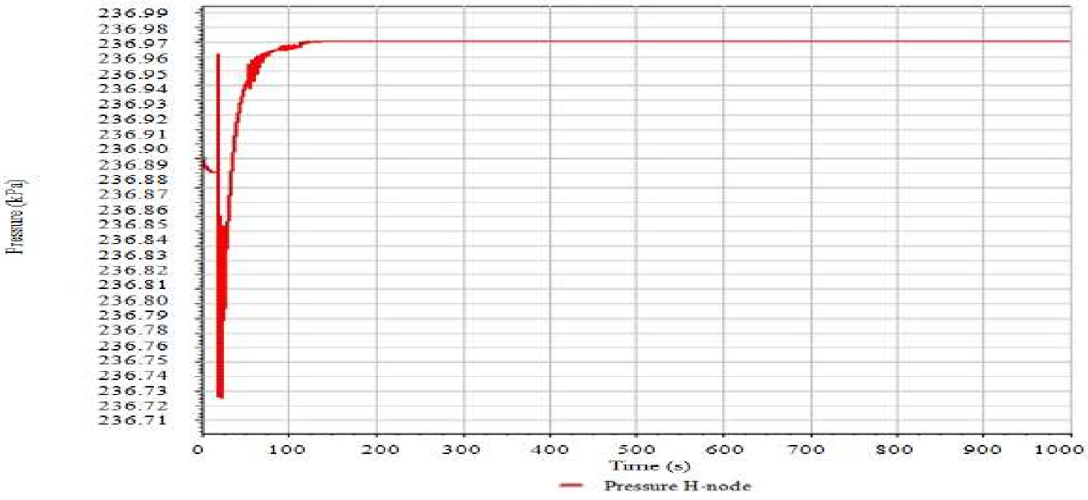

Fig. 17: Pressure at node H due to valve closure

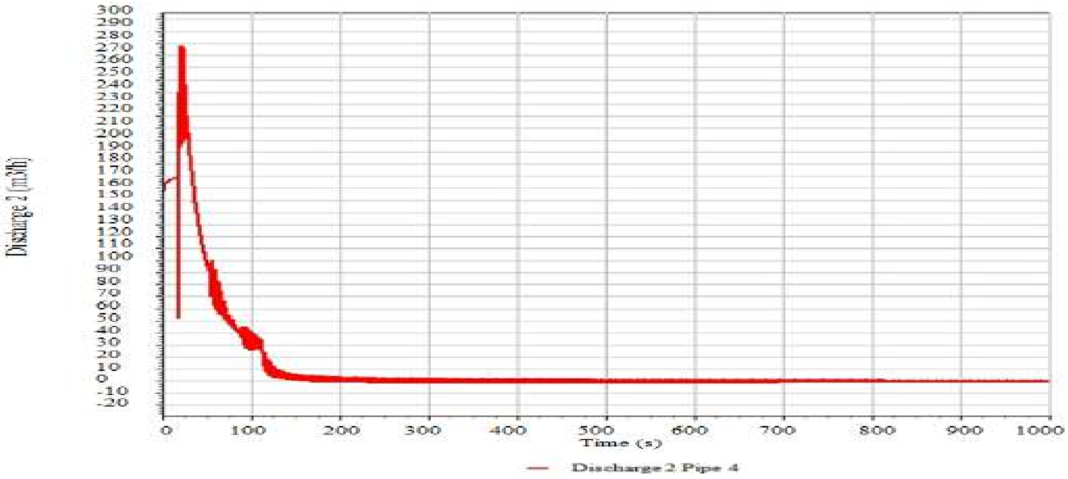

Fig. 18: Discharge at node G due to valve closure

4. CONCLUSION

The investigation of hydraulic transient due to instantaneous valve closure in a petroleum pipeline conveying dual purpose kerosene (DPK) using simulation approach was carried out in this paper. In this study, a hypothetical petroleum pipeline network is adopted for the research work. Data used in this research were obtained from measurement, literature, NNPC archives and the field. 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 pressure surge in the pipeline network due the instantaneous closure. It was observed in the study that pressure waves and discharges in the pipeline network oscillate between high and low pressure values as the result of the valve closure. It was also observed in this research that rise in pressure is highest at the node where the valve closure is taking place and also there is drastic drop in pressure at nodes just upstream of the pumps. 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 nodes B to curtail damages due to cavitations.

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