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TRANSIENT FLOW ANALYSIS OF FAST VALVE CLOSURE IN SHORT PIPELINES

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ABSTRACT

The present papers presents an analysis of transient pressure behavior in short pipelines for tanker's loading at a marine terminal. The analysis was focused on the interaction of several dynamic components that are present in the line, such as check, flow control and block valves, pump and pipe elasticity. The purpose of the analysis is to maximize flow rate through the line thereby minimizing tankers dockage time, without exceeding the allowable pressure limits. A commercial software was employed in the calculations that were able to reveal the complex interaction of the dynamic components present.

INTRODUCTION

Oil and product transfer from onshore tanks to ships at marine terminals are frequently conducted employing short pipelines, operating at elevated flow rates to minimize dockage time. These pipelines are normally composed by storage tanks, a pumping station and additional components like control, block and check valves.

In the case of longer pipeline systems, the components are relatively widely spaced along the line, and pressure waves originated from transient operations of these components may have enough time to dump along the long lines before encountering and interacting with pressure waves generated by another dynamic component. Unlike in the long pipeline systems, in short pipelines the relatively shorter distances among dynamic components can potentially trigger complex transient flow phenomena.

The present paper presents a study of the transient flow characteristics of a short pipeline during ship loading operations. This study was motivated by the increasingly strict constraints imposed by environmental authorities in Brazil regarding oil and products spills in sensitive areas like marine terminals. Due to the concern with leakages in these areas, valves are normally set to operate at very short closing times which, combined with the high flow rates necessary to minimize ship dockage time, may lead to complex fluid flow transients in the system. .

The surge pressure Δp generated by a velocity reduction Δv is usually estimated by a simplified equation, known as Joukowsky's equation (Wylie and Streeter,1967 and ISGOTT, 1996).

$$\Delta p = \rho a \Delta v \qquad (1)$$

Equation (1) shows that the pressure increase in a fluid resulting from a change in velocity is proportional to the sound speed in the fluid, a, its density, ρ, and the change of fluid velocity, Δv. In case the flow stops instantaneously, $\Delta v = Q/A$, where Q is the flow rate prevailing before valve closure.

The use of equation (1) provides an estimate for the pressure surges to be expected in simple transient problems. For more complex problems it is necessary to solve the set of differential equations governing mass conservation, linear momentum and energy. These equations, together with appropriate equations of state, boundary and initial conditions and models for each dynamic component of the pipeline, have been used with success by several academic and industrial researchers. The small diameter-to-length ratios of pipelines have contributed to the excellent results obtained with the use of one dimensional approximation of the governing equations.

In actual pipelines, there are several parameters that affect the intensity of the pressure surge phenomenon, such as fluid velocity, valve discharge coefficient curve, pump curve, presence of a check valve, fluid properties, pipeline mechanical properties, etc. In the present paper, the relative importance of some of these parameters will be studied by means of numerical simulations of a typical loading pipeline of a marine terminal.

DESCRIPTION OF THE PIPELINE MODELED

The pipeline modeled in this paper was a crude oil transfer line that connects the onshore tanks located in Fazenda Alegre (Espírito Santo, Brazil) and the oil tanker docked at Terminal Norte Capixaba. This transfer line is composed of 3.5 km, of a

16” OD, rigid line, connected to a 250-m long, 12”OD flexible line.

Figure 1 presents a schematic representation of the pipeline modeled. The oil flow is driven by a centrifugal pump (BO20) and controlled by a control valve located at the pump exit (VCONT), followed by a check valve (BC3) and a block valve (V1). The rigid line (T200) connects the upstream block valve to the downstream block valve (V2). A 31-m-long subsea rigid line (T210) connects the block valve to the 250-m-long flexible line (T300). A motorized block valve (V9N) connects the flexible line to the tanker. The characteristics of all the elements of the pipeline described are listed in Table 1.

The oil used in the simulations is typical in operations at this terminal, and presented a density of 943.7 kg/m^3, an absolute viscosity of 8.3 x 10^{-3} Pa.s, and a bulk modulus of 1.381 GPa. All the properties were taken at 65^{o}C, a typical operational temperature.

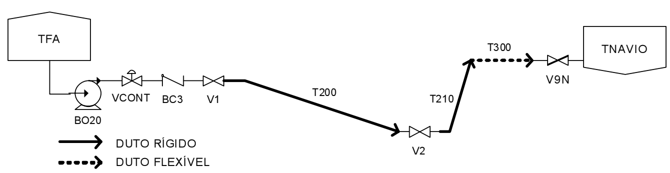

Figure 1. Schematic of the pipeline modeled.

Table 1. List of the modeled equipments

Equip. ID	Equipment	Description
TFA	Take tank (onshore)	Pressure setpoint: 98.06 kPa
BO20	Centrifugal Pump	917 kW @ 1200 RPM
VCONT	Control valve	CV: 500 gpm/psi$^{0.5}$. Flow setpoint: 0.222 m^3/s (800 m^3/h).
BC3	Check valve	CV: 5000 gpm/psi$^{0.5}$. Closing time: 0.06 s
V1, V2	Block Valve	CV: 5000 gpm/psi$^{0.5}$ Gate valve
T200	Rigid line (buried)	D_o: 406.4 mm (16”). *e*: 14.27 mm (0,562”). *L*: 3500 m
T210	Rigid line (subsea)	D_o: 406.4 mm (16”). *e*: 25,4 mm (1”). *L*: 31 m
T300	Flexible line	D_o: 304,8 mm (12”). *e*: 25,4 mm (1”). *L*: 250 m
V9N	Motorized block valve (Butterfly)	CV: 5000 gpm/psi$^{0.5}$. Closing time: 60 s
TNAVIO	Delivery tank (tanker)	Set pressure: 98.06 kPa (1kg/cm^2)

QUALITATIVE DESCRIPTION OF THE PROBLEM MODELED

The scenario modeled is characterized by the closing of the tanker valve (V9N) after operation at steady state conditions. As the tanker valve closes, the flow rate is reduced causing a pressure raise that can be estimated by equation (1). The information of flow reduction and pressure increase travels through the pipeline at acoustic speed. In response to flow reduction, the discharge pressure of the pump increases according its characteristic curve. The control valve starts to open, in an attempt to return the flow rate to the adjusted setpoint. When the surge pressure becames greater than the maximum allowable pump pressure (shut-off value), the pressure gradient prevailing in the line tends to produce reverse flow. At this moment, the check valve starts to close and, depending on its response time, some relief of the pressure can occur due to a pump reverse flow. When the check valve closes, another pressure pulse is induced in an opposite direction. As consequence, the pipeline gets closed at both ends, pressurized and with a pressure wave traveling between the ends, that is gradually dumped.

The qualitative scenario just described is illustrated in Figures 2a and 2b, for different closing times of the motorized block valve (V9N). In the figures, the blue curve represents the flow rate referenced to the right ordinate. The green and red curves represent, respectively, the pressure values monitored at the check valve at the pump exit (BC3) and at the tanker block valve (V9N). In Fig. 2(a) the closing time for the block valve is equal to 60 seconds, while in Fig. 2(b) is only 1 second, representing an instantaneous closing of the valve. It should be noted the higher pressure levels obtained for the conditions of Fig.2(b).

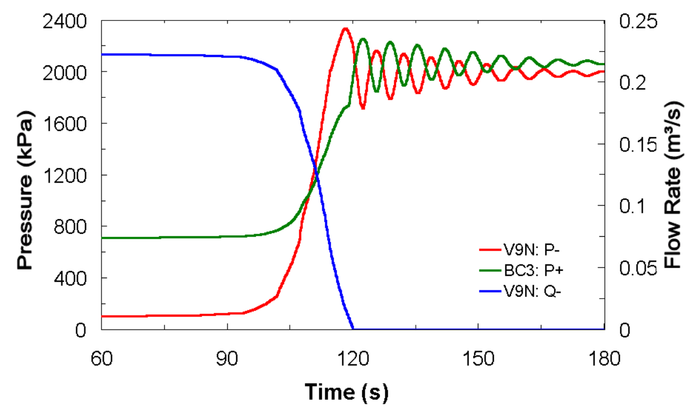

Figure 2a. Pressure transient at check and block valves for a 60-second closure time of the block valve (V9N).

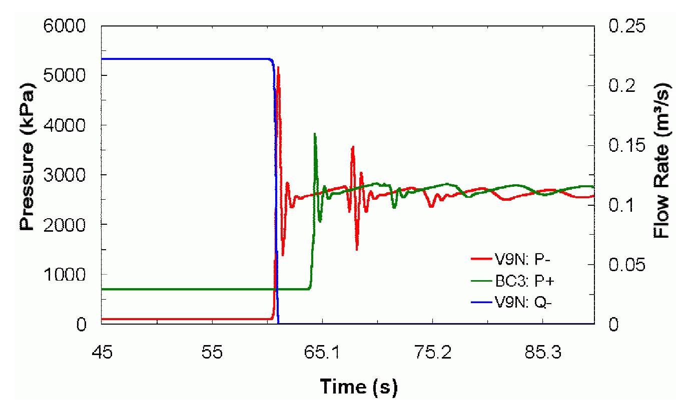

Figure 2.b. Pressure transient at check and block valves for an instantaneous closure (1 second) of block valve (V9N).

CHARACTERISTICS OF THE MODELS

Since the surge pressure effects are observed in seconds, the heat exchange between the fluid and the environment was not considered once it involves larger periods of time. So, all the analysis was carried out at isothermal condition at 65^{o}C.

The pipeline was modeled using Stoner Pipeline Simulator 9.3 (SPS) and Pipeline Studio Simulator (TELNET), both traditional simulation programs used by the oil pipeline industry.

Figure 3 presents the steady-state situation used as the initial condition for the transient analysis. All transients were generated when the motorized block valve V9N, located at the tanker, was closed. During these transients, the control valve responds according to the models programmed in the softwares. In SPS, the flow is controled through a control valve, actuator and a PID controller with derivative and integral time constant of 1 and 0.3 respectively that can be considered typical field values.

In TLNET, the model of the control system requires only the setting of the flow rate and the valve coeficient. In order to evaluate the effect of this element in the simulations, several comparative tests were carried out. In these tests, the control valve was replaced by a static element with an equivalent head loss that generated the set flow rate. Typical results obtained are presented in Fig.4. In the tests the block valve V9N was modeled as a gate valve with a closing time of 60 seconds.

It can be seen in Fig. 4 that the distributions of maximum pressure obtained by both softwares are similar when the control valve is removed. However, when the control system is considered, the maximum pressures produced by TLNET are greater than the ones obtained by the SPS. In addition, it is also observed that the valve actuation turns the transient more severe in both simulators.

All the analyses were performed using the results obtained from SPS and TLNET, however, only the SPS' results were chosen for presentation in this paper, due to space limitations.

INFLUENCE OF OPERATING AND DESIGN PARAMETERS

The simulation results were used to help understand the transient behavior of the tanker loading operation at the terminal. The influence of some operating and design parameters on the transient pressure profiles inside the pipeline was studied. These results are presented next.

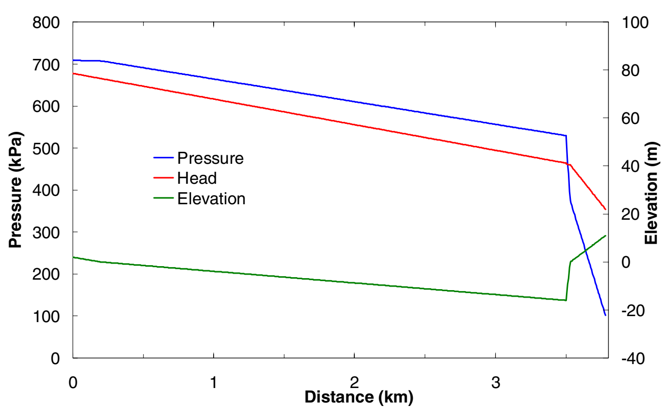

Figure 3. Pressure, head and elevation profiles at steady state.

Influence of Valve Closing Time

Valves with smaller closing time produce stronger pressure surges, for the same operating conditions, once the closing time is directly related to the deceleration of the flow. For many years, researchers searched for techniques to operate valves as quickly as possible and still maintain pressure surges under tolerable limits. Quick (1927) and Wood (1973), developed studies that produced dimensionless valve-motion charts. Analytical procedures have been developed by Streeter (1963 and 1967), Propson (1970) and Goldberg and Karr (1987).

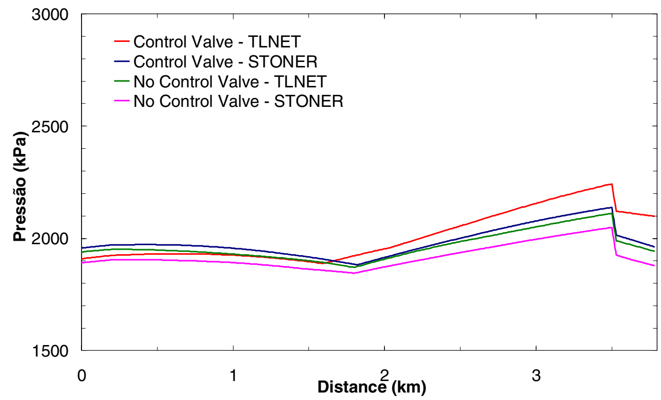

Figure 4. Maximum pressure profile for 60-second valve closure time. Results from SPS and TLNET with and without a flow control system.

To emphasize the effect of the closing time on the pressure profile, the V9N buterfly valve was closed at a constante rate, the most common closing procedure used in commercial block valves. It can be observed in Fig. 5 that shorter closure times, which are normally used in valves for leakage control, can produce overpressures significantly greater than the normal operational pressure.

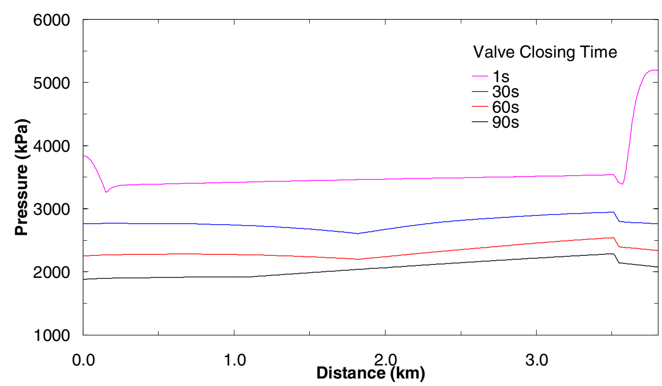

Figure 5. Maximum pressure profile for different valve closing times.

In field operations there is always the possibility of increasing the valve closing time in order to minimize the over pressure produced. However, the increase in valve closing time is limited by the primary purpose of a block valve.

Closing times of the order of the pipe period (2L/a) can be considered as instantaneous closure (ISGOTT, 1996). This condition is presented in Fig. 5 for t = 1 s. According to Eq. (1), for Δv = 4.4 m/s, ρ = 943 kg/m³ and a = 1237 m/s, Δp = 5.13 MPa (52.3 kgf/cm²) in the valve, that adds to the steady state pressure (100 kPa) resulting in 5230 kPa, almost the same value observed in Fig. 5 (5190 kPa or 53.0 kgf/cm²). However, for greater closing times, the reflected pressure wave returns to the valve, which is still partially openned, what produces a significant reduction on the maximum pressure in the valve and in the whole pipe, since part of the pressure rise is relived by the flow through the valve.

Influence of Valve Curve

The characteristic valve curve represents the dependence of the valve discharge coefficient with the stem position, and determines the way the flow rate through the valve varies with the opening fraction.

The characteristic curves used in this topic are presented in Fig. 6. Works for determining the ideal procedure for valve closing, for a particular situation, that produce the smaller pressure rise have been developed by Cabelka and Franc (1959) for frictionless flow and by Streeter (1963 and 1967) and Wood and Jones, (1973) for frictional flows. Azoury et al (1986) showed that the smaller pressure rises occur when the flow varies lineary with the valve opening fraction.

For one specific valve configuration, it is possible to modify the valve closing procedure by changing the closing rate through the actuator curve. In the present study, the actuator curve was set so that valve position was a linear time function between the fully open and the fully closed situations. Typically, gate valves produce significant flow variation only when they are almost closed. On the other hand, sphere and butterfly valves produce a more gradual variation of the flow rate during the closure period.

The results presented in Fig. 7 characterize the different behaviors of the valves. The more significant flow deceleration produced by the gate valve generates pressures that are greater than the ones given by the closure of a butterfly or a sphere valve. In the simulations all closing times were equal to 60 seconds.

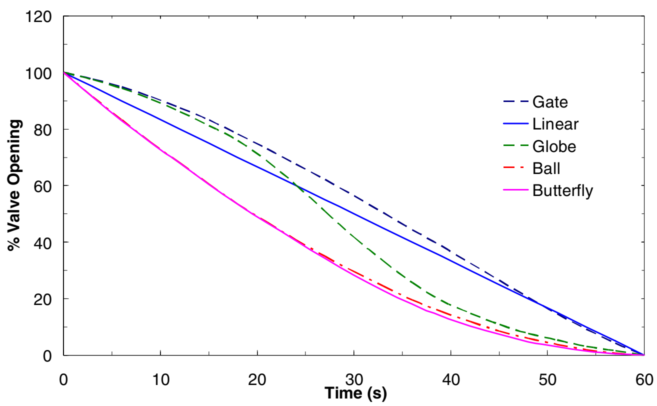

Figure 6. Closing curve of the block valve V9N.

Influence of Operating Flow Rate Varied by the Control Valve

In marine terminals, due to the high costs of tanker's dockage, the best operational procedure, from the economical point of view, indicates that the pipeline should be operated with the highest possible flow rates.

Simulations with four different values of flow rate, changing the control valve (VCONT) set point, have been performed and compared in Fig. 8. In these simulations, the butterfly type valve V9N has been closed in 60s. It should be noted that an increase of the operational flow rate by 25%, from $0.222 m^3/s$ to $0.278 m^3/s$, produces values for the maximum pressure that are 5.4% greater at the valve V9N, as illustrated in the figure. At the flow line design stages, the maximum pressure profile should be compared with the maximum allowable operating pressure in order to set the maximum operating flow rate. The proportionality between flow and pressure, as described by Eq. (1), does not hold due, mainly, to the 60-second closing time, which cannot be considered as an instantaneous closing of the valve.

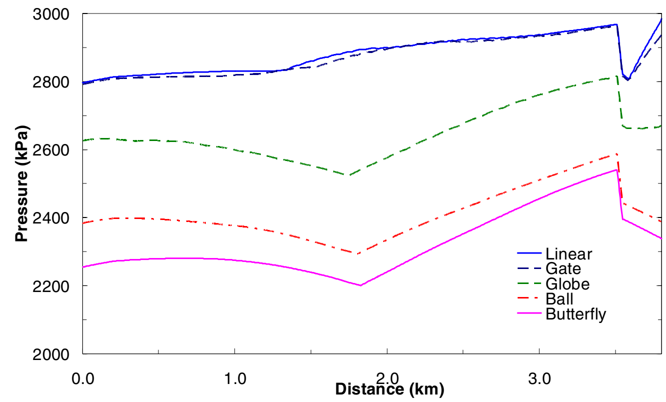

Figure 7. Maximum pressure profile for different types of block valves.

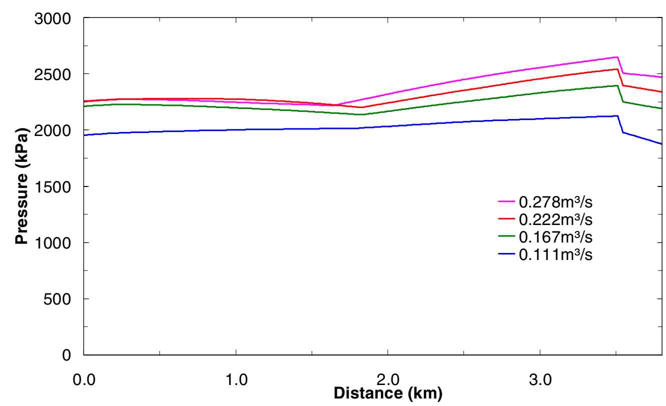

Figure 8. Maximum pressure profile for different flows regulated by flow control valve (PCV)

Influence of Operating Flow Rate Varied by Pump Speed

In the design or upgrade phases of a pipeline, an alternative way to control the flow rate using a valve is to use a pump driven by a system that allow speed control. In this case, the similarity laws for centrifugal pumps describe the pump curves for different rotations.

In order to analyze this situation, the control valve was removed from the model and the different flow rates were obtained by modifying the pump angular speed. The maximum pressure profiles obtained from the simulations are presented in Fig. 9 for different flow rates and the corresponding angular speeds. As expected, greater flow rates produce higher maximum pressures. However, a comparison of the results shown in Fig. 9 with the corresponding results presented in Fig. 8, reveal that the maximum pressures obtained are lower than those observed when the a control valve is used. The reason for these comparative lower surge pressures can be attributed to the removal of the control valve from the system that produces a reduction in the head loss. For a smaller head loss, the pump works at a smaller speed to produce the same flow rate. At this new reduced speed, the stagnation pressure (shut-off) is lower yielding comparatively lower surge pressures.

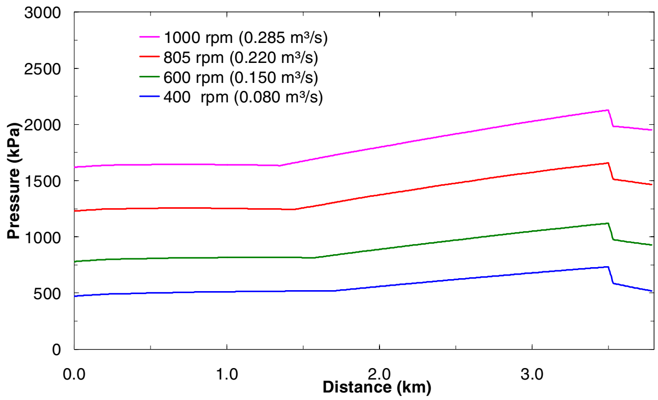

Figure 9. Maximum pressure profile for different flow rates obtained by the variation of pump rotation.

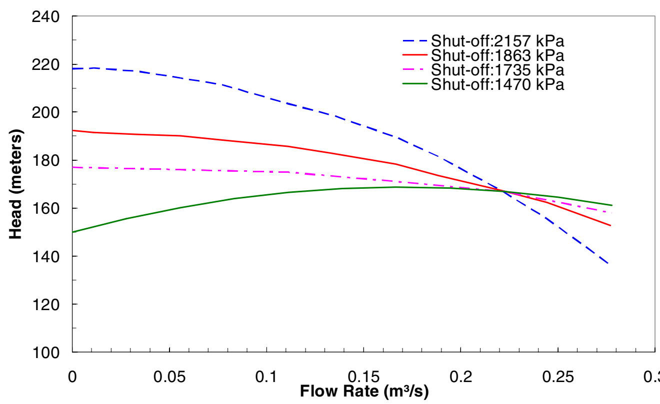

Figure 10. Modified pump curves with the same point of operation.

Pump Curve: Influence of Shut-off Value

The influence of the discharge pressure at zero flow rate (stagnation pressure or shut-off) was analyzed considering different pump curves, operating at the same point (0.222 m^3/s or 800 m^3/h), as shown if Fig.10. It can be noticed in the figure that when the pressure wave arrives at the pump location it induces a reduction of the flow and, as consequence, a modification of the discharge pressure, dictated by the pump curve. When the flow rate reaches zero, the discharge pressure is kept constant and the maximum pressure at this point is the sum of the maximum discharge pressure with the value produced by the pressure pulse. As a consequence, pumps with lower shut-off values produce lower surge pressures, as illustrated in the results presented in Fig. 11.

If the block valve were instantaneously closed, the resultant overpressure at the valve position would be independent of the pump curve. However, for a no instantaneous closing (60s), the pump shut-off value affects the whole profile of maximum pressure, as seen in Fig. 11.

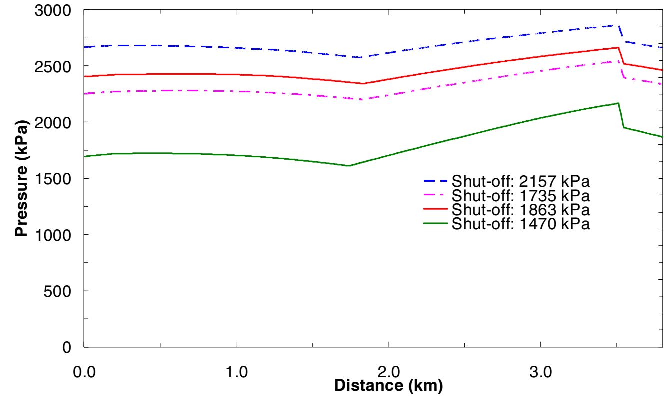

Figure 11. Maximum pressure profile generated by modified pump curves. Influence of shut-off value.

Influence of Check Valve

Check valves are usually installed at pump discharge to prevent backflow when the pump is turned off and to prevent that the pressure waves cruising in the reverse direction of the flow put at risk the integrity of the equipment. However, the operation of the check valve may disturb the maximum pressure profile, since its closure tends to enhance the reflection of the primary pressure wave. Rehymer (1993) and Thorley (1989) analyzed the behavior of check valves during transients and provided parameters for the selection of these valves for specific applications. Uspuras et al (2001) evidenced the influence of the moment of inertia of the disc in the pressure pulse generated by check valve closure in nuclear reactor cooling systems.

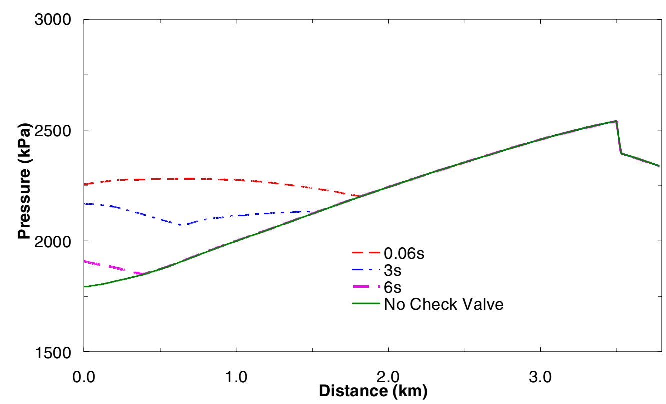

Figure 12. Maximum pressure profile as a function of check valve closing time.

Characteristic closing times for check valves are between 0.01 the 0.06 s. Figure 12 presents the maximum pressure distribution results obtained for different response times of check valves, when the block valve V9N is closed in 60 s. It can be seen in the figure that the typical shape of the maximum pressure profile, presents an inflection near midpoint due the check valve closing. A fast response of the check valve generates another waterhammer effect, increasing the pressure at this end of the line. However, for closure times greater than 6 seconds (a value only occurring for malfunctioning valve), the system responds as is the check valve were not present, thereby allowing for a total flow reversal through the pump.

Influence of Pipeline Mechanical Material Properties

The acoustic wave speed, a, is a function of thermodynamic fluid properties (compressibility modulus, K and density, ρ) and pipe properties (diameter, D, thickness, e, and elasticity modulus, E) as defined in Eq. (2).

$$a^2 = \frac{\frac{K}{\rho}}{1 + \frac{K}{E} \cdot \frac{D}{e}} \qquad (2)$$

Flexible pipes are composed by layers of distinct materials such as, steel, polymers, rubber, etc. From manufacturer's data, it can be verified that the acoustic speed in flexible pipes can experience a reduction of the order of 2/3 of the speed prevailing in a rigid pipeline. All calculation performed in the present work have assumed that the elasticity modulus of the flexible pipe was equal to that of the rigid steel pipe. This strategy was used in order to make the simulations performed with SPS and TLNET compatible, since in the latter software the effects of this variable are not considered.

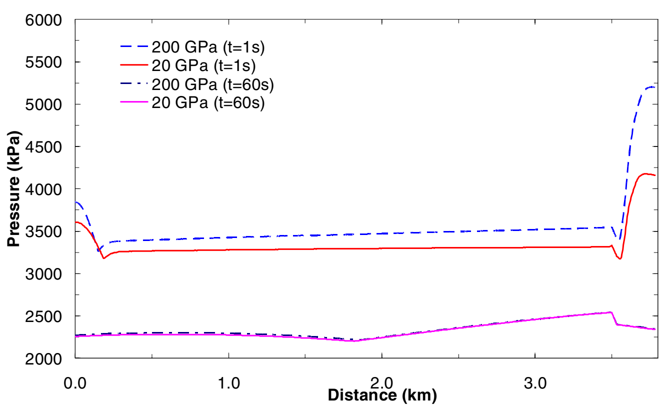

Figure 13. Influence of flexible pipe modulus of elasticity on maximum pressure profile

Equation (2) shows that a 10-fold reduction in the modulus of elasticity (20 GPa) produces a reduction in the acoustic speed in the duct to a value equal to 895 m/s. For closing times of the block valve (V9N), of the order of 60 seconds, the variation of the modulus of elasticity of the flexible line does not change the profiles of maximum pressure. However, for an instantaneous closing of the valve, of the order of 1 second, it is verified that the maximum pressure at the block valve V9N experiences a reduction of 11.33 kPa (10 kgf/cm^2), when compared with the case in which the modulus of elasticity of the flexible pipe is assumed to be equal to that of a steel rigid pipe. Figure 13 shows these results.

Influence of Fluid Properties: Density and Viscosity

We now turn our attention to estimate the influence of fluid properties on the transient pressure profiles during a tanker loading operation after a block valve is closed.

Density is a relevant property to the problem since it is related to the wave propagation speed in the pipeline, which controls transient behavior. Moreover, denser fluids increase the pump discharge pressure and the shut-off value, what causes greater overpressures during transients.

Figure 14 presents the results of maximum pressure profiles obtained from the simulation conducted for five different values of fluid density. The viscosity was kept constant for all case. It can be seen in the figure that the variation of density shifts the whole maximum pressures profile through out the pipeline, presenting a nearly proportional variation between pressure and density.

A change in fluid viscosity affects, mainly, the steady state pressure gradient of the flow. The flow speed at the block valve, the pump stagnation pressure and the valve characteristics do not change appreciably with fluid viscosity. For a particular valve closing time, a change in fluid viscosity practically does not produce any significant effect on the maximum pressure profiles, as illustrated in Fig. 15. In the simulations all closing times of the block valve V9N were equal to 60 seconds

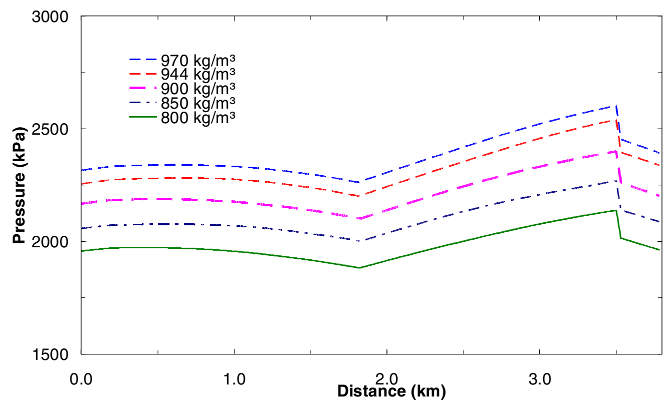

Figure 15. Influence of fluid density on the maximum pressure profile. Viscosity kept constant.

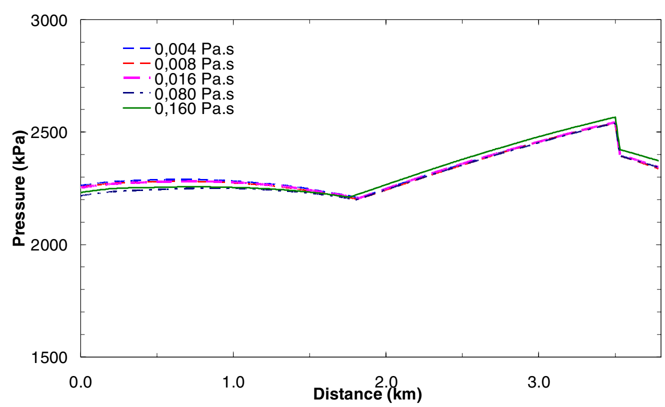

Figure 16. Maximum pressure profile for different viscosities mainteining the density constant.

CONCLUSIONS

The transient flow behavior in loading operations in a pipeline marine terminal was modeled and analyzed. The focus of the transient analysis was on the rapid closing of a block valve located at tanker. A commercial simulation software was utilized in the study.

The results obtained have shown that good approximation of the overpressure generated by the transient flow can be obtained by the simple Joukowsky equation, in the case of an instantaneous valve closing. The instantaneous closing is characterized by closing times less than $2L/a$, where L is the pipeline length and a the wave propagation speed in the line.

For valve closing times greater than $2L/a$, a complex transient behavior takes place as a result of the action of the several dynamic components present in the line, such as pump, check and control valves. In this case only a detailed simulation can predict the actual behavior of the transient pressure profiles.

The simulations conducted explored the effects on the transient pressure profiles of block valve curve and type, control valve action, variable pump speed, pump shut-off value and check valve action. Also, a parametric study was conducted of pipe elasticity and fluid properties.

The results obtained have demonstrated, as it is already well known, the importance of valve closing time and valve type on the pressure profile transient behavior. The results have also shown that the maximum pressure profile within the line is strongly influenced by other parameters like the presence check valves, pump shut-off value and fluid flow density. A viable alternative for increasing flow rate and, thereby, decreasing tanker's dockage time, was shown to be the usage of variable pump speed. This can be an alternative to the installation of surge relief valves and tanks.

NOMENCLATURE

CV: valve coefficient
D_o: outer diameter
e: wall thickness
L: pipe lengh
p: pressure
ρ: density
v: velocity
a: acoustic wave speed
K: compressibility modulus
E: elasticity modulus

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