CEAI, Vol.10, No. 4, pp. 42-48, 2008 Printed in Romania

On Modelling And Simulating Natural Gas Transmission Systems (Part II)

Bichiş Constantin Dorin *, Dragomir Toma –Leonida**

** National Gas Transmission Company "TRANSGAZ" SA Medias*
Department of Design and Research
551025 Mediaş, Unirii str., No. 6, Romania
e-mail: dorin.bichis@transgaz.ro
*** "Politehnica" University of Timisoara*
Department of Automation and Applied Informatics
300223 Timişoara, Bd. Vasile Parvan No. 2, Romania
e-mail: toma.dragomir@aut.upt.ro

Abstract: Natural gas transmission systems stand for mathematical modeled complex systems as systems with distributed parameters having the form of differential equations with partial derivatives. In view of studying some practical situations, such as the process of flow along a natural gas pipeline, a simplified mathematical model may be used. Practical operation with this model demands a spatial and temporal discretization of functions of interest (pressure and weight/flow rate). The paper develops one such model and analyses the necessary discretization processes needed for numeric integration. Using an implicitly numeric integration method three case studies suitable to some flow processes through pipelines in distinct situations are developed. As the results obtained by computation are very close to the experimental ones, the case studies acknowledge both the validity of the developed simplified model and those of the calculation procedures used.

Keywords: natural gas transmission systems, modeling, numeric integration methods, transitory regime, case studies.

1. INTRODUCTION

The framework of the modeling and simulating of the flow process through gas transmission systems, the main terms and the main results are described in the first chapter of paper [3]. On this basis, in chapter 2, of this first part, there are discussed the fundamental modeling equations and its systemic interpretation. These permitted to present the assumptions which allow the use of some simplified mathematical models of the process in certain conditions of technological exploitation (chapter 3), to define and to simulate the systemic model of the process, from the perspective of a process with distributed parameters (chapter 4)., and finally, in the absence of an analytical solutions of the mathematical model of the flow process, to validate the latter one by numerical simulation and by comparison with data measured in real operating conditions mentioned in chapter 5 for a pipe segment as in Fig. 1.

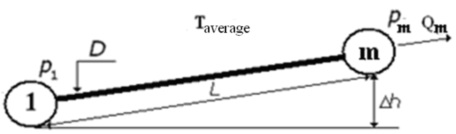

Fig. 1. Pipe segment and afferent parameters

For the experimental validation of the spatial discrete model introduced in [3] in this second part of paper three case studies are presented. They enable comparisons between the

$$\begin{cases} \dfrac{dp_j}{dt}(t)+\xi_1\left(p_j(t)\right)\cdot\delta Q_j(t,\Delta x)=0 \\ \delta p_j(t,\Delta x)+\xi_2\left(p_j(t)\right)\dfrac{Q_j^2(t)}{p_j(t)}+p_j(t)\xi_3\left(p_j(t)\right)=0 \end{cases} \tag{1}$$

characteristic variables of the gas flow process (pressures and flows) resulted after numerical simulations and the same characteristic measured in real operating conditions. Each case relives new aspects regarding the flow regimes.

2. CASE STUDY 1 (CS1)

We consider an equivalent pipe segment with $D=400mm$, $L=33km$, $\Delta h=0$. The gas flow is supposed to run in isothermal thermodynamics regime at the average temperature: $T_{average}=7^0C$. Experimentally, in the inlet node of the pipeline section, a pressure step from $p_1\left(t_{initial}=0\right)=5,6bar$ to $p_1\left(t_{final}=\tau_f\right)=9,6bar$ has been achieved, provided the constant outlet flow is maintained constant in the pipe segment, at a value of about $Q_m(t)=9.500Nm^3/h$ within the time range $t\in\left[t_{initial},t_{final}\right]$. The pressure variation measurements $p_m(t)_{measured}$, respectively the mass flow $Q_m(t)_{measured}$, within the time range $t\in\left[t_{initial},t_{final}\right]$ were made by means of the sampling step $\Delta t_{measurement} = 1\min$.

To calculate the hydraulic loss factor λ of the pipeline, an absolute roughness of $k = 0,02cm$, corresponding to a relatively new, clean transmission pipeline is adopted. The loss factor λ was calculated, based on the Colebrook-White formula, for the stationary regime $t = t_{inițial}$, for the inlet and outlet nodes of the pipe segment [2]. Practically, we obtain the same value $\lambda = 0,017$ for a Reynolds number $\text{Re} = 0,6 \times 10^6$. It indicates a transitional hydraulic regime for the pipe segment, so that the computed value for the loss factors λ doesn't vary significantly during the transitory regime.

Considering a spatial discretization by using $m = 11$ points, a system of $m - 1 = 10$ differential equations (8) is obtained. This reduced number of differential equations of the system justifies the use of an implicitly numerical solving method [1].

The pressure variation acquired for the outlet node $\left\{p_m(t)_{computed} / t \in \left[t_{initial}, t_{final}\right],\right\}$ by numerical simulation with a discrete-time step $\Delta t = 1\min$ is graphically represented in figure 2. In the same figure the measured pressure curve $\left\{p_m(t)_{measured} / t \in \left[t_{initial}, t_{final}\right],\right\}$ is also illustrated. The two curves are correlated with a relative error of maximum 2.5 % in absolute value according to figure 3.

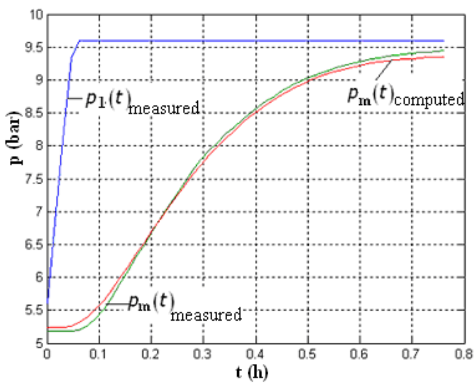

Fig. 2. Pressure characteristics (CS1)

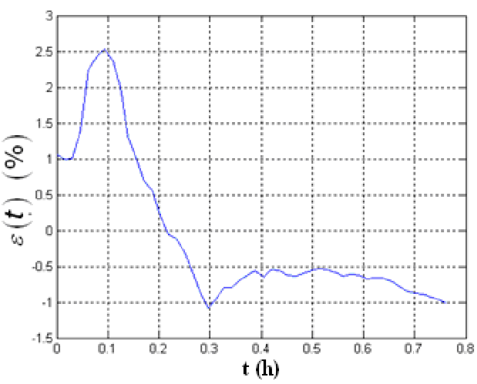

Fig. 3. Error of estimated pressure (CS1)

3. CASE STUDY 2 (CS2)

For the second case it is considered an equivalent pipe segment with: $D = 1.200mm$, $L = 183km$, $\Delta h = 0$ Gas flow is supposed to run in isothermal thermodynamics regime at an average temperature $T_{average} = 9^0 C$.

For this pipe segment, the inlet pressure $p_1(t)_{measured}$, the outlet pressure $p_m(t)_{measured}$ and of the outlet flow $Q_m(t)_{measured}$ are measured at every hour, i.e. $\Delta t_{measurement} = 1h$, during $t \in [0, 1929]\, h$. The results are represented in figures 4 and 5.

The recordings show that during the time range, [530, 700] hours, the flow regime may be interpreted like a quasi-stationary one, characterized by small variations of pressure and flow values. This regime will be considered as a reference for the determination of a loss pressure factor λ.

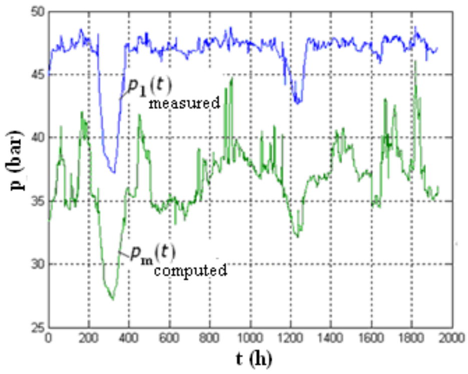

Fig. 4. Pressure characteristics (CS2)

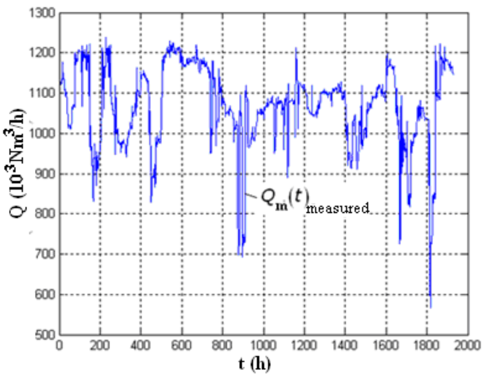

Fig.5. Flow characteristics (CS2)

The average pressure $p(t)_{average}$ of the pipe segment and the outlet volume flow $Q_m(t)_{measured}$ on the considered time range are represented in figure 6, respectively 7. They have the average values (global average value) $p_{average} = \underset{t=530h}{\overset{700}{M}} \left\{p(t)_{average}\right\} = 41,04bar$, respectively $Q_{average} = \underset{t=530h}{\overset{700}{M}} \left\{Q_m(t)_{measured}\right\} = 1.189.500 Nm^3 / h$.

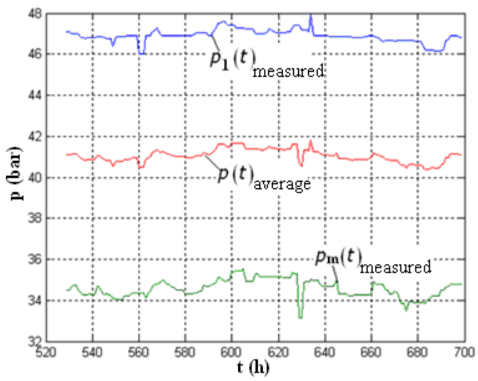

Fig. 6. Pressure characteristics (CS2)

On this basis, for the pressure loss factor $\lambda(t)_{average}$ for the time range considered, results the variation in figure 8 [2]. It takes place around the average value $\lambda_{average} = \underset{t=530h}{\overset{700}{M}}\left\{\lambda(t)_{average}\right\} = 0{,}0113$.

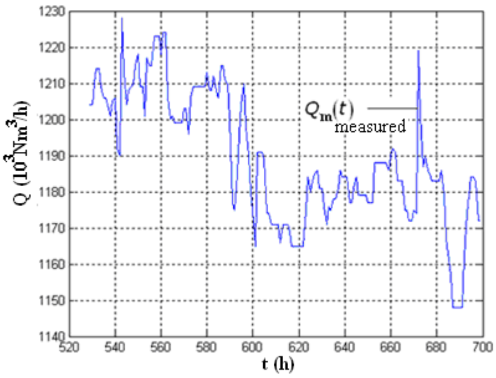

Fig. 7. Error of estimated pressure (CS2)

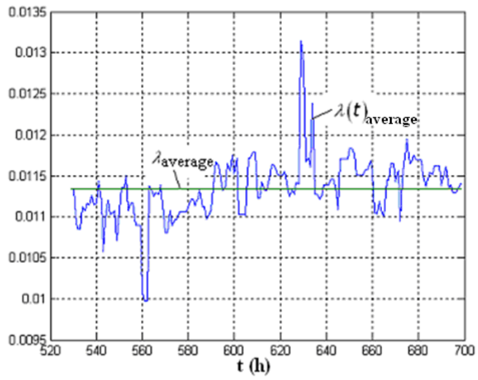

Fig. 8. Characteristics of the loss factor (CS2)

Figure 9 illustrates the variation of Reynolds number $\mathrm{Re}(t)_{average}$ in the considered time range, determined in the hypothesis that the gas flow $Q_m(t)_{measured}$ stands to medium pressure $p(t)_{average}$. The variation takes place around the average value

$$\mathrm{Re}_{average} = \underset{t=530h}{\overset{700}{M}}\left\{\mathrm{Re}(t)_{average}\right\} = 24{,}3\times10^6$$

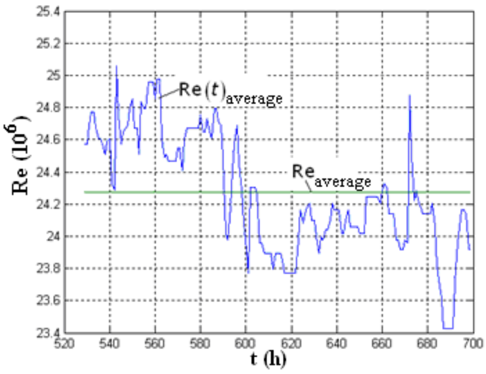

Fig. 9. Reynolds number variation (CS2)

which means a turbulent flow regime when great variations of the pressure loss factor is not recorded [2].

In this context, according to Colebrook-White equation, the variation of the absolute interior roughness of pipe segment $k(t)_{average}$ is as in Figure 10. It's average value is $k_{average} = \underset{t=530h}{\overset{700}{M}}\left\{k(t)_{average}\right\} = 0{,}0087cm$.

By using these average values of variables and parameters of the quasi-stationary flow process for the determination of the pressure loss factor λ by means of the Colebrook-White equation, we obtain $\lambda = 0{,}0114$. This result is very close to value $\lambda_{average} = 0{,}0113$, calculated initially and which, for each set of measurements, the individual calculated values.

Now, the following aspect regarding equation (see eq.(3.b) in [3])

$$\frac{\partial p}{\partial x} + \xi_2(p)\frac{Q^2}{p} + p\xi_3(p) = 0 \quad (2)$$

is to be discussed: for a horizontal pipe segment and an average value of the compressibility factor $Z_{average} = 1 - \tau p_{average}$ equation (2b) is rewritten as

$$\frac{\partial p^2}{\partial x} + \frac{\lambda Z_{average} RT_{average}}{DA^2} Q^2 = 0. \quad (3)$$

Considering the approximation: $\frac{\partial p}{\partial x} \cong \frac{p_m^2 - p_1^2}{L}$, from (3) we obtain

$$p_1^2 - p_m^2 = \lambda \frac{L}{DA^2} Z_{average} RT_{average} Q^2 \quad (4)$$

By introducing the notations:

$$a(t) = Q(t)^2 \quad (5)$$

$$b(t) = p_1(t)^2 - p_m(t)^2 \quad (6)$$

$$c(\lambda) = \lambda \frac{L}{DA^2} Z_{average} RT_{average} \quad (7)$$

the equality (4) may be rewritten as:

$$b(t) = c(\lambda) a(t) \quad (8)$$

In figure 11 is illustrated, in the time range $t \in [0, 1929]\, h$, the outcome experimental points corresponding to parametric dependence (time parameter) $\{a(t), b(t)\}$, respectively the average line that introduces an average slope $c_{average}$.

We can assert that the representation in figure 11 furnishes on the basis of the experimental set

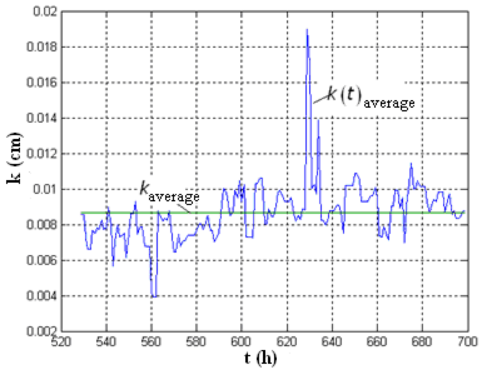

Fig.10. Absolute roughness characteristics (CS2)

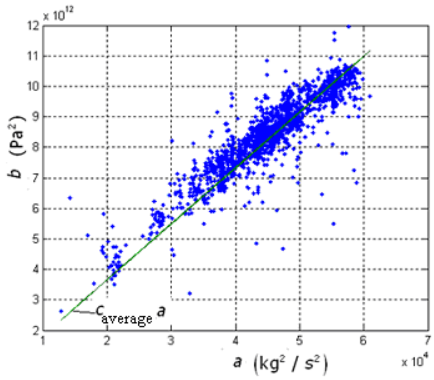

Fig. 11. Experimental determinations b(a) and their approximation (CS2)

of values $\{a(t), b(t)\}$ on the time range $t \in [0, 1929]\, h$ the functional characteristics of the stationary regimes $b(t)_{estimated} = c_{average} a(t)$.

The dispersion of points $\{a(t), b(t)\}$ around this line reflects the non-stationary character of gas flow through the pipe section. The smaller the dispersion the closer the flow situates itself to a stationary regime and the measured values of pressure and flow check up with a greater accuracy the stationary regime equations on whose bases the pipeline parameters may be determined (inner roughness, loss of pressure factor).

The character of "apparent linearity" of the dependence $\{a(t), b(t)\}$ manifests itself for values of pressure and flow which places the pipeline in a transitional hydraulic regime, when the loss of pressure factor λ varies not as significantly as the Reynolds number increases.

This approach may be used for the implementtation of some estimators of the transmission pipeline parameters, mainly, the inner roughness or the hydraulic pressure loss factor.

Numerical simulation was performed by using an implicit numerical method [1], considering $m = 11$ points of spatial discretization and a discrete time step: $\Delta t = 10\,\text{min}$.

From the values of $p_1(t)_{measured}$, $p_m(t)_{measured}$ and $Q_m(t)_{measured}$ measured within an hour interval, intermediate values corresponding to the discrete time step $\Delta t = 10\,\text{min}$ were calculated through linear interpolation.

Through numerical simulation based on the input pressure $p_1(t)_{measured}$ and the outlet flow $Q_m(t)_{measured}$, the outlet pressure $p_m(t)_{computed}$ represented in figure 12, beside the curve of measured pressure $p_m(t)_{measured}$, has been calculated.

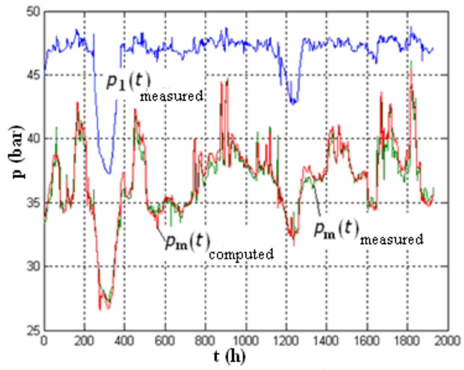

Fig.12. Measured pressure and calculated pressure (CS2)

Figure 13 indicates the relative error of the calculated outlet pressure versus the measured real value.

A rather good correlation between the calculated value $p_m(t)_{computed}$ and the measured value $p_m(t)_{measured}$ of outlet pressure is to be

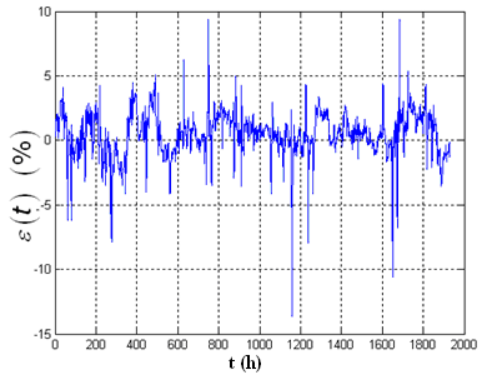

Fig. 13. Error of calculated pressure in relation to the measured one (CS2)

observed, with the average value of the relative errors: $\varepsilon_{average} = \underset{t=0}{\overset{1929h}{M}} \{\varepsilon(t)\} = 0,5\%$, where

$$\varepsilon(t) = \frac{p_m(t)_{measured} - p_m(t)_{computed}}{p_m(t)_{measured}} \times 100 .$$

4. CASE STUDY 3 (CS3)

Let's consider a pipeline segment with the following characteristics:

$D = 700mm$, $L = 123,9km$, $\Delta h = 170m$.

Gas flow along this pipeline segment is considered to run in isothermal thermodynamics behavior at an average temperature of: $T_{average} = 5,5^{o}C$.

Values of the input pressure $p_1(t)_{measured}$, output pressures $p_m(t)_{measured}$ and exit volume flow at intervals of an hour, during two time periods, respectively $t_a \in [0, 93]\,h$ and $t_b \in [0, 145]h$ have been recorded.

The time variations for these quantities are represented in figures 14 and 15 for the t_a time interval, respectively in figures 16 and 17 for the t_b time interval.

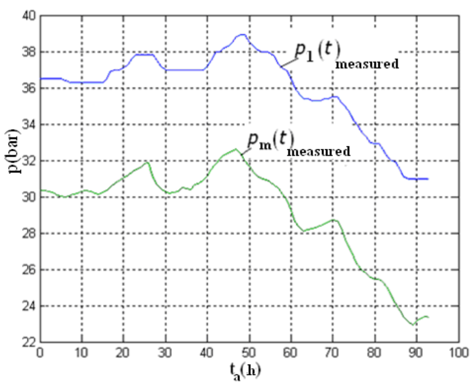

Fig. 14. Pressure characteristics (CS3)

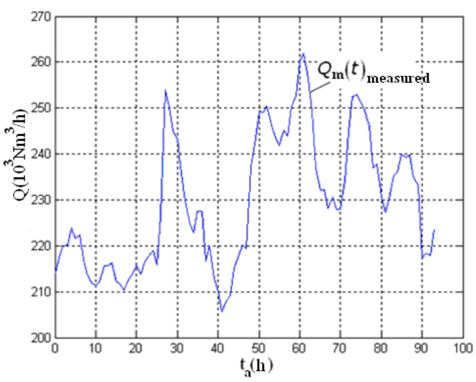

Fig. 15. Flow characteristics (CS3)

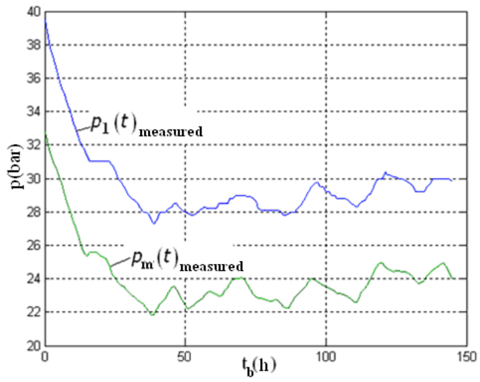

Fig. 16. Pressure characteristics (CS3)

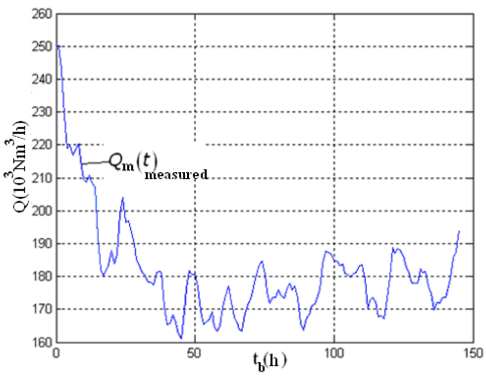

Fig. 17. Flow characteristics (CS3)

For an average value of the pressure loss factor, $\lambda_{medie} = 0,013$, the numerical simulation performed with model (see eq. (9.1) and (9.2) in [3])

$$\delta \underline{X}_p(k+1,\Delta t) = \theta \underline{\Psi}\left(\underline{X}_p(k+1), \underline{u}(k+1), \Delta x\right) + (1-\theta)\underline{\Psi}\left(\underline{X}_p(k), \underline{u}_k(k), \Delta x\right) \quad (4.1)$$

$$\underline{X}_Q(k+1) = \Xi\left(\underline{X}_p(k+1), p_1(k+1), \Delta x, \Delta t\right), \quad (4.2)$$

by the use of an implicit numerical method, with $m = 11$ spatial sampling points and a step of time digitization on the two time intervals under consideration, has led to the computed output pressures $p_m(t)_{measured}$, represented in figures 18 and 20, alongside with the measured pressure curves $p_m(t)_{measured}$.

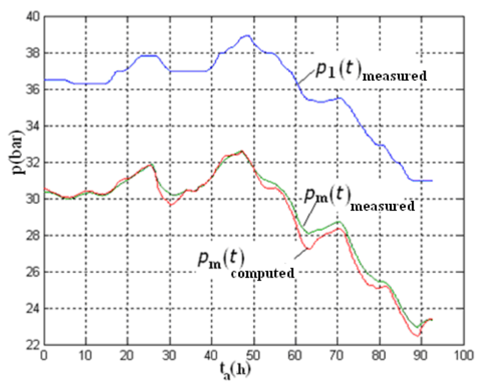

Fig. 18. Measured pressure and calculated pressure (CS3)

Figures 19 and 21 relieve the relative errors of the output pressure values relative to the real measured values.

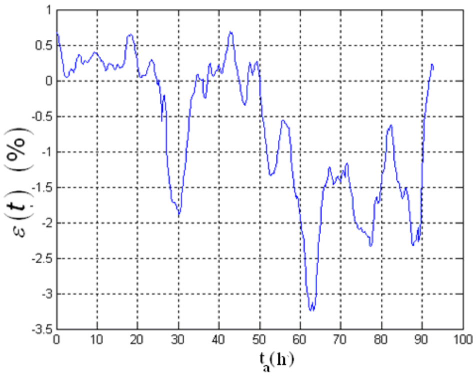

Fig. 19. Error of calculated pressure in comparison to the measured one (CS3)

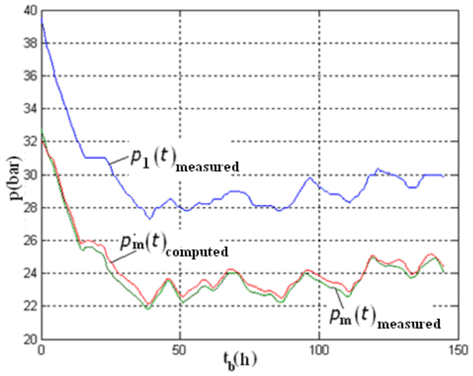

Fig. 20. Measured pressure and calculated pressure (CS3)

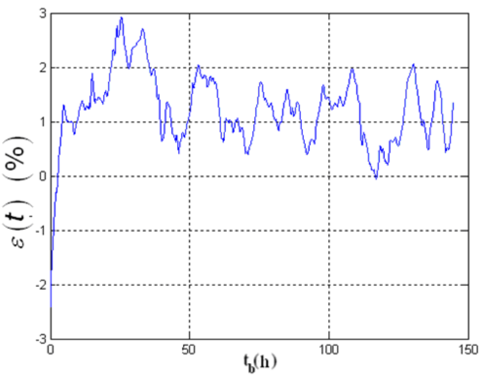

Fig. 21. Error of calculated pressure in comparison to the measured one (CS3)

The average values for the errors determined within two time intervals, respectively

$$\varepsilon_{average} = \underset{t=0}{\overset{93h}{M}}\left\{\varepsilon(t)\right\} = -0,7\%$$

and

$$\varepsilon_{average} = \underset{t=0}{\overset{145h}{M}}\left\{\varepsilon(t)\right\} = 1,2\%,$$

show a rather strong correlation of the calculated values with the measured pressure values in the exit junction.

5. CONCLUSIONS

The mathematical models of gas flow process through the transmission systems are complex systems with distributed parameters. In a first approximation and depending on the operating conditions, simplified mathematical models can be successfully used. In this context, in the first part, the paper describes an approximating method. This method uses, for real, usual working conditions relative to a pipe segment, the simplified model under the spatial discrete form (1). Three case studies, presented in the second part of the paper, illustrate a good correlation of measured values to calculated values through simulations. For the case studies, a relative simple discretization grid has lead both to an approximation model of reduced complexity, and, consequently, to the use of an implicit numerical method for simulation.

A generally valid numerical method, for the numerical simulation by means of the mathematical model, cannot be specified. The analysis carried out in [3] (chapter 4) systematizes aspects relative to numerical simulation which can be used for choosing and analyzing the numerical simulation method. In the same time, the analysis justifies the methods used in the case studies.

The resulted errors for the three case studies are comparable with those specified in the results of other analyses, considering the sampling time periods and pipe segments lengths.

Therefore, in [4] it is performed a detailed comparative analysis of the modeling errors. There were compared the pressure and flow rate values, numerically calculated with the measured values, at every 10 minutes. The experiments have been carried out on four pipeline sections with lengths of 25km, 53km, 123km and 160km, with diameters respectively of 0,5m, 0,6m, 0,9m and 0,75m. The pressures range was (30-50) bar and the flow rates range was (100.000-500.000) Nm^3/h. The elevation profile was specified for every pipe segment. For the numerical simulation, it was used a simplified mathematical model and for the numerical integration, an implicit model. The comparative analysis of the pressure has led to percentage relative average error between (0,1-0,45)%, with the maximum percentage deviation between (0,7-2,8)%.

More recently, in [1], using the SIMONE dedicated software and a SCADA informational infrastructure implemented at the level of a transport system have led to percentage relative values of the average error attaining 3%. The analyzed system comprises three main pipe segments with lengths of 91 km, 122 km and 178 km, respectively diameters between (0,7-0,9) m and three compression stations. The numerical simulations of the flow model has considered measured data with a sampling period of 1 hour The pressures range was (40-50) bar and the transported flow rates range (400.000-700.000)Nm^3/h.

Regarding the estimated errors in the three studied cases, it must be emphasized that these are cumulative errors (modeling errors considered by hypothesis and calculation errors due to both the used numerical method and selected parameter for discretization). More sophisticated comparisons referred in [5] [6] [7] [8] have not led to significant differences between the resulted modeling errors values for the different study cases taken into account. Considering the aspects mentioned above, the final conclusion is that the flow process modeling can be carried out with a sufficient accuracy through the use of some simplified numerical models.

REFERENCES

Aalto, H., - Real-time Receding Horizon Optimization Of Gas Pipeline Networks, University Of T7echnology, Helsinki, 2005.

Bichiş, C. D. - Contribuții la modelarea şi controlul proceselor de transport a gazelor naturale, (report), U.P.Timişoara, 2008.

Bichiş, C. D., Dragomir, T.L., - On modelling and simulating natural gas transmission systems (Part I), CEAI, vol. 10, No.3, pp. 27-36, 2008

Hannah, K.W., Batey, E.H., Wilkinson, J.F., Holliday, D.H., - Transient Flow of Gas, Underground Storage Committee Pipeline Research Committee of Pipeline Research Council International, Inc. 1964.

Lewandowski, A., - New Numerical Methods For Transient Modeling Of Gas Pipeline Networks, American Management System, Inc, 1995 (www.psig.org).

Osiadacz, A. J., - Diferent transient models. Limitations, advantages and disadvantages, 1996 (www.psig.org).

Osiadacz, A. J., - Comparison of isothermal and non-isothermal transient models, 1998 (www.psig.org).

Stringer, S. M., - The Use Of Robust Observers in the Simulation of Gas Supply Networks, phd thesis, University Of Reading, UK, 1993.