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USE OF A MATHEMATICAL MODEL FOR CFD ANALYSIS OF MUTUAL INTERACTIONS BETWEEN SINGLE LINES OF TRANSIT GAS PIPELINE

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The article describes the determination of the temperature field around every line of transit pipeline during transportation of natural gas. Method of elementary balances (counts temperatures in three directions) was used to solve the complex temperature field. On the basis of the analysis, it is possible to determine whether it will be influence and to what extent may be influence of individual gas-pipelines. Formulas for calculations used in these models are specified in this article. The results of each models and simulations are shown in the graphical dependences. For the analyses were used: Autodesk Inventor Professional, Matlab, Autodesk Simulation Multiphysics.
Key words: temperature field determination, transit pipeline, natural gas transportation.

Primjena matematičkog modela za CFD analize međusobnim interakcijama između pojedinih linija tranzita plinovoda. Članak opisuje određivanje temperaturnog polja oko svake linije tranzitnog plinovoda tijekom transporta prirodnog plina. Koristi se metoda elementarnih bilanci (računanje temperature u tri pravca) za rješavanje složenog temperaturnog polja. Na temelju analize, moguće je utvrditi da li će biti utjecaj i u kojoj mjeri može biti utjecaj pojedinih plinovoda. Formule korištene za izračune u tim modelima navedene su u ovom članku. Rezultati svakog modela i simulacija prikazani su u grafičkoj ovisnosti. Za analizu su korišteni: Autodesk Inventor Professional, Matlab, Autodesk Simulation Multiphysics.
Ključne riječi: određivanje temperaturnog polja, prolaz cjevovoda, prijevoz prirodnog plina.

INTRODUCTION

Defining the temperature field gives information about course of temperature in the soil to the ground surface. By this information it is possible to set heat loss to the surrounding area. It is very difficult to determine thermal field because of interference of many factors, which physical properties vary with time. Long-term measurement of daily temperature and amplitude determination of the surface temperature are necessary to determination of temperature course in the soil. [1]

METHODOLOGY SOLUTION OF TEMPERATURE FIELDS

For the analysis of interaction with individual lines of gas-pipelines, following points should be determined:

- calculation of soil temperature in the pipe axis for different soil conditions (without affecting gas-pipeline)
- calculation of the pressure and temperature drop during gas transportation in gas-pipeline
- calculation of temperature fields for individual line of the transit gas-pipeline
- graphic evaluation of individual temperature fields

Temperature course in the soil

Soil temperature significantly affects the heat transfer from gas to the environment. Differences in soil temperatures depend on air temperature changes and are characterized by daily and annual course. The rate of change is mainly dependent on physical properties of soil e.g. ability of the soil to absorb solar energy, thermal conductivity and heat capacity. [4]

Based on long-term measurements of air temperature (by determining the average daily temperature, amplitude of the surface temperature, amount of rainfall) and physical properties of soil it is possible to determine temperature course in soil by calculation (1).

$$t_h = t_0 + A_0 \cdot e^{-\frac{h}{B}} \cdot \sin\left(\omega \cdot \tau - \frac{h}{B}\right) \quad [°C] \quad (1)$$

$$B = \sqrt{\frac{2 \cdot a}{\omega}} = \sqrt{\frac{\tau \cdot a}{\pi}}$$

where:

t_h - soil temperature in depth [°C]

t_0 - middle surface temperature in the monitored period [°C]

A_0 - amplitude of the surface temperature [K]

h - depth [m]

B - depth at which the amplitude of the soil temperature is equal to 1/e of the surface temperature amplitude [m]

ω – constant

τ - period (12 months)

a - heat conductivity [$m^2 \cdot s^{-1}$]

Based on the physical properties of soil (Tab.1) calculations for determination of the temperature course at different air temperatures were made. Temperature course was being calculated to the depth of deposit for the whole gas-pipeline route (KS01 – RU, 410 km). Based on the physical properties of the soil (Tab. 1) and on the daily average air temperature can be calculated course of temperature in the soil in case the non-affected of a soil temperature of natural gas (Fig. 1 – 3).

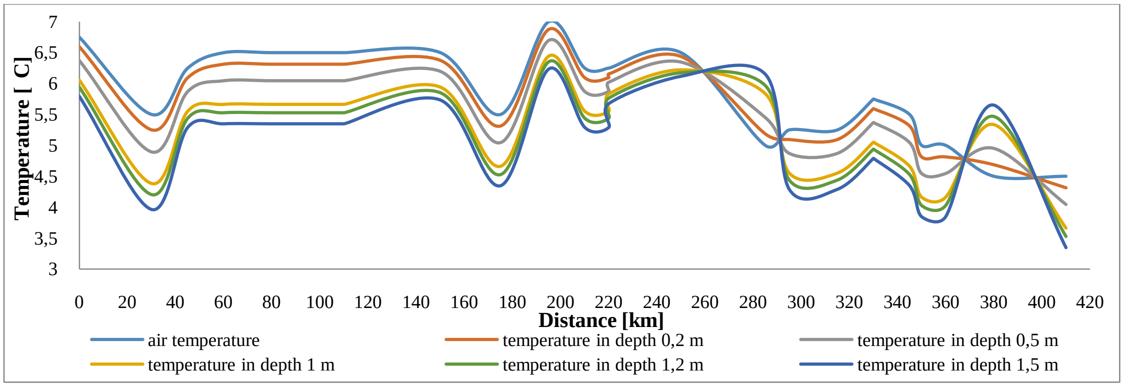

Figure 1. Temperature course in dry soil at positive air temperature
Slika 1. Tijek temperature u suhom tlu pri pozitivnoj temperaturi zraka

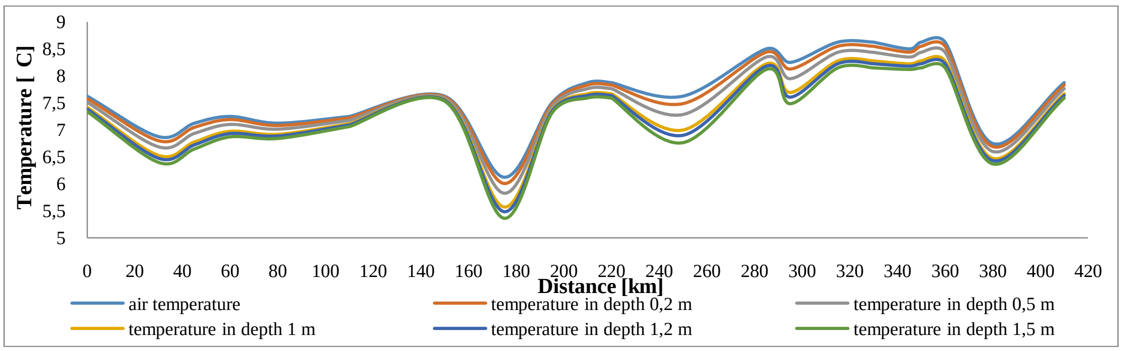

Figure 2. Temperature course in humid soil (precipitation totals 203 mm)
Slika 2. Tijek temperature u vlažnom tlu (ukupne oborine 203 mm)

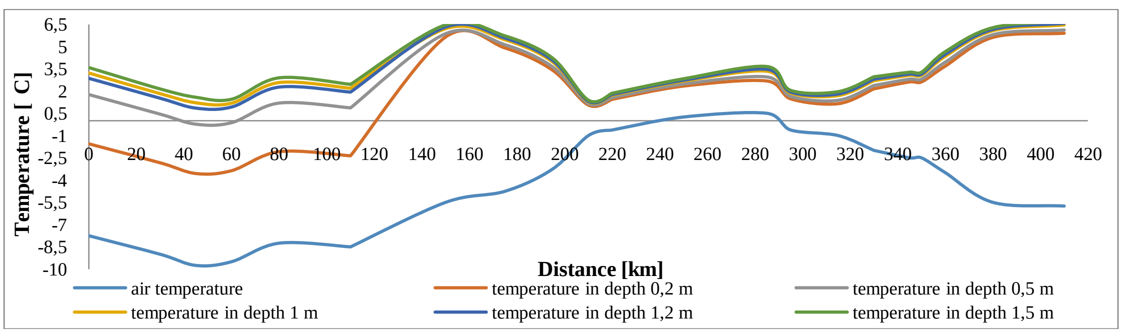

Figure 3. Temperature course in frozen soil at low air temperature
Slika 3. Tijek temperature u smrznutom tlu pri niskoj temperaturi zraka

Table 1. Physical properties of soil
Tablica 1. Fizikalna svojstva tla

Physical properties	Soil state		
	dry	humid	frozen
Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]	0.63	1.93	1.63
Specific heat capacity c_p [$J \cdot kg^{-1} \cdot K^{-1}$]	1756	2104	1485
Density ρ [$kg \cdot m^{-3}$]	1600	1700	1500
Heat conductivity a [$m^2 \cdot s^{-1}$]	$2.24231 \cdot 10^{-7}$	$5.39588 \cdot 10^{-7}$	$6.86027 \cdot 10^{-7}$

Conclusions from measurements and calculations:
- at air temperature higher than 5°C there is decrease in temperature in the soil
- at minus air temperatures soil freezes at certain depth
- at 1 m, the temperature stays in positive numbers regardless of the air temperature

Calculation of temperature and pressure drop of the natural gas

During transportation of natural gas, pressure significantly affects decrease in temperature. For calculation of pressure losses in each elementary sections formula for horizontal gas-pipeline was used (2). [1]

$$p_p^2 - p_k^2 = \frac{\lambda \cdot m^2 \cdot Z \cdot r \cdot T_s \cdot x}{F^2 \cdot d_1} \quad \text{[MPa]} \qquad (2)$$

where:

p_p - initial pressure [MPa]
p_k - final pressure [MPa]
λ - resistance coefficient
m - mass flow of the gas in the pipeline [kg·s^{-1}]
Z - compressibility factor
r - specific gas constant [J·K^{-1}·kg^{-1}]
T_s - middle gas temperature [K]
x - elemental section of pipeline [m]
F - pipeline surface [m^2]
d_1 - internal diameter [m]

When determining the pressure loss for the entire transit system it is necessary to take into account the profile of gas-pipeline route. In section between KS01 and KS02 difference in height reaches 200 m. For this reason, it is necessary to calculate this section with formula of pressure drop in taking into account the relief routes (pipeline with cant) (3). [5]

$$p_p^2 - p_k^2 \cdot e^b = \lambda \cdot m^2 \cdot \frac{Z \cdot r \cdot T_s \cdot x}{F^2 \cdot d_1} \cdot \frac{e^b - 1}{b}$$

[MPa] (3)

$$a = \frac{2 \cdot g}{Z \cdot r \cdot T_s}; \quad b = a \cdot \Delta z$$

where:

g - gravity acceleration [m.s^{-1}]
Δz - pipeline superelevation [m]

Temperature of the flowing gas in the pipeline depends on physical conditions of the gas movement and heat exchange with surrounding. For the calculation of the gas temperature decrease after each elementary section is valid following formula:

$$T = T_{ok} + \left(T_p - T_{ok}\right) \cdot e^{-A \cdot l} - D_{J-T} \cdot \frac{p_p - p_k}{l} \cdot \frac{1 - e^{-A \cdot l}}{A} \quad [\text{K}]$$

(4)

where:

T_{ok} - temperature of the surrounding area [K]
T_p - natural gas temperature [K]
A - base flat [m]
l - total length of the pipeline [m]
D_{J-T} - Joule-Thomson coefficient [K·MPa]

Equation (4) characterizes the temperature distribution along the length of the gas-pipeline. The last term in equation characterizes the Joule-Thomson effect. The influence of Joule-Thomson effect causes a temperature drop in the interval 4 – 6°C. Fig. 4 and 5 shows temperature and pressure drop along the whole length of the gas-pipeline (Places with rapidly increasing temperature and pressure because of the increase both physical parameters at the outlet of the compressor station). [2]

To determine the pressure and temperature differential it was necessary to set boundary conditions shown in Tab. 2 (calculations were performed with use of official flows from Eustream company).

The calculation is performed on the entire route transit pipeline, resp. between all compressor stations (distance between single compressor station is cca. 110 km) (Fig. 4).

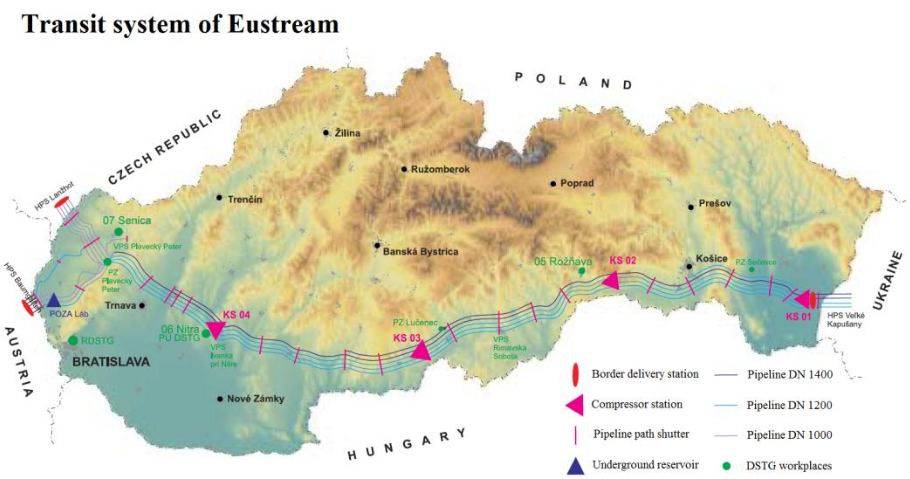

Figure 4. Transit gas pipeline
Slika 4. Prolaženje plinovoda

Table 2. Input data for the calculation of the pipeline temperature regime
Tablica 2. Ulazni podaci za izračun režima temperature plinovoda

Compressor station	Value						
	Output temperature [°C]	Output pressure [MPa]	Flow [mld.m^3/day]	Air temperature [°C]		Temperature in the pipeline axis [°C]	
				Sim 1	Sim 2	Sim 1	Sim 2
KS01	40	6.5	289	6.3	-8.79	5.18	2.34
KS02	30	6.5	288.5	6.3	-3.93	5.37	3.67
KS03	30	6.5	288	5.6	-0.58	5.21	2.54
KS04	40	6.5	287.5	5.04	-3.625	4.3	4.52

On the basis of input data (Tab. 2) calculation was made for pressure and temperature drop of natural gas during transport in transit pipeline for dry and frozen soil (Fig. 5 and 6). The result of calculations of the temperature profile of the transit pipeline consists of initial conditions for the calculation of temperature in soil at influenced by natural gas temperature.

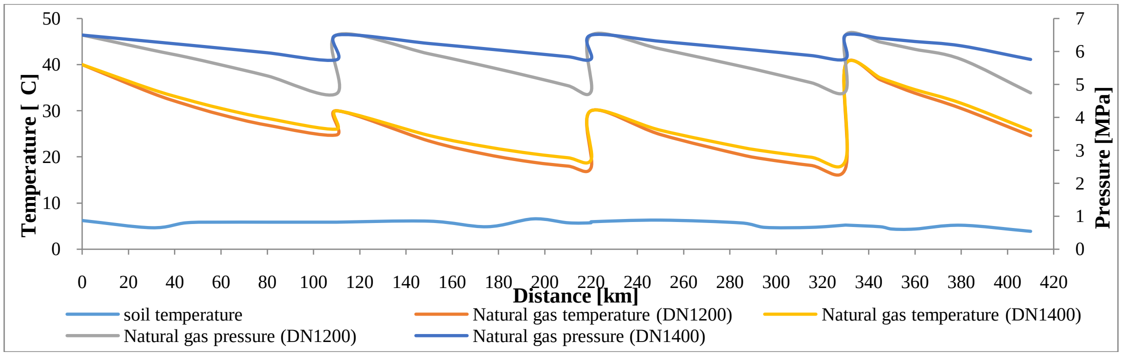

Figure 5. Temperature and pressure course of natural gas at pipeline DN1200 and DN1400 (dry soil), Sim1

Slika 5. Tijek temperature i tlaka prirodnog plina u cjevovodima DN1200 i DN1400 (suho tlo), Sim1

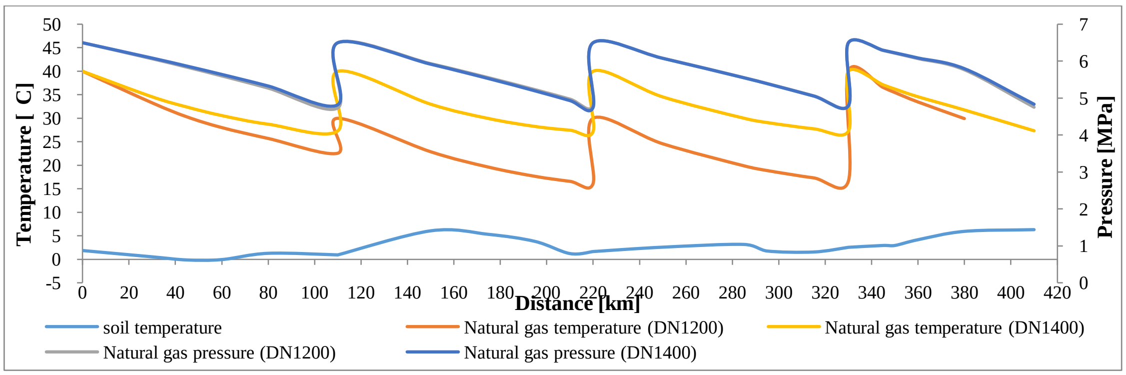

Figure 6. Temperature and pressure course of natural gas at pipeline DN1200 and DN1400 (frozen soil in depth 0.5 m), Sim2

Slika 6. Tijek temperature i tlaka prirodnog plina u cjevovodima DN1200 i DN1400 (smrznuto tlo na dubini 0.5 m), Sim2

Temperature field around gas-pipeline

For solving transient heat transfer in three-dimensional temperature field was used method of elementary balances. This method is based from dividing object to elementary blocks (Δx, Δy, Δz). For each elementary block is formulated balance equation and from the way of solving it is possible to create an algorithm for whole temperature field. For values Δx, Δy, Δz uses the following simplifications:

- inside each elementary block are isothermal surfaces parallel
- heat flux passing through within the interval ($i.\Delta\tau$, $(i+1)\Delta\tau$) by specific area is proportional to the temperature gradient at time ($i.\Delta\tau$)
- enthalpy change of elementary block is a function of temperature change in the middle of an elementary block

Transient heat transfer by conduction in the elementary block is in interval <$i.\Delta\tau$, $(i+1)\Delta\tau$ > characterized by:

- enthalpy change due to the heat transfer by conduction between neighboring elementary blocks through each layers of elementary block.
- by the enthalpy change of elementary block there is a change of temperature in elementary block. [6]

When there are known temperatures in all nodal points of the entity at time $i.\Delta\tau$, then at the time of $(i+1)\Delta\tau$ temperatures in the relevant points can be calculated with following formula:

$$\frac{b}{2}\cdot\left(t_0^{(i+1)}\right)^2+a\cdot t_0^{(i+1)}=t_0^i\cdot\left[\frac{b}{2}\cdot\left(t_0^i\right)+a-2\cdot\lambda\left(t_0^i\right)\cdot\frac{\Delta t}{\rho}\cdot\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}\right)\right]+\frac{\Delta\tau}{\rho}\cdot\lambda\left(t_0^i\right)\left[\frac{\left(t_1^i+t_2^i\right)}{\Delta x^2}+\frac{\left(t_3^i+t_4^i\right)}{\Delta y^2}+\frac{\left(t_5^i+t_6^i\right)}{\Delta z^2}\right] \quad (5)$$

To guarantee the stability of the solution of the equation (5), the following condition must be fulfilled:

$$\frac{b}{2}\cdot\left(t_0^i\right)+a-2\cdot\lambda\left(t_0^i\right)\cdot\frac{\Delta\tau}{\rho}\cdot\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}\right)\geq 0 \quad (6)$$

Calculations were made for specific points within a certain distance from the pipeline. Heat transfer was being monitored upwards from the pipeline axis (Fig. 6, 7, 8) and heat transfer in the pipeline axis from the pipeline (transverse temperature gradient, Fig. 9 and 10). Scheme of pipeline deposition with marked points is in Fig. 9 and 10.

By setting the temperature drop along the length of the pipeline may perform a simulation for calculation of temperature in the soil. Input data are shown in Tab. 3, while the simulations performed for dry, wet and frozen soil (Fig. 7 – 9).

Table 3. Input data
Tablica 3. Ulazni podaci

Compressor station	Air temperature at different condition soils [°C]				1.line	2.line	3.line	4.line	5.line
	dry	humid	frozen						
KS01	6.3	7.2	-8.79	Depth [m]	1.6	1.9	2.1	2.1	1.7
KS02	6.3	7.37	-3.93						
KS03	5.6	8.25	-0.58						
KS04	5.04	8.16	-3.62						

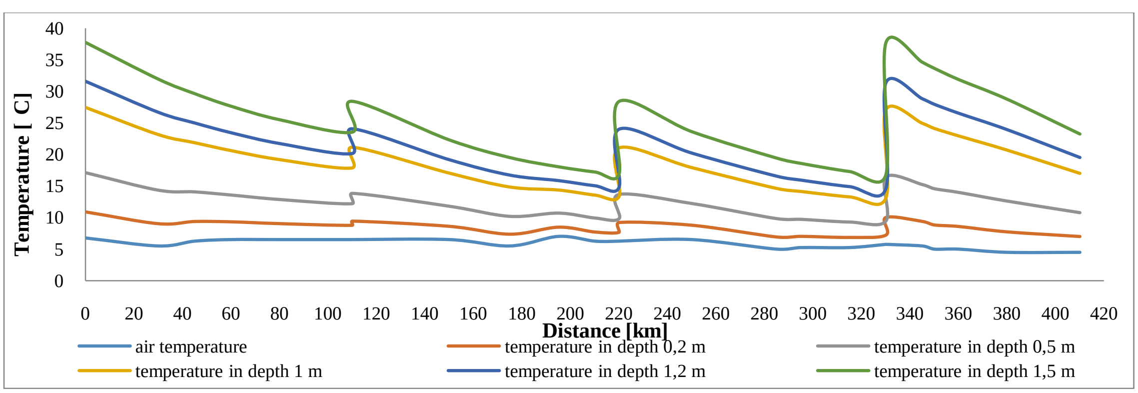

Figure 7. Temperature course in dry soil at interaction transit gas pipeline
Slika 7. Tijek temperature u suhom tlu pri interakciji prolaza plina cjevovodom

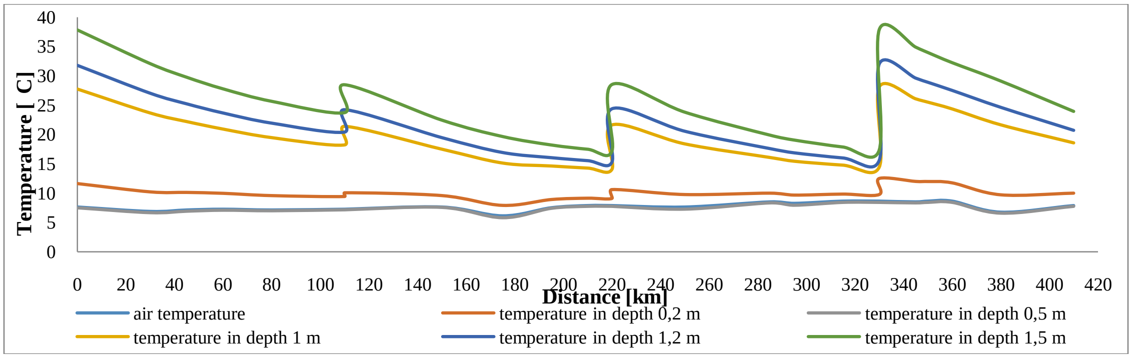

Figure 8. Temperature course in humid soil at interaction transit gas pipeline
Slika 8. Tijek temperature u vlažnom tlu pri interakciji prolaza plina cjevovodom

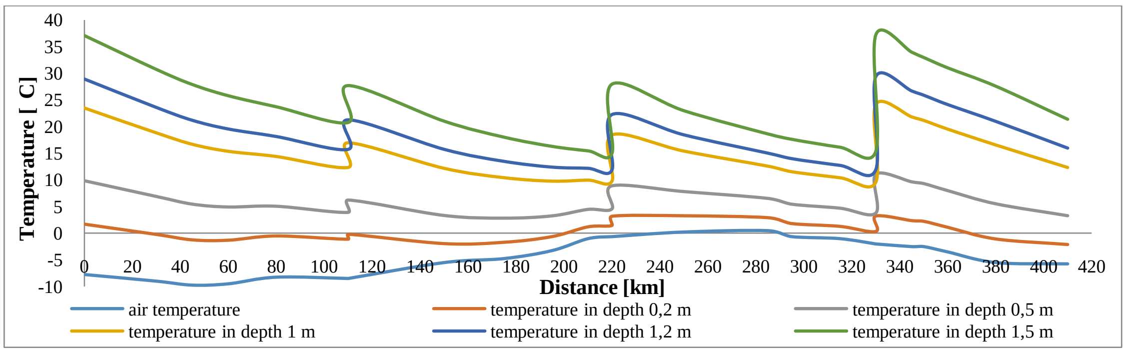

Figure 9. Temperature course in frozen soil at interaction transit gas pipeline
Slika 9. Tijek temperature u smrznutom tlu pri interakciji prolaza plina cjevovodom

Result analysis

The deposit depth of the individual lines of transit gas-pipeline are shown in Tab. 3, distance between each pipeline is circa 30 m. By mathematical model created with the help of software called Matlab Simulink it was found that although there is adequate distance between gas-pipelines from each other, there is an influence of temperature fields of each pipeline (Fig. 10 and 11, moist soil (blue), dry soil (red), frozen soil (orange)). The next step was to carry out the simulations in Autodesk Simulation Multiphysics (Fig. 12 and 13), while results were consistent with the mathematical model.

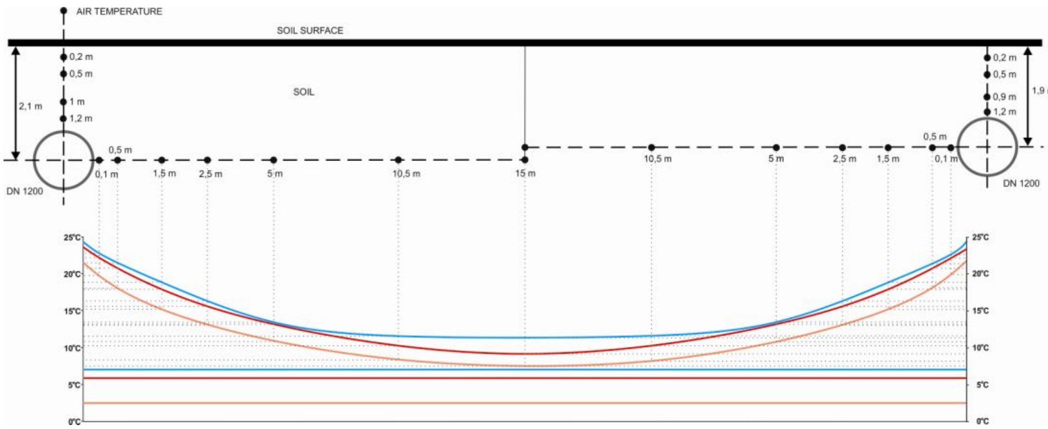

Figure 10. Temperature course between 2. and 3. line of transit gas pipeline
Slika 10. Tijek temperature između 2. i 3. linije prolaza plina cjevovodom

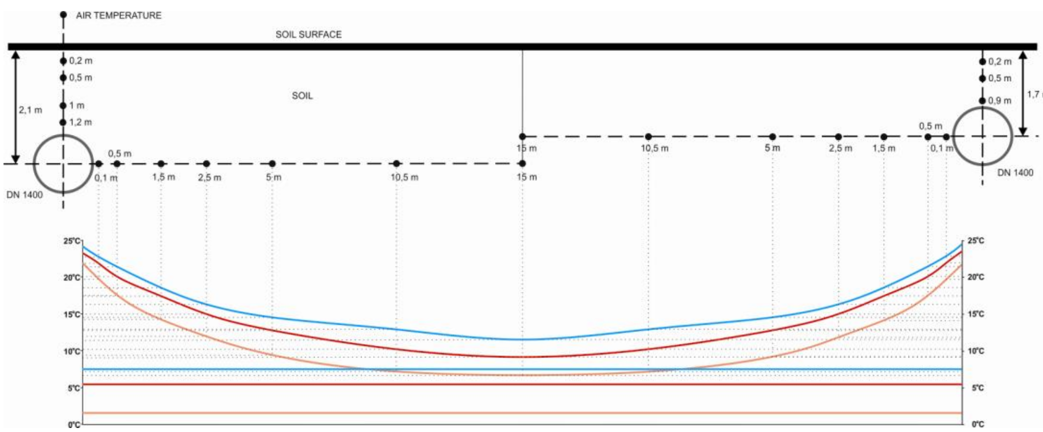

Figure 11. Temperature course between 4. and 5. line of transit gas pipeline
Slika 11. Tijek temperature između 4. i 5. linije prolaza plina cjevovodom

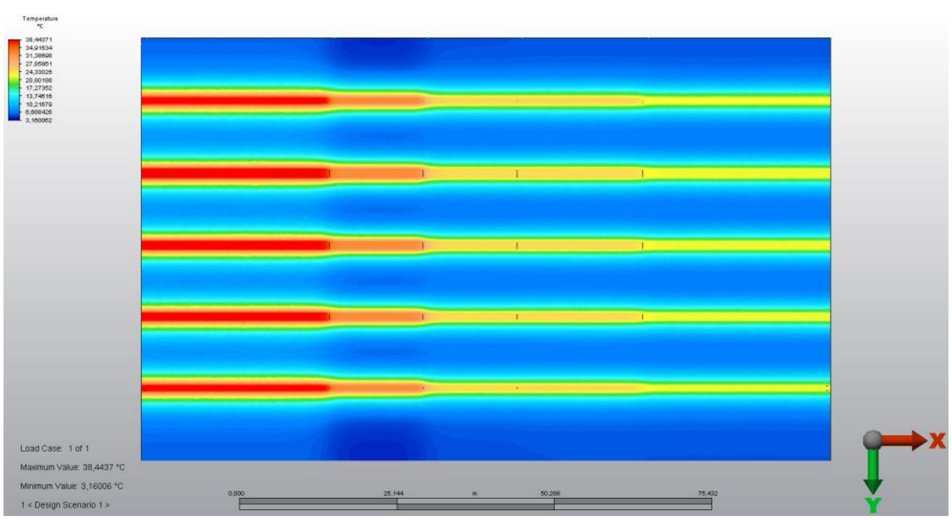

Figure 12. Section of temperature field transit gas pipeline
Slika 12. Presjek temperaturnog polja prolaza plina cjevovodom

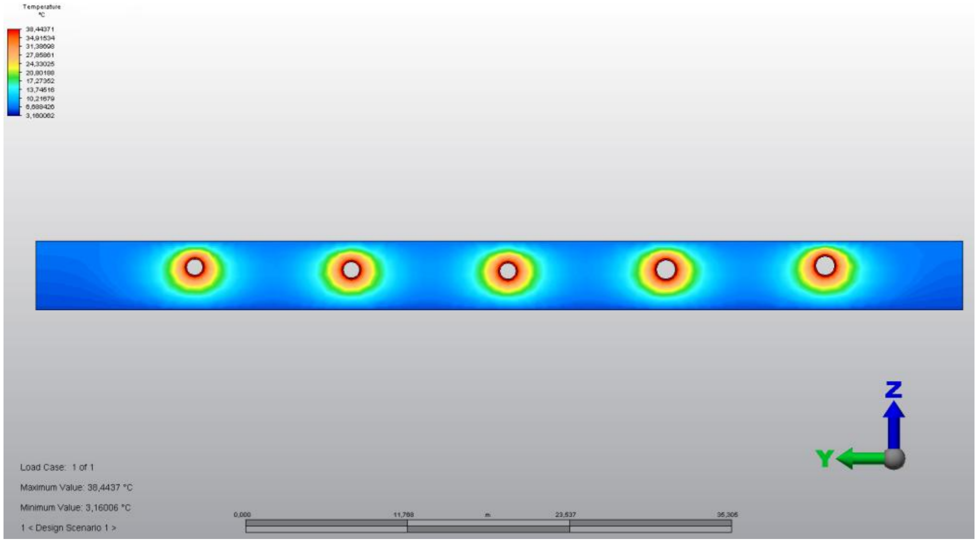

Figure 13. Visualisation of mutual interaction between single lines of transit gas pipeline
Slika 13. Vizualizacija međusobne interakcije između pojedinih prolaza plina cjevovodom

CONCLUSION

The main aim of this paper was to calculate temperature course in soil during transportation of the natural gas in transit gas-pipeline. In the first place we calculated temperature course in soil to deposit depth of transit gas-pipeline for the whole route of gas-pipeline. For the performed calculations we used program MS Excel whereby output is in the form of a graphical dependencies (Fig. 1 - 3). In the next step temperature and pressure profile of natural gas was being calculated in program Matlab Simulink (Fig. 5 and 6). These calculations were used as input data for calculation of temperature field (Fig. 7 - 9). When comparing the temperature courses in soil, it is obvious that transit gas-pipeline greatly affects soil temperature field, character of temperature course is completely changing. In the next step affection simulations of lines of gas-pipeline were performed. Temperature course was calculated with the method of elementary balances. On the basis of calculations and outputs of a mathematical model following was found:

- decrease in flow does not have cardinal importance in the temperature and pressure decrease of natural gas
- on the gas temperature drop has higher impact Joule-Thomson effect more than temperature of surrounding area
- temperature drop through the pipe wall reached 0.25°C at different pipe diameter and various gas temperature.
- gas temperature greatly influences the temperature course in soil towards ground surface and also at transverse temperature gradient.
- At the distance 30 m from individual lines of gas-pieplines there is an influence of soil temperature, it does not matter whether the pipes has various diameters.
- The highest temperature drop was being observed at frozen soil, where soil was frozen to a depth of 0.5 m. Temperature in the gas-pipeline was in the range 30 – 40°C and temperature in depth of 0.2 m reached minus temperatures.

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