Proceedings of COBEM 2005
Copyright © 2005 by ABCM

18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

DESIGN AND CONTROL OF PIG OPERATIONS THROUGH PIPELINES

Sueli Tiomno Tolmasquim
Petrobras Transporte S.A.
Avenida Presidente Vargas 328, Centro, 20091-060, Rio de Janeiro, RJ, Brasil.
sueli@petrobras.com.br

Angela Ourivio Nieckele
Departamento de Engenharia Mecânica – Pontifícia Universidade Católica de Rio de Janeiro
R. Marques de São Vicente 225 – Gávea, 22453-900, Rio de Janeiro, RJ, Brasil
nieckele@mec.puc-rio.br

***Abstract**. In the oil industry, pigging operations in pipelines have been largely applied for different purposes: pipe cleaning, inspection, liquid removal and product separation, among others. An efficient and safe pigging operation requires that a number of operational parameters, such as maximum and minimum pressures in the pipeline and pig velocity, to be well evaluated during planning stage and maintained within stipulated limits while the operation accomplishment. With the objective of providing an efficient tool to assist in the control and design of pig operations through pipelines, a numerical code was developed, based on a finite difference scheme, which allows the simulation of two fluid transient flow, like liquid-liquid, gas-gas or liquid-gas products in the pipeline. Modules to automatically control process variables were included to employ different strategies to reach an efficient operation. Different test cases were investigated, to corroborate the robustness of the methodology.*

***Key words:** pig; oil displacement; gas-liquid; control*

1. Introduction

Pipelines are frequently serviced with the utilization of pigs. In general terms, a pig is a solid plug that is introduced in the pipeline to be serviced. Fluid is pumped upstream of the pig to provide the necessary force to set the device in motion, and to perform the desired task, i.e., removing deposits on the pipe wall, remove water from the pipeline or driving an inspection tool. The use of pigs has become a standard industry procedure. A great variety of pig models is available for each particular application. A difficulty often faced by the engineer when designing a pigging operation is the lack of reliable tools for the prediction of the many variables related to the motion of the pig through the pipeline. Most of the available knowledge is based on field experience. Hence, selecting the best pig, estimating its speed, required driving pressure and the amount of back and forward bypass of fluid, often involve some guesswork and, consequently, a degree of uncertainty.

The pipeline network all over the world is getting older and at the same time the concern to environment is greatly increasing. Herewith, the pipeline operators are investing in inspection and maintenance with the objective to extend lifetime of their pipelines, resulting sometimes, for the execution of repairs, in the necessity to evacuate the entire pipeline or sections between pump stations, keeping valves and accessories installed. In many cases, oil is displaced from the pipeline by injection of inert gas, employing a sealing pig in the interface of the fluids. The pig velocity is directly related to the sealing efficiency of the pig, demanding that the liquid flow rate be maintained within certain limits and the pipeline operating tide, avoiding slack flow. The operation design shall also account for the influence of the profile at the expected pressures along the pipeline considering its behavior when gas flows in a section of the pipeline while liquid in another section. Figure 1 illustrates a typical sealing pig. The pig is formed by piston-type cups attached to a cylindrical body. In order to produce efficient sealing, pigs have nominal diameters larger than the pipe diameter. Gas pumped upstream of the pig provides the necessary pressure difference to overcome the contact force at the wall, to displace the liquid downstream of the pig and to accelerate the pig.

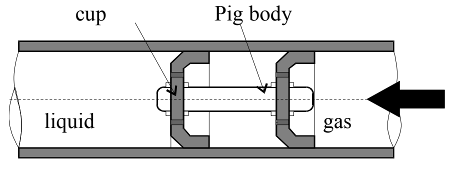


Figure 1 - Schematic view of a sealing pig.

A literature survey reveals very few papers dealing with the motion of pigs in pipelines. Webb et al (1987) investigated the use of an inert gas to displace oil from a long pipeline, and mention the control of the oil flow by an outlet valve. Santos et al. (1997) modeled the pig dynamics for pig-lift applications. Vianes Campo and Rachid (1997), Nguyen et al (2001) and Kim et al (2003) studied the dynamics of pigs through pipelines using the method of characteristics and Nieckele at al (2001) using the finite difference method. Nieckele at al (1998, 2000) investigated the dewatering operation in a riser for an isothermal and non-isothermal situation, based on the finite difference method.

The objective of the present work is to simulate the transient oil displacement of a pipeline employing a sealing pig. To be able to reach an efficient operation, a method was developed to automatically control process variables. Test cases are presented to illustrate the robustness of the methodology.

2. Mathematical Modeling

The motion of a pig inside a pipeline during an operation to displace oil by injection of nitrogen can be obtained by the solution of the fluid flow problem coupled with a model to predict the pig motion. The upstream fluid is a gas, while the downstream fluid is a liquid. Both are considered to be Newtonian. At the present work, the fluid flow is isothermal. The pipeline is inclined in relation to the horizontal, with angle α. Pipe deformation due to pressure variations along the flow is considered. The governing equations for the fluid are the continuity and momentum equations. The mass conservation equation can be written as (Wylie and Streeter, 1978),

$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \frac{\rho a^2}{\xi}\frac{\partial V}{\partial x}x + \frac{\rho a^2}{\xi}\frac{V}{A}\frac{\partial A}{\partial x} = 0 \tag{1}$$

where V, P and A are the velocity, pressure and cross section area, respectively. The fluid properties are: density ρ and speed of sound a. ξ is given by $\xi = 1 + \rho\, a^2\, 2\, C_D\, (D/D_{ref})$ where D and D_{ref} are the pipeline diameter and the reference diameter determined at atmospheric pressure p_{atm}. The pipe deformation due to pressure is accounted by the coefficient C_D, given by $C_D = (1-\nu^2)\, D_{ref}/(2\, e\, E)$, where e is the pipe wall thickness, E the Young's modulus of elasticity of the pipe material, and ν the Poisson's ratio. The linear momentum equation can be written as

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{f}{2}\frac{|V|V}{D} - g\,\sin\alpha \tag{2}$$

where g is gravity and f the hydrodynamic friction coefficient factor, which depends on the Reynolds number $\mathbf{Re} = \rho\,|V|\,D/\mu_f$, where μ_f is the absolute viscosity. In the turbulent regime the friction factor is also a function of the relative pipe roughness ε/D. To simplify the solution, the friction factor is approximated by its fully developed expression. For a laminar regime, $\mathbf{Re} < 2000$, it is specified as $f = 64/\mathbf{Re}$. For the turbulent regime, $\mathbf{Re} > 2500$, the friction factor is approximated by Miller's correlation (Fox and McDonald, 2001), $f = 0.25\ \{\log\,[(\varepsilon/D)/3.7 + 5.74/\mathbf{Re}^{0.9}]\}^{-2}$. Between $\mathbf{Re} = 2000$ and 2500, it was assumed a linear variation of the friction factor with the Reynolds number.

The coupling of the pig motion with the fluid flow in the pipeline is obtained through a balance of forces acting on the pig, together with an equation that represents the fluid pressure drop across the bypass holes in the pig (Azevedo et al., 1996). The force balance on the pig can be written as

$$m\,\frac{dV_p}{dt} = (P_1 - P_2)\,A - m\,g\,\sin\alpha - F_{at}(V_p) \tag{3}$$

where, V_p is the pig velocity, m the pig mass, P_1 and P_2 the pressure on the upstream and downstream faces of the pig, α is the angle of the pipe axis with the horizontal.

The term $F_{at}(V_p)$ represents the contact force between the pig and the pipe wall. The contact force depends on x_p, the pig axial coordinate, indicating that the contact force can be allowed to vary along the pipe length. When the pig is not in motion, the contact force varies from zero to the maximum static force F_{stat}, in order to balance the pressure force due to the fluid flow. Further, since the pig may resist differently to being pushed forward or backward, the maximum static force for a negative pressure gradient is F_{stat}^{neg}, while for a positive pressure gradient is F_{stat}^{pos}. Once the pig is set in motion by the flow, the contact force assumes the constant value, F_{din}, representing the dynamic friction force that is generally different from the static force. As in the previous situation, two different values for the dynamic contact force are allowed, F_{dyn}^{neg} and F_{dyn}^{pos}, depending on the direction of the pig motion.

$$F_{at}(V_p) = F(x_p) \quad \text{where} \quad -F_{stat}^{neg}(x_p) \le F(x_p) \le F_{stat}^{pos}(x_p) \ \text{ if } V_p \approx 0 \quad \text{and} \quad F_{at}(V_p) = \begin{cases} -F_{din}^{neg}(x_p) & \text{if} \quad V_p < 0 \\ F_{din}^{pos}(x_p) & \text{if} \quad V_p > 0 \end{cases} \tag{4}$$

2.1 Moving Coordinates

Since the pig moves in the computational domain, it is convenient to employ a coordinate system η, that stretches and contracts in the pipe, depending on the pig position. The fluid flow conservation equation must then be written for the new coordinate system (Monteiro et al., 1998) as

$$\frac{\partial}{\partial t}\begin{pmatrix} P \\ V \end{pmatrix} + \frac{\tilde{V}}{h_\eta}\frac{\partial}{\partial \eta}\begin{pmatrix} P \\ V \end{pmatrix} + \begin{bmatrix} \dfrac{\rho\, a^2}{h_\eta\, \xi} \\ \dfrac{1}{h_\eta\, \rho} \end{bmatrix}\frac{\partial}{\partial \eta}\begin{pmatrix} V \\ P \end{pmatrix} = \begin{bmatrix} \dfrac{\rho\, a^2\, \tilde{V}}{\xi\, A\, h_\eta}\dfrac{\partial A}{\partial \eta} \\ -\, g\, \sin\alpha \end{bmatrix} - \begin{bmatrix} 0 \\ \dfrac{f\ |V|}{2D} \end{bmatrix}\begin{pmatrix} P \\ V \end{pmatrix} \tag{5}$$

The absolute velocity V is equal to $\tilde{V} + u_g$, where $\tilde{V}$ is the relative velocity and $u_g = (\partial x/\partial t)_\eta$ *is* the grid velocity. $h_\eta = (\partial x/\partial \eta)_t$ is the metric which relates the two coordinates.

2.2 Fluid Properties

The gas is considered to behave as an ideal gas. Therefore for an isothermal flow,

$$\rho = P\,/\,a^2 \qquad \text{where} \qquad a = \sqrt{z\ R_{gas}\ T_{ref}} \tag{6}$$

where R_{gas} is the gas constant, T_{ref} the reference temperature and z the compressibility factor.

For the liquid, the following relationship between density and pressure was considered,

$$\rho = \rho_{ref} + (P - P_{ref})\,/\,a^2 \tag{7}$$

where ρ_{ref} is the reference density evaluated the reference pressure P_{ref}, and a is the sound speed.

For both fluids, the fluid absolute viscosity was considered constant for the present analysis as function of pressure in accordance to the following expression

$$\mu_f = \mu_{ref}\ \mathbf{exp}[c_{\mu,p}(P - P_{ref})] \tag{8}$$

where, μ_{ref} is the absolute viscosity evaluated at the reference pressure P_{ref}, with coefficient $c_{\mu,P}$.

2.3 Initial and Boundary Conditions

The operations investigated here, begin with the pipeline filled with liquid and with no flow. Therefore, the initial condition corresponds to a zero velocity along the pipeline, and a hydrostatic pressure distribution, which is obtained from the following expression beginning from the known pressure at the highest elevation of the pipeline.

$$P_{s+ds} = P_{ref} + \frac{\left(P_s - P_{ref}\right)}{e^{(g\Delta z)/a^2}} + \frac{\rho_{ref}\, g\Delta z}{(g\Delta z)/a^2}\left(e^{-(g\Delta z)/a^2} - 1\right) \tag{9}$$

To solve the conservation equations, Eq. (5), two boundary conditions are necessary, which can be: known pressure, known mass flow rate or a valve. For the last case, the mass flow rate at inlet and/or outlet are determined from

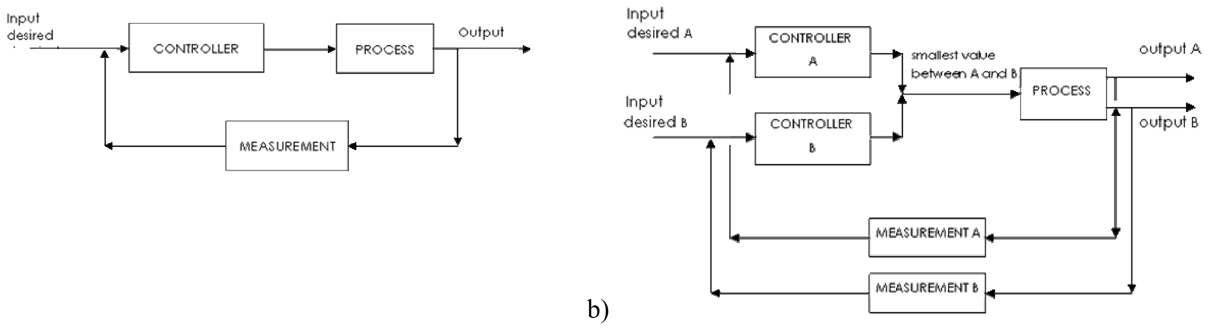
$$\dot{m}_{in} = \rho_{in}\left(Cd\ \ Ag\right)_{o,in}\ \chi\ \sqrt{\frac{2\left(Pt_{in} - P\right)}{\rho_{in}}} \qquad \dot{m}_{out} = \rho_{out}\left(Cd\ \ Ag\right)_{o,out}\ \chi\ \sqrt{\frac{2\left(P - Pt_{out}\right)}{\rho_{out}}} \tag{10}$$

where $(C_d\ A_g)_o$ is the product of the valve discharge coefficient by the area for the valve completely open. P_t is the reservoir pressure, upstream or downstream of the valve and χ is the percentage of valve opening.

3. Process Control

The main goal of the systems developed to control processes consists in maintaining certain variables of the process within desired operational limits. This control can operate in an opened or closed loop. At the present work, a closed loop was employed, where the value of the desired variable is used as re-feed the system, in order to compensate external and internal perturbations of an industrial process, as illustrated in Fig. 2. The controller compares the desired value with the measured value, and if there is a discrepancy between these values, the controller manipulates its output in order to eliminate the error. For example, if the measured pig velocity is not the desired value, the opening of a valve at the outlet of the pipeline is altered, in order to maintain the process variable within the desired value, compensating external perturbations and non linearities of the system.

There are situations where it is necessary to control simultaneously two variables of the process. Figure 2b illustrates this situation, where the smallest output from the two controllers is employed to re-feed the system.



a) b)

Figure.2 – Control system in a closed loop. (a) one variable (b) two variables

3.1. PID Controller

A PID controller generates its output proportionally to the error between desired and measured quantity, the integral of the error and the derivative of the error. Its output $u(t)$ is given by the following expression (Isermann, 1981)

$$u(t) = K\,[e(t) + \frac{1}{T_I}\int_0^t e(\tau)\,d\tau + T_D\,\frac{de(t)}{dt}] \qquad (11)$$

where, $e(t)$ is the error and the multiplier factors K, T_I and T_D are known as the controller gain, the integral time and derivative time, respectively.

The controller error can be defined as (Campos,1999)

$$e(t) = (VP(t) - SP) \times AC \quad ; \quad AC = 1 \text{ or } -1 \qquad (12)$$

where $VP(t)$ is the process variable, SP is the set point to control the process variable and AC is the controller action. This action can be direct or reverse. For a controller with a direct action, when the process variable increases, the output of the controller also increases, i.e., the variable is maintained at the set point or above it. The controller with reverse action decreases its output when the process variable increases, therefore, maintaining the variable at or below its set point.

4. Numerical Method

The set formed by equations represented by Eq. (5), together with the appropriate boundary and initial conditions, require a numerical method to obtain the desired time-dependent pressure and velocity fields. These equations were discretized by a finite difference method. A staggered mesh distribution was selected to avoid unrealistic oscillatory solutions, as recommended by Patankar, (1980). The equations were integrated in time using a semi implicit method, that is, the equations are integrated by a totally implicit method, but the coefficients are locally linearized. The space derivatives were approximated by the central difference method around the mesh point. The resulting coefficient matrix is penta-diagonal, and can be easily solved a direct penta-diagonal algorithm.

The total number of grid points inside the pipe was maintained constant in the numerical calculations of the flow field upstream and downstream of the pig, as well as for the pig dynamics calculations. However, as the pig moves along the pipe, it is convenient to rearrange the node distribution. The number of grid points upstream and downstream of the pig was made proportional to the length of the pipe at each side of the pig. Further, the mesh was concentrated near the pig, to better resolve the flow variables at this location.

5. Study Cases

Two study cases are presented here to illustrate the methodology of control of the inlet or outlet valve opening to maintain the pig velocity as well as the maximum and minimum pressure values inside the pipeline under desirable limits.

5.1. Pig Velocity and Minimum Pressure Control

The first test case consists on the oil removal from a horizontal pipeline by the injection of nitrogen. A constant mass flow rate of nitrogen equal to 7.0 kg/s is imposed at the entrance and a valve is implemented at the pipeline outlet. The reservoir pressure after the valve is $P_t = 2$ kgf/cm^2, and the fully open valve discharge coefficient is $(C_d\, A_g)_o = 0.02$ m^2. The oil properties are: $P_{ref} = 1$ atm, $\rho = 900$ kg/m^3, $a = 1318$ m/s; $\mu_f = 70$ cP, while the nitrogen properties are: $R_{gas} = 296.9$ N·m/kg·K; $P_{ref} = 1$ atm; $T_{ref} = 20^{o}$C, $z = 1.04$ and $\mu_f = 1{,}5 \times 10^{-5}$ N·s/m^2. The pipeline characteristics are: length = 40 km, diameter = 18 in, wall thickness = 9.53 mm, roughness = 0.04572 mm, Young's modulus of elasticity = 2.1×10^5 MPa, Poisson's ratio = 0.3 and the maximum allowable operating pressure, MAOP = 39kgf/cm^2.

The pig mass is 20 kg and its contact are: $F_{stat}^{neg} = F_{stat}^{pos} = F_{dyn}^{neg} = F_{dyn}^{pos}$ =29.572 KN, corresponding to a ΔP = 2.0 kgf/cm^2 across the pig. The hydrostatic pressure distribution is prescribed at time equal zero, where the minimum pressure was set as 5.2 kgf/cm^2.

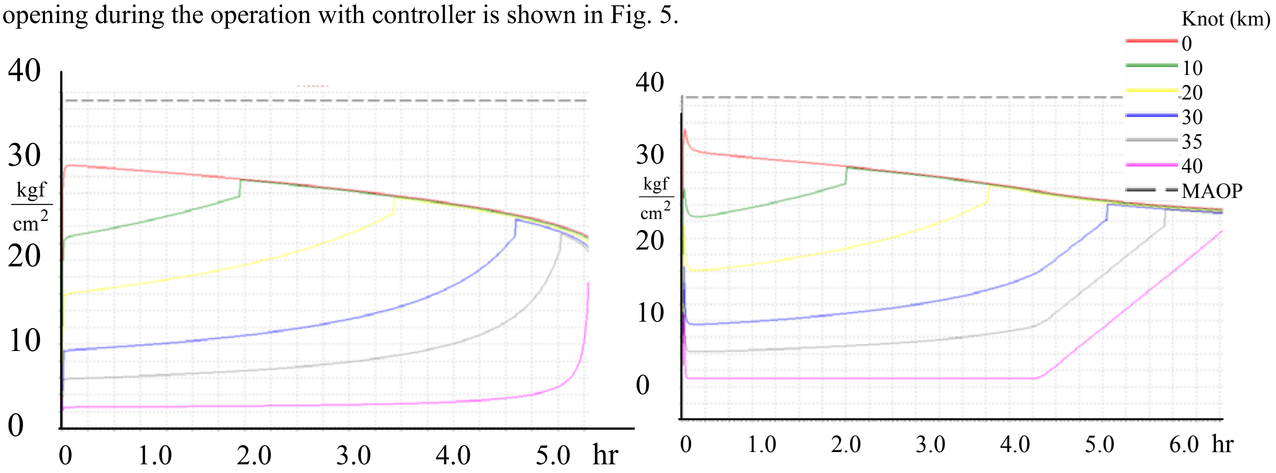
During the operation it is desirable to maintain the pig velocity around 2 m/s, and a minimum pressure along all the pipeline of 5 kgf/cm^2.

Initially the problem is solved without any control. At time equal zero, the outlet valve is completely opened in 1 second and kept this way. Then, to illustrate the performance of the control methodology, both pig velocity and minimum pressure are controlled by a control valve at the outlet of the pipeline. The controller parameters are shown in Table 1.

Table 1 – Controller Parameters

Controller	Controlled Variable	Gain	Derivative time	Integral time	Set point
A	**Pig velocity**	10	0 s	20 s	2 m/s
B	**Minimum Pressure**	10	0 s	20 s	5 kgf/cm^2

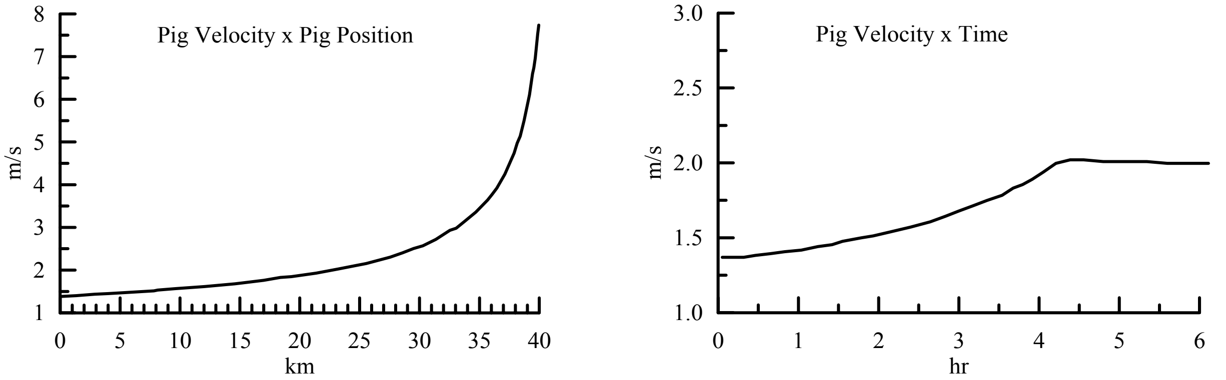
Figure 3 presents the pressure variation with time at six positions uniformly distributed along the pipeline. Figure 3a corresponds to the case without control valve and Fig. 3b with control valve. The dashed line indicates the maximum allowable operating pressure. Figure 4a shows the pig velocity with position when there is no control valve, while Fig. 4b illustrates the variation of the pig velocity with time when there is a control valve. The variation of the outlet valve opening during the operation with controller is shown in Fig. 5.



(a) No control valve

(b) With control valve

Figure 3 – Pressure variation with time



(a) No control valve. Pig velocity with Pig position

(b) With control valve. Pig velocity with time

Figure 4 – Pig velocity

It can be seen in Fig. 3a that due to the presence of the pig, there is a very large pressure gradient at the entrance at beginning of the flow. For this case, the maximum pressure is not a problem, since all pressures are always inferior to MAOP. Note that, since at the pipeline entrance the mass flow of nitrogen is constant, the pressure needed to maintain the flow rate diminishes as the oil is replaced by the nitrogen. At the other positions, it can be seen that the pressure increases until the pig passes through that position. The pressure drop across the pig can be easily seen by the vertical pressure variation at each location. After the passage of the pig, since the gas head loss is very small, the pressure distribution is very similar to the entrance pressure. Note also that the pressure at the exit of the pipeline keeps, during almost all the operation period, close to the reservoir pressure 2 kgf/cm^2, and rapidly increases as the head loss through the valve also increases due to the high flow rate of the liquid. Analyzing Fig. 4a it can be seen that the pig velocity continuously increases with time, since the oil resistance becomes smaller.

When the process control is activated, it can be seen a delay in the opening of the outlet valve (Fig. 5). Further, in order to guarantee the minimum desired pressure, only 40% of the valve is opened. Then the valve is gradually opened, but at time equal to 1500 s, it begins to close to maintain the pig velocity at 2 m/s, as it can be seen in Fig. 4b.

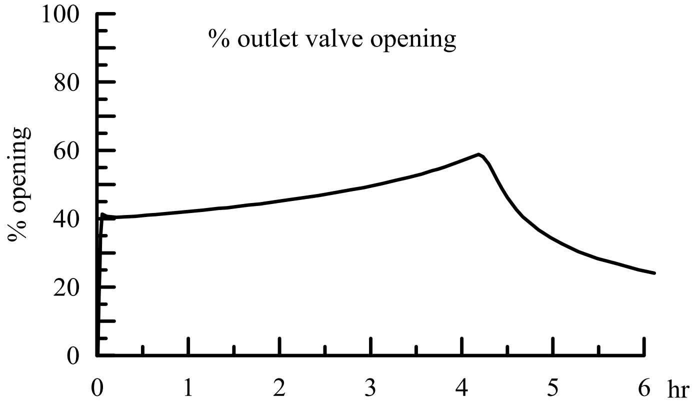


Figure 5 – Percentage of outlet valve opening

5.2. Pig Velocity and Maximum Pressure Control

The second test case has a variable topography as shown in Fig. 6, where each pipeline segment is equal to 5 km. The same pipe and oil as in the previous example were employed, with the maximum allowable operating pressure, MAOP = 46 kgf/cm^2. The pig mass is 27 Kg and its contact are: $F_{stat}^{neg}=F_{stat}^{pos}=F_{dyn}^{neg}=F_{dyn}^{pos}$=18.413 KN, corresponding a ΔP = 1.0 kgf/cm^2 across the pig. The hydrostatic pressure distribution was prescribed at time equal zero, where the pressure was set as 3.0 kgf/cm^2 at the highest point of the pipeline. A constant mass flow rate of nitrogen equal to 9.0 kg/s was imposed at the entrance and a valve was considered at the pipe outlet. The reservoir pressure after the valve is P_t= 1 kgf/cm^2, and the fully open valve discharge coefficient is $(C_d\,A_g)_o$=0.025 m^2.

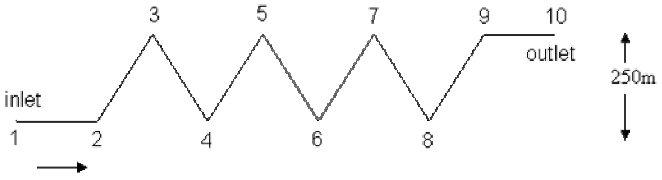
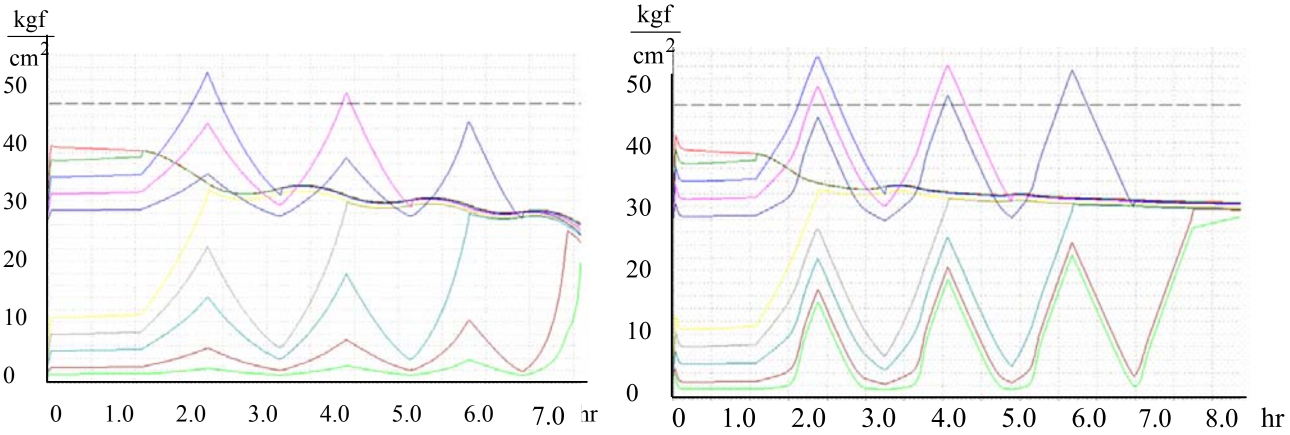


Figure 6 – Pipeline topography

Again, both pig velocity and minimum pressure are controlled by the outlet valve opening. The same control parameters were defined for the pig velocity and minimum pressure: gain=1, derivative time=0 s, integral time = 16 s. The pig velocity set point was 1.6 m/s and minimum pressure was 1 kgf/cm^2. Without controller, the outlet valve was completely opened in 120 s.

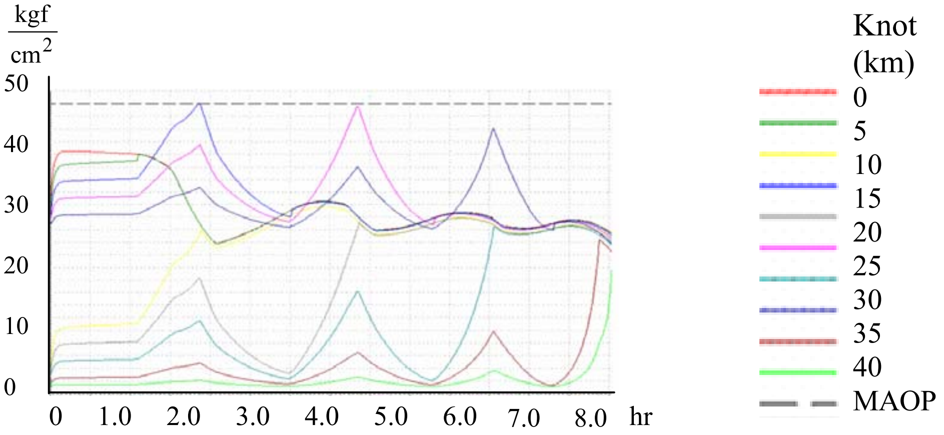
In this example, the pressure distribution (Fig. 7) depends on two combined effects, i.e., reduction of head loss by the substitution of the oil by nitrogen, and the elevation effect. At the uphill regions, the hydrostatic pressure to be overcome reduces as the pig approaches the highest peak, leading to a strong pressure reduction. At downhill, the opposite occurs, explaining the periodic behavior of the pressure variation with time. After the pig has passed by a certain location, the gas pressure variation is very small and similar to the other stations filled with gas. It can be seen in Fig. 7a that, without control valve the MAOP limit is surpassed, however, the minimum pressure limit is always satisfied. Figure 8a shows the pig acceleration uphill due to reduction of pressure head and deceleration downhill. Although all peaks have the same attitude, the pig accelerates a little more as it moves along the pipeline due to the smaller head loss of N_2. At the last segment, very high pig velocities can be seen, since there is no more a descending segment to reduce its velocity.

Two controlled operations are examined. Initially the pig velocity and minimum pressure are simultaneously controlled. Figure 9a presents the percentage of the outlet valve opening with time. To control the pig velocity (Fig. 8b) the valve is periodically opened and closed. As time passes, the valve stays less time fully opened and to control the pig velocity at the last segment it is only 18% open. Note, however that although the pig velocity was controlled and the minimum pressure was never attained, the maximum pressure was again surpassed (Fig. 7b).



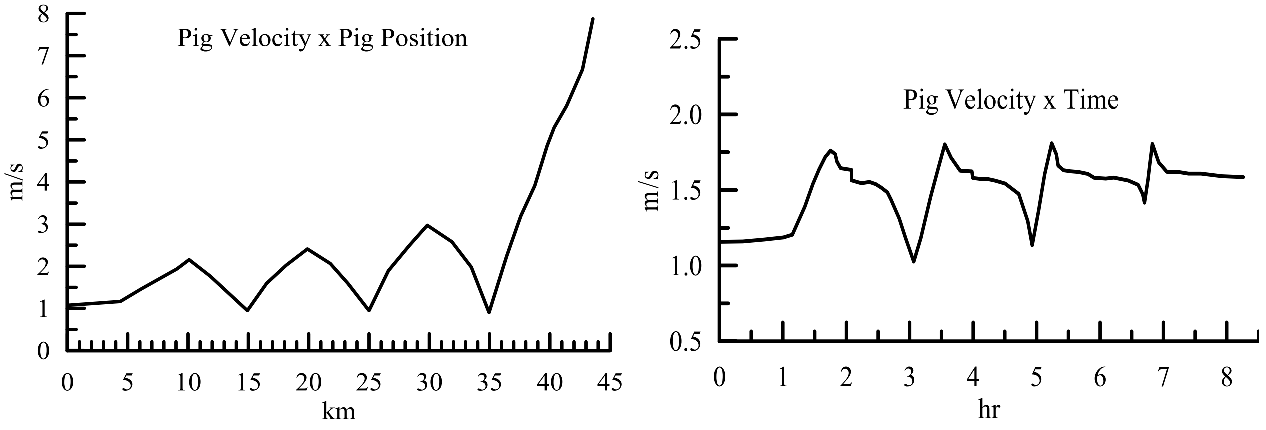
(a) No control valve

(b) With controlled V_{pig} and P_{min}. Outlet control valve



(c) With controlled P_{max}. Inlet control valve

Figure 7 – Pressure variation with time



(a) No control valve. Pig velocity with Pig position

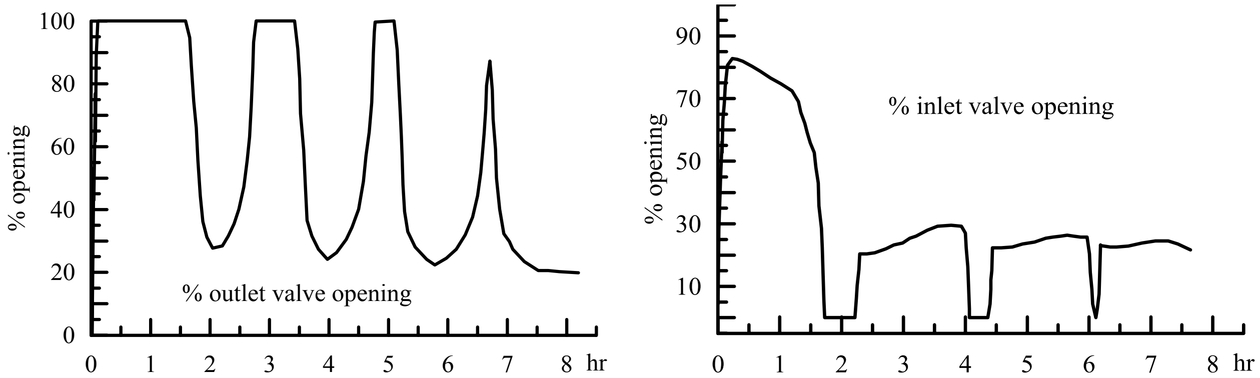
(b) With outlet control valve. Pig velocity with time

Figure 8 – Pig velocity

To control the maximum pressure, an inlet valve was then considered and the control methodology was applied to it. The set point for the maximum pressure was defined as MAOP/1.15, in order to absorb the overshoot of the control system, with gain = 1, derivative time = 0 and integral time = 20s. Figure 7c presents the pressure variation with time, where it can be clearly seen that now the MAOP limit was satisfied. Figure 9b illustrates the percentage of the inlet valve opening, which is never equal to 100%. At the beginning of the operation the valve is opened up 83 %. As the pressure increases the valve is closed to control its value. As time passes less nitrogen is needed to displace the pig, and to assure the desired pressure limits and the valve is periodically closed and opened, but at each time with a smaller percentage.

6. Final Remarks

To guarantee an efficient and safe pigging operation, maximum and minimum pressures in the pipeline as well as pig velocity must be maintained within stipulated limits. With the objective of providing an efficient tool to assist in the control and design of pig operations through pipelines, a numerical code was developed, based on a finite difference scheme, which allows the simulation of gas-liquid transient flows in the pipeline. Modules based on the PID controller methodology to automatically control process variables were included to employ different strategies to reach an efficient operation. Both inlet and outlet valves opening can be controlled. The test problems presented illustrated the effectiveness of the methodology.



(a) Pig velocity and minimum pressure control. Outlet valve

(b) Maximum velocity control. Inlet valve

Figure 9 – Percentage of valve opening

7. Acknowledgement

The second author thanks CNPq for the support during the development of this work.

8. References

Azevedo, L.F.A., Braga, A. M. B. & Gomes M.G.F.M., 1996, “Study of Pig Motion in Pipelines”, VI ENCIT-VI LATCYM, Florianópolis, SC, Brazil, vol. III, pp. 1423-1428.

Campos, M. V., 1999, “Sintonia de Controladores PID”, Comunicação Técnica CT-DIPRIN-034/1999. Rio de Janeiro: CENPES/DIPRIN/SEPROJ.

Fox, R. W. and McDonald, A. T., 2001, “Introdução à Mecânica dos Fluidos”, Livros Técnicos e Científicos Editora, 5a. Ed.

Isermann, R. 1981, “Digital Control Systems**”,** Revised and enlarged translation of Digitale Regelsysteme 1977, Germany: Springer-Verlag Berlin Heidelberg NewYork.

Kim, D. K.; Cho, S. H.; Park, S. S.; Rho, Y. W.; Yoo, H. R.; Nguyen, T. T.; Kim, S. B., 2003, “Verification of the Theoretical Model for Analyzing Dynamic Behavior of the Pig from Actual Pigging” Korean Society of Mechanical Engineers KSME International Journal, v. 17, n. 9, p. 1349-1357.

Monteiro, C., Nieckele, A. O., Braga, A. M. and Azevedo, L. F. A., 1998, “Simulation Of Transient Pig Motion Through Liquid And Gas Pipelines”, IV Congresso Norte Nordeste de Engenharia Mecânica, Fortaleza, CE.

Nieckele, A.O., Azevedo, L.F.A., Braga, A.M.B., 1998, “Simulation of Fluid Flow and Pig Dynamics in Dewatering Operations in Pipeline”. In: Encontro Nacional De Ciências Térmicas – ENCIT, Rio de Janeiro, V.2, pp.1025-1030.

Nieckele, A.O., Azevedo, L.F.A., Braga, A.M.B., 2000,“Temperature Influence in Dewatering Operations in a Riser”. In: Congresso Nacional De Engenharia Mecânica - CONEM 2000, Natal, RN. código MC8862, CD-ROM

Nieckele, A.O., Azevedo, L.F.A., Braga, A.M.B., 2001, “Transient Pig Motion Through Pipelines”, Journal of Energy Resources Technology of ASME, Vol. 123, pp.260-269.

Nguyen, T. T.; Kim, S. B.; Yoo, H. R.; Rho, Y. W., 2001, “Modeling and Simulation for Pig Flow Control in Natural Gas Pipeline”. Korean Society of Mechanical Engineers, KSME International Journal, v. 15, n. 8, p. 1165-1173.

Patankar, 1980, “Numerical Heat Transfer and Fluid Flow”, Hemisphere Publishing Corporation.

Santos, O. G., Alhanati, J.S. & Bordalo, S. N., 1997, “Modeling and Performance of Pig-Lift”, *XIV COBEM*, SP, Brasil, COB260, CD-ROM

Vianes Campo, E. & Rachid, F.B., 1997, “Modeling of Pig Motion Under Transient Fluid Flow”, *XIV COBEM*, SP, Brasil.

Webb, S.; Bogucz, E.; Levy, E.; Barret, M.; Snyder, C.; Waters, C., 1987, “Evacuation of a Residual Oil Pipeline by Inert Gas Displacement” Society of Petroleum Engineers – SPE: Production Engineering, pp.45-50.

Wylie & Streeter, 1978, "Compressible Flow in Pipes", McGraw Hill

9. Responsibility notice

The authors are the only responsible for the printed material included in this paper.