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Deployment of a Gas Pipeline City-Gate Simulation Tool for Training Purposes
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Abstract

The appliance of Real Time Simulation (RTS) systems for gas pipelines is essential for supervisory and control rooms, providing safer and more efficient operations and complementing Supervisory, Control and Data Acquisition System (SCADA) functionalities. Another common usage of these softwares is for training purposes in order to simulate critical variations on system parameters or failure scenarios of the involved equipment, based on up-to-date operational conditions.

Since the implementation of its RTS system for gas pipelines, the Natural Gas National Operational Control Center (CNCO/Gas) of Petrobras Transporte S.A. - TRANSPETRO has been facing the need of developing a more specific tool to simulate gas city-gate and their processes in details. Based on that, an initiative was launched and a tool called SimPE was developed with the additional intention of integrating it to the existent RTS system that simulates the thermo-hydraulic behavior of gas pipeline networks. This article presents a brief description of this RTS, including: real time monitoring module, predictive module, look-ahead module and trainer module.

The development of the SimPE is described in four phases: (1) modeling an existent city-gate based on its equipment and historical operational conditions (prototype); (2) development of a new communication interface between SimPE and RTS to share the station process variables; (3) programming of city-gate failure scenarios through SimPE and verification of their impact on the gas pipeline during an RTS trainer session; (4) upgrade the simulator, creating three additional models aiming to cover the maximum possible number of different characteristics among the city-gates operated by TRANSPETRO.

The simulator SimPE, sponsored and owned by TRANSPETRO, has been already validated and is able to reproduce real transient behavior of the gas city-gates' main equipment, such as: filtering systems, shut-down valves (SDV's), pressure control valves (PCV's) and their failure mode, flow metering systems and gas heaters, including their automation and programmable logic control.

It is also discussed in the present work the development and integration of these different simulation tools (RTS and SimPE) with SCADA through a shared data platform that connects all three softwares using Modbus-RTU protocol and giving the trainee a reproduction of city-gates real operation with the highest possible fidelity. Finally, the whole work has been conceived and carried out in order to support and to improve CNCO/Gás' training and certification processes.

1. Introduction

A pilot project was initiated at Transpetro (CNCO/Gas) targeting to evaluate the RTS system advantages in gas pipeline operators training and certification programs. Part of the project scope is the development of a software called SimPE that can simulate and mimic the behavior of gas city-gates with different equipment layouts submitted to abnormal operational conditions. The results obtained from a first model based on a real city gate station of Aparecida, that will be depicted in this study, were fundamental to develop other types of city-gate station models (Norte Fluminense, Capuava, Camaçari-Manati) and create a more complete training experience for gas operators.

The main objective of this paper is to present an overview of the development of a training environment using SimPE, RTS and SCADA interface, and its implementation process. From results, the potential of this training

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environment could be foreseen as an important tool for operator training and certification processes. Additionally, important points gained during this project experience were emphasized.

The SimPE is a software that calculates the thermo-hydraulic behavior of city-gate equipments, including filters, control valves and heaters, and sends this information to an RTS software that calculates the whole gas pipeline network. The Figure 1 illustrates the SimPE/RTS/SCADA communication scheme composed of software and hardware elements. In the online mode, the data from real-time instrumentation is delivered through an ODBC service to both SimPE and RTS, and then information is processed in real-time speed. The online mode is used to obtain an initial operational condition and to create a historic of simulated data for tuning and comparison later. In the trainer mode, RTS and SimPE shares city-gate upstream data using Modbus-RTU protocol and SCADA database. Trainer mode can run in real-time speed or faster than (up to 20 times the real-time speed). The trainer mode also allows the operator to monitor and interact with transient simulated scenarios using the SCADA console and its human-machine interface (HMI). In his turn, the instructor can run abnormal scenarios (gas leaks, valve failures, client-side blockages) to evaluate how is the operator response to abnormal conditions.
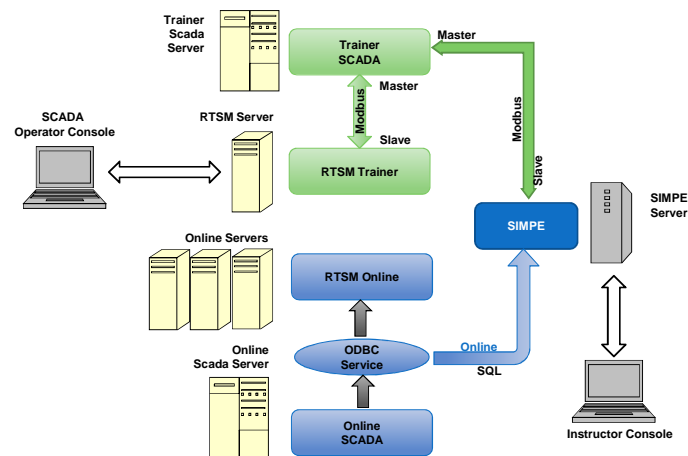

Figure 1. SimPE/RTS/SCADA Communication Architecture - Online and Trainer Modes

2. Gas City-Gate Description

The complete natural gas conditioning process in city gates occurs in five sequential zones: filtration, heating, pressure control, fuel control and metering. These process zones are presented in Figure 2.
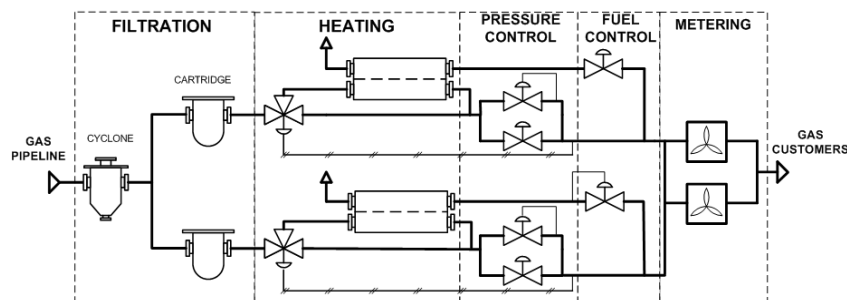

Figure 2. Common Processes in City-gate Stations - Schematic View

In the initial zone the gas cleaning takes place in cyclone and cartridge filters. The cyclone filters uses centrifugal energy to separate denser material (condensate) from the stream received by the pipeline. The centrifugal forces generated by the conversion of pressure energy into velocity enables significant amount of particles to be removed. The remaining solid and/or liquid particles are removed using filter cartridges that retain them as a combination of direct interception, inertial impaction and diffusional attraction effects. These two filters are necessary to avoid premature equipment downtime and ultimately failure of the downstream equipment within the station.

The gas heating zone is composed by three-way ball valves and indirect fired water bath heaters (IFWBH). The main purpose of the water bath heaters is to heat the high pressure gas prior to its pressure reduction phase, preventing external frost formation and gas temperature disqualification due to Joule-Thompson.

Fuel control is basically composed by control valves that regulate the flow and pressure of gas sent to combustion in the bath heater firetube.

The metering zone is composed by temperature and pressure sensors and a flowmeter. Flowmeter output is commonly used to calculate the volumetric gas flow at custody transfer conditions according to Brazilian regulation (20°C e 101,325 kPa).

Lastly, a typical pressure control section has two or more branches, each one dowered of control, shutdown and relief valves. The control valves reduce the downstream pressure to values compatible to local gas distribution system, whereas the shutdown and relief valves acts in case of unexpected valve closure or failure. The Figure 3 shows a pressure control area with two branches, each one with different setpoint adjustments for SDV's (shut down valves), monitor PCV's (pressure control valves), regulator PCV's and relief valves PRV's (pressure relief valves). The valves PCV02A/B are regulators configured on a fail-open mode and PCV01A/B are monitors configured on a fail-close mode. In this configuration, it is important to note that the regulator PCV02B adjusted with the setpoint P_{set1} will take control if the monitor PCV01B fails (considering branch *B* operational). The PRV's are designed to relief only small volumes. If the pressure continues to rise, one of the SDV's closes when the setpoint P_{set3} is reached.
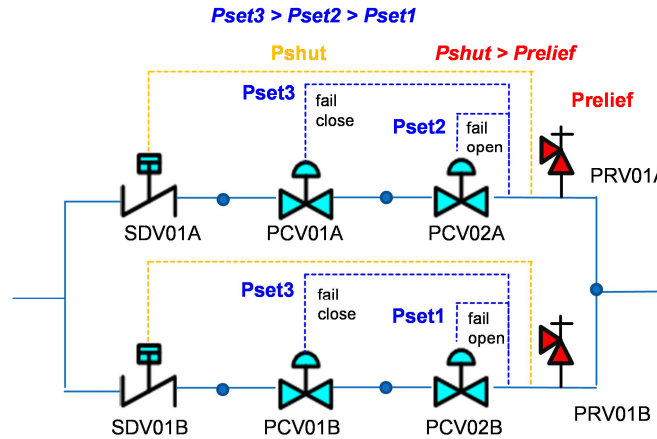

Figure 3. Pressure Control Zone Schematic

Backing to the gas heating zone, the need for a gas pre-heating system with three-way valves is conditioned by Joule-Thompson effect in the pressure control zone. Considering the solution of the Peng-Robinson equation of state (EOS) and fixed requirements forupstream temperature and downstream pressure, the Figure 4 indicates that a pre-heating system is necessary when downstream temperature is below itscity-gate lowest limit. Also, it's important to emphasize the influence of gas composition on this type of survey.

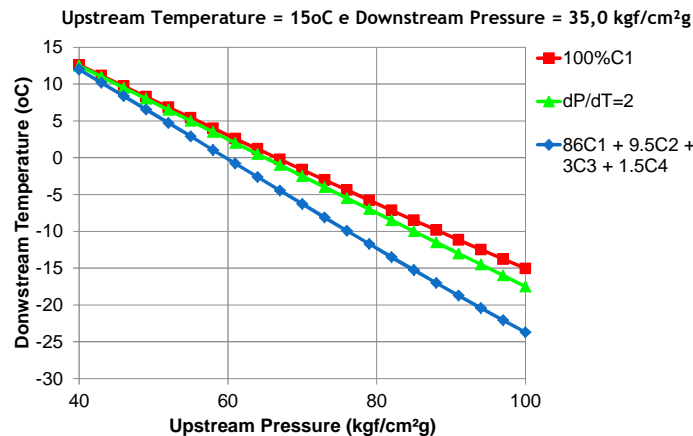

Figure 4. Joule Thompson Effect – EOS Peng-Robinson (3 gases)

3. SimPE Specification

The SimPE solver evaluates the solution of a single phase one-dimensional gas network with a topology defined by nodes and elements that represents a city gate station equipment: filters, heaters, three-way-valves, SDV's, PCV's, PRV's and flow meters. These elements are important to simulate the process inside a city-gate station as described in the item 2. For each solution step, a non-linear system of equations (for both elements and nodes) must be solved simultaneously using Newton method. The system of non-linear equations is composed of mass, energy and gas

composition balance at nodes and pressure drop and heat transfer formulas for elements. The transient solution is obtained with explicit differential equations, as solution for bath heater formula using Runge-Kutta 4th order approximation.

Inside SimPE, formulation includes a single phase gas approximation of cubic EOS Peng-Robinson and Soave-Redlich-Kwong with Van de Walls Mixture Rules. As proposed by Pratt (2001) the EOS formulas are used to calculate the natural gas thermodynamic properties (density, enthalpy, temperature) and thermodynamic behavior like Joule-Thompson effect.

The SimPE has a regularization method that identifies and deals with zero flow condition, that may occurs during failure and operational scenarios. A similar zero-flow technique in solving non-linear system equations for water distribution system is detailed by Elhay (2011) to solve the global gradient problem of Todini and Pilati (1988).

3.1. General Formulation

When a gas flows through an adiabatic throttle there is a change in temperature due the Joule-Thompson (JT) effect. For natural gas mixtures the μ_{JT} (Joule-Thompson Coefficient) is positive which means a temperature drop. This thermodynamic behavior is found in experimental JT inversion curves demonstrated by Hendricks (1972) and can be predicted using non-ideal gas EOS like Peng-Robinson where the intermolecular forces are considered in the enthalpy evaluation. The equation (1) shows the standard thermodynamic definition for JT coefficient. A temperature difference is obtained by a thermodynamic function of enthalpy and pressure T(h,p). For valve elements the effect is considerate assuming an isenthalpic process ($h_{in}=h_{out}$).

$$\mu_{JT} = \left(\frac{\partial T}{\partial p} \right)_h \tag{1}$$

The steady-state approximation for momentum and energy equations applied to equipment is shown in the (2) and (3) respectively. Where K uses the pressure resistance coefficient to normalize the gas transmissibility.

$$Q^2 K - \left(p_{in}^2 - p_{out}^2 \right) = 0 \tag{2}$$

$$m_{in} h_{in} - m_{out} h_{out} - q = 0 \tag{3}$$

3.2. Valves

For the complete modeling of the valve for steady-state and transient scenarios, it is necessary to specify the curve C_V versus valve position *fo* and time travel interval *Y*. With the valve curve defined, the simulator calculates the correct gas flow and downstream pressure and temperature as function of the valve position. The K_v represents the pressure resistance coefficient for valves; and its value can be converted to C_V provided by valve manufacturer using expression (4):

$$K_V = \frac{Z_{in} \cdot T_{in} \cdot \gamma_g}{C_V (fo)^2} \tag{4}$$

The valve flow can be evaluated using ANSI/ISA 75.01 (2002) formulas that uses valve coefficient C_V. These formulas are used for control valve sizing in subsonic (5) and sonic (6) flow conditions. The compressibility factor *Y* accounts for the expansion of compressible gases; and it is equal to 1.0 for incompressible fluids.

$$Q = C_v Y \sqrt{\frac{p_{in}^2 - p_{in} p_{out}}{Z \cdot G \cdot T}}, \frac{p_{in} - p_{out}}{p_{out}} < 1 \tag{5}$$

$$Q = 0.667 \cdot C_v \sqrt{\frac{p_{in}^2}{Z \cdot G \cdot T}}, \frac{p_{in} - p_{out}}{p_{out}} \geq 1 \tag{6}$$

The three-way valve element has one inlet and two outlets and is responsible to regulate the amount of gas passing through the water bath heater. The modeling equations for a three-way-valve are similar of two JT valves (with reciprocal C_V curves) connected to same upstream node.

The SDV element closes at a time interval in two situations, when downstream pressure is higher than its setpoint or in case of backward flow behaving oneself as a check valve.

3.3.   Filters

After experimental data analysis, Shepherd and Lapple (1940) established a relation between the pressure drop and the dimensions for a cyclone filter using a dimensionless number of gas inlet velocity heads ξ as shown in (7):

$$\xi = \left(\frac{a \cdot b}{D_s^{\,2}} \right) \tag{7}$$

Cyclone filter manufacturers commonly adopt dimensional relations among inlet height *a*, inlet width *b*, outlet diameter (*Do*), and external barrel diameter *D*. The expression (8) uses the number of gas inlet velocity heads based on filter geometry to evaluate the pressure resistance coefficient of filtration K_F:

$$K_F = \frac{p_{in}^2 - \left(p_{in} - \xi \left(\frac{1}{2} \rho_g v_{in}^2 \right) \right)^2}{Q^2} \tag{8}$$

3.4.   Heaters

The IFWBH model is a transient formulation provided to simulate the local thermodynamic behavior of a real equipment. In the IFWBH element, the heat is transferred at first from gas combustion to water mass (q_b), and afterward from water to gas stream (q_w). As shown in equation (9) the water temperature T_w varies with the energy accumulation indicated in the second term. The evaluation of the energy accumulation depends on some dimensional and thermal parameters like: water heat capacity ($m_w \cdot cp_w$), overall heat transfer area (*A*), global heat transfer coefficient (U), and log mean temperature difference (LMTD). Also, other variables as upstream gas flow rate or combustion heat transfer rate can interfere with water bath temperature and consequently the heater downstream temperature:

$$\frac{dT_w}{dt} - \frac{q_b - q_w}{m_w c_{pw}} = 0 \tag{9}$$

$$q_w - UA \cdot F \cdot LMTD = 0 \tag{10}$$

$$q_b = \eta \cdot Q_b \cdot \hat{h} \tag{11}$$

$$LMTD = \frac{(T_w - T_{out}) - (T_w - T_{in})}{\ln\left(\dfrac{T_w - T_{out}}{T_w - T_{in}} \right)} \tag{12}$$

A fourth order Runge-Kutta algorithm with explicit approach was implemented to evaluate the water temperature, an approach usually employed for the solutions of ordinary differential equations.

The idealized heater is the steady-state version of the IFWBH and can be employed when the dimensional and thermal properties of the water bath heater are not well-known. The idealized heater operates in two modes: downstream temperature mode or transfer rate mode. When transfer rate mode is chosen, the heater can be set for gas heating or gas cooling depending on the signal defined for heat transfer rate. Per convention, a positive value for heat transfer rate results of an increase in downstream temperature.

3.5.   Flowmeters

As well as for valves, the orifice meter equation relies on the pressure drop using a pressure drop coefficient parameter (Cmeter) and the orifice area (Ao) to compute fluid flow as per equation 13. According to the work of Andrews and Willians (1979), given a constant Cmeter the non-recoverable pressure drop is a function of the area ratio between the pipe and orifice. The orifice plate is the most commonly meter because of lower cost, but it creates a rather large non-recoverable pressure due to the turbulence around the plate and a accuracy of 2-4% of full span.

$$Q_{meter} = A_o V_o = C_{meter} Y A_o \sqrt{\frac{2(p_{in} - p_{out})}{\rho(1 - A_o^2 / A^2)}} \tag{13}$$

For turbine meters as fluid flows through the turbine, it causes the turbine to rotate with an angular velocity that is proportional to the fluid flow rate. The frequency of rotation can be measured and used to determine the flow. The differential pressure developed across a turbine meter at operating conditions can be estimated using the following formula 14 where the resistance coefficient for turbine K_T is obtained using the pressure drop at maximum flow rate of the meter:

$$K_T = \frac{\left(p_{in}^2 - p_{out}^2\right)_{\max}}{Q_{\max}^2} \qquad (14)$$

4. Real Time Simulation System

4.1. System Description

RTS is a gas pipeline simulation sofware platform at Transpetro (CNCO/Gas) based on state-of-art modeling technology that provides some advanced pipeline applications like automated forecasting, maintenance planning and operator training. The software is configured to model the entire gas network operated and maintained by CNCO/Gas, considering interface with the SCADA system in order to transfer real time pipeline data, such as gas flow, pressure and temperature measurements, used as baseline input for the model (see figure Figure 5). The idea is to enhance profitability by lowering operational costs and optimizing pipeline throughput.
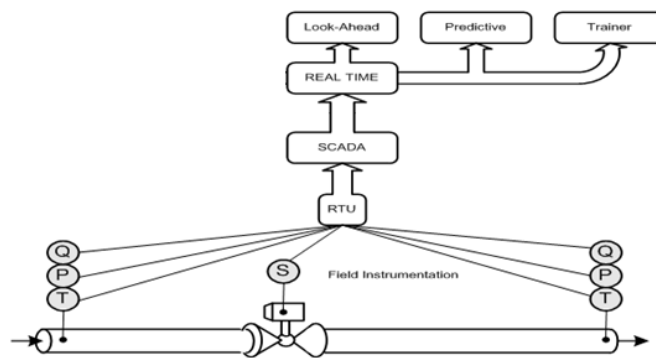

Figure 5. System Functional Illustration

The system provides full transient model capabilities and can be configured to automatically notify future events and alarms. Also, it is possible to calculate survival time at different locations throughout the gas pipeline network. It supports predictive analysis based on "what-if" scenarios, which helps in the daily decision making processes.

RTS also includes simulator training functionality that can provide a comprehensive and realistic training environment for the operator qualification and certification processes currently established at Transpetro.

4.2. System Functionalities

The RTS system currently used at CNCO/Gas for the entire gas network has the following types of functionalities:

- Real Time Model (RTM)
- Look Ahead Model (LAM)
- Predictive Model (PRED)
- Training Model (TRAIN)

By functionality is meant the various forms of simulation the system allows to perform. The last three functionalities listed above are always related to a respective model in RTM, which means having as initial state an instant data snapshot of an RTM.

Using both LAM and PRED, the system is capable of providing a future state based on an initial state (RTM). By running an LAM, there is no possibility of introducing any event that causes a simulation transient, *i.e.* the model simply starts from an RTM instant and then projects this condition through the desired time frame. On the other hand, PRED enables the possibility of interacting during the entire simulation time frame, thereby creating transient scenarios. TRAIN is similar to PRED, since that training requires interaction of the trainee.

5. Urucu-Coari Gas Pipeline

The pipeline crosses the state of Amazonas, linking productive province of Urucu to state capital, Manaus, where there is a refinery called Reman. It has a total length of about 380 km and nominal diameters of 18 inches, in the section between Urucu and Coari, and 20 inches, in the section between Coari and Manaus (Reman). Currently, the total

capacity of transportation in this gas pipeline is of approximately 6.9 x 10^6 m³ per day, at Petrobras standard measurement condition (20 ° C and 1 atm). Maximum operating pressure of 120 kgf/cm².

Some pressure regulating stations (PRS) were installed along the pipeline to feed secondary distribution branches to locations and industrial plants situated nearby the pipeline. Consequently, gas city-gates are found over these branches for conditioning and measurement of the gas delivered.

In one of these branches, called Aparecida, is situated the city-gate also of the same name and which provides natural gas to the location of Aparecida (Figure 6). Because of its simplicity, this was the city-gate chosen as a pilot for modeling and simulation in SimPE development.
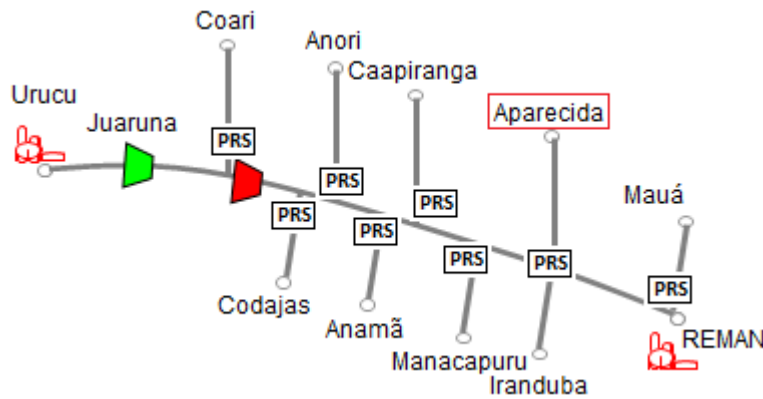

Figure 6. Location of Aparecida City-Gate Along the Urucu-Coari Gas Pipeline

6. Model Description

The dynamic formulation applied to develop SimPE is able to simulate the five process zones, although the pilot model of Aparecida has only three processes: filtering, pressure control and flow metering. The Figure 7 shows the Aparecida city-gate model with one supply from Urucu-Coari pipeline and two delivery points (city-gates UTE and CIGAS) that represents two customers with different downstream regulation conditions. The UTE is a thermoelectric plant that demands a minimal pressure of 46 kgf/cm² and CIGAS a gas distribution company that demands a minimal pressure of 17 kgf/cm².
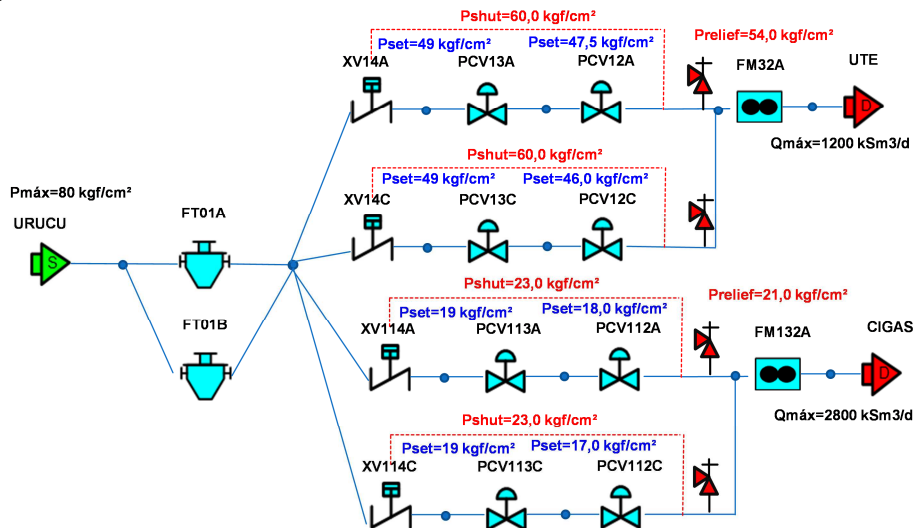

Figure 7. Aparecida City-gate Model – Schematic View

At first to build a city-gate simulation model is necessary to gather the equipment manufacturer information and city-gate design limits for a steady-state validation. In the Table 1 is shown the input parameters that were used in the pilot model. The normalized gas composition shown in Table 1 is the mean average obtained from Urucu-Coari pipeline chromatographer in a time interval of six months and was kept constant during the simulation. For trainer purposes the PRV's are modeled like a control valve where the setpoint is equal the surge relief pressure (p_{relief}) connected at delivery with a controlled flow rate of 1% of the maximum flow for each branch.

Table 1. Model Input Parameters – Pilot Model - Aparecida City-gate

Gas Supply: URUCU Pressure and Temperature Scenario Constant Molar Composition C1= 74.57%;C2=11.28%;C3=0.12; N2=13.85%;CO2=0.18%		Cyclone Filter FT01A/B Barrel Diameter D = 26 in Filter Dimensions a=0.5D; b=0.25D; D_{out}=0.5D	
SDVs XV14A/C Cv=5000 Pset=60.0 kgf/cm² Fail Mode: Close	**Monitor PCV13A/C** Cv_{open}=125 Pset=49.0 kgf/cm² Fail Mode: Close	**Regulator PCV12A** Cv_{open}=133 Pset=47.5 kgf/cm² Fail Mode: Open	**Regulator PCV12C** Cv_{open}=133 Pset=46.0 kgf/cm² Fail Mode: Open
SDVs XV114A/C Cv=5000 Pset=23.0 kgf/cm² Fail Mode: Close	**Monitor PCV113A/C** Cv_{open}=125 Pset=19,0 kgf/cm² Fail Mode: Close	**Regulator PCV112A** Cv_{open}=133 Pset =18.0 kgf/cm² Fail Mode: Open	**Regulator PCV112C** Cv_{open}=133 Pset =17.0 kgf/cm² Fail Mode: Open
PRVs 16A/C Pset = 54.0 kgf/cm²	**PRVs 116A/C** Pset =21.0 kgf/cm²	**Flowmeter FM32A** K_{max}=150 kPa/(m³/s)² Q_{max}: 1200 km³/d	**Flowmeter FM132A** K_{max}=29 kPa/(m³/s)² Q_{max}: 2800 km³/d
Delivery: UTE Flowrate Scenario		**Delivery: CIGAS** Flowrate Scenario	

The operational scenario must be collected from real instrumentation or simulated by RTS and transfer to SimPE establishes the group of boundary conditions at gas supply URUCU, and both deliveries points as shown in Figure 8. The chosen scenario represents two simultaneous conditions during four days: a ramp up flow rate for UTE and a normal distribution demand of CIGAS.
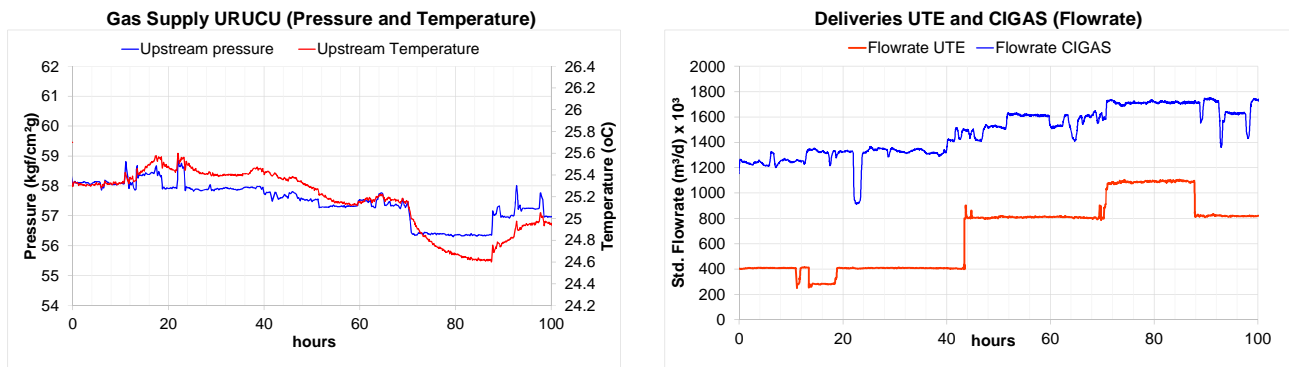

Figure 8. Input Operational Scenarios

7. Simulation Results for Online Mode (Normal Scenario)

During the trainer session the operator can monitor the valve position and acts in case of abnormal behavior in the pressure control zone. The simulation results of the control valve position and standard flow rates for a normal operational scenario are illustrated in Figure 9. The valves position of the regulators (FR12A and FR12C) can indicates if there is flow inside the control branch A or C (FQ12A, FQ12C). The valve position and standard flow rate history charts indicates that only branch A operates during normal operational scenarios. A similar behavior occurs with CIGAS pressure control system.
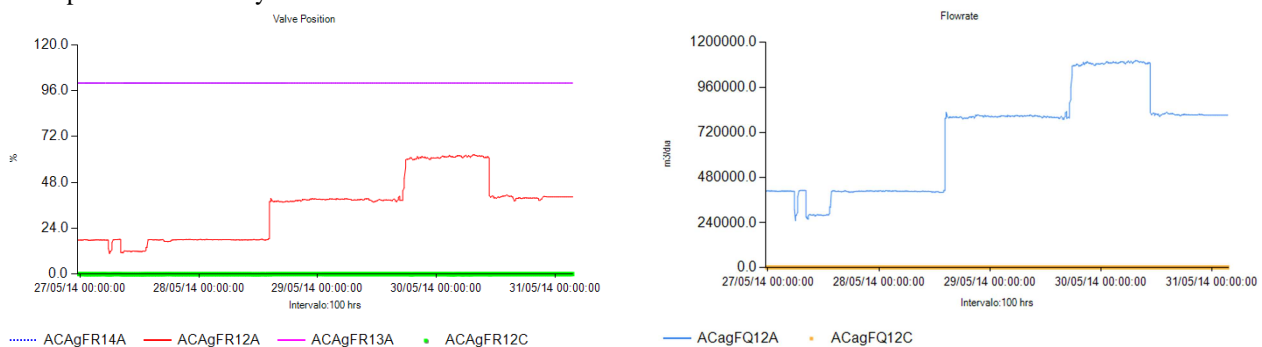

Figure 9. Position and Flowrate History for UTE Valves (Normal Scenario)

In online mode simulation it's possible a real time data comparison between simulation and SCADA instrumentation for delivery pressure and temperature. This procedure allows the calibration of the Joule-Thompson

coefficient and compressibility factor and in addition to measure the performance of EOS in predicting the gas properties. The simulation results using the Peng-Robinson EOS and fixed composition is show in Figure 10. The delivery temperature history charts indicates a maximum deviation between SimPE and SCADA of 0.6 °C at UTE and 1.0 °C at CIGAS. The delivery pressure history indicates that the downstream pressure calculated by SimPE approximates with the real pressure indicator.
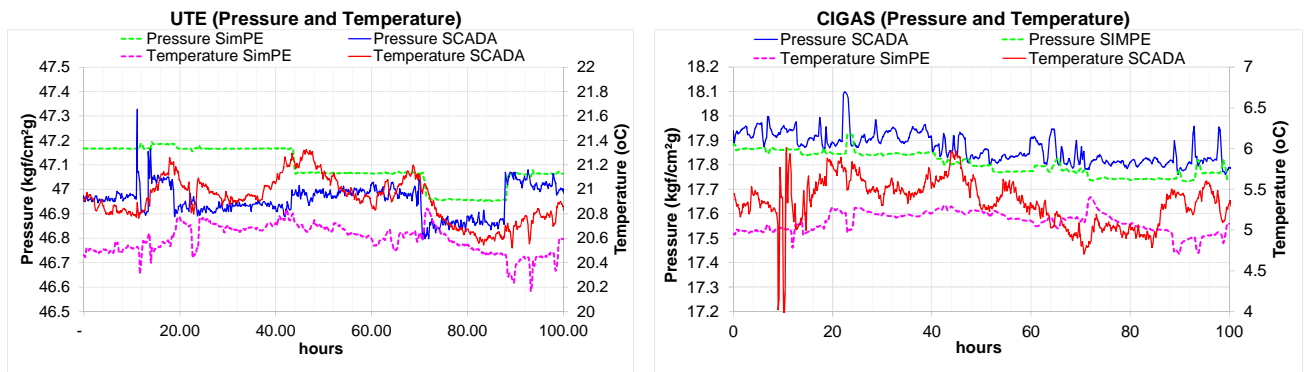

Figure 10. Delivery Pressure and Temperature History Comparison for UTE and CIGAS (Normal Scenario)

8. Simulation Results for Trainer Mode (Abnormal Scenarios)

The true reason for appliance of a numerical tool like SimPE is the simulation of abnormal situations in operational training as valve failures, filter clogged and heaters cool down.

In the trainer mode the pressure and temperature conditions for gas supply is simulated by RTS and the flow rate at deliveries is defined by SimPE using operational data scenarios. If a failure occurs in the city gate the total flow at supply URUCU must be sent back to RTS compute the network behavior.

One possible approach is to run the SimPE without RTS calculation and loading the input operational scenarios from history archives saved during online simulation. For trainer models running abnormal scenarios this hypothesis can be considered because of the slow transient of the gas pipeline network.

A hypothetical trainer session can reproduce an abnormal scenario as sequence of failures in the pressure control system: (1) regulator A failure (2) monitor A failure (3) regulator C failure (4) UTE cut flow. The simulation results of the abnormal scenario in UTE are plot in Figure 11.
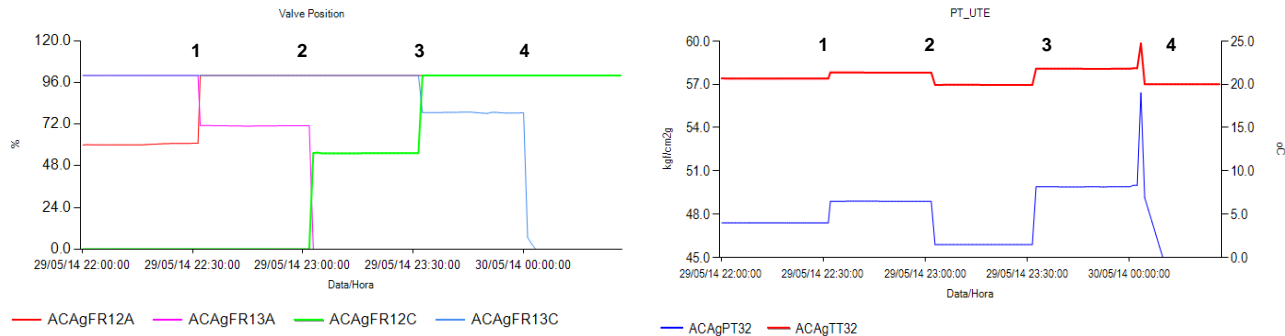

Figure 11. Valve Position and Pressure-Temperature History for UTE – Abnormal Scenario 1

Another trainer session called abnormal scenario 2 reproduces a sequence of failures in the SDVs at CIGAS: (1) XV114 close, (2) XV114C close. The action (3) represents the response of the operator to open the XV114A and reestablish the operation. The simulation results for this abnormal scenario in CIGAS are plot in Figure 12.
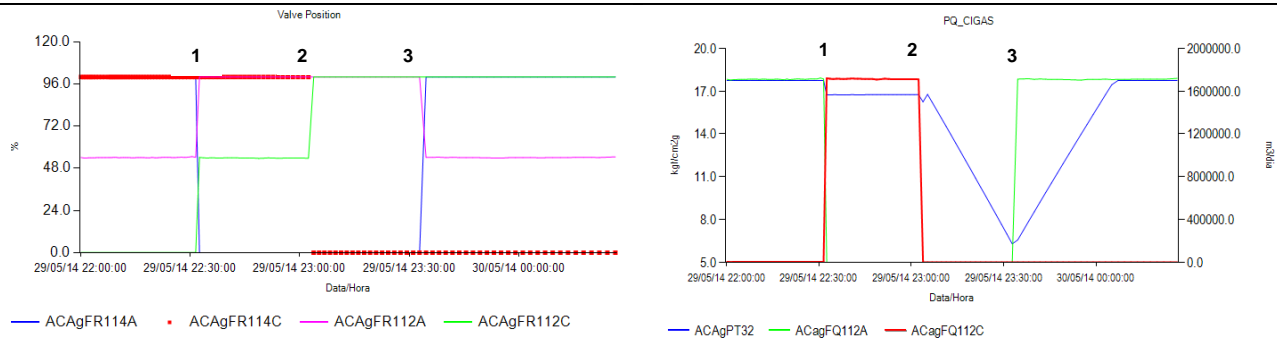
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Figure 12. Valve Position and Pressure-Flow History for CIGAS – Abnormal Scenario 2

9. Conclusion

The SimPE software integration project with RTS and SCADA systems started in 2014 and at present it is still being developed. The initial results obtained from pilot model of Aparecida city-gate were shown in this paper for two purposes: online simulation, to validate gas properties calculation, and trainer simulation, to study the abnormal condition of the pressure control system. Since that, a great effort has been applied on the development of the communication interface and software performance.

In this first model the gas composition was kept fixed, but it is taken for grant the development of a better solution, where the gas composition is obtained from online instrumentation, having the gas properties calculated on a real-time basis during online simulation. A more complete simulation model for trainer purposes with temperature control system, and flow control valves (FV) will be developed in the next phase of this project.

Another future appliance of the SimPE relies on a fast speed calculation to predict local survival time of the citygate based on its minimal contract pressure.

10. Acknowledgements

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