INFLUENCE OF WALL FRICTION ON FLOW PARAMETERS INNATURAL GAS TRANSMISSION PIPELINE

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A mathematical model and computational algorithm are derived for the prediction ofnatural gas pipeline flow.Non-isothermal and compressible steady state flow is considered. Heat transfer between gas flow and surroundings is taken into account together with the heat generation due to the gas friction on the inner pipeline wall. The computational algorithm is based on themarching procedure with defined initial conditions. The predicted thermal effect of the wall friction is validated by the simulation of a case that is available in the open literature.The influence of heat generation by gas wall friction in the long transmission pipeline on gas pressure and temperature is evaluated. Differences between results obtained with and without the heat generation due to gas wall friction are analysed. The heat generation due to gas friction on the pipeline inner wall has an influence on the gas temperature change along the pipeline, while its influence on the pressure drop is negligible.These detailed results are novelsince most of the previously published results on non-isothermal gas flow did not take into account the thermal effect of the gas wall friction or the influence of this effect was not evaluated.The presented results are a support to the gas pipeline design methods and operational analyses.

Key words: *Natural gas pipelines, compressible steady state flow, Non-isothermal flow, gas wall friction.*

1. Introduction

The prediction of flow parameters in natural gas pipelinesis important for the design and control of operation of these systems. It is achievable with the numerical simulation of compressible gas flow. The simulations are based on the development of natural gas flow models and their numerical solving with adequate computational algorithms. Plentiful efforts have been spent on development of mathematical models for the prediction of steady-state and transientcompressible gas flows. Governing equations of the compressible fluid flow through the pipe were described by Ouyang and Aziz [1], Rhoads [2] and Schroeder [3], to mention but a few. General flow equations of simple form are developed to account for the pressure drops due to friction and change of elevation and kinetic energy, as presented by Abbaspour[4].Later on Abbaspour et al. [5] applied a more general method basedon continuity, momentum, and energy balance equations of gas flow and a fully implicit finite-difference method for their solving. The results reported in [5] show the importance of modelling the non-isothermal effects of gas flow. It was also shown that the convective inertia term plays an important role in the gas flow analysis and cannot be neglected.Price et al.[6] presented a method for the determination of effective friction factor and overall heat transfer coefficient for a high-pressure natural gas pipeline under transient flow conditions. The predicted pipeline outlet

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pressure and temperature in [6] are in good agreement with measured pipeline data. Osiadacz and Chaczykowski[7] calculated the temperature of the gas along the pipeline by solving the energy equation. Also, they presented a comparison of isothermal and non-isothermal gas flow models for some practical examples.Chaczykowski[8] simulated slow and fast fluid transientsin high-pressure gas transmission pipelines with one-dimensional, non-isothermal gas flow model and with inclusion of the heat generation due to the gas wall friction. It was found that simplified flow model with steady-state heat transfer term overestimates the amplitude of the temperature fluctuations in the pipeline, which indicates that unsteady heat transfer model with the effect of heat accumulation in the surroundings of the pipeline should be used. Oosterkamp et al. [9] presented a study of heat transfer from the gas pipeline to the soil. Studied were one-dimensional steady and unsteady and two-dimensional unsteady models of the gas pipe flow with heat transfer to the surrounding soil. Effects of rapid changes in gas mass flow rate and temperature at the pipeline inlet were evaluated. The case presented is representative for export natural gas pipelines, containing offshore and buried sections along the route. Steady state flow of natural gas in buried pipelines was predicted by Zhou and Adewumi[10] with both the heat transfer between the flowing gas and the surroundings and the Joule-Thomson effect. The governing equations were the continuity, momentum and energy balance equations for the steady-state gas flow. A one dimensional, compressible, transient, and non-isothermal flow in a long transmission pipeline was simulated by Helgaker et al.[11], and the influence of different physical parameters on gas pressure temperature changes was investigated.Gharehasanlou et al. [12] proposed an improved semi-empirical model for the prediction of wall friction in two-phase gas-liquid flows in horizontal and near horizontal pipes. Pressure gradient and velocity profiles were validated against experimental data.Costa et al.[13] provided a steady–state gas pipeline simulation. In this simulation, the pipeline and compressors were selected as the building elements of a compressible flow network. The one-dimensional compressible flow equation was applied to describe the relationship between the pressure and temperature along the pipe and the flow rate through the pipe. The flow equation and the conservation of energy equation were solved in a coupled fashion to investigate the differences between isothermal, adiabatic and polytrophic flow conditions. Borujerdi and Rad [14] analysed the gas flow in high pressure buried pipelines subjected to wall friction and heat transfer. The governing equations for one-dimensional compressible pipe flow were derived and solved numerically. The effects of friction, heat transfer from the wall and inlet temperature on various parameters such as pressure, temperature and mass flow rate of the gas were investigated. The numerical scheme and numerical solution were confirmed by some previous numerical studies and available experimental data.Deen and Reintsema[15] introduced a technique that reduces the energy equation into a single parameter in the mass equation without the assumption of isothermal or isentropic flow. They used the method of characteristics in conjunction with a finite difference method with second-order truncation error.The existing analyses of integrated natural gas and power systems generally ignore gas temperature variations, which may misjudge gas pressure and jeopardize natural gas transmission Jiang et al. [16]. Hence, an efficient energy flow analysis method was proposed by Jiang et al. [16] for integratednatural gas systems withincluded temperature effects. The proposed method enables energy flow to be efficiently solved with low computational requirements. It was concluded that the reduction in the pressure and temperature of natural gas will increase with increasing lengths of gas pipelines in a natural gas system, and effects of temperature variations on a nodal pressure will increase with an increase in length of the gas pipeline between the node and gas source.The natural gas transient simulations were performed and compared by Koo [17] with the standard method of characteristics that uses an inertia multiplier and with the pressure-based finite volume method that uses a collocated mesh with the total variation diminishing scheme. It was found that the pressure-based finite volume method outperforms the method of characteristics for both slowand fast transient problems. The performed calculations solved the mass and momentum equations of gas flow, while the energy equation and thermal effects were not taken into account. New analytical solutions for the one-dimensional steady-state compressible viscousdiabatic flow of an ideal gas through a constant cross-section pipe was derived by Ferrara [18]. The obtained analytical solutions were successfully validated for both subsonic and supersonic flows. The solution includes energy equation, but the thermal effect includes only the heat transfer from the pipe to the surrounding, while the heat transfer due to the wall friction was not considered.

The above literature review shows that most of the researchers focused on non-isothermal gas flow conditions caused by the heat transfer between the gas and the surrounding soil or atmosphere through the pipe wall, while they neglected or did not evaluate in detail the effect of heat generation due to the gas friction on the inner wall of the pipeline. Therefore, this study investigates the influence of heat generation by natural gas wall friction in long transmission pipelines. A predicted thermal effect of the wall friction is validated by the simulation of a case that is available in the open literature.

2. Modelling Approach

2.1 Pressure change and flow rate relation

Starting from the Bernoulli equation for the compressible fluids in a pipeline at steady-state condition, the following general flow equation is derived[19]

$$Q_b = \pi \left(\frac{R}{1856} \right)^{0.5} \frac{z_b T_b}{p_b} \left(\frac{p_{in}^2 - p_{out}^2 - \dfrac{58 G \,\Delta H\, p_{ave}^2}{z_{ave} R T_{ave}}}{z_{ave} T_{ave} G L} \right)^{0.5} \frac{D^{2.5}}{\left(f/4 \right)^{0.5}} \tag{1}$$

where $Q_b$in (m^3/s) is thegas volume flow rate at the international standardmetric conditionsfor natural gas [20] – the standard conditions,R is the universal gas constant (8.314 J /molK), z_b is the compressibility of gas at the standard conditions ($z_b \approx 1$),T_b is the temperature at the standard conditions (288.15 K), p_b is the pressure at the standard conditions (101325 Pa), p_{in} and p_{out} are the inlet and outlet gas flow pressure, z_{ave},T_{ave}, and p_{ave} are respectively the average compressibility factor of gas, the average temperature, and average pressure of gas flow, G is the natural gas gravity defined as the ratio of the gas molar mass (M_{gas}) and the air molar masse (M_{air}), i.e. $G=M_{gas}/M_{air}$, L is the pipeline length, ΔH is the elevation change.Equation (1) relates the pressure drop with the flow rate and other gas flow properties.

The average flow temperature is determined as [19]

$$T_{ave} = \frac{T_{in} + T_{out}}{2} \tag{2}$$

The average pressure is determined according to [19] with the relation

$$p_{ave} = \frac{\int_{in}^{out} p^2 dp}{\int_{in}^{out} p dp} \tag{3}$$

which results into

$$p_{ave} = \frac{2}{3}\left[p_{in} + p_{out} - \frac{p_{in} p_{out}}{p_{in} + p_{out}} \right] \tag{4}$$

Derivation of Eq. (1) is based on the equation of state in the form

$$\frac{p}{\rho} = zR_g T \tag{5}$$

where the gas constant is defined as $R_g = R/M_{gas}$, the deviation from the ideal gas law is absorbed in the compressibility factor z, which is a function of pressure and temperature, and T is the absolute temperature. The available methods to calculate the compressibility factor are the Standing-Katz method, the Dranchuk, Purvis, and Robinson method, the American Gas Association (AGA) method, and the California Natural Gas Association (CNGA) method [21]. In this study CNGA method is used to calculate the compressibility factor of natural gas flow in pipelines because it is valid for the z factor predictions at high pressure and compared to other methods its application is simple and effective

$$z = \frac{1}{1 + \frac{5262.5 p \cdot 10^{1.785G}}{T^{3.925}}} \tag{6}$$

The Darcy friction coefficient f is calculated with the Haaland's equation [22]

$$\frac{1}{f^{0.5}} = -1.8 \log_{10}\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{e}{3.7D} \right)^{1.11} \right] \tag{7}$$

where e is the pipe roughness and D is the pipe diameter. The Reynolds number is calculated as $\mathrm{Re} = uD/\nu$, where ν is the kinematic viscosity.

The pressure at the downstream end of the pipeline segment can be calculated from Eq. (1) as

$$p_{out} = [p_{in}^2 - A - B]^{0.5} \tag{8}$$

where A is determined as

$$A = \frac{58 G \Delta H \, p_{ave}^2}{z_{ave} R T_{ave}} \tag{9}$$

and

$$B = \left(\frac{Q_b \, p_b}{C T_b} \right)^2 \frac{z_{ave} T_{ave} G L f}{4 D^5} \tag{10}$$

$$C = \pi z_b \left(\frac{R}{1856} \right)^{0.5} \tag{11}$$

2.2 Heat transfer between pipeline and environment

The mechanical energy dissipation due to fluid friction on the wall results in the pressure drop and the heat generation that is dissipated in the environment. In some cases, when the pipeline routes from north to south or from east to west and vice versa, the climatic changes along the year create relatively large difference in environmental temperature, which can pump the heat out from the gas reducing its pressure. For all these reasons, it is proposed in this study to include a heat transfer model that takes into consideration the heat transfer between gas and its surrounding and heat generation due to the friction between the flowing gas and the inner surface of the pipe wall.The thermal effect is evaluated for the steady-state non-isothermal flow condition. The temperature change along the main gas pipeline is predicted by solving the energy equation in the following form [23]

$$\frac{d(\rho u c_p T)}{dx} = f\,\frac{\rho u^3}{2D} - \frac{4k}{D}\left(T - T_s\right) \tag{12}$$

where the product of specific heat capacity at constant pressure (c_p) and temperature Trepresents enthalpy and k is the heat transfer coefficient from the gas to the surrounding soil at temperature T_s. The first term on the right hand side of equation (12) is the internal energy dissipation due to gas friction on the pipeline wall while the second term represents the energy exchange with the surrounding. Differential equation (12)is solved analytically in the closed form by applying the following relations and assumptions.The product of density and velocity ρu is constant under a steady-state condition and in a pipe of a constant diameter. The specific heat capacity is assumed constant for a certain range of natural gas pressure and temperature change along the pipeline, i.e.,its value is determinedwith the arithmetic average of the inlet and outlet gas temperature and pressure values for a certain natural gas pipeline length.The friction coefficient f in Eq. (12) is assumed constant since the gas flow is within the region of developed turbulent flow in the Moody chart [22], which is characterized with a slight friction coefficient change versus the Reynolds number change. It is assumed that the gas transmission pipeline is buried in the ground. The soil temperature depends on the ground surface temperature change, which is determined by the seasonal and day-night period changes, and on the soil conductivity. The soil conductivity changes along the pipeline, especially in cases with hundreds of kilometres long pipelines. The precise information about the soil characteristic is usually not available. Further, the soil temperature at some distance from the ground surface changes slowly with time and usually it can be assumed constant during a 24 hours day period [24]. The heat transfer coefficient k in Eq. (12) is determined for the heat transfer from the pipeline outer surface towards the surrounding soil. The resistance to the heat transfer from the gas to the pipeline inner wall by convection is neglected, since it is negligible compared to the heat transfer from the pipeline outer wall surface to the surrounding soil. The heat transfer rate per unit length of the buried pipeline is calculated as [25]

$$q_L = k_L\left(T - T_s\right) = \frac{2\pi\lambda}{\cosh^{-1}\left(\frac{2x}{D}\right)}\left(T - T_s\right) \tag{13}$$

which holds for $x \approx D$, where x is the depth from the ground surface to the centreline of the buried pipeline. The soil temperature in the massive of the ground is T_s, T is the gas temperature in the pipeline and λ is the soil thermal conductivity. The surface and linear heat fluxesare related as $q_L = \pi D q_A$. Since $q_A = k(T - T_s)$ and introducing Eq. (9), the expression for the calculation of the heat transfer coefficient k from the gas to the surrounding soil (which appears in Eq. (12)) is obtained in the following form

$$k = \frac{\lambda}{D} \frac{2}{\cosh^{-1}\left(\frac{2x}{D}\right)} \tag{14}$$

According to the above presented analyses, the parameters (ρu), u, c_p, f, k and T_s are approximated fairly well with constant values. Therefore, Eq. (12) is solved analytically in the following form:

$$T_{out} = \left(\frac{f \rho u^3}{8k} + T_s\right)\left(1 - \exp\left(-\frac{4k}{\rho u c_p D} x\right)\right) + T_{in} \exp\left(-\frac{4k}{\rho u c_p D} x\right) \tag{15}$$

where T_{in} is the gas temperature at the pipeline segment inlet and T_{out} is the temperature at the outlet of the pipeline segment.The temperature affects the pressure distribution along the pipeline as shown by Eq. (1). The average temperature directly appears in Eq. (1) and some gas parameters depend on temperature, such as the compressibility factor z and the kinematic viscosity that influences the Reynolds number and the friction factor.

2.3 Numerical procedure

A steady-state natural gas flow in a pipeline is defined with flow rate, pressure and temperature at the pipeline inlet. The volume flow rate at standard condition or the mass flow rate are constant in case of steady-state flow, while the pressure and temperature are flow dependant parameters. The pressure change along the pipeline can be calculated with Eqs. (8-11), while the temperature change along the pipeline can be calculated with Eq. (15). The numerical calculation procedure starts with the discretization of the pipeline length into *n-1* segments, which boundaries are determined with *n*nodes, as presented in Fig. 1. The segment 1 is located at the pipeline inlet and the pressure and temperature at the node *n=1* at the inlet are known.The pressure and temperature are sequentially calculated for other nodes along the pipeline with the following equations according to Eqs. (8) and (15)

$$p_{i+1} = [p_i^2 - A - B]^{0.5} \tag{16}$$

$$T_{i+1} = \left(\frac{f \rho u^3}{8k} + T_s\right)\left(1 - \exp\left(-\frac{4k}{\rho u c_p D} x\right)\right) + T_i \exp\left(-\frac{4k}{\rho u c_p D} x\right) \tag{17}$$

where i=1,2,…,n-2, n-1. The distance between the nodes in Fig. 1 is denoted as x_i, hence the pipeline length is $L = \sum_{i=1}^{i=n-1} x_i$. The change of elevation between two sequential nodes is ΔH_i and the elevation difference between the pipeline inlet and outlet is $\Delta H = \sum_{i=1}^{i=n-1} \Delta H_i$. The algorithm of the calculation is presented in figure 2.

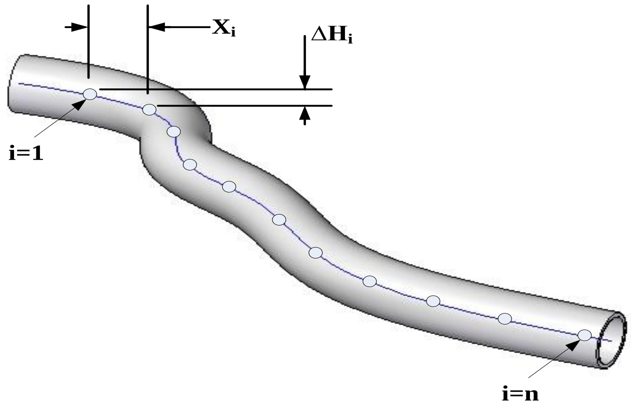

Figure 1. Discretization of the pipeline

Grid refinement tests showed that the calculation results of pressure and temperature are practically insensitive to the distance between nodes if this distance is shorter than 50 m, i.e. the relative difference between both pressure and temperature results along the pipeline obtained with the uniform distance between nodes of 50 m and 5 m is lower than 10^{-5}. Obtaining results with the 50 m distance between nodes is not at all a problem at personal computer even for the long transmission pipelines with a length of hundred kilometres. It is noted that both pressure and temperature along the pipeline are predicted with the analytical expressions and the numerical errors that appear in the calculation are introduced only by the truncation of the calculation results, i.e.by the number of significant digits used in the algebraic calculations. Therefore, the practical uncertainty of the engineering calculation results appears only due to the uncertainty of the input data, such as thermal conductivity of the soil in which the pipeline is buried, hydraulic roughness of the pipeline or natural gas thermophysical characteristics. The sensitivity of the results on the coefficient of heat transfer from the gas pipeline to the surroundings, as well on the roughness of pipe is presented in the Section 3 Results and discussion.

3. Results and discussion

A part of the real gas system Yamal — West Europe is considered. This gas transportation system shown in figure 3 consists of five compressor stations, installed on the Polish terrain [7]. Two or three centrifugal compressors are installed at each compressor station, which are driven by gas turbines. For the purpose of the present investigation, the pipeline between the compressor stations 3 and 4 was studied.

Calculations were carried out for the following parameters of pipeline and gas flow [7]:

• Pipe diameter is 1422 mm, the pipe wall thickness is 19.2 mm and the pipeline length is 122 km.

• Pressure and temperature at the pipeline inlet are 8.4 MPa and 315.5 K respectively.

• The volumetric flow rate is presented in standard cubic meters per hour Q_b =2019 950 m^3/h. The density of natural gas under standard conditions isρ_b =0.7156 kg/m^3 and the viscosity is μ= 0.135×10^{-4} kg/ms.

• The soil temperature is T_{soil} =285 K, the heat transfer coefficient is k_L=25 W/mK (k=5.9 W/m^2K at the pipe outside surface) and pipe roughness e=0.03 mm.

Results of the calculation with Eqs. (16) and (17) are shown in figure 4 for the same pipeline length of 120 km as applied in the analysis of Alghlam [26] and Osiadacz and Chaczykowski [7].

The previous researches Alghlam [26] and Osiadacz and Chaczykowski [7] neglected the heat generation due to gas wall friction and its influence on the gas flow parameters (pressure, temperature, density, velocity). Hence, it can be seen that their results show the same trend. On the other hand, the results of present code clearly show higher temperature values along the pipeline in comparison to the previous results, which is caused by the heat generation due to the wall friction – the effect that is taken into account by the model developed in the present research.

Numerical simulations were also performed with the aim to investigate the sensitivity of the temperature change along the pipeline on the heat transfer from the pipeline outer surface to the surrounding soil. For this purpose, the same pipeline diameter and inlet flow conditions as defined byOsiadacz and Chaczykowski [7] were considered, but the pipeline length was prolonged to 300 km.

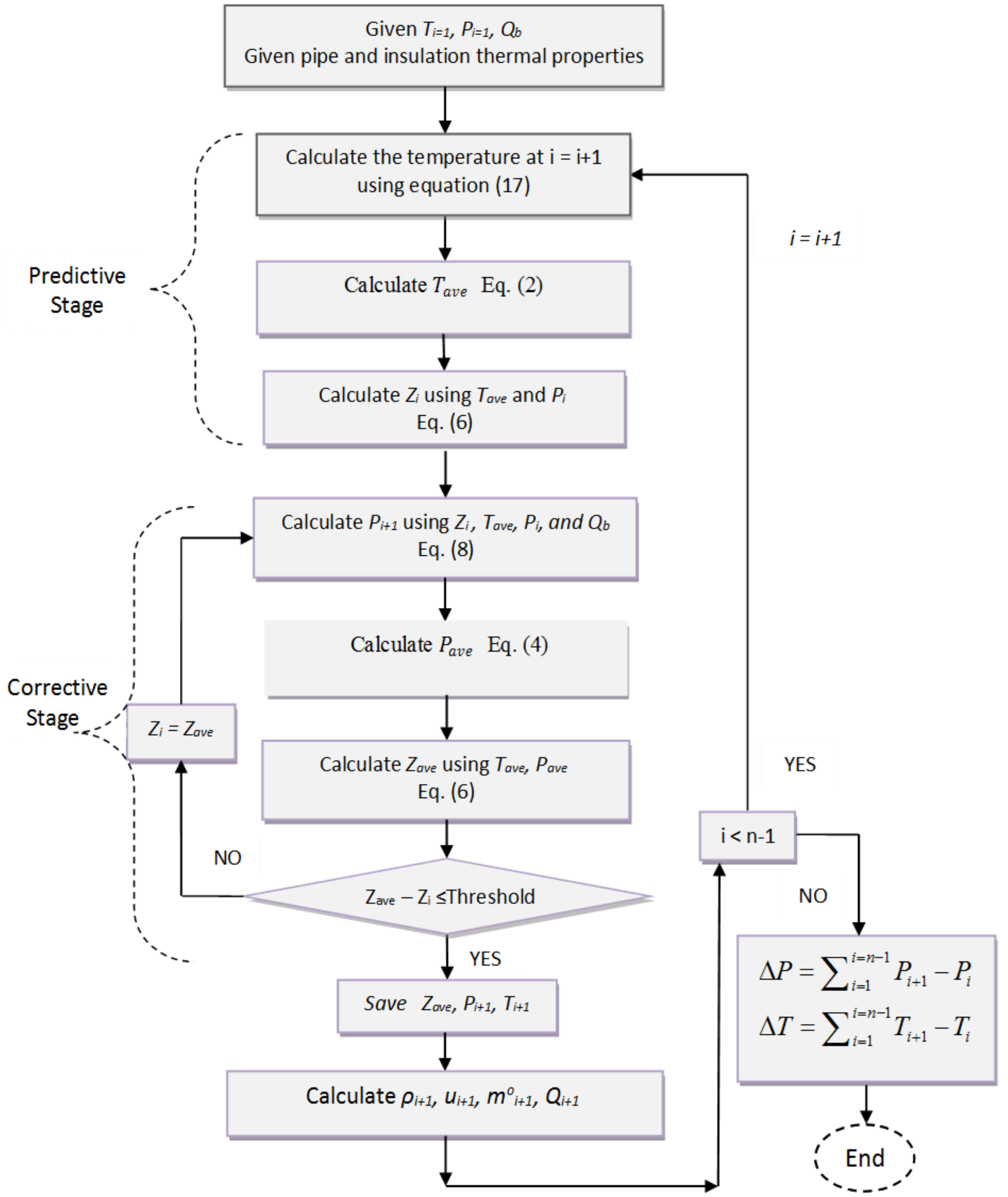

Figure 2. Flow chart of the numerical scheme

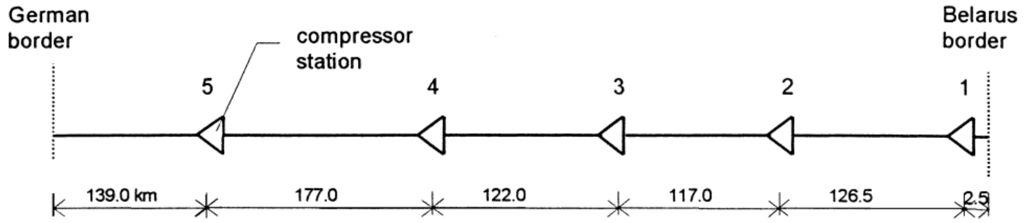

Figure 3. Structure of gas transportation system (Yamal - West Europe)

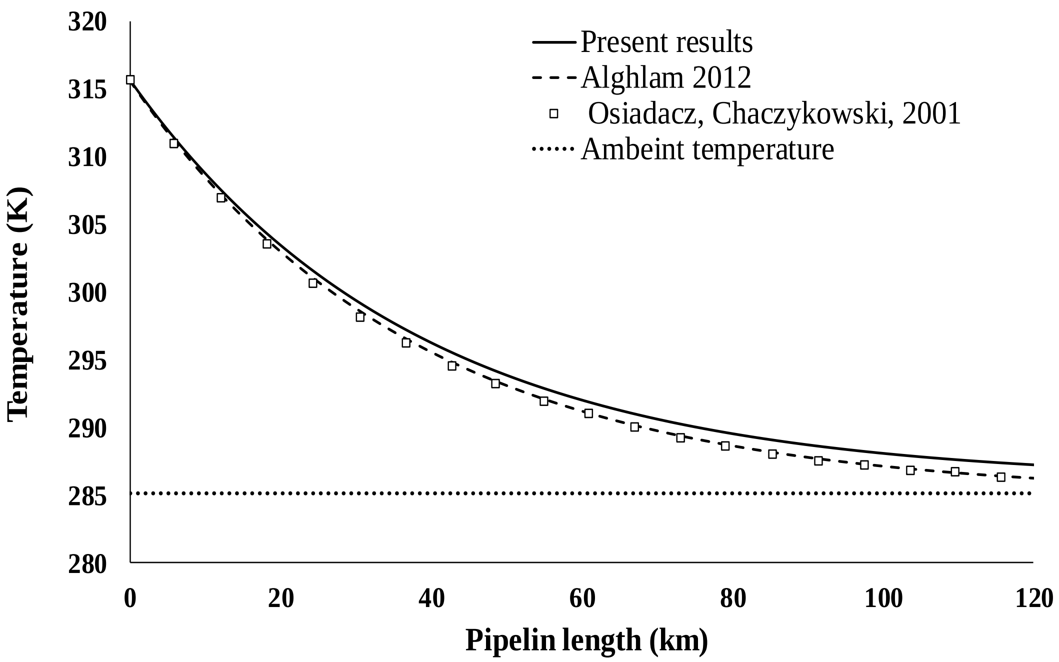

Figure 4. Temperature change along transmission gas pipeline

The simulations were performed for the flow with and without heat generation due to gas wallfriction and with three different values of the heat transfer coefficient from the pipeline outer wall to the surrounding 0.8, 1.6, and 5.9W/(m^{2}K). The heat transfer coefficient 0.8 W/m^{2}K is obtained with Eq. (14) for the thermal conductivity of sand λ=0.64 W/mK, the value 1.6 W/(m^{2}K)corresponds to the thermal conductivity of limestone λ =1.28 W/(m K), and the heat transfer coefficient 5.9 W/(m^{2}K) is the same as reported in [7].The constant absolute roughness of 0.03 mm was used. Calculated temperature values are presented in figure 5. These results show a clear difference between temperature profiles obtained with and without the heat generation due to the friction between pipe wall and flowing gas. This difference is more pronounced with the decrease of the heat transfer coefficient. As already mentioned, a very good agreement is obtained between temperature profiles obtained with the present model and calculated by Osiadacz and Chaczykowski [7] (the results presented in [7] correspond to the pipeline of the 122km length between two compressor stations, as already shown in figure 3). Also, figure 5 shows that the gas flow temperature reaches the ambient temperature at a distance of about 170 km in case with neglected heat generation due to friction of gas on the pipe wall. The related pressure profiles are presented in figure 6 for three different values of heat transfer coefficients and for cases with and without gas friction on the wall. There is no practical difference between pressure drops calculated with and without heat generated by friction of flowing gas on the pipe inner wall under the same heat transfer from the gas towards the surroundings, but the difference between pressure changes obtained with different heat transfer coefficients are obvious. The pressure drop in gas flow is 1.007 MPa in case with the lowest heat transfer coefficient of 0.8 W/m^2K. The highest heat transfer coefficient of 5.8 W/m^2K leads to the pressure drop of 1.110 MPa. Therefore, the influence of heat transfer coefficient on the pressure drop along the pipeline length is obvious.

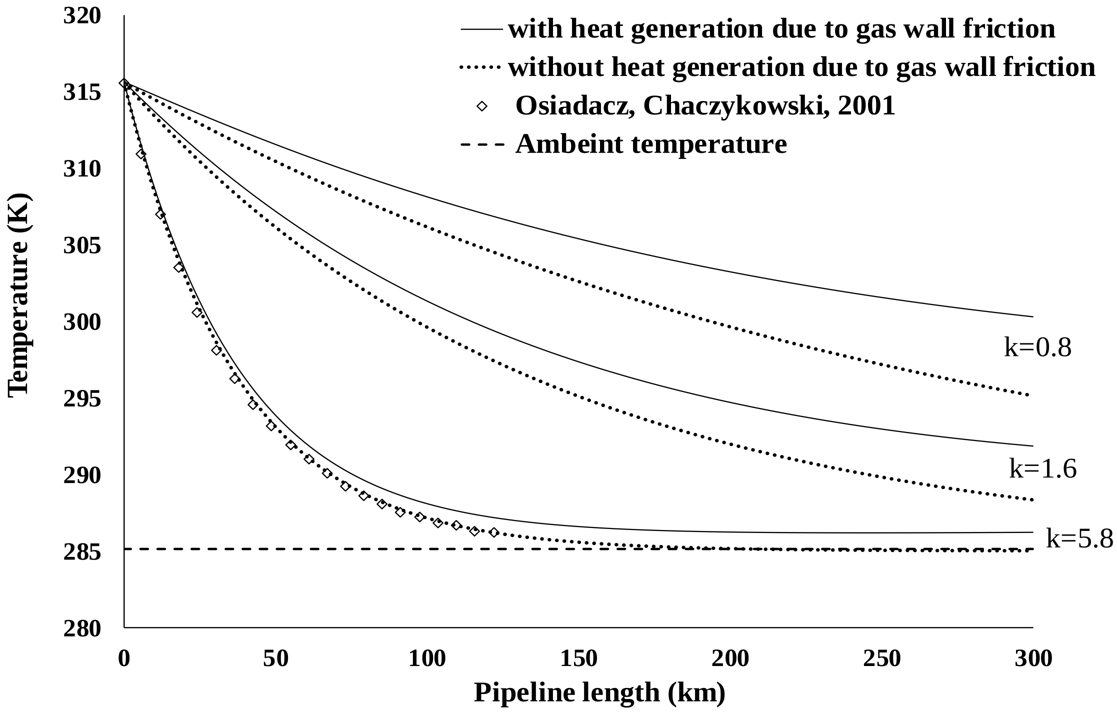

Figure 5. Temperature profilesalong the natural gas pipeline for three values of the heat transfer coefficient (W/m^2K) and flows with and without gas wall friction (the absolute roughness of the pipeline wall is e=0.03mm in all cases)

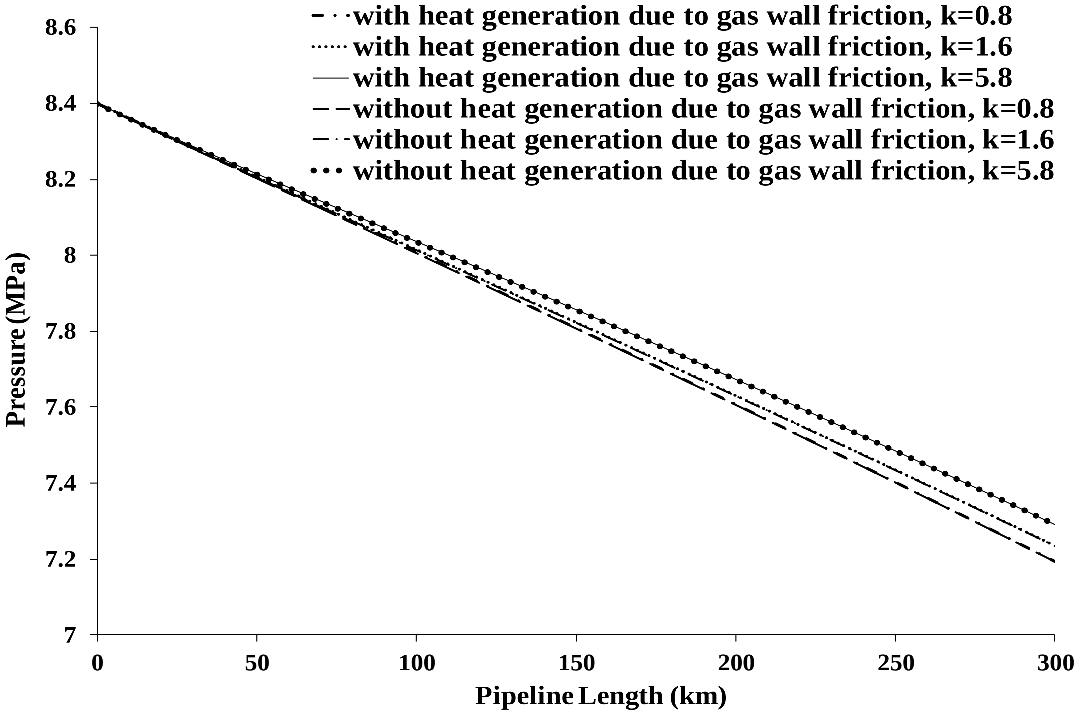

Figure 6. Pressure profilesobtained with and without heat generation due to the gas friction on the pipeline wall and for three different heat transfer coefficients (the absolute roughness of the pipeline wall is e=0.03mm in all cases)

The influence of the wall roughness on the temperature change along the pipeline and the pressure drop are presented respectively in figures 7 and 8. The calculations were performed with four different values of absolute roughness, for the pipe with the smooth wall (e=0.0 mm) and with the roughness that is equal to 0.01 mm, 0.02 mm and 0.03 mm and with the heat transfer coefficient k=1.6 W/m^2K. In addition, presented are results obtained for the gas flow in a smooth pipe and by neglecting the heat generation due to the gas wall friction. Figure 7 shows that higher absolute roughness of pipe leads to a lower drop of flow temperature, which means that the higher absolute roughness leads to the greater heat generation due to friction and a higher gas temperature profile along the pipeline. In other words, the higher absolute roughness leads to the higher friction factor coefficient, which results in an increased heat generation due to friction. Also, it is clearly seen that the results obtained under the assumption that there is no heat generation due to wall friction, as well as the flow in the smooth pipeline with the absolute roughness 0 mm leads to the lowest gas temperature along the pipeline.Figure 8 clearly shows that the biggest value of absolute roughness (0.03 mm) of pipe wall causes the greatest influence of friction, which results in the highest value of flow pressure drop by about 1.166 MPa. The flow in the smooth pipe leads to the smallest value of gas flow pressure drop of 0.642 MPa. Additionally, the pressure drop in the smooth pipe with and without the heat generation by friction is the same. The general conclusion on the basis of results presented in figure 8 is that the pipe roughness has a considerable influence on the pressure drop along the long transmission gas pipeline, while according to figures 6 and 8 the heat transfer from the gas in the pipeline to the surrounding media have a slight influence on the pressure drop and the heat generation due to friction has a negligible influence on the pressure drop. According to the results presented in figures 5 and 7 the influence of both heat transfer rate from the gas stream to the surrounding area and the heat generation due to friction have an influence on the gas temperature profile along the pipeline, while the heat transfer coefficient is more influential.

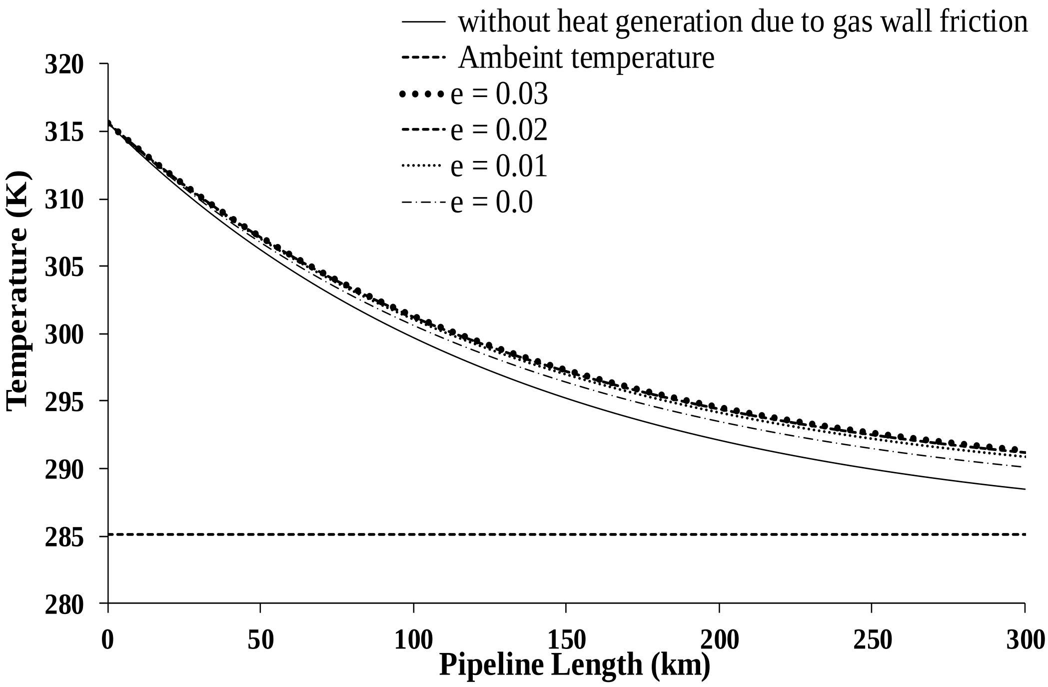

Figure 7. Temperature profile at heat transfer coefficient (k=*1.6 W/m*^{2}*K*) and different values of absolute roughness

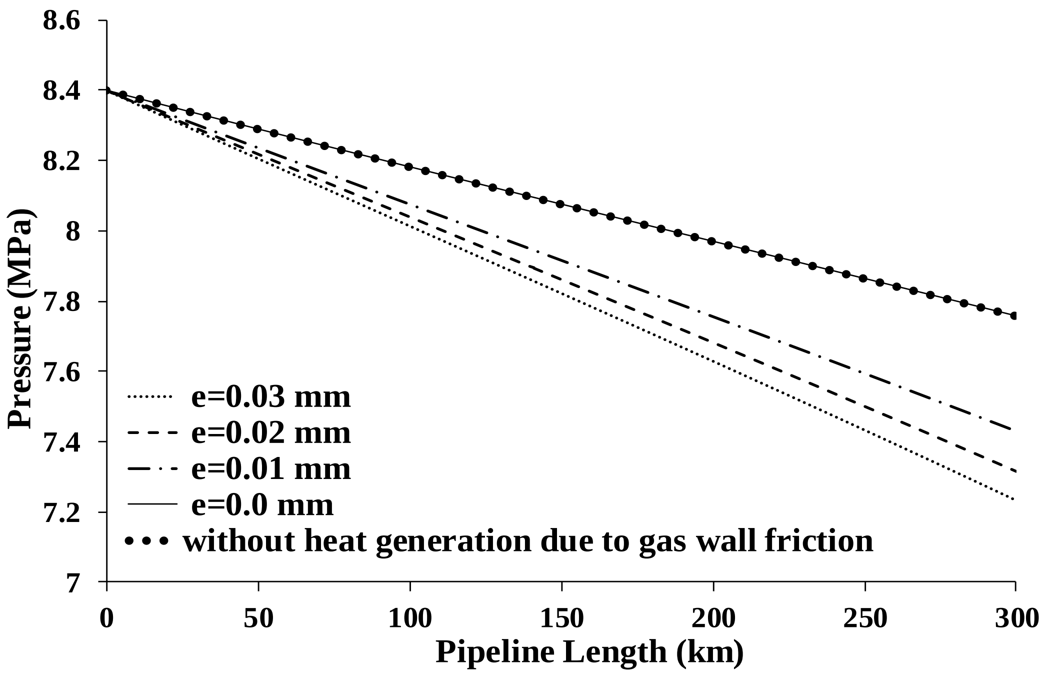

Figure 8.Pressure profile at heat transfer coefficient (k=1.6 *W/m*^{2}*K*) and different values of absolute roughness

4. Conclusion

The numerical model and computer code are developed for the prediction of steady state natural gas flows in transmission pipelines. The model is based on the one-dimensional compressible gas flow.The code is validated by computer simulation of thecase study of natural gas flow in the transmission pipeline reported in [7]. The influence of the heat generation due to the natural gas wall friction on flow parameters of transmission pipeline is investigated. The difference between temperature profiles along the pipeline obtained with and without the heat generation due to gas friction on the pipe wall is clearly shown from the pipeline inlet.Both heat transfer rate from the gas stream to the surroundings and the heat generation due to friction have an influence on the gas temperature profile along the pipeline, while the heat transfer coefficient is more influential. Furthermore, temperature profiles along the pipeline and the pressure drops are presented for different values of absolute roughness.Results of the sensitivity study show that the heat transfer rate from the gas to the pipeline surroundings has an influence on the pressure drop, while the heat generation due to gas friction on the pipeline inner wall has a negligible influence on the pressure drop.

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