IBP1275_09

Simulation Of Non-isothermal Transient Flow In Gas Pipeline

Luis Carlos Ferreira Jr[1], Matheus Soares[1], Cyro Muniz[2], Clarissa Côrtes Pires[2], Geraldo Rochocz[2], Enrique Luis Lima[1], José Carlos Pinto[1]

Abstract

Modeling of gas pipeline usually considers that the gas flow is isothermal (or adiabatic) and that pressure changes occur instantaneously (quasi steady state approach). However, these assumptions are not valid in many important transient applications (changes of inlet and outlet flows/pressures, starting and stopping of compressors, changes of controller set points, among others). Besides, the gas properties are likely to depend simultaneously on the pipe position and on the operation time. For this reason, a mathematical model is presented and implemented in this paper in order to describe the gas flow in pipeline when pressure and temperature transients cannot be neglected. The model is used afterwards as a tool for reconciliation of available measured data.

1. Introduction

The gas flow in pipeline networks is inherently unsteady, given the frequent disturbances on the pipeline operation conditions, such as those related to changes of inlet and outlet flows/pressures, starting and stopping of compressors, changes of controller set points, among others. Therefore, the works that assume the validity of the steady state hypothesis cannot be used in many important transient applications. In addition, it is commonly assumed that gas properties (density, specific heat, heat conductivity and composition) remain constant during the flow (Osiadacz, 2001; Tabkhi, 2008). However, it must be noted that the gas density exerts a direct effect on the gas velocity and head loss computations. Besides, the specific heat and heat conductivity affect heat transfer calculations (Bachman, 2003). Additionally, it is known that natural gas is a complex mixture of hydrocarbons, whose composition is subject to natural fluctuations and depends on the feed conditions. Modification of the gas composition certainly affects the remaining properties of the fluid. Finally, heat transfer effects are usually neglected during modeling of gas pipeline networks, which may lead to severe model limitations when disturbances are frequent and/or the pipelines are long, as the pipeline and the environment exchange heat (Bachman, 2003). Therefore, there are incentives for development and implementation of rigorous flow models for gas pipeline networks.

Dynamic pipeline models have been recently proposed by different authors and solved numerically with the help of the method of characteristics (Rao and Eswaran, 1993, Kessal, 2000), of finite difference schemes (Thorley and Tiley, 1987), of finite volume techniques (Greyvenstein, 2002; Osiadacz and Chaczykowski, 2001) and, more recently, of the TVD (total variation diminishing) method (Zhou and Adewumi, 2000; Ibraheem and Adewumi, 1999). However, in all these cases some of the model limitations discussed above have been introduced into the model structure. For this reason, the main objective of the present paper is the presentation of a mathematical model for gas flow in pipelines, based on the dynamic mass, momentum and energy balances and on the rigorous determination of the gas properties along the flow. The model is solved with the help of a finite difference scheme for discretization of the spatial coordinate. The resulting set of ordinary differential equations is solved numerically. As shown in the following sections, the proposed numerical scheme can provide solutions in reasonable simulation times, allowing for model implementations in real time. As an example, the model is used afterwards for reconciliation of available measured data.

[1] Programa de Engenharia Química/COPPE/UFRJ
[2] ChemTech

2. Modeling

The non-isothermal pipeline model equations are described elsewhere (Chapman, 2003) and are concisely presented below. As the flow velocities are high and the temperature variations along the length of real pipelines are not very steep, radial gradients are neglected.

Mass Balance Equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v)}{\partial t}=0 \tag{1}$$

Momentum Balance Equation

$$\rho\frac{\partial v}{\partial t}+\rho v\frac{\partial v}{\partial t}+\frac{\partial P}{\partial x}=-\frac{w}{A}-\rho g\sin\theta \tag{2}$$

Energy Balance Equation

$$\rho\frac{\partial h}{\partial t}+\rho v\frac{\partial h}{\partial x}-\frac{\partial P}{\partial t}-v\frac{\partial P}{\partial x}=\frac{\Omega+wv}{A} \tag{3}$$

In Equations (1-3), h is the gas enthalpy, v is the gas velocity, ρ is the gas density, P is the gas pressure, A is the cross-section area of the pipeline, g is the acceleration of gravity, θ is the elevation angle, Ω is the flow of heat into the pipeline, w is given by

$$w=\frac{f\rho v|v|\pi D}{8} \tag{4}$$

and f is the friction factor (see Reddy, 2006), given by

$$f=\frac{1}{\left(-1.8\log(6.9/\mathrm{Re}+(e/(3.7D))^{1.11}\right)^2} \tag{5}$$

The gas density can be described in the form

$$\rho=\frac{P}{ZRT} \tag{6}$$

and the enthalpy can be defined as

$$dh=CpdT+\left\{\frac{T}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_P+1\right\}\frac{dP}{\rho} \tag{7}$$

where Cp is the heat capacity at constant pressure (assumed to be a function of temperature as a linear combination of the heat capacities of the individual components). Inserting Equations (6-7) into Equations (1-3), after some algebraic manipulations one can obtain

$$\frac{\partial P}{\partial t}+v\frac{\partial P}{\partial x}+\rho V_w^2\frac{\partial v}{\partial x}=\frac{V_w^2}{CpT}\left[1+\frac{T}{Z}\left(\frac{\partial Z}{\partial T}\right)_P\right]\frac{\Omega+wv}{A} \tag{8}$$

$$\rho\frac{\partial v}{\partial t}+\rho v\frac{\partial v}{\partial t}+\frac{\partial P}{\partial x}=-\frac{w}{A}-\rho g\sin\theta \tag{9}$$

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial x}+\frac{V_w^2}{Cp}\left[1+\frac{T}{Z}\left(\frac{\partial Z}{\partial T}\right)_P\right]\left(\frac{\partial v}{\partial x}\right)=\frac{V_w^2}{CpP}\left[1-\frac{P}{Z}\left(\frac{\partial Z}{\partial P}\right)_T\right]\frac{\Omega+wv}{A} \tag{10}$$

where

$$V_w=\sqrt{\frac{ZRT}{\left\{1-\frac{P}{Z}\left(\frac{\partial Z}{\partial P}\right)_T-\frac{P}{\rho CpT}\left[1+\frac{T}{Z}\left(\frac{\partial Z}{\partial T}\right)_P\right]^2\right\}}} \tag{11}$$

The gas compressibility factor (Z) can be computed as (see Elsharkawy, 2000)

$$\begin{aligned}Z&=1+(A_1+A_2/Tr+A_3/Tr^3+A_4/Tr^4+A_5/Tr^5)\rho_r+(A_6+A_7/Tr+A_8/Tr^2)\rho_r^2\\&-A_9(A_7/Tr+A_8/Tr^2)\rho_r^5+A_{10}(1+A_{11}\rho_r^2)(\rho_r^2/Tr^3)\exp(-A_{11}\rho_r^2)\end{aligned} \tag{12}$$

where P_r is the reduced pressure, T_r is the reduced temperature and

$$\rho_r=0.27\frac{P_r}{ZT_r} \tag{13}$$

Equations (12-13) were solved simultaneously with a standard Newton-Raphson procedure. The reduced pressure and reduced temperature were calculated with the available gas composition as (see Elsharkawy, 2000, Piper et al., 1993):

$$J=\alpha_0+\sum\alpha_i y_i(T_c/P_c)_i+\alpha_4\sum y_j(T_c/P_c)_j+\alpha_5\left[\sum y_j(T_c/P_c)_j\right]^2+\alpha_6 y_{c7+}M_{c7+}+\alpha_7\left(y_{c7+}M_{c7+}\right)^2 \tag{14}$$

$$\begin{aligned}K&=\beta_0+\sum\beta_i y_i(T_c/P_c^{0.5})_i+\beta_4\sum y_j(T_c/P_c^{0.5})_j+\beta_5\left[\sum y_j(T_c/P_c^{0.5})_j\right]^2+\alpha_6 y_{c7+}M_{c7+}\\&+\alpha_7\left(y_{c7+}M_{c7+}\right)^2\end{aligned} \tag{15}$$

$$T_{pc}=\frac{K^2}{J} \tag{16}$$

$$P_{pc}=\frac{T_{pc}}{J} \tag{17}$$

$$P_r=\frac{P}{P_{pc}} \tag{18}$$

$$T_r=\frac{T}{T_{pc}} \tag{19}$$

where $y_i\in\{y_{H2S},y_{CO2},y_{N2}\}$, $y_j\in\{y_{C1},y_{C2},...,y_{C6}\}$, and α and β are constants (see Table 1).

Table 1 – Coefficients for Equations (14-15) (see Piper et al., 1993).

i	α_i	β_i
0	5.2073E-02	-3.9741E-01
1	1.0160E00	1.0503E+00
2	8.6961E-01	9.6592E-02
3	7.2646E-01	7.8569E-01
4	8.5101E-01	9.8211E-01
5	0.0	0.0
6	2.0818E-02	4.5536E-01
7	-1.506E-04	-3.7684E-03

Model equations were solved with the help of finite-difference schemes, as described by Pinto and Lage (2001). As a consequence, spatial derivatives were replaced by the finite-difference approximations presented in Equations (20-22) over a grid of interpolating points. The resulting set of ordinary differential equations was solved numerically on the time domain with the code DASSL (Pretzel, 1982), using a relative precision of $1.0\text{x}10^{-5}$ for all variables. It is important to emphasize that pressure, velocity and gas temperature profiles were calculated simultaneously, as all model equations are coupled. (Despite that, the energy equation is usually decoupled from the other balance equations in most commercial simulators.) It is also important to notice that the model was implemented in FORTRAN in a standard desktop computer (Pentium Dual Core @ 2.2GHz, 2 Gb RAM). In all cases, it took less than 10 seconds to perform the simulations, which allows for real time analysis of actual operation data. For this reason, the model is used as a toll for reconciliation of measure data, as shown afterwards.

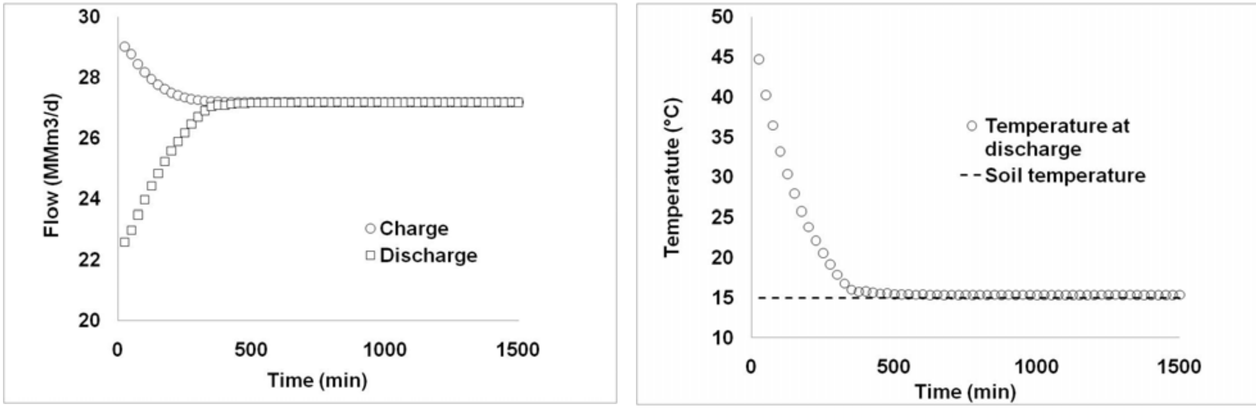
$$\frac{\partial P_i}{\partial x} = \frac{P_{i+1} - P_{i-1}}{2\Delta x} \tag{20}$$

$$\frac{\partial v_i}{\partial x} = \frac{v_{i+1} - v_{i-1}}{2\Delta x} \tag{21}$$

$$\frac{\partial T_i}{\partial x} = \frac{T_{i+1} - T_{i-1}}{2\Delta x} \tag{22}$$

3. Results

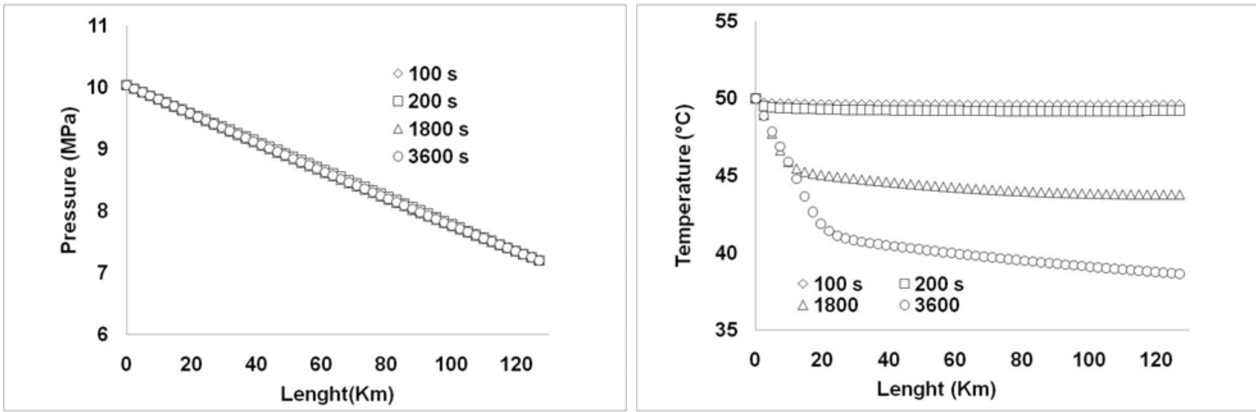
In order to perform the simulations, real data obtained from the first section of the Brazil-Bolivia gas pipeline were used. This section has 127 Km of length, diameter of 32’, discharge and suction pressures of 99 bar and 71 bar, respectively and soil temperature of 15°C. Typical gas compositions and inlet gas temperatures can be obtained from technical publications and are not presented here for lack of space (Santos, 1997). Preliminary grid analysis indicated that 30 discretization points were sufficient to provide accurate model simulations. It was assumed that initial temperatures were equal to the feed temperature (50 ^{o}C) and that the flow pressure decreased linearly along the pipeline. Figure 1 shows the dynamic trajectories of volumetric flowrates and temperatures along the simulation time at the discharge of the pipeline segment. It can be observed that the dynamic profiles evolve slowly, because of the length of the pipeline, so that the gas flow along the pipeline reaches the steady-state condition after 500 min of simulation. It can be observed that the flow temperature reaches the soil temperature at steady-state condition, as it might already be expected.



(a) **(b)**

Figure 1 – Dynamic trajectories of the volumetric flowrate (a) and temperature (b) along the simulation time.

Figure 2a shows the pressure profiles along the analyzed pipeline section. One may observe that the steady-state profile is essentially linear, as assumed initially. For this reason, when the linear profile is assumed as the initial condition, one cannot observe significant changes along the transient response. Figure 2b shows the very slow changes of the temperature profiles along the pipeline, when it is assumed that the initial gas temperature is equal to the feed temperature. As the average soil temperature (assumed here to be equal do 15 ^{o}C) is lower than the feed temperature, one observes the continuous decrease of the gas temperature along the time and along the pipeline. Given the pressure, temperature and compressibility factor variations, gas density falls from 93 Kg/m^3 to 63 Kg/m^3 along the gas flow, clearly showing that assumption of constant gas properties is not adequate.



(a) **(b)**

Figure 2 – Dynamic of pressure (a) and temperature (b) along the pipeline

In order to illustrate the importance of taking the soil temperature into consideration during simulations, the soil temperature profile along the pipeline was defined as shown in Figure 3, based on real temperature variations observed along the year. As shown in Figure 4, the obtained dynamic profiles for gas temperature and compressibility factor are completely different from the previous ones. This clearly shows that heat transfer rates cannot be neglected during simulations, given the very large pipeline length.

.

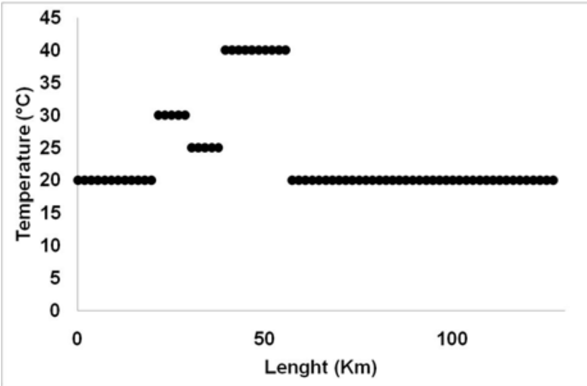
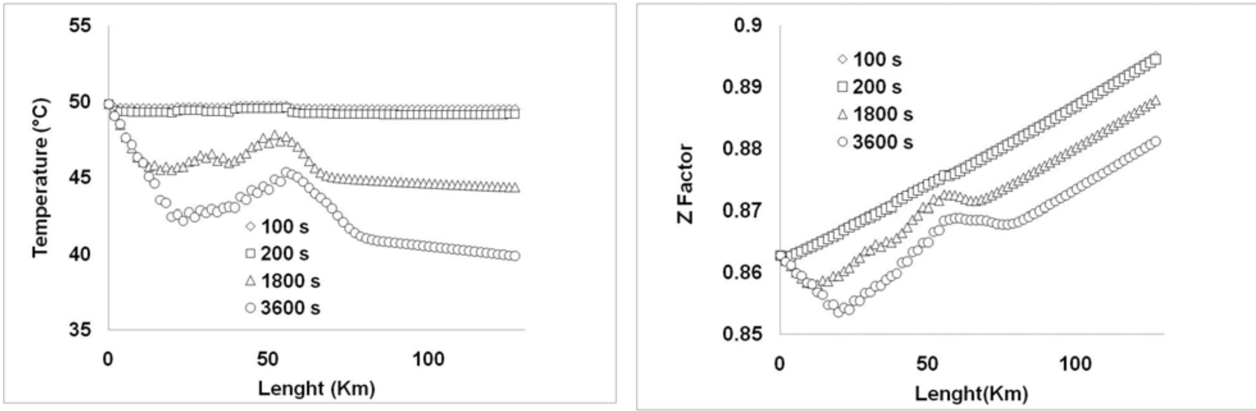


Figure 3 – Soil temperature profile along the pipeline (Santos, 1997).



(a) **(b)**

Figure 4 – Dynamic profiles for: (a) gas temperature and (b) compressibility factor. Initial temperatures were assumed to be equal to the gas feed temperature. The soil temperature is shown in Figure 3.

The importance of taking detailed gas composition into consideration during simulations is illustrated in Figure 5. As the composition of propane (C3) increases, one may observe a very significant decrease of the compressibility factor along the whole dynamic trajectory. As a consequence, the presence of heavier compounds leads to distinct volumetric flow rates, as shown in Figure 6. In both cases, model predictions agree very well with available operation data (Santos, 1997). Therefore, one may conclude that gas composition must be updated continuously during model-based analysis of pipeline operation conditions

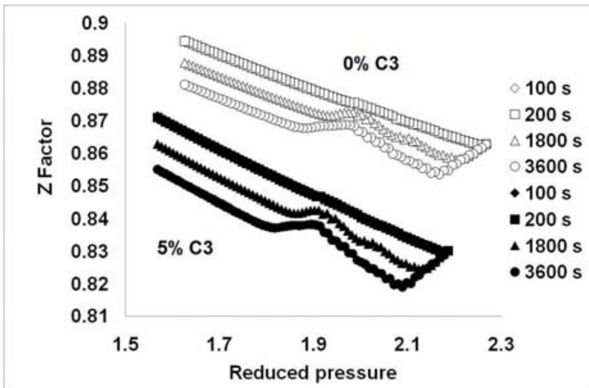


Figure 5 – Dynamic Z profiles for different gas compositions.

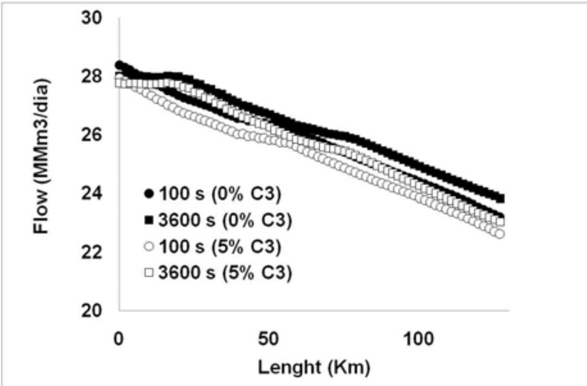


Figure 6 – Dynamic volumetric flow rate profiles for different gas compositions

As the model can provide reliable simulation results in real time, it can be used as a tool for reconciliation of measured data along the pipeline. In order to illustrate this application, it was assumed that temperature, pressure and flowrate measurements were available at the charge and discharge points, as usual. The data reconciliation procedure was performed as described by Prata et al. (2009), although details are not presented here for lack of space. In short, a stochastic algorithm was used to minimize the deviations between measured and calculated values at the two reference points. Results are presented in Figures 7(a-d) for the analyzed variables. It can be seen that data reconciliation can be performed successfully, encouraging the implementation of the proposed model and procedures in real gas compression stations.

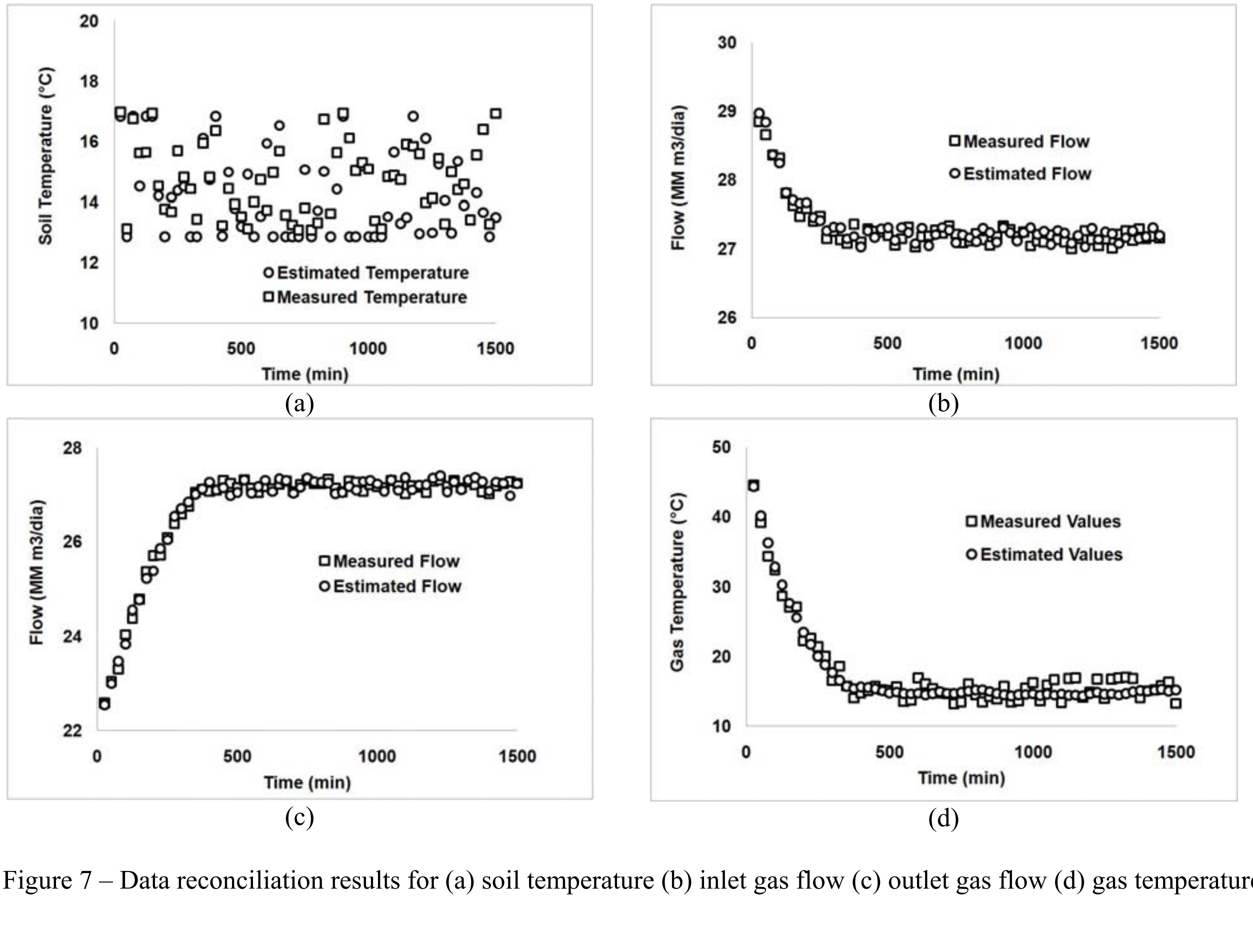


Figure 7 – Data reconciliation results for (a) soil temperature (b) inlet gas flow (c) outlet gas flow (d) gas temperature

4. Conclusions

A rigorous dynamic model was presented and implemented to describe the gas flow in pipelines. The implemented model was able to describe real operation data available for the first section of the Brazil-Bolivia gas pipeline. Model simulations indicate that varying flow temperatures and gas compositions may exert significant influence on the obtained results, which justify the implementation of more complex mathematical structures for analysis of real data. Despite that, model simulations can be performed in real time in a standard desktop computer. As a consequence, the model can be used successfully as a tool for reconciliation of measured data available at gas compression stations.

5. Acknowledgements

The authors thank CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and FINEP (Financiadora de Estudos e Projetos) for financial support and scholarships. The authors thank PETROBRAS for technical and financial support.

6. References

ELSHARKAWY, A. M., ELKAMEL, A. Compressibility Factor for Sour Gas Reservoirs, Society of Petroleun Engineers, SPE 64284, 2000.

CHAPMAM, K. S., ABBASPOURT, M. Non-isothermal compressor station transient modeling, Pipeline Simulation Interested Group, PSIG 03A3, 2003.

DURAN, M. A., GROSSMAN, I. E. A mixed-integer nonlinear programming algorithm for process systems synthesis. *AIChE J.*, v. 32, n. 4, p. 592-606, 1986b.

DURAN, M. A., GROSSMAN, I. E. An outer approximation algorithm for a class of mixed-integer nonlinear programs. *Math. Prog.*, v. 36, n. 3, p. 307-327, 1986a.

GREYVENSTEIN, G.P. An implicit method for the analysis of transient flows in pipe networks. Int. J. Numer. Methods Eng. n. 53, p.1127–1143, 2002.

IBRAHEEM, S.O., ADEWUMI, M.A., On total variation diminishing schemes for pressure transients. J. Energy Res. Tech.-Trans. ASME v. 121, n. 2, p. 122–130, 1999.

KESLER, M. G., LEE, B. LK, Improve prediction of enthalpy of fractions, Hidrocarbon Processing, Março, p. 153-158, 1976.

KESSAL, M., Simplified numerical simulation of transients in gas networks. Chem. Eng. Res. Design v. 78, n. A6, p. 925–931, 2000.

MAH, R. S. H. *Chemical processes structures and information flows*, Butterworth Publishers, 1990.

MOORE, R. G., BISHNOI, P. R., DONELLY, J. K. Rigorous design of high pressure natural gas pipelines using BWR equation of state. *Can. J. Chem. Eng.*, v. 58, n. 1, p. 103-112, 1980.

MURPHY, L. J., DANDY, G. C., SIMPSON, A. R. Optimum design and operation of pumped water distribution Systems. In: *Conference on Hydraulics in Civil Engineering*, Brisbane, Australia : Institution of Engineers, fev., 1994.

OSIADACZ, A. J., CHACZYKOWSKI, M. Comparison of isothermal and non-isothermal pipeline gas flow models, *Chem. Eng. J.*, v. 81, n. 1, p. 41-51, 2001.

OUYANG, L., AZIZ, K. Steady-state gas flow in pipes. *J. Pet. Sci. Eng.*, v. 14, n. 2, p. 137-158, 1996.

PINTO, J.C. and LAGE, P.L.C., Métodos Numéricos em Problemas de Engenharia Química, E-Papers, Rio de Janeiro, 2001.

PIPER, L. D., MCCAIN, W. D., CORREDOR, J. H., Compressibility factors for naturally ocurring petroleun gases, Society of Petroleun Engineers, SPE 26668, 1993.

PETZOLD, L. K., “Description of DASSL: A diferential/Algebraic system solver”, SAND82-8637, Sandia national laboratories, september, 1982.

RAO, C. V. K., ESWARAN, K., On the analysis of the pressure transients in pipelines carrying compressible fluids. Int. J. Pres. Ves. Pip. v. 56, n. 1, p. 107–129, 1993.

SANTOS, S. P. Transient analisys a must in gas pipeline design, Pipeline Simulation Interested Group, PSIG,1997.

TABKHI, F., PANTEL, AZZARO-PANTEL, C., PIBOULEAU, L., DOMENECH, S. A mathematical framework for modeling and evaluating natural gás pipeline networks under hydrogen injection, n. 33, p. 6222-6231, 2008.

THORLEY, A.R.D., TILEY, C.H., Unsteady and transient flow of compressible fluids in pipelines—a review of theoretical and some experimental studies. Int. J. Heat Fluid Flow v. 8, n. 1, p. 3–15, 1987.

ZHOU, J.Y., ADEWUMI, M.A., Simulation of transients in natural gas pipelines using hybrid TVD schemes. Int. J. Numer. Methods Fluids v. 32, n. 4, p. 407–437, 2000.

REDDY, H. P., NARASIMHAN, S., BHALLA,UMDI. M. Simulation and State Estimation of Transient Flow in Gas Pipeline Networks Using a Transfer Function Model, Ind. Eng. Chem. Res., n. 45, p. 3853-3863, 2006.

PRATA, D. M. Reconciliação Robusta de Dados para Monitoramento em Tempo Real, Tese de Doutorado, PEQ/COPPE/UFRJ, 2009.