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# SIMULATION AND PLANNING OF PIPELINE EMPTYING OPERATIONS

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## KEYWORDS
Nitrogen, emptying, pig, dynamic simulator, simulation, planning, Simdut, Transpetro, Brazil.

## ABSTRACT
The pipeline pigging operation for emptying purposes is a common practice in the petroleum and gas transport industry. The emptying operation is employed for removal of the pipeline liquid products and substitution for an inert gas like nitrogen. This operation is necessary before pipeline maintenance or hydrostatic test procedures. The emptying operation applied for oil pipelines usually demands large volumes of nitrogen because of the pressure difference that is necessary to maintain the pig in a velocity that guarantee an efficient and safe operation. The nitrogen that is originally stored inside cryogenic vessels in liquid phase is pumped and vaporized to be injected into the pig launcher, after heating the gas. The gas injection and expansion inside the pipeline propel the pig, delivering the product that was in the pipeline at the receiver station. It is common to cut the nitrogen injection in a certain instant of the operation, before the pig reaches its destination. From then on, the expansion of the gas is able to finish the operation alone.

A dynamic simulator called DESLOCAN2 was developed by SIMDUT/PUC-Rio to simulate the pig motion during emptying operations with nitrogen in TRANSPETRO crude oil and refined products pipelines. In the operation planning phase the simulator is used to evaluate the gas mass flow rate, the inlet gas pressure and the nitrogen cut instant that can propel the pig to its destination with a minimum volume of nitrogen. The outlet liquid pressure is calculated using two simultaneous controllers: outlet flow rate based on maximum pig velocity and minimum outlet pressure that avoids slack line condition. The dynamic simulator also can be used as a forecast monitor of the pipeline pigging operation given the current inlet gas and outlet liquid conditions, allowing the visualization of actual and forecasted pipeline pressure profile, the pig velocity and position, the accumulative gas inside the pipeline and the volume of product removed.

The main objectives of this paper are: Present the mathematical modeling and considerations built in the simulator; Validate the model's main hypothesis; Present the gained experience on building the model and planning an emptying operation of an existing pipeline: OSBAT 24;

## NOMENCLATURE
MAOP: Maximum Allowed Operational Pressure;
PGAS: input of gas pressure at the gas inlet;
QGAS: input of gas flow at the gas inlet;
PLIQ: input of liquid pressure at the liquid outlet;
QLIQ: input of liquid flow at the liquid outlet;
PSV: pressure safety valve;
DT: input time step;
$t$: time;
$t_t$: total time of the operation;
$t_c$: critical time;
$x_{pig}$: position of the pig;
$i_{pig}$: pig position index;
$i_c$: critical pig position index;
$n$: number of pig position indexes, number of time steps of the simulation;
$y_{pig}$: elevation of the pig;
$Q_{liq}$: liquid outlet flowrate;
$Q_{gas}$: standard gas inlet flowrate;
$p_{gas}$: gas pressure;
$A_{pig}$: transversal area of the pipeline at the pig's position;

$A_{out}$: transversal area of the pipeline at the liquid outlet;
$f$: friction factor between pipeline and fluid;
$cv_{out}$: flow coefficient of the delivery control valve;
$cv_{max}$: flow coefficient of the delivery control valve 100% opened;
$V_{pipe}$: geometric volume of the pipeline;
$\rho_{liq}$: density of the liquid to be removed;
$Ru$: roughness of the pipeline;
$p_{std}$: standard pressure;;
$D$: nominal diameter of the pipeline;
$D_{in}$: internal diameter of the pipeline;
$p_{crit}$: critical pressure;
$Sm^3$: Petrobras' standard cubic meters: at 20°C and 1atm.

## INTRODUCTION

This paper presents a methodology of planning and controlling an operation of emptying a pipeline, based on a real operation that occurred in Brazil in October 2011, which involved three different companies:

- Transpetro, the pipeline operator, which controlled the operation at the delivery station and hired the other two companies for this operation.
- White Martins, which was the company that injected the $N_2$ at the supply station.
- SIMDUT – PUC-Rio, which was responsible for the study that preceded the operational instructions.

SIMDUT developed a software called DeslocaN2 to simulate pipeline emptying operations. The mathematical modeling and premises built in this simulator are discussed in the item "Pig Motion Simulator".

The item "Planning an Operation" discusses how the simulations are executed, what considerations need to be done, and which important results the study that precedes the operational instructions can bring.

On "Operation Results", the data obtained through Transpetro's SCADA system, of the real operation as it happened will be shown and analyzed. After that, on "Comparison of Results", the simulated data will be compared with the one from the real operation, leading to the conclusions of this paper.

## PIG MOTION SIMULATOR

A pig motion simulator was developed to preview the behavior of an emptying operation with nitrogen pushing a pig. This simulator accepts many different input options from the user, which includes pressure and flow for both injection and delivery station, and also pig velocity and flow coefficient for the delivery control valve. All the boundary conditions can be set as function of the pig travel time or position of the pig. The other variables are calculated by the simulator, so the user can analyze the pig motion, liquid phase pressure profile and gas volumes for dynamic scenarios. It is also possible to run a one-step static scenario given the pig position and the boundary conditions. This is useful to monitor the operation while it is happening.

### Premises of the calculation

In the mathematical modeling of the DeslocaN2, several simplifying assumptions were considered. These are appropriate for simulating emptying operations with a pig propelled by nitrogen. The use of the simulator is recommended only in accordance to the following assumptions:

- Pressure drop in the liquid phase calculated by the Darcy-Weisbach equation [1]
- Friction factor in the liquid phase calculated by the implicit expression of Colebrook-White [2];
- Pressure drop in the gas phase isn't calculated due the low velocities of the gas phase;
- Isothermal flow in both phases at ambient temperatures;
- Constant pig pressure drop for the entire simulation.
- Pig inertia is negligible;
- Incompressible flow in the liquid phase;
- Pig velocity equal to the liquid speed at the delivery station, as seen on equation (1).

$$V_{liq}(t) = V_{pig}(t) \tag{1}$$

- Slow transient; Pig velocity between 0.5 m/s and 2 m/s;
- Gas thermodynamic properties calculated using Ideal Gas Law;
- Flowrate and gas volume calculated using Petrobras standard condition (20°C and 1atm);

### Hydraulic and pressure gradients

Consider an emptying operation in progress, in which the pig is located on an intermediate position of the pipeline ($X_{pig}$). At this moment, the hydraulic gradient for the liquid phase and the pressure gradient throughout the pipeline is shown on Figure 1.

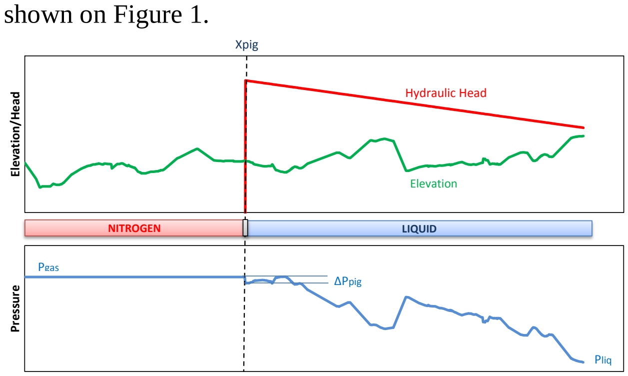


**Figure 1- Hydraulic and pressure gradients of the liquid phase**

On Figure 1, the upstream side of the pipeline until the pig is filled with nitrogen, and the downstream side is filled with the liquid to be removed of the pipeline. The pressure drop caused by the pig (assumed to be constant for the entire operation) can also be seen.

**Pig position and speed**

The pig position index $i_{pig}$ indicates the position of the pig on the elevation profile of the pipeline. Each position (in function of time) has a correspondent position in function of the pig position index.

$$x_{pig}(t) = x(i_{pig}) \tag{2}$$

If the position of the pig is between two points of the elevation profile, a new point (*k*) is created through linear interpolation, as shown on equation (3).

$$x_{pig} = x(k), \tag{3}$$

$$y_{pig} = y(k) = y(i) + [y(i+1) - y(i)] \times \left[ \frac{x_{pig} - x(i)}{x(i+1) - x(i)} \right]$$

In the dynamic simulation, the position of the pig is estimated by the actual speed of the pig, as shown on equation (4).

$$x_{pig}(t + \Delta t) = v_{pig}(t) \cdot \Delta t \tag{4}$$

The time step of the dynamic simulation is constant and defined by the user. However, this value is readjusted when the pig is next to the delivery station, as shown on equation (5).

$$x(t) + v_{pig}(t) \cdot \Delta t > x(i_{out}) \rightarrow \Delta t = \frac{x(i_{saida}) - x(t)}{v_{pig}(t)} \tag{5}$$

The pig velocity is calculated through the liquid flow at the delivery station, as shown on equation (6).

$$v_{pig}(t) = \frac{Q_{liq}(t)}{A_{out} \cdot \left( A_{out} / A_{pig} \right)} \tag{6}$$

If the user inputs the boundary condition for the delivery station as the maximum pig velocity VPIG, equation (6) is inverted to obtain the liquid flow at the delivery station, as shown on equation (7).

$$Q_{liq}(t) = v_{pig}(t) A_{out} \cdot \left( A_{out} / A_{pig} \right) \tag{7}$$

**Local pressure**

The pressure gradient of the pipeline is updated according to the actual position of the pig $x_{pig}$. Local pressures are obtained through equations (8) and (9).

$$x(i) \leq x_{pig} \rightarrow p(i) = p_{gas} \tag{8}$$

$$x(i) > x_{pig} \downarrow$$

$$p(i) = p_{gas} - \Delta p_{pig} + \Delta p_{est}(i-1) + \Delta p_{slack}(i-1) - \Delta p_{din}(i-1) \tag{9}$$

**Head**

The head profile is plotted on the hydraulic gradient, in the same scale as the elevation profile. It indicates the available energy in liquid column meters, and is calculated through the equation (10). The hydraulic profile of DeslocaN2 only shows the head profile for the liquid phase of the pipeline.

$$x(i) > x_{pig} \rightarrow H(i) = y(i) + \frac{p(i)}{(\rho g)} \tag{10}$$

**Pressure portions**

In order to calculate the local pressure *p(i)* and head for the liquid phase, it is necessary to obtain the portions of this pressure that correspond to: the variation of the gravitational potential energy $\Delta p_{est}$; the pressure drop on the pig $\Delta p_{pig}$; the pressure drop through viscous friction between the liquid and the pipeline $\Delta p_{din}$; and the pressure difference for slack line flow $\Delta p_{slack}$. The equations for each one of these are shown from equation (11) to (15).

**Static pressure difference**

$$i = i_{pig} \rightarrow \Delta p_{static}(i) = 0 \tag{11}$$

$$i > i_{pig} \rightarrow \Delta p_{static}(i) = \left( \sum_{j=1}^{i-1} \Delta p_{static}(j) \right) - \rho\, g\, [y(i) - y(i-1)]$$

**Dynamic pressure difference**

$$i = i_{pig} \rightarrow \Delta p_{din}(i) = 0 \tag{12}$$

$$i > i_{pig} \rightarrow \Delta p_{din}(i) = \left( \sum_{j=1}^{i-1} \Delta p_{din}(j) \right) - \frac{8 Q_{liq}{}^{2} f\, \rho\, (x(i) - x(i-1))}{\pi^{2} D_{in}(i)^{5}}$$

The friction factor *f* and Reynolds are calculated iteratively until convergence. The first guess of *f* is determined explicitly through the Halland equation [3] for the friction factor (14), and then iterated through Colebrook-White's equation [2]. With the converged values of the flow and friction factor, the simulator calculates de dynamic pressure difference.

$$\mathrm{Re} = \frac{4 \rho Q_{liq}}{\pi\, D(i)\, \mu} \tag{13}$$

$$\frac{1}{\sqrt{f}} = 1.7368 - 0.7818 \cdot \ln\left[\left(\frac{Ru}{2D(i)}\right)^{1.11} + \frac{63{,}635}{\mathrm{Re}}\right] \quad (14)$$

$$\frac{1}{\sqrt{f}} = -0.87 \cdot \ln\left[\frac{Ru}{3{,}7D(i)} + \frac{2{,}51}{\mathrm{Re}\sqrt{f}}\right] \quad (15)$$

**Slack line flow pressure difference**

This portion is only calculated when the boundary condition for the delivery station, defined by the user, is an upstream pressure for the delivery control valve (PLIQ) that imposes slack line flow.

For other delivery boundary conditions, the simulator calculates the minimum pressure at the delivery station to keep the pressure profile of the pipeline at least 1.0 kgf/cm² higher than the vapor pressure of the product. This is done by reducing the flow coefficient of the delivery control valve, which simulates its closing.

Even though the simulator calculates the pressure profile for slack line flow, this is usually avoided on real pipelines emptying operations, in order to keep the operation under control.

The example operation and all simulations analyzed on this paper avoid slack line flow, keeping the pipeline pressurized enough for this.

**Flow Coefficient**

The flow coefficient of the delivery control valve (CVLIQ) can be used as a boundary condition at the delivery station. This is useful when the fraction opened of the valve is a known parameter, along with its maximum flow coefficient ($cv_{max}$ [gpm/psi$^{0.5}$]).

$$cv_{out}(t) = FR(t) \cdot cv_{\max} = Q_{liq}(t)\left(\frac{(\rho_{liq}/\rho_{water})}{\Delta p_{valv}(t)}\right)^{0.5} \quad (16)$$

If the flow coefficient is not an input to the simulator, it will be an output, calculated through the equation (16).

**Pressure, volume and flow of the gas phase**

In an isothermal flow, an ideal gas behaves according to Boyle-Marriote's law, in which the product between the volume occupied by the gas and its pressure is constant. This can be seen on equation (17).

$$p_{gas}(t) \cdot V_{pipe}(t) = p_{gas}(t+\Delta t) \cdot V_{pipe}(t+\Delta t) \quad (17)$$

The ideal gas law approximation can only be adopted for $N_2$ at ambient temperatures (20$^{o}$C) because its Z-Factor varies from (1.0 to 0.98), for pressures ranging from 1.0 bar to 100 bar.

The volume of the pipeline occupied by the gas ($V_{pipe}$) is obtained through the current position of the pig $x_{pig}(t)$, as shown on equation (18).

$$V_{pipe}(t) = \int_{x=0}^{x=xpig(t)} x \cdot A(x)\, dx \quad (18)$$

The volume of gas on standard conditions can be calculated using the pressure of the gas, which is assumed to be constant through the entire gas phase section of the pipeline, as shown on equation (19).

$$V_{gas}(t) = V_{pipe}(t) \cdot \frac{p_{gas}(t)}{p_{std}} \quad (19)$$

That same volume can be calculated integrating the gas standard flowrate on time, as shown on equation (20).

$$V_{gas}(t) = \int_{0}^{t} Q_{gas}(t)\, dt \quad (20)$$

**Control method for the injection station**

The boundary conditions for the injection station can be defined as gas pressure (PGAS) or gas standard flowrate (QGAS) on simulator. The boundary condition type can also be changed during the operation, defining different variables for each period of the simulation.

When the gas pressure (PGAS) is the defined parameter by the user, the injection flow is calculated through the rate of variation of the gas volume, combining equations (19) and (21).

$$Q_{gas}(t) = \frac{V_{gas}(t) - V_{gas}(t-\Delta t)}{\Delta t} \quad (21)$$

When the gas flowrate is the boundary condition defined by the user, the simulator calculates the injection pressure through the ratio of the total injected gas volume and the volume of the pipeline occupied by the gas phase, as shown on equation (22). The total injected gas volume is determined by the equation (20).

$$p_{gas}(t) = p_{std}\,\frac{V_{gas}(t)}{V_{duto}(t)} \quad (22)$$

**Control method for the delivery station**

The user can select from four different control methods for the delivery station: pressure upstream of the delivery control valve (PLIQ), liquid flow at the outlet of the pipeline (QLIQ), maximum pig velocity (VPIG) or delivery control valve's flow coefficient (CVLIQ). As discussed before, only the (PLIQ) method can impose a condition of slack line flow, all others controls will avoid this condition automatically, by reducing the opened fraction of the delivery control valve.

Similar to the injection control, the user can change the control method during the operation. When the parameter associated with the control method is an input all other variables are outputs and will be evaluated using the equations from (2) to (16).

## PLANNING AN OPERATION

A real operation will be used as an example of the methodology developed to plan and monitor an emptying operation.

SIMDUT was requested to elaborate a simulation report of the emptying operation of OSBAT 24 with the developed simulator. The objective of the simulation was to provide the necessary parameters to elaborate the operational procedure, which should:

- Minimize the amount of $N_2$ required;
- Keep pressure and flowrates below the operational limits for the gas inlet, and liquid outlet;
- Avoid slack line flow;
- Keep the pig velocity between 0.5 m/s and 1.1 m/s;
- Reduce the total time of the operation.

For the modeling of the operations, the following general considerations were adopted:

- The pipeline elevation profile was provided by Transpetro;
- The pipeline will be initially filled with oil described by Transpetro, and pressurized with a static head enough to avoid slack line;

The following assumptions were adopted:

- The pig pressure drop was assumed to be 0,5 kgf/cm²;
- The nitrogen volumes were calculated at the Petrobras standard conditions (20°C, 1atm);
- Isothermal flow at 20°C;
- Slack line flow was avoided for all simulations, keeping the pressure at least 1.0 kgf/cm² over the vapor pressure of the product, for the entire pipeline;
- The maximum pressure profile along the pipeline can't be over the MAOP.
- The pressure on the delivery station must be 2.0 kgf/cm² below the setpoint of the PSV.

The main inputs for the emptying operation simulator are:

- Pipeline Elevation Profile. The elevation profile of the pipeline used in the example operation is shown on Figure 2 and varies from 0m to 200m through the 120.8km of its extension;
- Geometry and mechanical properties of the pipeline: external diameter and thickness (inputted along with the elevation profile) and roughness. The following values were used on the example operation:
    - $D$ = 24 in
    - $Ru$ = 0.0018 in
    - Thickness of the pipeline is 0.469 in, 0.438 in or 0.312 in depending on the location.

- Maximum allowed operational pressure (MAOP), inputted as a function of the location, ranging between 57 kgf/cm² and 97 kgf/cm² for the pipeline used on the example operation;
- Properties of the liquid to be removed: density and dynamic viscosity at a reference temperature, vapor pressure. The values for the example operation are given in the temperature that the isothermal flow occurs (20°C):
    - $\rho_{liq}$ = 910 kg/m³;
    - $\mu$ = 245 cP;
    - $p_{vapor}$ = 1.0 kgf/cm².

- Boundary Conditions, as discussed on "Control method for the injection and delivery station"
    - Nitrogen injection pressure or flow, or a combination of both;
    - Liquid outlet pressure or flow, or the actual valve flow coefficient ($c_v$) of the delivery control valve, or maximum pig velocity.
- Time step (DT) of 36 seconds;

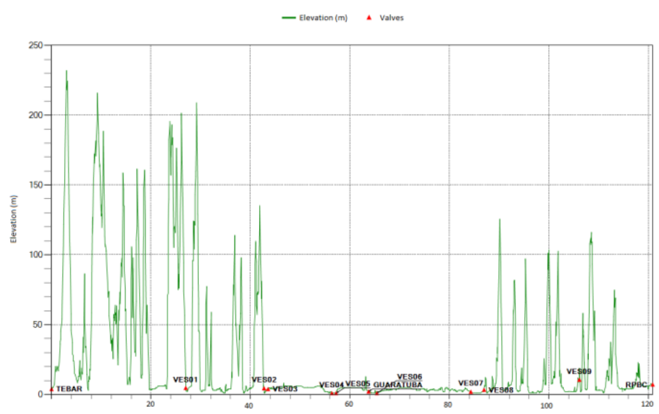


**Figure 2- Elevation profile of OSBAT24**

In order to estimate the minimum volume of $N_2$ required for the operation, the user must find the critical pig position index ($i_c$). This corresponds to the location where the pig will be when the $N_2$ injection is interrupted, that is, after a given amount of nitrogen is injected. The injection volume can be calculated using an arbitrary location or evaluated using an iterative routine.

$$p_{crit} = p_{static}(i_c) + p_{din}(i_c) + \Delta p_{pig} \quad (23)$$

The pressure drop of the pig is assumed to be constant throughout the pipeline, and equal to 0.5 kgf/cm². Static pressure is calculated through equation (24) and dynamic pressure through (25). The friction factor calculation is discussed on "Dynamic pressure difference" item.

$$p_{static}(i_c) = \rho\, g\,(y(i_{end}) - y(i_c)) \quad (24)$$

$$p_{din}(i_c) = \frac{8 Q_{liq}{}^2 f\, \rho\,(L - x(i_c))}{\pi^2 D_{in}(i_c)^5} \quad (25)$$

The total $N_2$ injection volume needed to be injected until critical point ($i_c$) is then estimated through the equation (26).

$$V_{gas}(i_c) = V_{duto}(i_c) \cdot \frac{p_{crit}}{p_{std}} \quad (26)$$

The nominal flow of the $N_2$ injection system is provided by the company that will execute the injection. In the example operation, White Martins informed that the nominal flow that would be used on the operation was $Q_c$ = 10900 Sm³/h.

The injection time can later be estimated through the total volume $V_{gas}(t_c)$.

$$t_c = \frac{V_{gas}(i_c)}{Q_c} \quad (27)$$

After this procedure, the boundary conditions for the injection station are defined, in terms of gas flow. QGAS will be the nominal flow of the $N_2$ injection system ($Q_c$ ) until $t_c$, when it changes to zero for the rest of the operation. The results for the example operation are found on Table 1 and on Figure 3.

**Table 1 – Gas boundary conditions for the planning simulations - Example operation**

| | |
|---|---|
| Injection Time (h) | 38 |
| Gas Flow (QGAS) (Sm³/h) | 10900 |

### Liquid boundary condition

The gas boundary condition is now simulated with different control methods for the delivery station, analyzing the system limits, the pig velocity and the hydraulic gradients. The objective is to develop a control schedule for the delivery station, for a stabilized, safe, easy and optimal operation.

For the example operation, the first simulations were done with a flow control at the delivery station; this will be called Case 1. The objective was to find a flow that could be maintained throughout the operation, without imposing a condition of slack line flow, and keep the pig velocity between the desired range. The results of the simulations for the case 1 are shown on Table 2, Figure 3 and Figure 4.

**Table 2 – Results of the planning simulations for Case 1**

| **Delivery flow (m³/h)** | **443** |
|---|---|
| Total operation time (h) | 75.5 |
| Gas pressure when $N_2$ injection stops (kgf/cm²g) | 25.4 |
| Maximum pressure at delivery (kgf/cm²g) | 33.8 |
| Minimum pressure at delivery (kgf/cm²g) | 11.9 |
| Gas pressure at the end of operation (kgf/cm²g) | 12.3 |
| Pig velocity (m/s) | 0.444 |

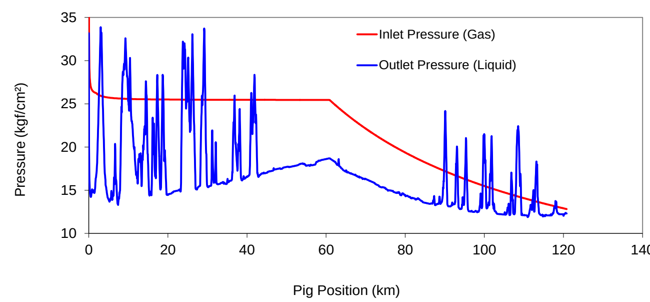


**Figure 3- Inlet and outlet pressure versus pig position - Case 1**

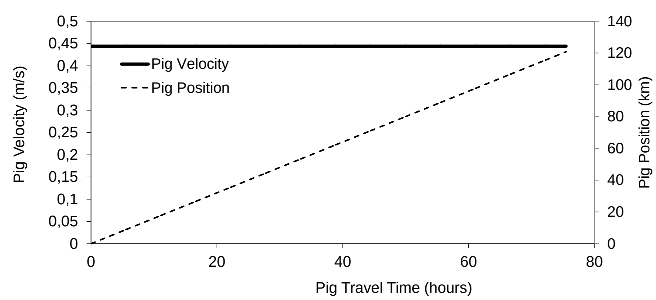


**Figure 4- Pig velocity versus travel time - Case 1**

The maximum outlet pressure at the delivery station for this case was greater than the setpoint of the PSV installed there (27.0 kgf/cm²), and the pig velocity was slightly under 0.5 m/s. These results showed that this operation could not be controlled with a constant setpoint for the liquid flowrate.

After that, a new case was studied, involving pressure control at the delivery station since the beginning of the operation and then a flow control for the rest of the operation (Case 2). This would avoid slack line flow and would keep the delivery scraper pressure under the PSV set point.

The results for the simulations for the Case 2 are shown on Table 3, Figure 5 and Figure 6.

**Table 3 – Results of the planning simulations - Case 2**

| | |
|---|---|
| **Liquid pressure (PLIQ) until pig reaches V-03 (kgf/cm²g)** | **14.0** |
| Liquid flow (QLIQ) after pig reaches V-03 (m³/h) | 600 |
| Total operation time (h) | 60.0 |
| Gas pressure when N2 injection stops (kgf/cm²g) | 21.0 |
| Maximum pressure at delivery (kgf/cm²g) | 22.8 |
| Minimum pressure at delivery (kgf/cm²g) | 11.4 |
| Gas pressure at the end of operation (kgf/cm²g) | 12.3 |
| Maximum pig velocity (m/s) | 1.0 |
| Minimum pig velocity (m/s) | 0.3 |

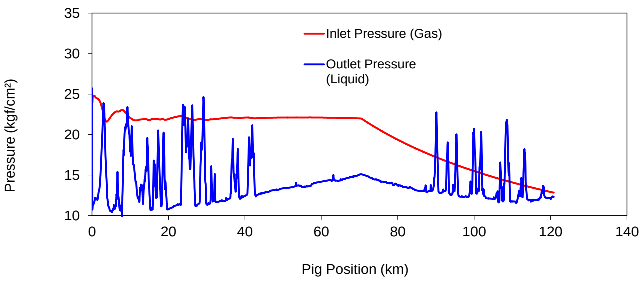


**Figure 5- Inlet and outlet versus pig position - Case 2**

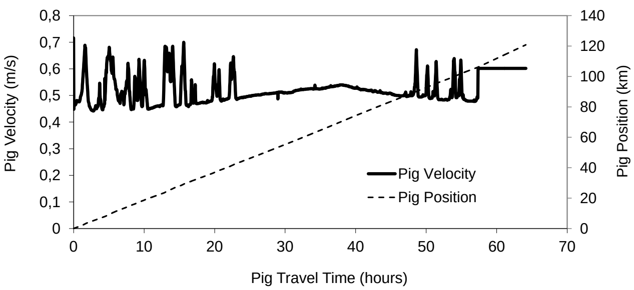


**Figure 6- Pig velocity versus time - Case 2**

Using the control plan proposed by Case 2 for the delivery station would imply in a minimum pig velocity of 0.3 m/s, which could lead the pig to stop, due to the combination of inertia and static friction forces acting between the internal pipe and the pig surface.

Case 3 consists on imposing a constant valve flow coefficient (CVLIQ) for the delivery control valve until the pig reaches block valve V-09. This simulates the delivery control valve with a constant opening position until pig reaches block valve V-09. The control is then changed to liquid flowrate (QLIQ), in order to stabilize the end of the operation. The main results of the simulation for this case are shown on Table 4, Figure 7 and Figure 8.

**Table 4 – Results of the planning simulations- Case 3**

| | |
|---|---|
| **Delivery control valve flow coefficient (gpm/psi)** | **160** |
| Total operation time (h) | 64.1 |
| Gas pressure when $N_2$ injection stops (kgf/cm²g) | 22.0 |
| Maximum pressure at delivery (kgf/cm²g) | 24.8 |
| Minimum pressure at delivery (kgf/cm²g) | 9.35 |
| Gas pressure at the end of operation (kgf/cm²g) | 12.3 |
| Maximum pig velocity (m/s) | 0.716 |
| Minimum pig velocity(m/s) | 0.442 |

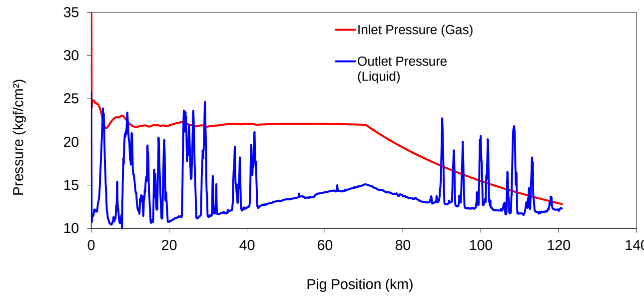


**Figure 7- Inlet and outlet pressure versus pig position - Case 3**

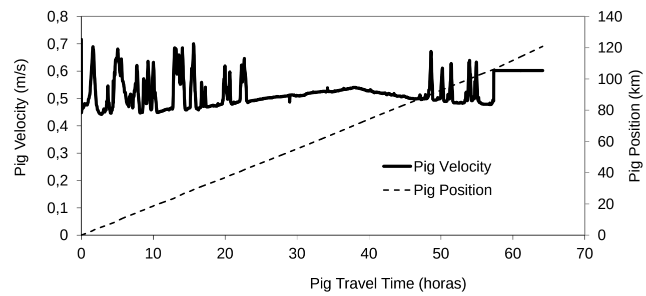


**Figure 8- Pig velocity versus travel time - Case 3**

Case 3 resulted in pig velocities between 0.44 m/s and 0.71 m/s, and a pressure at the delivery scraper between 9.4 kgf/cm² and 25.0 kgf/cm² during the operation. This case is also the easiest for the operation, because it doesn't depend on a control system: it is only necessary to keep the valve at a constant opened fraction for the major part of the operation. This was the control method suggested by SIMDUT to Transpetro.

## OPERATION RESULTS

The delivery control valve of OSBAT24 doesn't have an automatic control system for upstream pressure or flow attached to it. The only way to control it is through the opened fraction. Transpetro didn't keep this valve at a fixed opened fraction, as suggested on planning phase Case 3. The Flow Coefficient $c_v$ history of the delivery valve in the real operation is shown on Figure 12. The flow coefficient of the delivery valve for each instant of the real operation was calculated through the flow, upstream pressure and downstream pressure of this valve, as shown on equation (16).

In the real operation, two pigs were sent with a batch of 850m³ of the same oil to be removed, between them. This was simplified in the simulations with only one pig. The first pig arrival indicated that the nitrogen arrival time was near.

Transpetro operated the delivery control valve as suggested by White Martins. The procedure is described below.

- Keep the control valve upstream pressure below 25.0 kgf/cm² and the flow between 443 and 1108 m³/h;
- After the total injection of $N_2$, flow can be controlled between 900 and 1108 m³/h, until the first pig reaches the delivery station, when flow must be controlled between 120 and 443 m³/h.

All the data from the real operation was obtained from the instruments historical data of Transpetro's SCADA system. The pig position was evaluated using the equation (1). Since the pig position was tracked during the operation, the pig position hypothesis could be validated with the arrival time on each intermediary valve for the real operation, as shown on Figure 9.

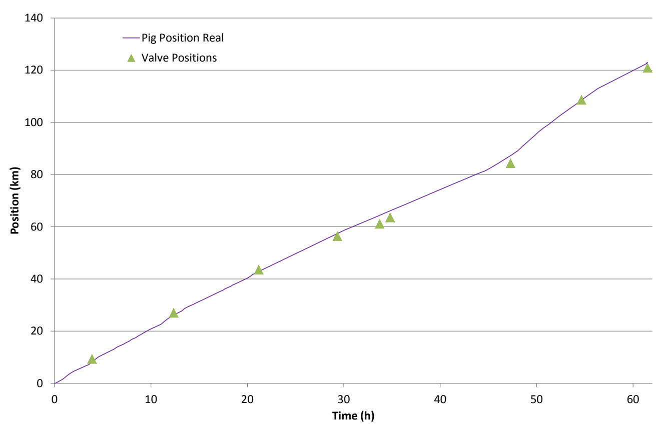

**Figure 9- Pig Position Validation**

The results of the real operation are shown on Table 5, Figure 10 and Figure 11. The initial and final 10 minutes of the operation were not considered for the maximum and minimum pig velocity.

**Table 5 – Results - Real operation**

| | |
|---|---|
| Total operation time (h) | 61.5 |
| Injection Time (h) | 50 |
| Average $N_2$ Flow during Injection (m³/h) | 10630 |
| Gas pressure when $N_2$ injection stops (kgf/cm²g) | 16.3 |
| Maximum pressure at delivery (kgf/cm²g) | 25.3 |
| Minimum pressure at delivery (kgf/cm²g) | 11.5 |
| Gas pressure at the end of operation (kgf/cm²g) | 14.2 |
| Maximum pig velocity (m/s) | 1.4 |
| Minimum pig velocity (m/s) | 0.4 |

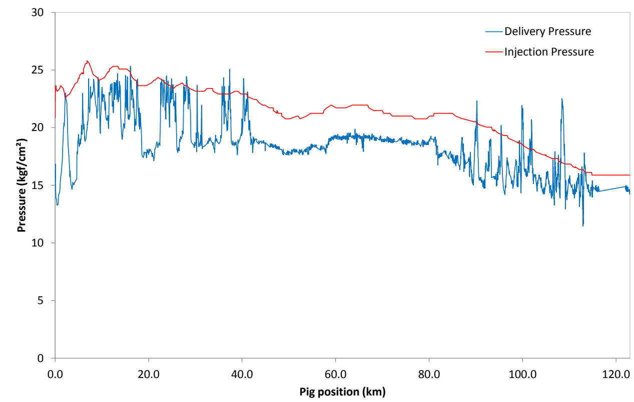

**Figure 10- Pressure at injection and delivery stations x pig position - Real operation**

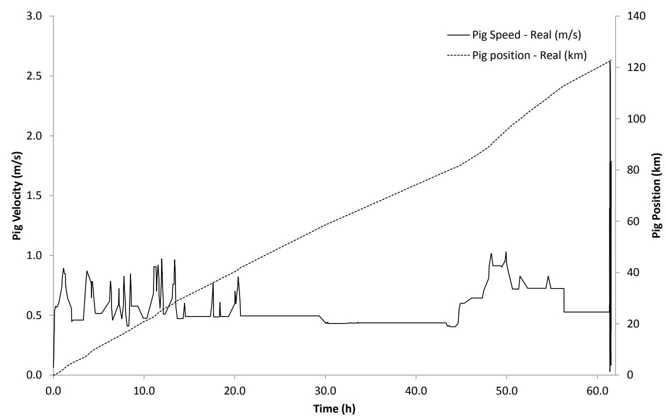

**Figure 11- Pig velocity x time - Real operation**

## COMPARISON OF RESULTS

The real operation was a success. The flow history of the gas injection of the real operation was not available for this study, because the ultrasonic flow sensor of the pipeline system doesn't work for gas. However, the difference of total injected volumes between the real operation and the simulation of Case 3 indicates that the real operation adopted a different critical condition with higher vapor pressure gap (>1.0 kgf/cm²) that increased considerably the gas pressure at the end of the operation

The real operation was accomplished following the procedure elaborated by White Martins, which is a conservative and safe procedure. However, the simulation results presented in this paper shows that the operation could be done with a $N_2$ volume reduction of 21%.

The results comparison between the simulation of Case 3 and the real operation for each variable are shown from Figure 12 to Figure 15.

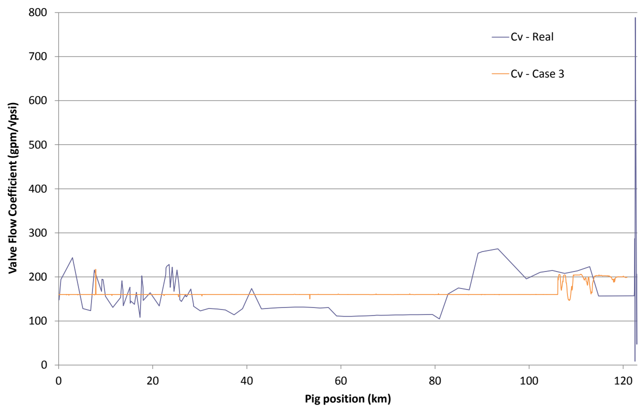


**Figure 12- Cv of the delivery control valve - Real operation and Simulation of Case 3**

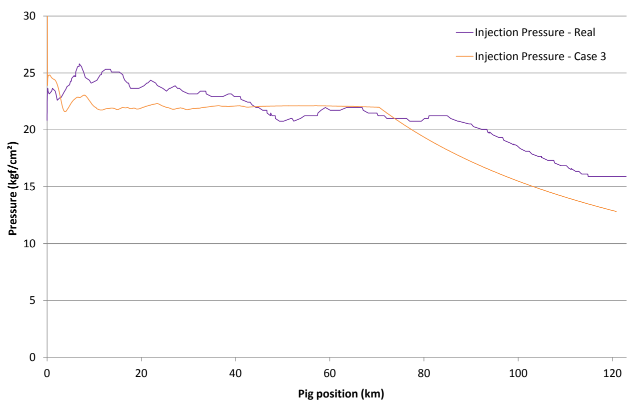


**Figure 13- Injection pressure - Real operation and Simulation of Case 3**

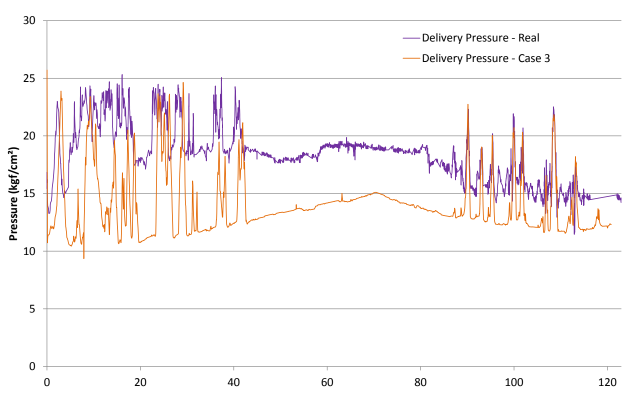


**Figure 14- Delivery pressure - Real operation and Simulation of Case 3**

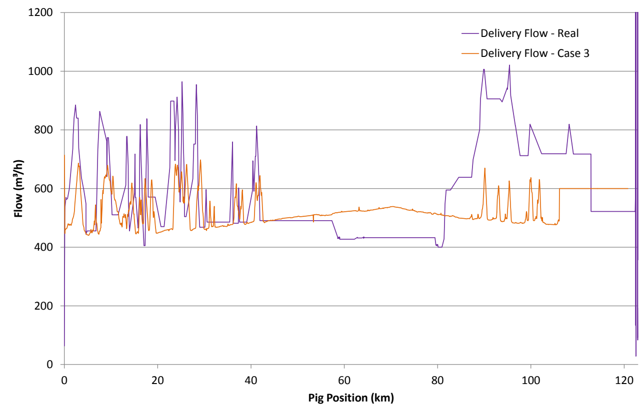


**Figure 15- Delivery flow - Real operation and Simulation of Case 3**

## CONCLUSION

The dynamic simulation of an emptying operation assists the decision-making of how to control the operation and develop an operational procedure for a safe, and cost efficient operation. It can also reveal potentially unsafe control methods for the delivery station, which can impose a slack line flow, pig velocity out of the recommended limits, or high pressures that surpass the relief valves setpoints and ultimately reach the pipeline's PMOA.

The main hypothesis of the developed pig motion simulator, that is, the pig velocity is equal to the pipeline liquid velocity at the delivery valve, was validated through the comparison of the flow data obtained on Transpetro's SCADA system and the history of when the pig reached the intermediary valves, which was provided by White Martins.


## ACKNOWLEDGMENTS

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