Journal of Engg. Research Vol. 8 No. (3) September 2020 pp. 219-239 https://doi.org/10.36909/jer.v8i3.6651

الطريقة الحاسوبية لتصميم ونمذجة أنظمة محاكاة الجريان المتغير في أنابيب النفط الخام

شكر الله إناتيمي بووي وأولوسيجون ديفيد صموئيل
قسم الهندسة الميكانيكية، الجامعة الاتحادية للموارد البترولية، ولاية دلتا، نيجيريا

الخلاصة

يهتم مصممي خطوط الأنابيب وأنظمة محاكاة الجريان المتغير بشكل كبير باستخدام أدوات ديناميكا الموائع الحسابية، حيث أنهم يفضلون استخدام برنامج الجريان المتغير مع ميزات واجهة المستخدم الرسومية القوية (GUI) بسبب تكلفتة المعقولة وامكانية الاستخدام المباشر. في هذه الدراسة، تم تطبيق آلة لحل الظواهر المتغيرة مع واجهة مستخدم رسومية موثوقة لتصميم نموذج حاسوبي لنظام أنابيب نقل النفط الخام بطول 52 كم ويُستخدم لاستكشاف أحداث الجريان المتغيرة الشائعة والمختلفة مثل إغلاق الصمام المفاجئ والمضخات التي تعثرت على الفور. تشير نتائج المحاكاة إلى أن 15 ثانية من وقت إغلاق صمام التفريغ أثناء عملية تحميل النفط الخام وتفريغه كانت معقولة لنظام خطوط الأنابيب مع نظام تخفيف الضغط القابل للتشغيل، وتم تخفيف ما يقرب من 80% من الضغط الهيدروليكي في نظام خطوط الأنابيب باستخدام صمامات تخفيف الضغط. كان تأثير نظام الجريان المتغير أثناء تعثر المضخات في غضون 5 ثوانٍ كبيراً على نظام خط الأنابيب مما أدى إلى انتشار موجة الضغط وحالات تجويف المضخة. لذلك، تم اقتراح قواعد تصميم مُعدلة للنمذجة الحاسوبية للجريان المتغير والتي يمكن أن تدعم برنامج تدريب للمهندسين المسئولين عن الجريان للتنبؤ بالمخاطر والعمل على تخفيفها وتقييم تأثير أنظمة خطوط الأنابيب المماثلة في مرحلة التصميم الأمثل.

Computer-based method of design and modeling of transient flow in crude oil pipeline system

ThankGod Enatimi Boye*,** and Olusegun David Samuel*

*Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, PMB 1221, Effurun, Delta State, Nigeria
**Corresponding Author: boye.thankgod@fupre.edu.ng

Submitted: 03/04/2018
Revised: 20/10/2019
Accepted: 25/03/2020

ABSTRACT

The utilization of computational fluid dynamics tools continues to gain growing interest from pipeline designers and transient flows simulators. Transient flow software with robust graphical user interface (GUI) features is arguably preferred because of cost effectiveness and being straightforward in use. In this study, a transient solver with credible GUI is applied to design a computer-based model of a 52 km crude oil transportation pipeline system and used to explore different common transient flow events such as sudden valve closure and pumps tripped instantaneously. The simulation results suggest that 15 seconds of discharge valve closure time during crude oil loading and off-loading operation was reasonable for a pipeline system with functionable pressure relief system, and approximately 80% of hydraulic pressure in the pipeline system was mitigated aided with the use of pressure relief valves. The effect of transient flow regime during pumps tripped within 5 seconds was significant on the pipeline system, which resulted in pressure wave propagation and pump cavitation occurrences. Therefore, a modified design rule was proposed for computer-based modeling of transient flow, which could support the training program of flow engineers for predicting, risk mitigation, and impact assessment of similar pipeline systems at the optimization design stage.

Keywords: Computer-based design; transient flow; pipeline; risk assessment; mitigation.

INTRODUCTION

The use of pipeline for transporting petroleum products is increasingly growing, arguably remaining the most cost effective means of transportation of oil and gas (Kennedy, 1993). Pipelines affect day-to-day living worldwide. In today's environment, where energy plays an indispensable role in the lives of modern people, oil and gas are major donors in the supply of energy, and pipelines are the primary means by which they are transported. Mohitpour et al. (2007) argued that it is no coincidence that an extensive pipeline network goes hand-in-hand with a high standard of living and technological progress.

To ensure oil and gas supply for electrical power generation, recovery processes, refinery processes, and other uses, pipelines are utilized to transport the products from their sources. Pipelines are mostly buried or laid on the inlands or swapping areas, while offshore pipeline are mostly exposed in the sea bed and float through the sea depths and operate without disturbing normal pursuits. They carry large volumes of natural gas, crude oil, and other products in continuous streams (Mohitpour et al., 2007).

Pipeline system designs are usually carried out in stages, which include initial conception, feasibility studies design, functional design, and optimization and risk assessment (Thorley, 2004). Details of all the stages associated in pipeline design are captured in Thorley (2004), Mohitpour et al. (2007), Gary et al. (2017), and Kennedy (1993).

The optimization and risk assessment stages, which incorporate economics and hazards analysis during the constructions and operations, respectively, of the pipeline system, are of special interest to the present work, especially, the aspect of risk assessment of the operational pipeline system that deals with flow assurance to determine the desirable operating conditions, risk mitigation, and control for the intended pipeline system. In fact, one of the major operating conditions that should get priority during this stage is the fluid flow requirements of the intended system. In the design stage, unacceptable operating conditions are also identified. Fluid transient may constitute unacceptable operating conditions and should be a major part of the risk assessment in the pipeline system reported in Boulos et al. (2005). Transients flow analysis should be critically examined in the final stage of the design process before construction commences, because any changes to the physical design of the pipeline system may undermine the hydraulic transient analysis conducted as reported by Thorley (2004). Thus, this research paper presents a conceptual design to explore transient flow events occurrence at the design phase of crude oil transporting pipeline system utilizing computer-based method. The designed computer-based crude oil transporting pipeline system can be used to support training, risk assessment, and impact assessment investigation by field and safety engineers.

Transient flow

Column separation of fluid in enclosed pipe was first reported in Carpenter, Barraclough (1894). Transient phenomena can be referred to as column separation, which is the breaking of liquid columns in fully filled pipelines stated in Don et al. (2005) and Bergant et al. (2006). This is a case where the fluid flow is unsteady and exists in many other situations due to disturbances induced by the change in the discharges, the maneuvers at the valves, or some kind of accidents. The unsteady motion in hydraulic surge system is produced by the transition from a steady flow regime to unsteady flow regime, which can be referred to as hydraulic transient regime (Thorley, 2004). The rapidly varied motion is characterized by large amplitudes and frequencies of the pressure oscillations (column separations) developed and is strongly influenced by the fluid compressibility and elasticity of the pipe material reported by Galante & Pointer (2002) and Afshar & Rohani (2008). Popescu et al. (2003) also confirmed that, during rapidly varied motion of a liquid, the mass transfer is negligible. Typically, the occurrence of rapidly varied motion of a liquid in pipeline can also be referred to as *Water-hammer* stated in Simpsonb & Tijsselingc (2006) and AFT (2007). In the rest of the paper, transient flow and water-hammer are used interchangeably.

The demand of oil and gas products for the world energy consumption increases rapidly due to the growing world population (Joel, 2004 & IEEJ, 2017). These have led to more complex pipeline system designs, construction, and commission for the ease of products transportation from one place to another, and as well increased exploration of oil and gas in challenging and remote environments such as deep offshore (Cordes et al., 2016) and artic sea (Jon et al., 2009). Transportation of oil and gas from remote locations poses safety challenges due to the terrain that increases the likelihood of transient flow event occurrence. These challenges should be tackled during design stage, which could result in significant cost reduction of commissioning and mitigating catastrophic risks to human life, plants, and the environment.

The transmission of crude oil from recovery fields to storages or refinery in most case depends on complex pipeline systems, which are usually in hundreds of miles or kilometers of distance, equipped with sophisticate control and monitoring facilities to prevent and control hydraulic transient (water-hammer) phenomena occurrence that is practically inevitable in surge systems. Therefore, for efficient pipeline design, it must become the norm to perform water-hammer calculations, by predicting the highest and lowest pressure fluctuations, which could be experienced in the pipeline (Popescu et al., 2003, Taheri & Afshar, 2010). Some dangerous transients' flow phenomenon can cause rupture of pipe and pump castings, pipeline collapse, pipefittings and support deformation, excessive pipe displacement, vapour cavity formation (cavitation, column separation), vibration, etc. (Boulos et al., 2005 & Mohitpour et al., 2007). The main objective of the paper is focused on the design of a computer-based pipeline system model for the simulation of crude oil flow in pipeline system and predicting as a result of transient flow events. A crude oil transportation pipelines system was designed on an industrial water-hammer software known as IMPULSE 4.0 developed by Applied Flow Technology (AFT). The developed computed-based crude oil transportation pipelines system model was used to explore common transient flow events for control-mitigation and risk assessment. The IMPULSE 4.0 solver performs fluid flow calculations using the fundamental laws of fluid flows such as the conservation of mass and momentum and treats the governing equations as the classic method of characteristics (MOC).

Several literatures captured the use of the MOC for analytical computational and computer-based simulation of transient flows in pipe systems. Hossein et al. (2010) conducted numerical computational for transient flow of pipes network. The study involved implementing the finite difference coupled with the method of characteristics for the application of fixed-grid method of the characteristics of transient flow in multipipe systems. The work results in a developed transient solver using the MOC techniques majorly.

Tushar et al. (2017) conducted a comprehensive review of the various transients flows analysis techniques and reported that the MOC remains the mostly widely used procedure for numerically modeling of transient flows problems. Don et al. (2005) conducted a numerical method to study and modeling transient flow in distribution systems with the aim to compering the MOC and the wave characteristics method (WCM) with the ability to solve partial differential transient equations of pipe flow for varied degrees and complexity. It was reported tha, both MOC and WCM demonstrated the capability of accurately solving the transient pressure in pipe flow of water distribution networks, although WCM has more efficient use of computational resources. If execution times need to be trade-off with higher accuracy on the numerical solutions, then the MOC will be desired. Roman (2006) investigated transient flows in pipes also using the concept of fix grid of the MOC, and the results show good agreement with experimental data. Thanapandi & Prasad (2000) conducted theoretical and experimental study on the transient characteristics of a centrifugal pump during start and stop periods using the MOC for the numerical model. The result shows that the numerical model predicts well the trend of the dynamic head characteristics during transient's regime, and the method (MOC) can be extended to the analysis of purely unsteady cases, where the pump operation is not quasi-steady.

More recently, Wang & Yang (2015) presented a study of water-hammer by combining the MOC and method of explicit-implicit (MOI) to simulate pipeline unsteady flow and hydropower transient processes. It was reported that the results of the coupled method are effective in simulating water hammer in pipelines and transient processes of hydropower system. Note that available literatures for over three decades reveal that the method of characteristics has been widely used for both numerical and computer-based studies of transient flow phenomena. Therefore, the MOC forms the principle technique to enable easy simulation of transient flow of any complex pipeline geometric or network.

As the power of computer continues to increase, it provides the capability of developing efficient transient solvers with high user-friendly features. Transient solvers with high user-friendly features such as graphic user interface (GUI) for postprocessing data and capability of modelling pipefittings components such as valves, pumps, surge tanks, and reservoir, among others are sought for nowadays by pipe and water-hammer engineering community. Thus, the computer-based method is adopted for the modelling and prediction of transient flow in crude oil transportation pipeline systems.

The next section includes the pipeline configuration, operational design limits, the crude oil properties, selection and modelling of the main and booster pumps sizing, and the developed computer-based models. The results and discussion section includes results from the performance test of pipeline system model, results, and their interpretation of common transient events that were explored such as discharge valves closure, booster pump tripped due to mechanical failure, and main pumps tripped due to power failure. Also, modified design rules for transient flow in pipeline system were presented. Finally, the conclusion and further work are stated in the last section.

MATERIALS AND METHODS

In this paper, as mentioned earlier, the AFT Impulse 4.0 is applied for the design and modelling of an offshore oil terminal facility. The crude oil pipelines system for the computer-based model design process includes the selection and sizing of pumps, pipes, discharge valve, check valves, and safety valves (pressure relief valve), and thereafter the simulation of common transient's flow events. The design of the computer-based crude oil pipeline model strictly conforms to the international recommended practices of American Petroleum Institute (API) and American National Standards Institute (ANSI). A typical 52-kilometer crude oil transportation pipeline system from oil tanks farm to a tanker vessel was mimicked as depicted in figure 1 (a & b). Standard boundary and operational conditions are carefully imposed on the design of the computer-based models for the transient's flow study.

Boye et al. (2017) conducted a validation exercise on the industrial water-hammer software AFT Impulse 4.0 using published experimental data from a specialized transient flows laboratory (Popescu et al., 2003). The results from the Impulse 4.0 show reasonable agreement with experiment data, which justified its credibility as a design tool capable of modelling transient flow.

Brief description of the governing equations

The following equations are generally utilized for computer-based hydraulic modelling for transient flow in a pipe.

The time-dependent, one-dimensional flow of a fluid in an inclined conical conduit is briefly described as follows:

Continuity equation

$$\frac{\partial H}{\partial t} = -\frac{c^2}{gA}\left(\frac{\partial Q}{\partial x}\right), \quad (1)$$

The momentum (Newton's second law of motion) equation

$$\frac{\partial H}{\partial t} = -\frac{1}{gA}\left(\frac{\partial Q}{\partial x}\right) * f(Q), \quad (2)$$

where H is the pressure head (pressure/specific weight), Q is the volumetric flow rate, c is the sonic wave speed in the pipe, A is the cross-sectional area, g is the gravitation acceleration, $f(Q)$ represents a pipe resistance term, which is a nonlinear function of the flow rate.

The transient flow software solves Equations 1 and 2 simultaneously in a discretized form in the computer. Details of the derivation if the governing equations and MOC can be found in Bergant et al. (2006) and standard text.

DESIGN AND MODELING

Design standards used

Global acceptable standards are strictly followed for the design of the computer-based pipeline system, which include the following:

1. Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design) API RECOMMENDED PRACTICE 1111 THIRD EDITION, July 1999.

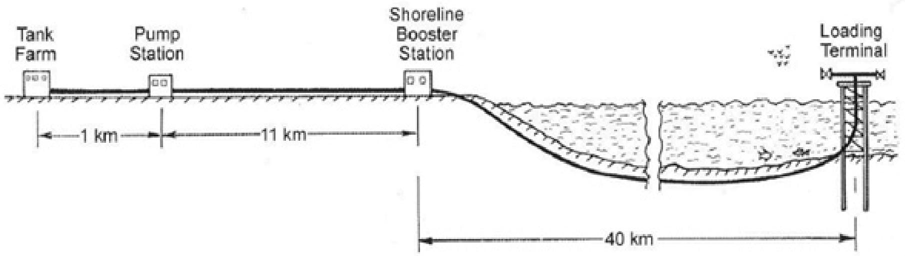
2. Pipeline Transportation System for Liquid Hydrocarbons and other Liquids ANSI/ASME B31.4 ASME Code for Pressure Piping, B31 March 2010.

Design specification for offshore pipeline oil terminal

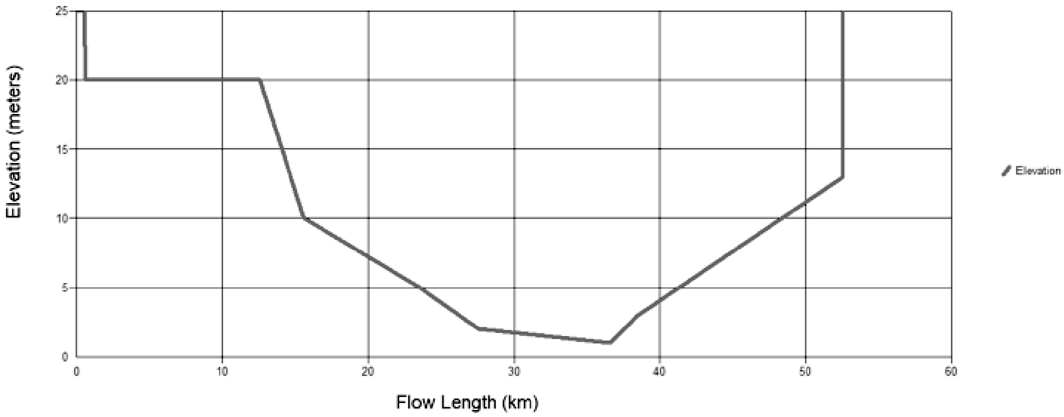
The 52 km pipeline system shown in Figure 1 is adopted for the computer-based design of the crude oil transportation pipeline system. To perform transient flow analysis in AFT Impulse 4.0, transient events such as pumps tripped and rapid closing of the discharge valve within 5 and 15 seconds, respectively, are simulated. Transient flow is time dependent, and the simulation run time is set for 60 seconds, which is adequate to represent a best-case scenario for the occurrence of transient flow regime and the recovering of the system if control and mitigation strategy is deployed within this period. The design specification of the pipe numbers, pipe diameters, wave propagation speed, and pipe wall thickness are captured in Table 1. The pipe elevation and the total length of the computer-based crude oil pipeline system are shown in figure 1 (b), while the pipe numbers and distance are captured in Table 2.

Computer-based terminal design assumptions

The Crude oil is not associated with gases (one-phase fluid) with standard physical properties shown in table 3. The pipe roughness is assumed to be constant in all sections of the pipeline. The temperature of the system is constant; there is no pressure loss at the pipe fittings. The wave propagation speed in the pipeline is constant in pipe numbers 1 to 18 except pipe number 10 as captured in Table 1; the discharge valve is mounted on the pipeline not the tanker and valve closure time ≤ 15 seconds. Table 4 provides the design limitation of the systems. The three main pumps except the booster pumps are of the same capacity. The pumps' capacities are shown in figure 3 (a & b).



(a)



(b)

Figure 1. Schematic offshore oil loading terminal of 52 Km (a) adopted from Thorley (2004) and (b) Computer-based pipeline model profile/route in AFT Impulse work space.

Transient simulation and modeling procedures

The design and modeling procedures include the following:

- A pipeline system offshore oil terminal denoted as Oil Loading Terminal I was developed without pressure relief system first, and then pressure relief system was fitted on the model in compliance to the design specifications. The pump selection, performance characteristics curves, check valve selection, valve open and close time settings, and pipes selection are modelled with the capability of AFT Impulse software as shown in figure 2 (a & b).
- Transient flow analysis is performed based on two common transient events in pipe system, which are pump tripped instantaneously and the effect of rapid closure of discharge valve.

Table 1. Pipeline Mechanical configuration information.

Description	Unit (mm)
Internal diameter (pipe no. 1-18) expect pipe no. 10	808.5
Internal diameter pipe no. 10 (discharge pipe)	759.5
Pipe absolute roughness	0.04572
Outer diameter (pipe no. 1-18) expect pipe no. 10	821
Outer diameter 10 (discharge pipe)	772
Wall thickness	12.5
Wave propagation speed	**Unit (m/s)**
All other Pipeline wave propagation speed	1159.8
Pipe 10 wave propagation speed	1170.3
Pipe material	**Type**
All other pipe material	Steel ANSI B31.4 Schedule 20
Pipe 10 pipe material	Steel ANSI B31.4 Schedule 20

Table 2. Pipe number and distance.

Pipe No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Distance (km)	0.5	0.1	0.01	0.02	0.9	0.1	0.01	0.02	10.9	40	0.6	0.1	0.8	0.25	0.6	0.01	0.7	0.3	52

Table 3. Crude oil properties.

Oil properties according to API 48	
Oil temperature	20^{o}C
Density of oil at 20oC	800 kg/m^3
Oil Bulk Modules	1530.36 Mpa
Oil viscosity	10 Pa-s
Atmospheric pressure	1 bar

Table 4. Boundary and operational conditions of pipeline system.

Operational design limitation	
Minimum allowable operating pressure	1 bar-g
Maximum allowable operating pressure	550 bar-g
Maximum discharge pipe pressure	100 bar-g
Initiating station inlet pressure	7 bar-g
Initiating station discharge pressure	135 bar-g
Default station discharge pressure	450 bar-g
Pump efficiency	100%
Pump station suction/discharge losses	20 bar-g

The design and modeling of figure 1(a) in the AFT impulse workspace were challenging. Care and considerable effort are required to achieve it. Special training and computer simulation skills are also required to complement the prerequisite knowledge of fluid dynamics and pipeline design.

Pumps sizing

The pumps performance characteristics curves were obtained after running the Oil offshore terminal I model in AFT Impulse. The pipeline system model without any relief system was ran in steady-state flow. An assigned volumetric flow-rate of 0.75 m^3/s is used to obtain the duty points of the all the pumps. The duty points generated are for the selection of adequate pumps capacity available from pump manufacturer. The pumps characteristics curves are shown in Figure 3.

RESULTS FORMULATION AND DISCUSSION

The transient simulation results of the offshore oil terminal models with no relief system and the other with relief system in different transient's events are presented.

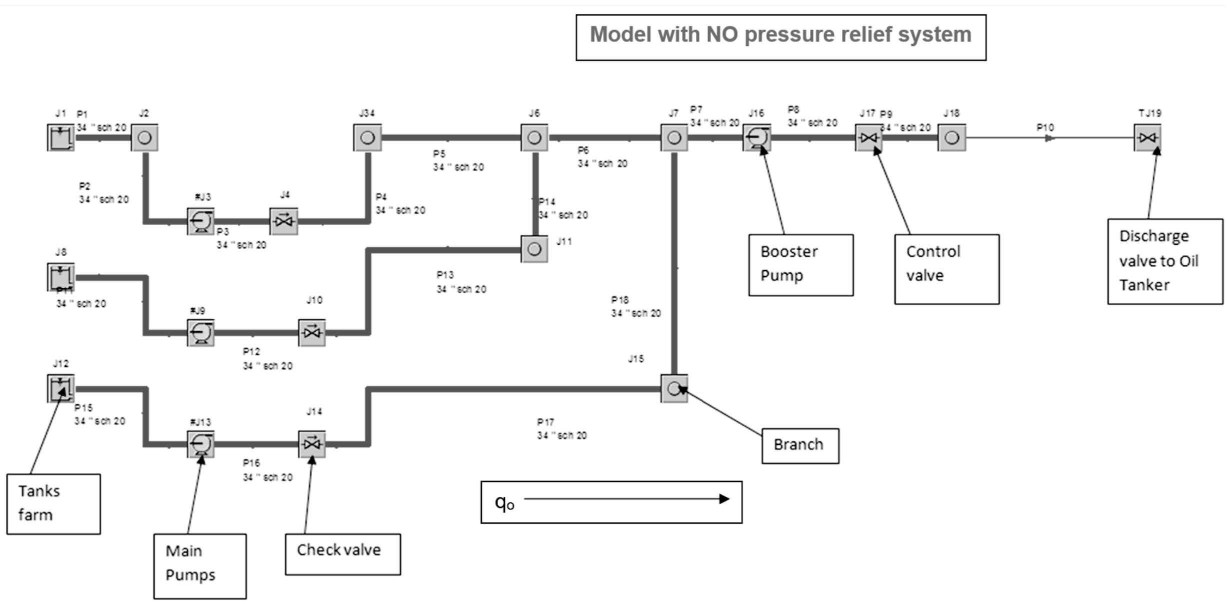


Fig. 2 a. 2D View of offshore (Oil Loading Terminal I) model without pressure relief system developed in AFT Impulse workspace.

The three Main pumps arranged in parallel to deliver crude oil after 11 km to a single pipeline, which is the inlet of the booster pump and located at the shoreline.

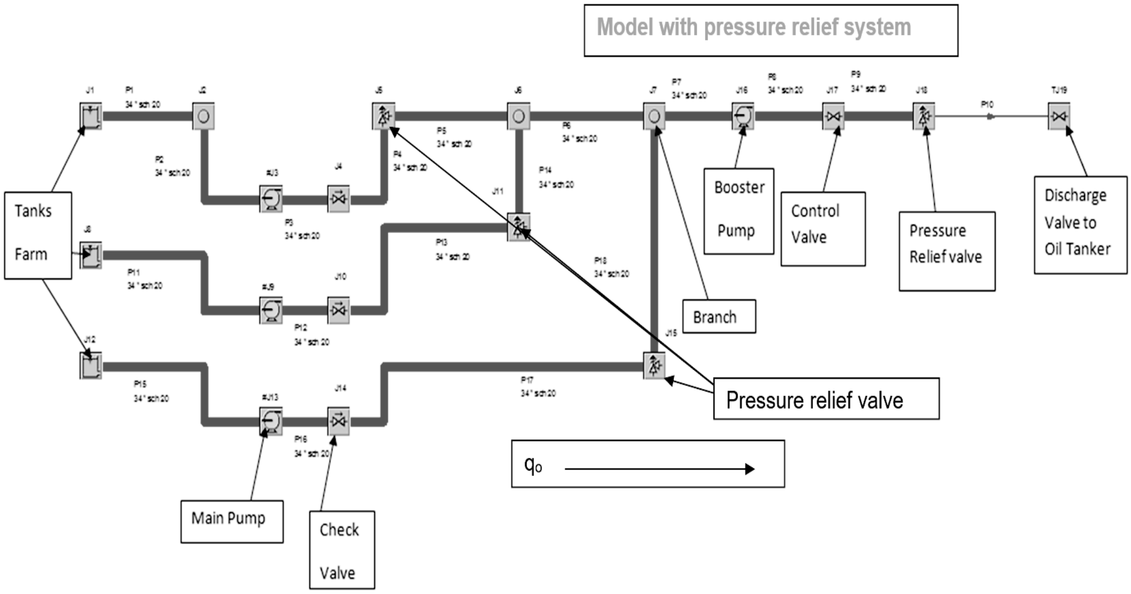
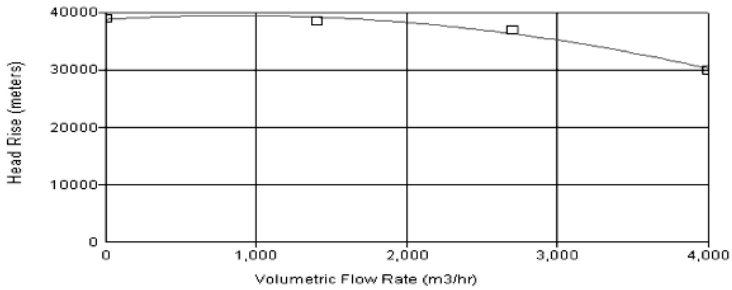
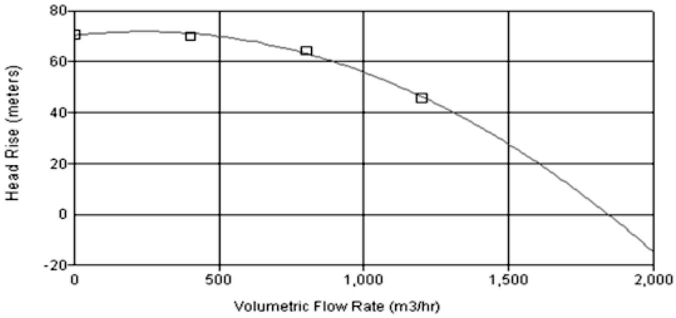


Fig. 2 b. 2D view of offshore (Oil Loading Terminal I) model with pressure relief system developed in AFT Impulse workspace.

Four pressure relief valves are installed at downstream of each the pump after the non-return valve at a distance of 700 meters from the pump to relief excessive pressure build-up during transient regime in the pipeline system to keep the operating pressure under control. All four relief valves are modelled and sized in AFT Impulse with flow coefficient (Cv) = 700.



(a)



(b)

Figure 3. The Pumps characteristics curves: (a) Main pumps characteristics curves and (b) Booster pumps characteristics curves of the computer-based crude oil transportation models.

The worst-case scenarios transient's events that are likely to occur in the pipelines system are considered for the risks assessments. Therefore, the worst-case value in time is set as the transient's data and input into the transient windows on the models to initiate the transient actions in the system during simulation.

The stipulated simulation time of both offshore oil pipelines models is set at 60 seconds in all cases for the reason mentioned earlier in the design specification for offshore pipeline oil terminal subsection. The worst-case scenario of transient events is presumed to be instantaneous, which is the vessel discharge valve to close within 15 seconds and pumps tripped in less than 5 seconds.

Transient event results for offshore oil terminal with no pressure relief system

This is a scenario where the crude oil is transported through the pipeline system from the tanks farm to the oil tankers at the offshore loading/offloading terminal, and the discharge valve is closed within 15 seconds. Note that these transient flow results in this subsection show the test results of the computer-based pipeline system model. Figures 4, 5, 6, 7, 8, and 9 show the transient results of the pipeline model with no pressure relief system. The transient event that occurred is the discharge valve closed within 15 Seconds.

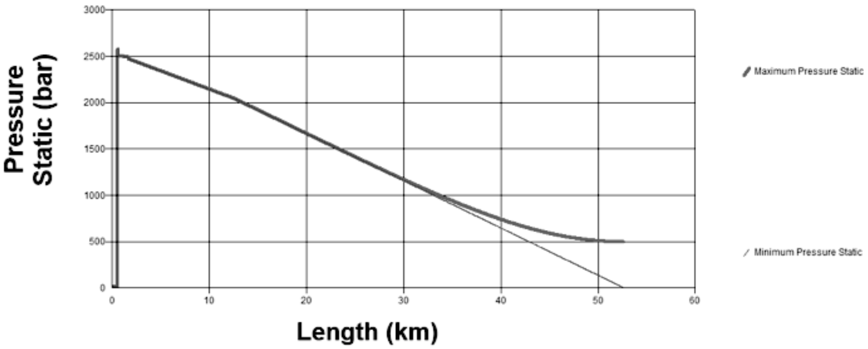


Figure 4. Pressure profile against flow length.

Figure 4 shows the maximum and minimum pressure during transient flow regime, which is similar to that of the steady state flow results not shown here. The transient flow result shows the maximum pressure of 500 bar acting on the downstream of the discharge pipe 10, although the pressure is still well above the maximum discharge required in pipe 10 as it was specified for the pipeline.

Figure 5 suggests that the crude oil flow-rate drops significantly to 0 barrels/hr at the downstream of the discharge pipe 10 from the maximum flow-rate after the rapid discharge valve of the oil tanker closed within 15 seconds. The final value of the oil flow-rate at the downstream pipe 10 indicated that crude oil stops flow after the valve has been closed. This indicates that the computer-based pipeline model is responding to the transient flow modeling and the design is functional.

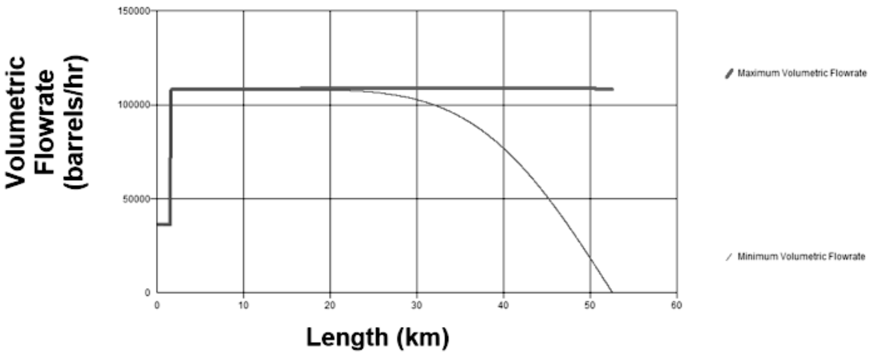


Figure 5. Volumetric flow-rate profiles against flow length.

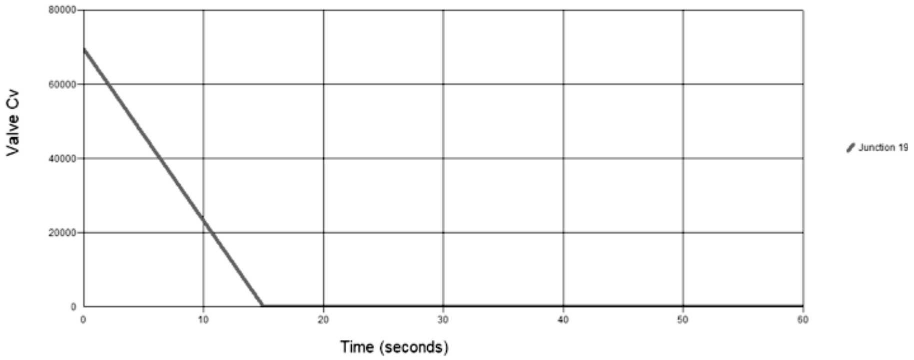


Figure 6. Discharge valve flow coefficient against time.

Figure 6 suggests that oil has stopped flowing to oil tanker in offshore after the discharge valve closed within 15 seconds of the simulation. Pipe 10 outlets predict accurately the discharge valve closing time and the stop of oil flow to the offshore vessel is evident.

Figure 7 shows the pressure acting upstream and downstream of the booster pumps pipe 7 and pipes 8, 9, and 10, respectively. The extreme high pressure from the downstream of the main pumps continues along the pipeline system but drops slightly at the inlet of pipe 10 and then drops dramatically to 0 bar in the discharge pipe 10 outlet. This is an indication of the effect of valve closure within 15 seconds of the transient's flow events, rising immediately after transient's flow events have occurred. The transient surge wave propagation of the system is insignificant due to the already very high pressure experienced in the pipeline system.

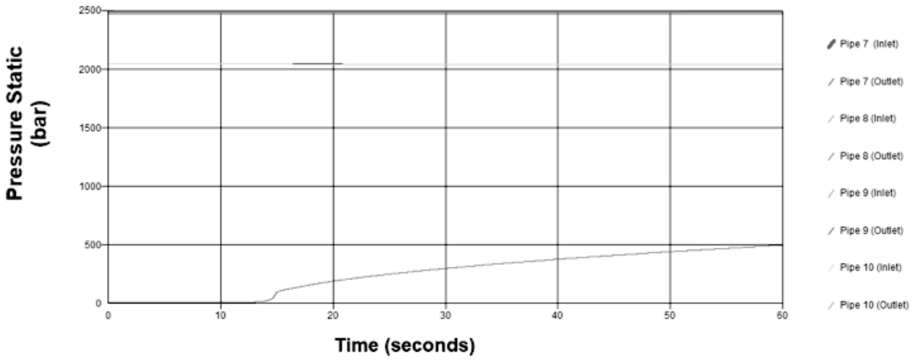


Figure 7. Pressure against time.

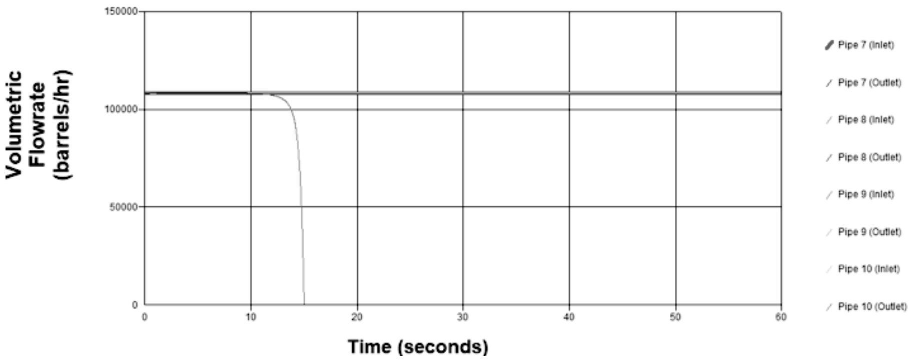


Figure 8. Volumetric flow rate against time.

The volumetric flow rate drops instantaneously within 15 seconds in response to the transient regime, which is induced by the discharge valve at the end of pipe 10. This indicted that the pipeline model is credible, and it meets the functional design requirements irrespective of the extreme pressure build-up observed. This is because there is no pressure relief system fitted on the pipeline system. The vessel discharge valve closes within 15 seconds, and all other pumps including both the main and booster are still running as shown in Figure 10. This means that the rapid valve closure within 15 seconds will not cause the booster pumps to trip.

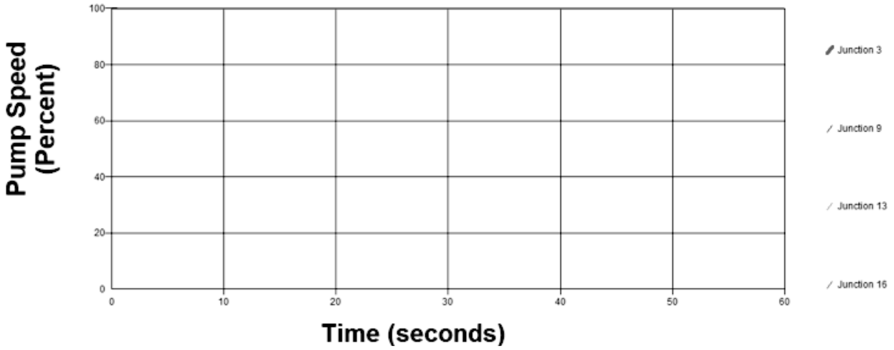


Figure 9. Pumps speed profile against time.

In that situation, the pumps shutting down procedure should commence starting from the booster pump and then the main pumps. However, it also indicated that the very high pressure is observed in the pipeline system, which is a factor that the pumps are still running. These are typical cases of transient flows events that do occur in the pipeline system.

Transient event results for offshore oil terminal with pressure relief system

The computer-based model with no pressure relief valves and simulation results shown in Figure 2 (a) demonstrated that the pipeline system experienced transient flow phenomena. The transient flow regime is not safe for a facility of this kind, and it could cause catastrophe damage to life and the environment. To ensure safety measures, control and risk mitigation are taken into consideration to prevent such destructive transient flow events in the crude oil transportation pipeline system. The strategy of installing pressure relief systems on the pipeline system is considered. Pressure relief valves is one of the safety equipment used to control high pressure in a pipe system (Popescu et al., 2003). Therefore, adequate pressure relief valves are strategical located in the pipeline system model as shown in Figure 2 (b) in order to control and mitigate excessive high-pressure propagation wave during transient flow regime in the pipeline system.

Oil tanker discharge valve closure transient case

Figures 10, 11, 12, and 13 are transient's results of the model with pressure relief system. The discharge valve is closed within 15 seconds to model a common transient flow event of sudden closure of discharge valve. The transient's event in this case is discharge valve, which is closed within 15 seconds for the model with pressure relief valves.

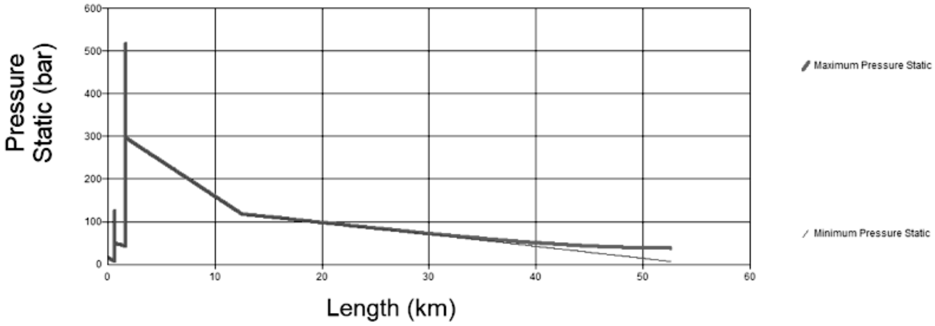


Figure 10. Pressure static profiles against pipeline length.

Figure 10 shows the effect of the pressure relief valves added to the crude oil transportation pipeline system (Offshore Terminal I). The extreme high transient pressure in the system reduced drastically to approximately 520 bars at downstream of the main pumps and continued to drop to approximately 120 bars at the downstream of the booster pump. The effect of the pressure relief valves is evident in the pipeline system, and as a result the extreme high pressure is controlled and mitigated during the transient flow regime.

The maximum and minimum pressure at the downstream at the discharge pipe 10 are less than 50 bars, which is an acceptable pressure level for the system as specified. The transient pressure is above the minimum allowable operating pressure of the pipeline system. Therefore, the risk of cavitation to occur is negligible during the rapid closure of discharge valve. The overall pressure relieved from the pipeline system is estimated to be approximately 80% compared to that of the model without any relief system.

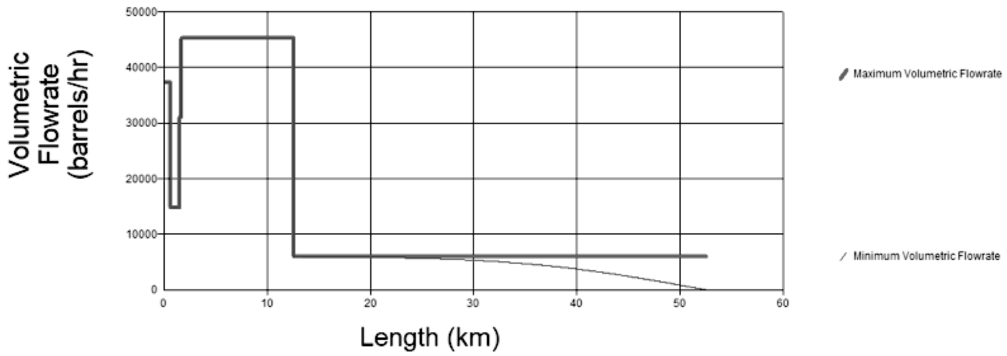


Figure 11. Volumetric flow-rate profiles against pipeline length.

The volumetric flow-rate of the crude oil reduced significantly when compared to Figure 8. The relief valve vented out the excess pressure, which is associated with crude oil from the pipeline when the pressure exceeds its preset pressure point. The sharp reduction of the maximum flow-rate at the distance of 12 km is attributed to the relief valve mounted after the booster pump. The gradual reduction of the minimum volumetric flow-rate at the distance of 28 km is due to the response of the discharge valve closure. This indicates that there is no oil flow at the downstream of the discharge pipe 10. The maximum flow-rate level at figure 8 is the actual flow-rate before the discharge valve was closed within 15 seconds, which triggered the transient flow regime. It should be noted that the volume of crude oil that is vented out along the excessive pressure in the system could be channeled to a storage /surge tank.

Figure 12 presents the pressure in the downstream of the main pumps after the discharge valve is closed. The pressure in pipe 8 is greater than any other pipe shown, which is the booster-pump discharge pipe at the upstream of its check valve. Pipe 10 outlets show the transient pressure in response to the valve closure time.

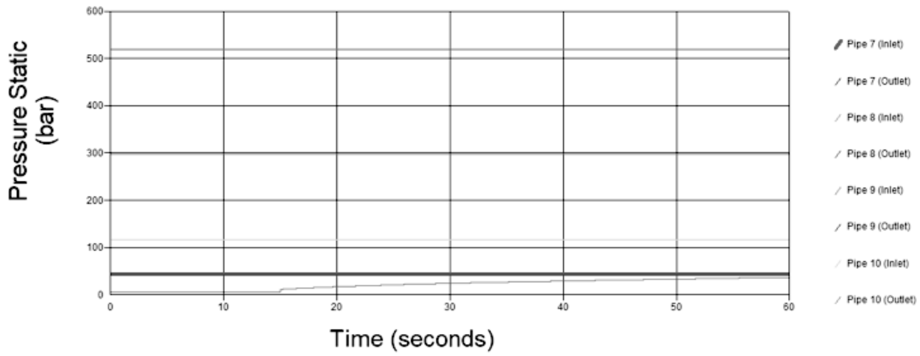


Figure 12. Pressure static against time (pipes 7 to 10).

Generally, figure 12 indicates that the pressure in the pipelines system model is below the maximum allowable operating pressure, and the risk of cavitation during rapid closing of discharge valve is negligible in the pipeline system with relief valves.

Figure 13 shows the flow-rate profile with respect to simulation time of 60 seconds and the valve closure time of within 15 seconds. The fully developed oil flow has been established in the pipeline system before the vessel discharge valve is closed. Pipe 10 outlet also indicates the time the discharge valve closes, which corresponds to the stop of crude oil flowing into oil tanker vessel in offshore.

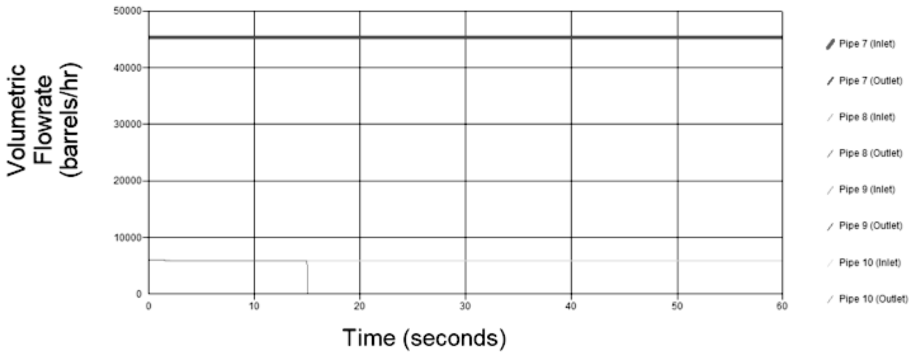


Figure 13. Volumetric flow-rate against time (pipes 7 to 10).

The graph further indicates that there is no transient flow or column separator of wave propagation in the pipeline due to the rapid closure of the discharge valve. Therefore, this suggests that 15 seconds is adequate for the discharge valve to close or open during loading or unloading operations.

Booster pump tripped due to mechanical failure

In this case, the booster pump tripped instantaneously due to mechanical failure when the crude oil flow is fully developed in the pipeline and the discharge valves is still open, while the main pumps are still running. The transient event occurs as a result of the booster pump tripped within 5 seconds.

Figures 14, 15, 16, 17, 18, and 19 are transient results of the computer-based pipeline model with pressure relief system.

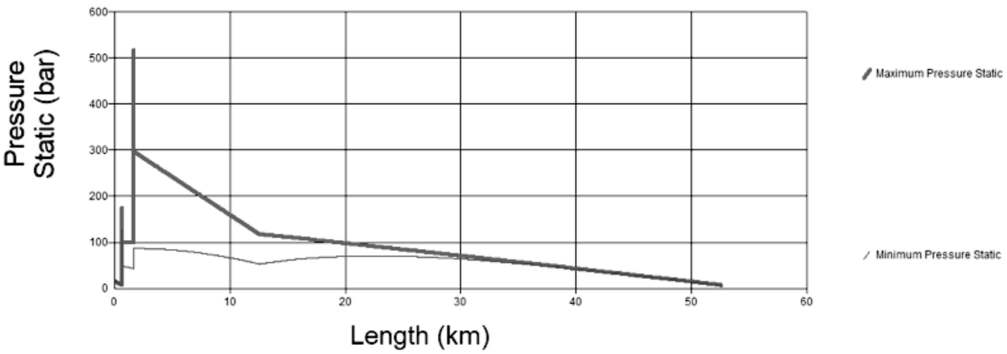


Figure 14. Pressure static profiles against pipelines length.

The minimum pressure static profile in Figure 14 shows the effect of the booster pump tripping instantaneously within 5 seconds. This caused a sudden drop of the system pressure at the downstream of the booster pump and sudden significant pressure loss at the upstream of the booster pump. The result also suggested that transient pressure exists between location 1 km and 30 km of the pipeline length. This situation is not far from cavitation occurring at the downstream of the booster pump when compared with Figure 10.

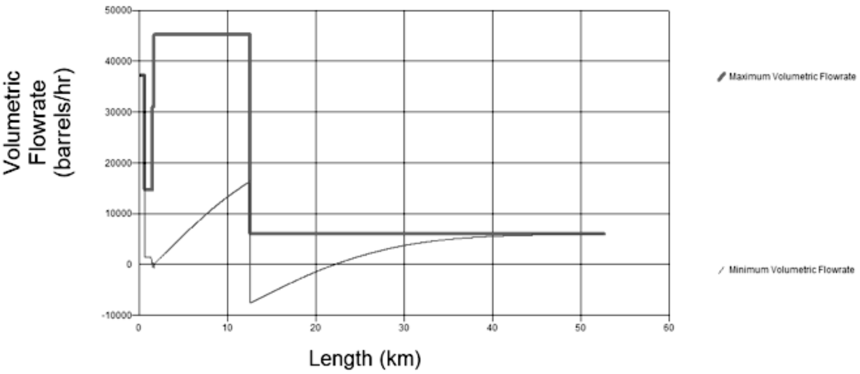


Fig. 15. Volumetric flow-rate profiles against pipelines length.

The minimum volumetric flow-rate along the length of the pipeline system shown in Figure 15 indicates transient flow regime of booster pump tripped within 5 seconds. The sudden drop of oil flow to negative region on the graph in both the upstream and downstream section of the booster pump indicates that the effect of the booster pump tripped instantaneously. The transient flow profiles show serious negative effect of the volumetric flow-rate in the pipeline including the main pumps. These transient flow regimes in the pipeline system make the system vulnerable to pump cavitation and pipe rapture.

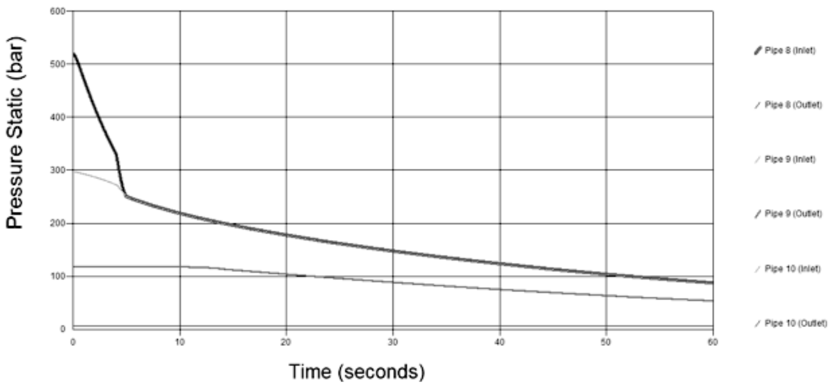


Figure 16. Pressure static against time (pipes 8 to 10).

There is an instant pressure loss observed in pipe 8 to pipe 9 inlets within 5 seconds of the booster pump tripped that corresponds to the time of transient event. Pressure continues to drop rapidly at the downstream of booster pump pipes (8 to 10) in 60 seconds of simulation, which suggests that the system is more vulnerable to pumps cavitation as shown in Figure 16.

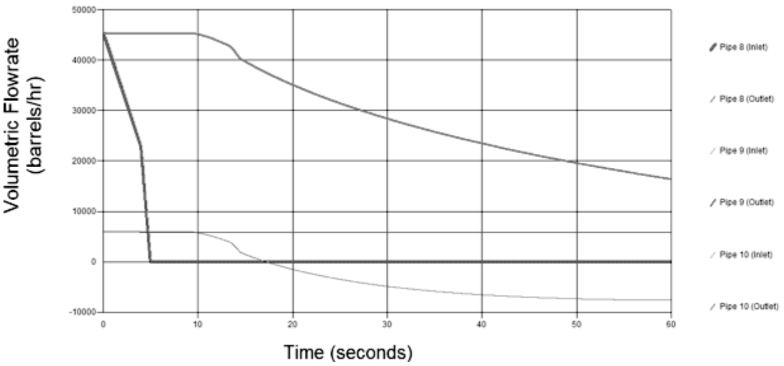


Figure 17. Volumetric flow-rate against time (pipes 8 to 10).

The volumetric flow-rate in the system during the transient regime of the booster pump tripped within 5 seconds is shown in Figure 17, which suggests that the downstream pipes 8 to 10 experienced cavitation, as a result of the negative volumetric flow observed after 15 seconds and the significant drop of system pressure close to the atmospheric pressure in the pipeline system as shown in Figure 18.

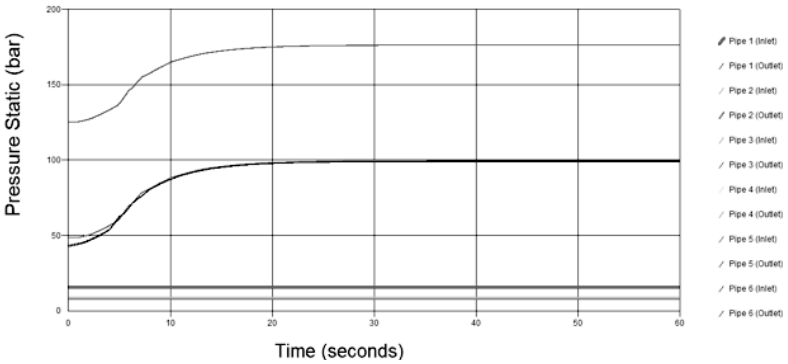


Figure 18. Pressure static against time (pipes 1 to 6).

The booster pump tripped in 5 seconds and simulated for 60 seconds as shown in Figure 18. The results suggested that there is no significant pressure loss or rise in the upstream pipes of the booster pump. The pressure in pipes 1 to 6 of the main pumps are stable irrespective of the transient event that occurred in the booster pump and the transient flow regime observed at the downstream pipes of the booster pump. Note that, due to limited space, the booster pump speed, pressure static, time, and volumetric flow-rate of the various sections of the pipeline system could not be presented in the paper.

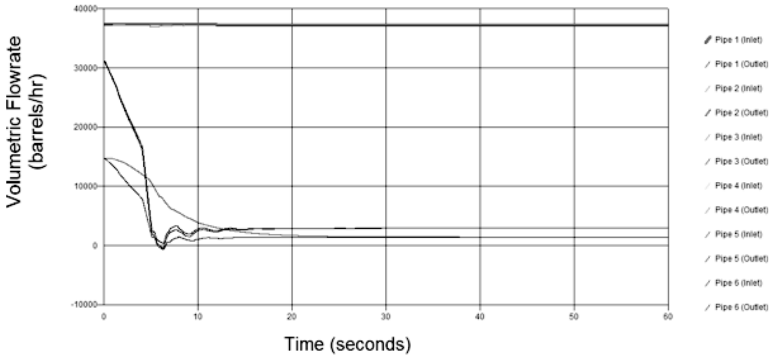


Figure 19. Volumetric flow-rate against time (pipes 1 to 6).

The effect on the volumetric flow-rate of the booster pump tripped within 5 seconds is obvious at downstream of the main pump's pipes (3, 5, and 6) and slightly obvious on pipe 4 between the first 20 seconds of the simulation and the volumetric flow-rate reducing considerably at pipe 6. This sudden fluctuation of mass during the transient flow regime could have serious hydraulic transient effect on the entire offshore crude oil terminal.

Main pumps tripped due to power failure case

In this case, the main pumps tripped within 5 seconds due to power failure and the booster pump are still running, while the discharge valve is still open. The transient event occurs as a result of the main pumps tripped within 5 seconds. Figures 20, 21, 22, 23, 24, and 25 are transient's results of the model with pressure relief system.

The result shown in Figure 20 is the maximum and minimum pressure static profiles along the pipeline length of 52 km during transient regime of the three main pumps tripped within 5 seconds due to power failure. The minimum pressure between 0 and 3 km of the pipeline indicted that cavitation has occurred in the main pumps' upstream pipes at a distance within 3 km of the pipeline length.

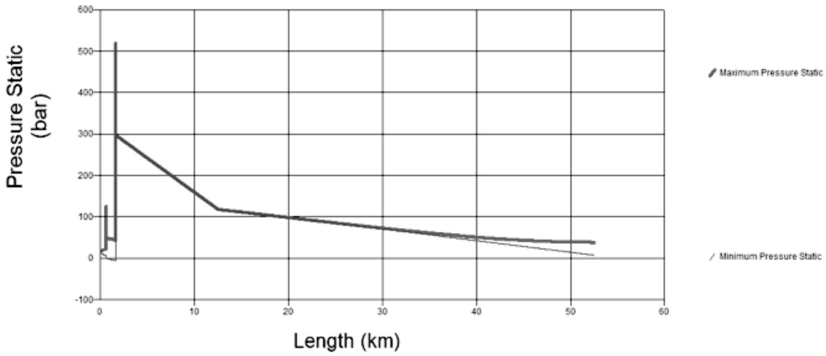


Figure 20. Pressure static profiles against pipeline length.

The minimum pressure is below the main pumps suction pressure and below the minimum allowable operating pressure of the pipeline system of 1 bar. This transient's flow regime enhances the occurrence of cavitation, which is very dangerous to the pipeline facility and especially to the pumps. Safety measure must be provided to prevent this type of transient event.

The effect of the main pumps tripped transient's event is significant in the volumetric flow-rate of the pipelines system where crude oil flow-rate instantly dropped to the negative region of approximately -10000 barrels/hr. at the upstream to zero barrels/hr. at the downstream of the offshore oil terminal pipeline length as shown in Figure 21. This suggested that the transient flow event that occurred in the main pumps has a trickle down-effect on the booster pump, which causes it to trip as well.

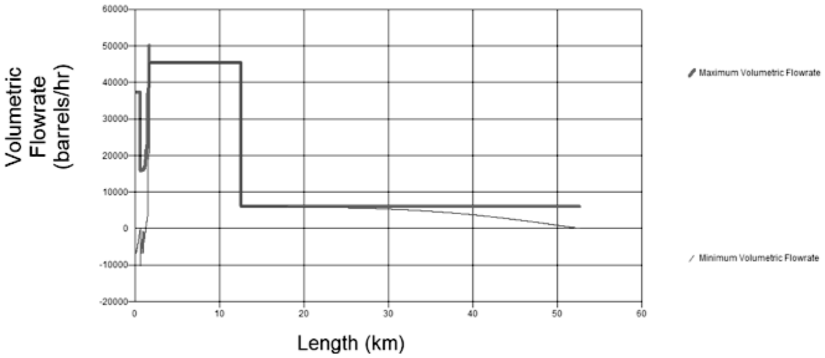


Figure 21. Volumetric flow-rate profiles against pipeline length.

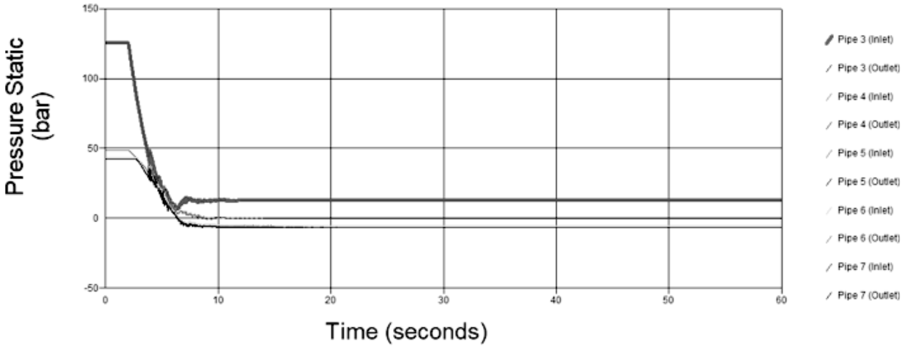


Figure 22. Pressure static against time (pipes 3 to 7).

Figure 22 shows the transient pressure wave propagation on downstream (pipes 3 to 7) of the main pumps. This result shows a clear hydraulic transients' wave in the first 20 seconds of the simulation and cavitation on pipes (pipes 4 to 7) in the pipeline. The negative pressure observed along the main pumps downstream pipes will affect the booster pump. This transient flow regime indicates dangerous effects on the pipeline system such as deformation of pipelines, fittings and support facility, pipeline and pump casting rupture, and excessive vibration. Note that, due to limited space, the booster pump speed, pressure static, time, and volumetric flowrate of the various section of the pipeline could not be presented in the paper.

Figure 23 clearly shows the transient flow (water-hammer) in the upstream pipes as the main pumps tripped within 5 seconds. The magnitude of the transient flow wave between 0 to 10 seconds of the volumetric flow-rate is an indication of severe cavitation occurrence due to instantaneous tripped of the main pumps resulting from power failure. Note that, due to limited space, the booster pump speed, pressure static, time, and volumetric flowrate of the various section of the pipeline could not be presented in the paper.

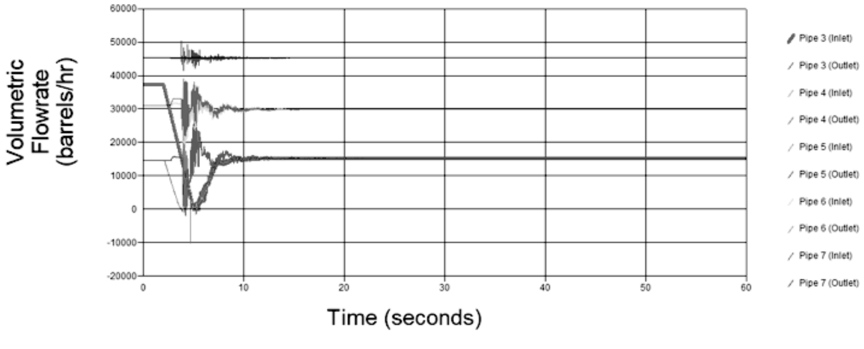


Figure 23. Volumetric flow-rate against time (pipes 3 to 7).

Design rules for transient control and risk mitigation of crude oil pipelines

The flow chart in Figure 24 shows slightly modified (Boulos et al., 2005) design rules developed to mitigate and control transient flows in crude oil transportation pipelines. It should be noted that the modified design rules using computer-based method for the design, control, and risk mitigation of transient flow in crude oil pipeline system are developed based on the analysis of the results and understanding derived from this work.

CONCLUSIONS

The design and modeling of transient flows in crude oil pipeline system using computer-based method have been presented. The pipeline system model without any pressure relief system and with pressure relief system is utilized to explore common transients' flow events such as sudden closure of discharge valve and pumps tripped instantaneously.

The simulation results of the various transient flow scenarios considered in this research work provide evidence of the credibility and reliability of the computer-based pipeline model for the prediction of transient flows regime. It was found that the discharge valve closure time within 15 seconds was adequate for crude oil loading and off-loading operations.

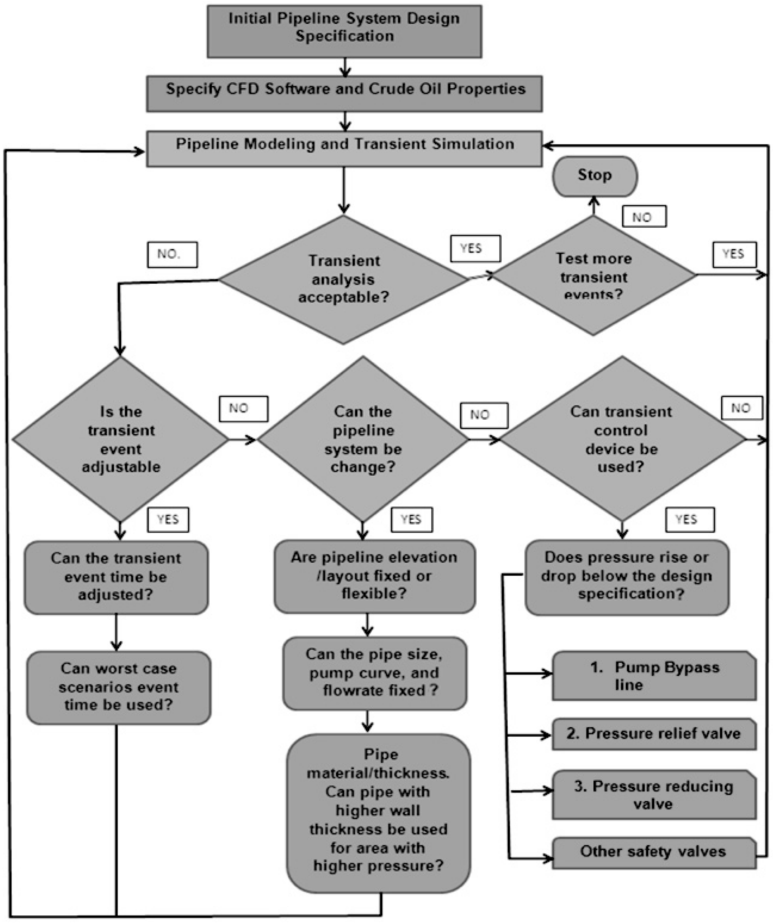


Figure 24. Flow chart for design rules of transient flow control and risk mitigation of crude oil pipeline system.

In addition, transient flow regime can occur due to sudden changes on the operational conditions of the pipeline system. However, pressure relief valves remain an effective method to control and mitigate water hammer pressure in crude oil pipeline. It was demonstrated in the study that pressure relief valve strategically installed at different locations of the 52 km crude oil transportation pipeline system mitigated the hydraulic pressure to approximately 80% during transient flow event of sudden closure of the discharge valve, which supports the well-established innovative used of relief valves.

The effect of transient flow due to pumps tripped instantaneously (within 5 seconds) was significant on the pipeline system and increased the chance of pump cavitation and pressure wave propagation, which could cause serious pipe deflection and rupture of pipe during the transient flow regime. Moreover, these adverse effects have been identified and can be resolved during the pipeline risk assessment and mitigation design stage with relative low cost.

Generally, this verified computer-based pipeline model and the modified design rules proposed could be used to support training activities of safety and flow assurance engineers for predicting, risk mitigation, and impact assessment of transient flow in similar pipeline systems at the optimization design stage.

Finally, other common transient's events such as check valve slams, high temperature, and pipe rapture should be simulated using the computer-based model to improve the prediction, risk mitigation, and impact assessment of transient flows in crude oil transportation pipeline system.

ACKNOWLEDGMENT

The authors acknowledge the immense help received from the scholars whose articles are cited and included in references of this manuscript. Special thanks are due to the provider of the industrial water-hammer software AFT Impulse 4.0 used to conduct this research work (Mr. Brian MC Manus - PISCES Engineering services U.K.). **Boye** wishes to express his profound gratitude to **Prof. Adrian Cole** for his expert advice during the project at **Birmingham City University**.

REFERENCES

Afshar M.H. & Rohani M. 2008. Water hammer simulation by implicit method of characteristic. International Journal of Pressure Vessels and Piping; 85:85, 1–9.

Applied Flow Technology AFT. 2007. AFT impulse 4.0 waterhammer user guide.

Berganta A., Simpson A.R & Tijsseling A.S. 2006. Water hammer with column separation: A historical review, Journal of Fluids and Structures 22, 135–171.

Boulos, P.F., Wood D.J., Lingireddy S. & Karney B. 2005. Hydraulic Transient Guidelines for Protecting Water Distribution Systems, Journal of Americal Water Works Association 97:5, 104-115.

Boye T.E, Nwaoha C.T, Samuel D.O. & Ashiedu F.I. 2007. A Validation Method of Computational Fluid Dynamics (CFD) Simulation against Experimental Data of Transient Flow In Pipes System, American Journal of Engineering Research (AJER) Volume-6, Issue-6, pp-67-79.

Carpenter R.C. & Barraclough S.H. 1894. Some experiments on the effect of water hammer. Transactions of the ASME 15, 510–535.

Cordes et al. 2016. Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies, Deep-sea impact review, Frontiers in Environmental Science, Volume 4, Article 58.

Don J.W., Srinivasa L., Boulos P.F., Bryan W.K. & David L.M. 2005. Numerical Methods for Modeling transient flow in distribution systems, Journal American Water work association AWWA, peer-review 97:7 104-115.

Galante, C. & Pointer S. 2002. Catastrophic water hammer in a steam dead leg. IChemE Loss Prevention Bulletin 167, 16–20.

Gary J. & Gumm, P.E. 2017. Pipeline design manual, Washington suburban sanitary commission, regulations 301-206-WSSC (9772).

Hosseien M.V. S. & Alireze K. 2010. Transient flow in pipe networks, Journal of Hydraulic research, 40:5, 637-664.

Institute of Energy, Environment and Economy IEEJ Outlook 2017. Prospect and Challenges until 2050, Energy, Environment and Economy IEE Japan.

Joel D. 2004. Energy and population, Resources for the future, issue brief 04-10.

Jon R.H., Urban K. & Ole H. 2009. Decision on oil and gas exploration in an Arctic area: Case study from the Norwegian Barents Sea Safety Science Volume 47, Issue 6, Pages 832-842.

Kennedy, L.J. 1993. Oil and gas Pipeline Fundamentals, 2nd edition, Pennwell publishing company.

Mohitpour M., Golshan H. & Murray A. 2007. Pipeline design and construction: A practical approach., third edition, ASME Press, New York.

Popescu M., Arsenie, D. & Vlase, P. 2003. Applied hydraulic transients for hydropower plant and pumping stations, Swets & Zeitlinger Publishers.

Roman W. 2006. Hydraulic Transients Analysis in Pipe Networks by the Method of Characteristics (MOC) Archives of Hydro-Engineering and Environmental Mechanics Vol. 53, No. 3, pp. 267–29.

Taheri R. & Afshar M.H. 2010. Simulation of transient flow in pipeline systems due to load rejection and load acceptance by hydroelectric power plants. International Journal of Mechanical Sciences, 52: 103–115.

Thanapandi P. & Rama P. 1995. Centrifugal pump transient characteristics and analysis using the method of characteristics International Journal of Mechanical Sciences, Volume 37, Issue 1, 1995, Pages 77-89.

Thorley, D.A.R. 2004. Fluid transient in pipeline systems, John Wiley & Sons; second edition.

Tushar S., Tinish G. & Nitish. 2017. Hydraulic Transient Flow Analysis using Method of Characteristics International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6, Issue 7, 14813-14827.

Wang C. & Yang J.D. 2015. Water Hammer Simulation Using Explicit–Implicit Coupling Methods, Journal of Hydraulic Engineering 141(4):04014086.