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MATHEMATICAL MODEL OF TEMPERATURE PROFILE OF THE TRANSIT GAS-PIPELINE LAID IN THE GROUND

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Abstract: The article describes behavior of the temperature field for the transportation of natural gas in transit gas-pipeline. The most important factors influencing the temperature field are: temperature of the natural gas, flow, thermo-technical parameters of the gas-pipeline material composition and surrounding soil, soil temperature etc. Mathematicals formulas given in the article for the temperature course callculation uses mathematical modeling software Autodesk Simulation Multiphysics. Calculations were performed at different temperatures of natural gas and surrounding environment. With the help of the modeling software heat fluxes, thermal resistances and specifically temperatures in every layer of pipeline and soil were calculated. The result of the mathematical modeling is shown in the graphical form and numeric values where these values were compared with the experimental measured values.

Keywords: temperature field, transit gas-pipeline, mathematical model, model algorithm, Autodesk Simulation Multiphysics

1. INTRODUCTION

The purpose of the task to determine the temperature field from pipeline to the environment is to define the heat flux passing through the pipeline and soil. Temperature field helps to set up the depth and intensity in which transported natural gas can influence on surrounding soil in terms of temperature. It is necessary to solve out factors which influence on the temperature distribution such as temperature of the transported natural gas, material composition of the pipeline, depth of deposit and setting up the thermal properties of the pipe and soil. [1]

2. CHARAKTERISTIC OF PIPING SYSTEM

For international transportation of the natural gas mass transit gas-pipelines held in the soil are used. This pipeline has a diameter DN 1400 with operating pressure 75 bar and depth of deposit 1,2 m over the outer surface of the pipeline. Temperature of the transported natural gas is approximately 40°C (after compressor station).

Transit gas-pipeline is composed from several layers where steel pipeline is essential, it has protective coating on both walls (inner and outer). Steel used in under U.S. standards API X70 Steel, on the inner wall of the pipeline protective epoxy coating is applied. Mechanical spraying of the polyurethane is used as the protective unsulation (Figure 1). The thicknesses of the individual layers of the transit gas pipeline [2, 3]:

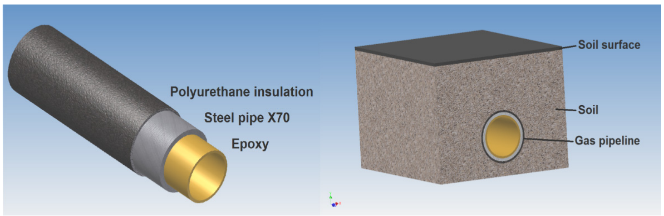

Figure 1: Material composition and imposition of transit gas-pipeline in soil

- Polyurethane insulation (3 – 5 mm)
- Steel pipeline (15 mm)
- Epoxy coating (1 mm)

3. MATHEMATICAL DESCRIPTION OF THE SOLUTION

3.1.Determination of thermal resistance

Linear thermal resistance of the soil layer above in the ground will be set from equation of linear thermal resistance of the body (soil) which surrounds solo cylindrical body (pipeline) in half-limited solid environment. Linear thermal resistance of the pipeline $R_{pipeline}$ and soil R_{soil}:

$$R_{potrubie} = \frac{1}{\alpha_1.D_1} + \frac{1}{2.\lambda_1}.\ln\frac{D_2}{D_1} + \frac{1}{2.\lambda_2}.\ln\frac{D_3}{D_2} + \frac{1}{2.\lambda_3}.\ln\frac{D_4}{D_3} + \frac{1}{\alpha_2.D_4} \ [\mathrm{m.K.W^{-1}}] \tag{1}$$

$$R_{ze\min a} = \frac{1}{2.\lambda_4}.\ln\left[\frac{4}{D_3}.\left(H + \frac{\lambda_4}{\alpha_2}\right)\right] [\mathrm{m.K.W^{-1}}] \tag{2}$$

where: D_1 – inner pipeline diameter [m]; D_2 – outer epoxy diameter [m]; D_3 – steel pipe diameter [m]; D_4 – insulation diameter [m]; D_5 – soil layer diameter [m]; H – depth of pipeline deposit [m]; α_1 – coefficient of heat transfer from the gas to the inner pipe wall [$W.m^{-2}.K^{-1}$]; α_2 – coefficient of heat transfer from the ground to the air [$W.m^{-2}.K^{-1}$]; λ_1 – coefficient of the epoxy thermal conductivity [$W.m^{-1}.K^{-1}$]; λ_2 – coefficient of the steel pipe thermal conductivity [$W.m^{-1}.K^{-1}$]; λ_3 – coefficient of the insulation thermal conductivity [$W.m^{-1}.K^{-1}$]; λ_4 – coefficient of the soil thermal conductivity [$W.m^{-1}.K^{-1}$];

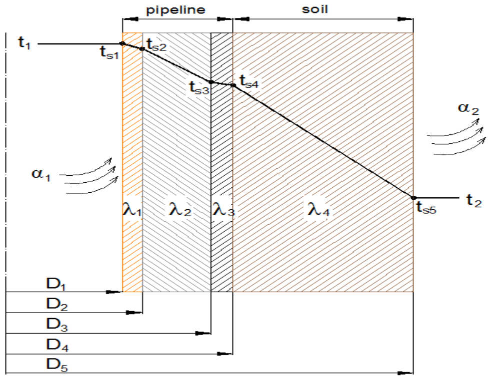

Figure 2: The course of temperature in gas-pipeline and soil

3.2. Determination of heat flow density

Linear density of the dissipation heat flux *q* from gas in pipeline to air above ground and total heat flux *Q* will be determined from these formulas [4]:

$$q = \frac{\pi.(t_1 - t_2)}{R_{tl}} \ [\mathrm{W.m^{-1}}] \tag{3}$$

$$Q = q.L \ [\mathrm{W}] \tag{4}$$

where: t_1 – temperature of transported narutal gas [°C]; t_2 – air temperature [°C]; R_{tl} – total linear thermal resistance [$m.K.W^{-1}$]; L – length of the pipeline [m]

3.3. Determination of temperature in contact of each layer with pipeline and soil

Calculation of temperature t_{s1} on the inner wall of the epoxy coating:

$$\Delta t_1 = \frac{q}{\alpha_1.\pi.D_1} \ [°\mathrm{C}] \tag{5}$$

$$t_{s1} = t_1 - \Delta t_1 \ [°\mathrm{C}] \tag{6}$$

Calculation of temperature t_{s2} (epoxy – steel pipe):

$$t_{s2} = t_{s1} - \frac{q}{2.\pi.\lambda_1}.\ln\frac{D_2}{D_1} \ [°\mathrm{C}] \tag{7}$$

Calculation of temperature t_{s3} (steel pipe – insulation):

$$t_{s3} = t_{s2} - \frac{q}{2.\pi.\lambda_2}.\ln\frac{D_3}{D_2} \ [°\mathrm{C}] \tag{8}$$

Calculation of temperature t_{s4} (outer surface of insulation):

$$t_{s4} = t_{s3} - \frac{q}{2.\pi.\lambda_3}.\ln\frac{D_4}{D_3} \ [°\mathrm{C}] \tag{9}$$

Calculation of temperature t_{s5} on the ground surface:

$$\Delta t_2 = \frac{q}{\alpha_2.\pi.D_5} \ [°\mathrm{C}] \tag{10}$$

$$t_{s5} = t_2 + \Delta t_2 \ [°\mathrm{C}] \tag{11}$$

3.4. Determination of the coefficient of heat transfer

Heat transfer coefficient by convection α depends on liquid properties, its state of motion, used insulation. Heat transfer coefficient is difficult function of greater number of variables determing the whole heat transfer process. [5] Formula for calculation α_1 for forced wrap gas with velocity $v > 1\ m.s^{-1}$ and for inner diameter $D > 0,3\ m$:

$$\alpha_1 = 11,63.\frac{v^{0,7}}{D^{0,3}}\ [\mathrm{W.m^{-2}.K^{-1}}] \tag{12}$$

Formula for calculation α_2 is being acquired from Stefan-Boltzmann law:

$$\alpha_2 = c.\frac{\left(\frac{t_1+273,15}{100}\right)^4 - \left(\frac{t_2+273,15}{100}\right)^4}{t_1 - t_2}\ [\mathrm{W.m^{-2}.K^{-1}}] \tag{13}$$

4. METHODOLOGY SOLUTIONS OF MATHEMATICAL MODEL

4.1. CFD model proposal

CAD pipeline model has been created in 3D drawing software Autodesk Inventor Professional subsequently this model was submitted to simulation in mathematical modelling software called Autodesk Simulation Multiphysics.

Table 1: Thermo-technical parameters of natural gas, for individual materials of the pipeline and soil

	Epoxy	Steel pipeline	Polyurethane insulation	Soil	Natural gas
λ [W.m^{-1}.K^{-1}]	0,35	55	0,02	0,63	0,035
c [J.kg^{-1}.K^{-1}]	1000	500	1540	1756	2200
ϱ [kg.m^{-3}]	1400	7800	45	1670	421

λ – thermal conductivity, c – specific heat capacity, ϱ - density

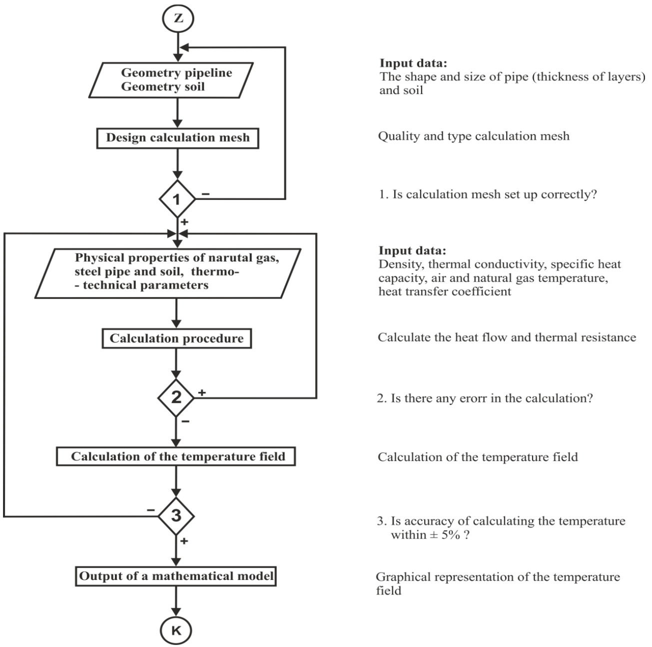

Figure 3: Autodesk Simulation Multiphysics algorithm

4.2. Algorithm solution of field temperature

Physical and thermo-technical parameters, boundary conditions for the determination of total and partial values of thermal resistance, heat flux densities and temperatures in the contact area of each layer of pipeline and soil were added as input into the model.

5. RESULT OF COMPUTER SIMULATION

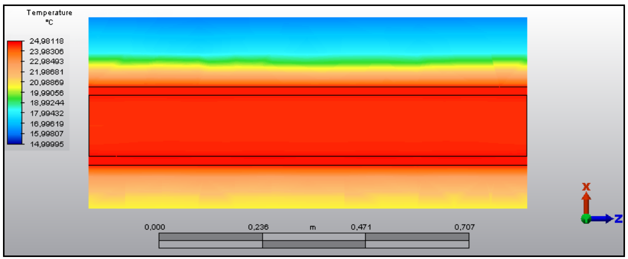

Figure 4: Temperature filed at a temperature of natural gas 26 °C and air 18,3 °C – portrayal after lenght (simulation no. 1)

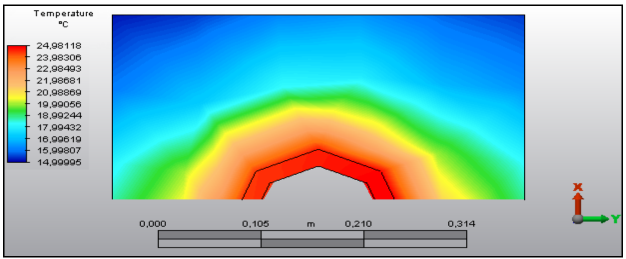

Figure 5: Temperature filed at a temperature of natural gas 26 °C and air 18,3 °C – portrayal in the cut (simulation no. 1)

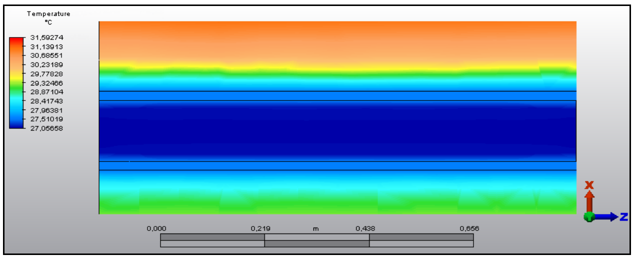

Figure 6: Temperature filed at a temperature of natural gas 28 °C and air 34,1 °C – portrayal after lenght (simulation no. 2)

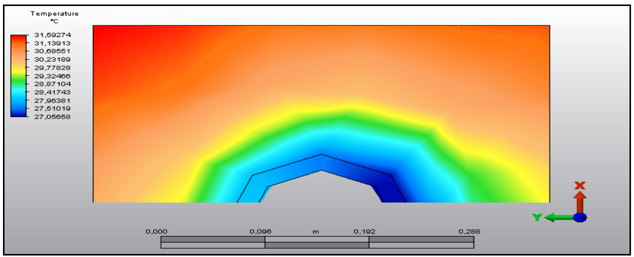

Figure 7: Temperature filed at a temperature of natural gas 28 °C and air 34,1 °C – portrayal in the cut (simulation no. 2)

6. COMPARSION OF MATHEMATICAL MODEL VALUES WITH MEASURED VALUES

The measurement was being performed in sumer-time at air temperature 18,3 °C and 34,1 °C and the temperature of natural gas moved in range of 26 – 28 °C. Temperature process was being observed at different distances from gas – pipeline (Fig. 6).

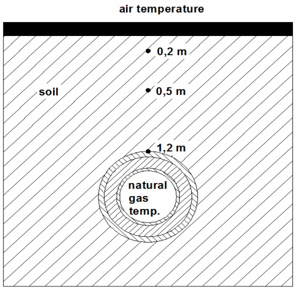

Figure 8: Places measurements of soil temperature

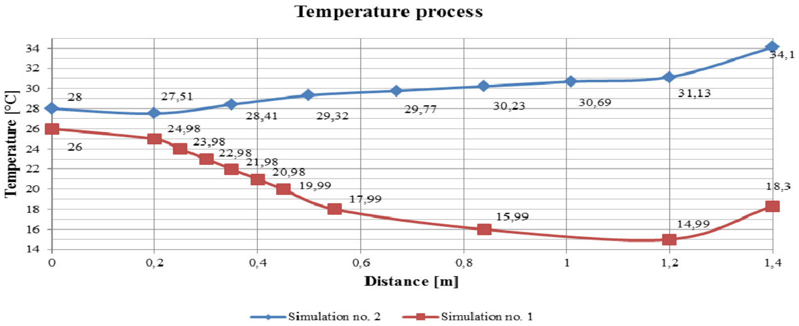

Figure 9: Graph of temperature calculated for both simulations

Table 2: Table of measured and calculated values of the temperature at different soil depths

Depth [m]	Air temperature 18,3 °C; Temperature of transported natural gas 26 °C			Air temperature 34,1 °C; Temperature of transported natural gas 28 °C		
	Measured values [°C]	Calculated values [°C]	Deviation [%]	Measured values [°C]	Calculated values [°C]	Deviation [%]
1,2	13,4	14,99	10,6	29,6	31,13	5
0,5	16,3	17,99	9,4	27,1	29,32	7,6
0,2	25,3	24,98	1,3	27,9	27,51	1,4

8. SUMMARY

By entering the input thermal and physical parameters, initial temperatures and boundary conditions, the temperature process calculation was being done with the help of simulation software called Autodesk Simulation Multiphysics. Result of mathematical model is temperature process from natural gas through layers of transit gas-pipeline and soil on the ground surface. Two simulations for different temperatures of the transported natural gas and surrounding air were preformed. Output of mathematical model is graphical representation of the temperature process (Figure 4 - 7) and graphical dependence (Figure 9). Temperature decrease in pipeline is about 1 °C and more significant change occurs in soil, which is being affected by the air temperature. Values calculated by the simulation program were compared with the measured values in three different spots – on the outer surface of the gas-pipeline, 0,5 m and 0,2 m below ground. Divergences in temperature values are given in Table 2. In technical practicedivergence ± 5 % is allowed. To reduce the divergences there is possibility to change quality settings of the mathematical net of choosing different type of the mathematical net instead, alternatively we could also subdivide model to the a greater number of layers.

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