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APPLICATION FOUR DIMENSIONAL MATRIX IN CYLINDRICAL COORDINATES FOR ANALYSIS OF GAS PIPELINE TEMPERATURE FIELD

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Abstract: The paper discusses about the calculation of temperature in the frozen soil, pressure and temperature regime of natural gas with a subsequent effect on the temperature field of the transit gas pipeline. Determinig the isotherms around the pipeline include certain sequence calculation. The first step is the calculation of temperature in the soil (change of physical parameters) for boundary condition $\tau = 0$. The second step is to calculate the pressure and temperature regime of natural gas between compressor stations. The third step is the determination of the temperature field of the transit pipeline, which provides methods for elementary balance (three dimensional temperature field). The result for the mathematical model is the extent to which it affects the natural gas temperature of the surrounding environment.
Keywords: temperature field, transit pipeline, temperature and pressure drop of natural gas

1. 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]

2. METHODOLOGY SOLUTION OF TEMPERATURE FIELD

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 soil conditions
- calculation of the pressure and temperature drop during gas transportation in gas-pipeline
- calculation of temperature field for one line of the transit gas-pipeline
- calculation of computing mesh for temperature field
- analysis of temperature fields by using computer simulation
- graphic evaluation of temperature fields

2.1. 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).

$$t_h = t_0 + A_0.e^{-\frac{h}{B}}.\sin\left(\omega.\tau - \frac{h}{B}\right)\ [^\circ C], B = \sqrt{\frac{2.a}{\omega}} = \sqrt{\frac{\tau.a}{\pi}} \qquad (1)$$

where t_h is soil temperature in depth [°C], t_0 is middle surface temperature in the monitored period [°C], A_0 is amplitude of the surface temperature [K], h is depth [m], B is depth at which the amplitude of the soil temperature is equal to 1/e of the surface temperature amplitude [m], ω is constant, τ is period (12 months), a is heat conductivity [m^2.s^{-1}]

In the case of negative air temperature the soil freezes at some depth. At the time $\tau = 0$ there is the temperature changes suddenly on the surface of humid soil to a value T_W, which is less than the freezing temperature T_Z. Based on the above a frozen layer of various thicknesses $\xi = \xi(\tau)$ creates. The lower limit of freezing soil have always temperature T_Z. At this borderline it will transform from one phase to another with discharged released latent heat $l_{2,1}$ (Figure 1). On the condition that there is only heat transfer by conduction, calculation applies [2]:

$$\frac{\partial T_1(x,\tau)}{\partial \tau} = a_1 \frac{\partial^2 T_1(x,\tau)}{\partial x^2}; (\tau > 0, 0 < x < \xi); T_1(x,0) = T_0 = \text{konst.} \quad (2)$$

$$\frac{\partial T_2(x,\tau)}{\partial \tau} = a_2 \frac{\partial^2 T_2(x,\tau)}{\partial x^2}; (\tau > 0, 0 < x < \infty); \frac{\partial T_2(\infty,\tau)}{\partial x} = 0 \quad (3)$$

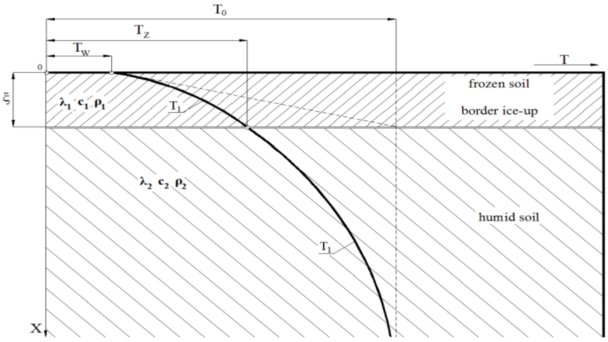

Figure 1. Frozen soil

Ice-up border:

$$T_1(\xi,\tau) = T_2(\xi,\tau) = T_Z = \text{konst.} \quad (4)$$

The 5[th] type boundary condition:

$$\lambda_1 \frac{\partial T_1(\xi,\tau)}{\partial x} - \lambda_2 \frac{\partial T_2(\xi,\tau)}{\partial x} = l_{2,1}.W.\rho_2.\frac{d\xi}{d\tau} \quad (5)$$

Table 1. Physical properties of soil

Physical properties	Soil state		
	dry	humid	frozen
Thermal conductivity λ [W.m^{-1}.K^{-1}]	0,63	1,93	1,63
Specific heat capacity $c\rho$ [J.kg^{-1}.K^{-1}]	1756	2104	1485
Density ρ [kg.m^{-3}]	1600	1700	1500
Heat conductivity a [m^2.s^{-1}]	2,24231.10^{-7}	5,39588.10^{-7}	6,86027.10^{-7}

Based on the physical properties of soil (Table1) 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).

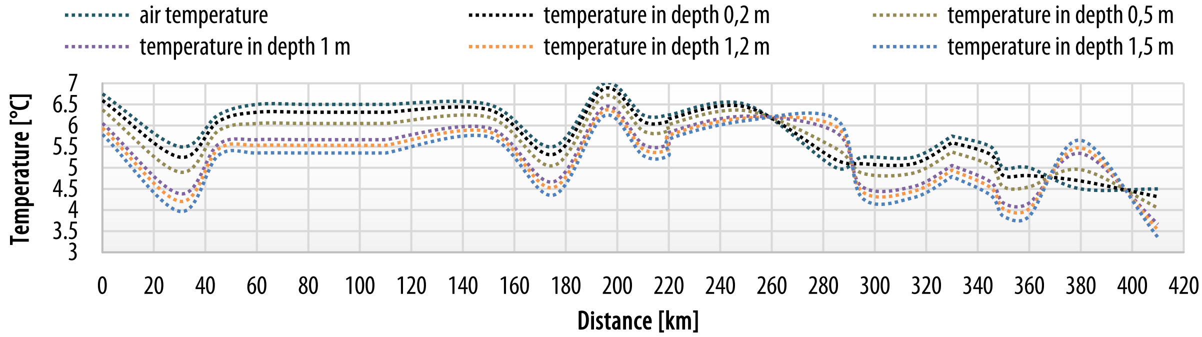

Figure 2. Temperature course in dry soil at positive air temperature

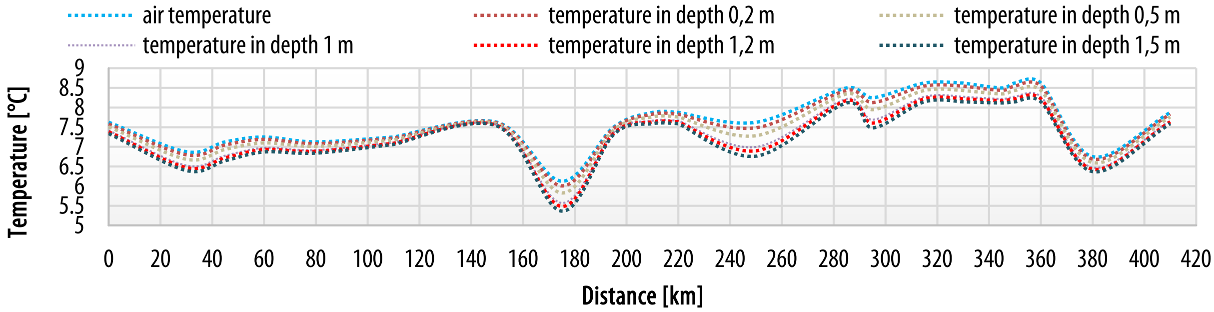

Figure 3. Temperature course in humid soil (precipitation totals 203 mm)

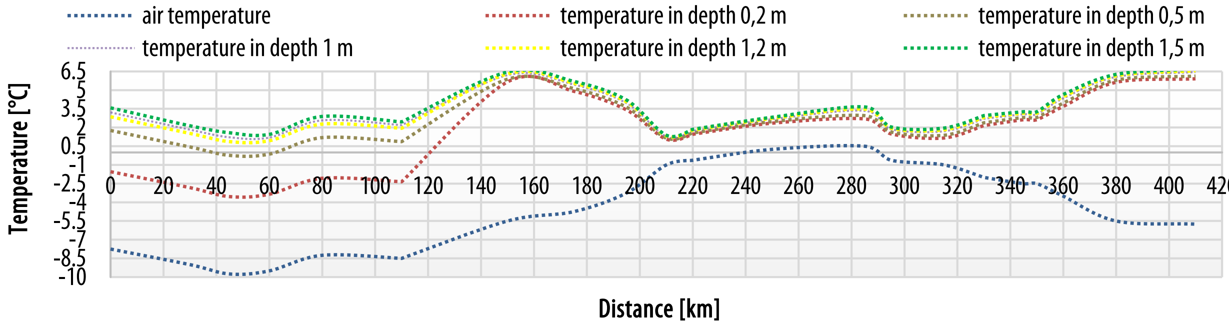

Figure 4. Temperature course in frozen soil at low air temperature

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

2.2. Temperature and pressure drop of 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 (6). [6]

$$p_p^2 - p_k^2 = \frac{\lambda . m^2 . Z . r . T_S . x}{F^2 . d} \; [\mathrm{MPa}] \tag{6}$$

where p_p is initial pressure [MPa], p_k is final pressure [MPa], λ is resistance coefficient, m is mass flow of the gas in the pipeline [kg.s^{-1}], Z is compressibility factor, r is specific gas constant [J.K^{-1}.kg^{-1}], T_s is middle gas temperature [K], x is elemental section of pipeline [m], F is pipeline surface [m^2], d is 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) (7). [6]

$$p_p^2 - p_k^2 . e^b = \lambda . m^2 . \frac{Z . r . T_S . x}{F^2 . d} . \frac{e^b - 1}{b} \; [\mathrm{MPa}], a = \frac{2 . g}{Z . r . T_S}, b = a . \Delta z \tag{7}$$

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

The basic prerequisite for the calculation of pressure drop in the pipeline is to determine the appropriate value of the coefficient of resistance, which in itselt implies the complex nature of flow effects resulting from the properties of the pipe (diameter, surface roughness of the pipe). Equation for the area of roughness pipes, Re > Re_{k2}

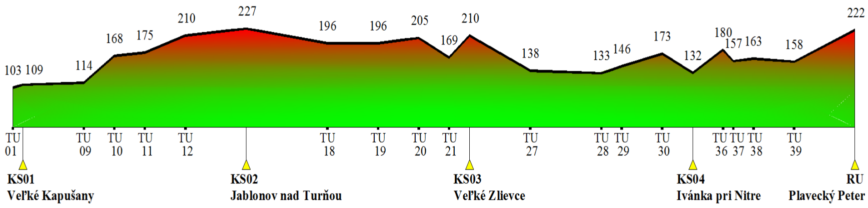

Figure 5. Superelevation of transit pipeline

$$\lambda = 0{,}111 . \left(\frac{\delta}{d} \right)^{0{,}25} \tag{8}$$

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:

$$T = T_{ok} + \left(T_p - T_{ok} \right) . e^{-A.l} - D_{J-T} . \frac{p_p - p_k}{l} . \frac{1 - e^{-A.l}}{A} \; [\mathrm{K}] \tag{9}$$

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

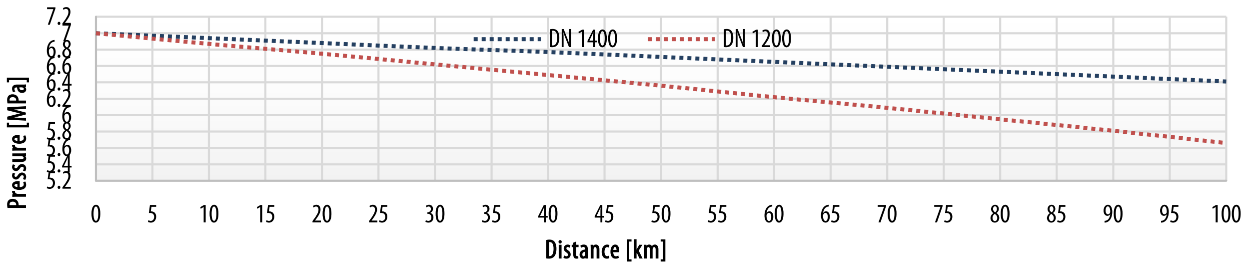

Figure 6. Pressure drop between two compressor stations

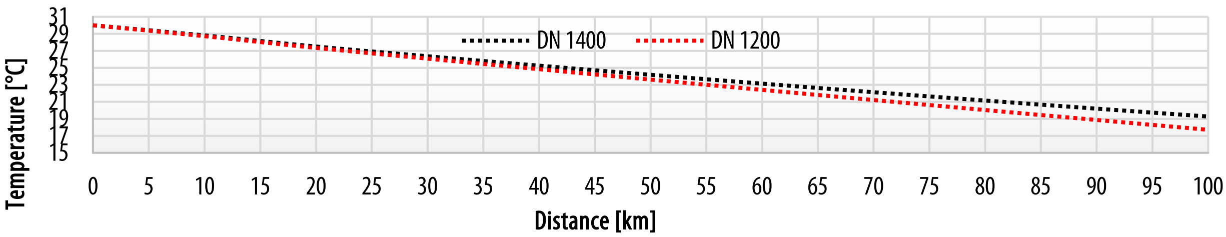

Figure 7. Temperature drop between two compressor stations

Equation (9) 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. Figure 6 and 7 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]

During transport of the natural gas in transit pipeline, ball valves, gas collectors and other gas systems there is a change of pressure and temperature of transported natural gas in consequence of expansion or compression of natural gas. This phenomenon is characterized by the Joule-Thomson effect and the value μ_{J-T} and it is called the Joule-Thomson coefficient. In the process of expansion when the gas is in thermodynamic equilibrium, this process is called isentropic expansion. In this case gas performs work during expansion and its temperature is lowered. In the expansion gas does not do any work, and it does not absorb any heat, internal energy of the gas is maintained. Ideal gas temperature remains constant, but the real gas temperature may change depending on the temperature and the pressure. If the gas pressure drops to 0,1 MPa, its temperature drops to 0,25°C. [4]

$$D_{J-T}=\left(\frac{\Delta T}{\Delta p}\right)_H \tag{10}$$

2.3. Heat transfer through the cylindrical wall

Equation to calculate the heat transfer coefficient has the following form:

$$k=\frac{1}{\frac{1}{\alpha_1.d_1}+\frac{1}{2.\lambda_1}\ln\frac{d_2}{d_1}+\frac{1}{2.\lambda_2}\ln\frac{d_3}{d_2}+\frac{1}{2.\lambda_3}\ln\frac{d_4}{d_3}+\frac{1}{\alpha_2.d_4}}\left[W.m^{-1}.K^{-1}\right] \tag{11}$$

where α_1 coefficient of heat transfer from the gas flow to the inner pipe wall[W.m^{-2}.K^{-1}], α_2 coefficient of heat transfer from the outer surface of the pipes to the surrounding environment[W.m^{-2}.K^{-1}], λ_1 thermal conductivity of steel pipeline [W.m^{-1}.K^{-1}], λ_2 epoxy thermal conductivity [W.m^{-1}.K^{-1}], λ_3 thermal conductivity of insulation [W.m^{-1}.K^{-1}], d_1 inner diameter of pipeline [m], d_2 outer diameter of the steel pipe layer [m], d_3 outer diameter of the eposy layer [m], d_4 outer diameter of the insulation layer [m]

Calculation of α convection is determined from the Nusselt criterion equation:

$$\alpha_1=\frac{\dfrac{\left(\frac{\xi}{8}\right).Pr.Re}{1+12{,}7\sqrt{\frac{\xi}{8}}.\left(Pr^{\frac{2}{3}}-1\right)}.\left[1+\left(\frac{d}{l}\right)^{\frac{2}{3}}\right].\lambda}{d}\left[W.m^{-2}.K^{-1}\right] \tag{12}$$

Calculation of α radiation is determined from the Stefan-Boltzmann law:

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

where $c = 5{,}68$ [W.m^{-2}.K^{-4}]

Table 2. Values thermo-physical parameters for the transfer of heat through the cylindrical wall

Distance [km]	Pressure [MPa]	Temp. [°C]	DN 1200			DN 1400			
			k [W.m^{-1}.K^{-1}]	q [W.m^{-1}]	t_1 [°C]	k [W.m^{-1}.K^{-1}]	q [W.m^{-1}]	t_1 [°C]	t_2 [°C]
0	7	30	10,98	491,64	29,9	12,8	572,89	29,9	30
10	6,87	28,72	10,8	431,38	28,63	12,58	502,67	28,63	28,72
20	6,75	27,42	10,61	405,51	27,34	12,36	472,54	27,34	27,42
30	6,63	26,16	10,43	340,94	26,09	12,15	397,3	26,09	26,16
40	6,5	24,91	10,25	286,82	24,85	11,94	334,23	24,85	24,91
50	6,37	23,69	10,07	267,11	23,63	11,74	311,27	23,63	23,69
60	6,24	22,48	9,9	193,84	22,44	11,54	225,88	22,44	22,48
70	6,1	21,28	9,74	176,8	21,24	11,35	206,03	21,24	21,28
80	5,96	20,1	9,57	123,31	20,07	11,16	143,7	20,07	20,1
90	5,82	18,93	9,41	42,28	18,92	10,97	49,28	18,92	18,93
100	5,68	17,78	9,26	44,49	17,77	10,79	51,85	17,77	17,78

t_1 – temperature on the outer wall, t_2 – temperature on the inner wall

Table 3. Temperature difference on the inside and outside of the steel pipe for diameters DN1200 and DN1400

Distance [km]	10	20	30	40	50	60	70	80	90	100
	Temperature different[°C]									
DN 1200	0,081	0,076	0,064	0,054	0,05	0,036	0,033	0,023	0,008	0,008
DN 1400	0,081	0,076	0,064	0,054	0,05	0,036	0,033	0,023	0,008	0,008

Linear thermal resistance of the soil layer above the buried pipelines is determined from the equation of linear thermal resistance of the body (soil) surrounding a solitary cylindrical body (pipeline).

$$\text{for } H \langle 2D \Rightarrow R_{soil} = \frac{1}{2.\lambda_{soil}} \ln\left[\frac{2.H}{D} + \sqrt{\left(\frac{2.H}{D}\right)^2 - 1}\right] \left[m.K.W^{-1}\right] \quad (14)$$

$$\text{for } H \rangle 2D \Rightarrow R_{soil} = \frac{1}{2.\lambda_{soil}} \ln\frac{4.H}{D} \left[m.K.W^{-1}\right] \quad (15)$$

where *H* is depth in soil [m], *D* is outer diameter of pipeline [m], R_{soil} is linear thermal resistance of soil [m.K.W^{-1}]

Linear thermal resistance of the heat transfer from natural gas in the pipe through the pipe wall with insulaiton and soil above him in the air above the soil is defined by[2]

$$R = \frac{1}{\alpha_1.D} + \frac{1}{2.\lambda_{ins}} \ln\frac{D_{ins}}{D} + \frac{1}{2.\lambda_{soil}} \ln\left[\frac{4}{D_{ins}}.\left(H + \frac{\lambda_{soil}}{\alpha_2}\right)\right] \left[m.K.W^{-1}\right] \quad (16)$$

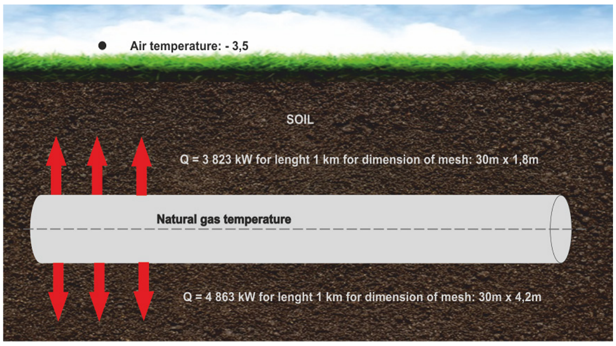

Figure 8. Heat flux from the natural gas into the soil

2.4. Calculation of temperature field in cylindrical wall

The method of elementary balances was used to resolve unsteady heat transfer in three dimensional temperature field. For each element is formulated balance equation and from the way of solving it is possible to create an algorithm for whole temperature field. For values *Δr, Δφ, Δz* uses the following simplifications:

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

Transient heat transfer by conduction in the element is in interval <*i.Δτ, (i+1)Δτ*> characterized by:

- enthalpy change due to the heat transfer by conduction between neighboring elements through each layers of element
- by the enthalpy change of element there is a change of temperature in element [5]

Transit pipeline has a cylindrical shape so it is necessary to perform a calculation in cylindrical coordinates. The beginning of the coordinate system is placed in a thermally isolated suface of the cylinder, the axis of the cylindrical coordinates will by placed on the axis of the cylinder. System of equation of heat transfer in a cylindrical wall has the form:

$$\tau \rangle 0; r_1 \langle r \langle r_2; 0 \langle \varphi \langle 2\pi; 0 \langle z \langle L \quad (17)$$

$$\frac{\partial T(r,\varphi,z,\tau)}{\partial\tau} = a.\left[\frac{\partial^2 T(r,\varphi,z,\tau)}{dr^2} + \frac{1}{r}.\frac{\partial T(r,\varphi,z,\tau)}{dr} + \frac{1}{r^2}.\frac{\partial^2 T(r,\varphi,z,\tau)}{d\varphi^2} + \frac{\partial^2 T(r,\varphi,z,\tau)}{dz^2}\right] \quad (18)$$

The principle is to create elements, in which temperatures are monitored. Each element has determined spatial coordinate system at a distance *Δz* diversions according to the angle *Δφ* and spacing depending on the radius *Δr*. Points corresponding to the individual surfaces of the element are indicated as *0, a, b, c, d, e, f* (Figure 9), while the value of the temperature at the point *0* is determined by the listed points. [1,4]

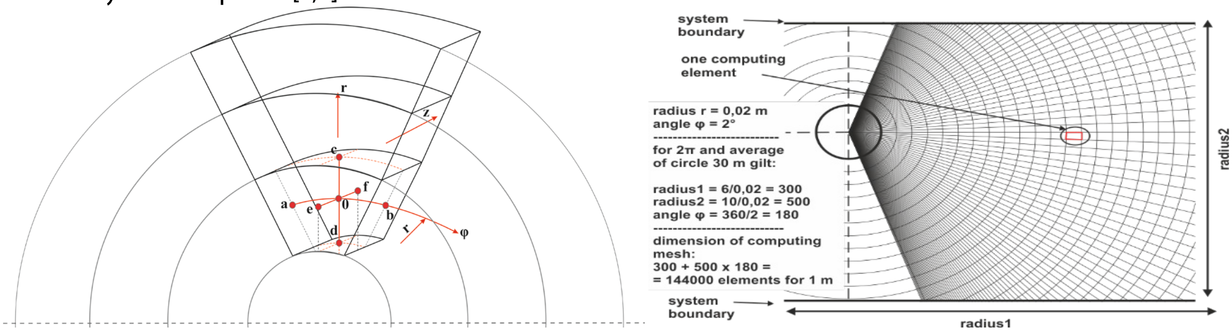

Figure 9. Calculate of element of computing mesh

Computing mesh:

- In the direction of the radius 0, 1, 2, 3, ... i-1, i, i+1
- In the direction fo the axis z 0, 1, 2, 3, ... m-1, m, m+1
- In the tangential direction 0, 1, 2, 3, ... n-1, n, n+1

- $T_{i,n,m,k}$ – temperature value at the point of computing mesh 0 (r_i, φ_n, z_m)
- $T_{i-1,n,m,k}$ – temperature value at the point of computing mesh d (r_{i-1}, φ_n, z_m)
- $T_{i+1,n,m,k}$ – temperature value at the point of computing mesh c (r_{i+1}, φ_n, z_m)
- $T_{i,n-1,m,k}$ – temperature value at the point of computing mesh a (r_i, φ_{n-1}, z_m)
- $T_{i,n+1,m,k}$ – temperature value at the point of computing mesh b (r_i, φ_{n+1}, z_m)
- $T_{i,n,m-1,k}$ – temperature value at the point of computing mesh e (r_i, φ_n, z_{m-1})
- $T_{i,n,m+1,k}$ – temperature value at the point of computing mesh f (r_i, φ_n, z_{m+1})

On the basis of Taylor polynom is determined by the temperature T, which is a function of four variables:

$$T_{i+1,n+1,m+1,k+1} = T_{i,n,m,k} = \frac{1}{1!}.\left(\frac{\partial}{\partial r}\Delta r + \frac{\partial}{\partial \varphi}\Delta\varphi + \frac{\partial}{\partial z}\Delta z + \frac{\partial}{\partial \tau}\Delta\tau\right)T_{i,n,m,k}\frac{1}{2!}.\left(\frac{\partial}{\partial r}\Delta r + \frac{\partial}{\partial \varphi}\Delta\varphi + \frac{\partial}{\partial z}\Delta z + \frac{\partial}{\partial \tau}\Delta\tau\right)T_{i,n,m,k} + \ldots + \varepsilon_1 \quad (19)$$

$$\varepsilon_1 = \frac{1}{(l+1)!}.\left(\frac{\partial}{\partial r}\Delta r + \frac{\partial}{\partial \varphi}\Delta\varphi + \frac{\partial}{\partial z}\Delta z + \frac{\partial}{\partial \tau}\Delta\tau\right)^{i+1}.T(r_1 + \beta_1\Delta r, \varphi_n + \beta_2\Delta\varphi, z_m - \beta_3\Delta z, \tau_k + \beta_4\Delta\tau) \quad (20)$$

For the temperature in the next time step is:

$$T_{i,n,m,k+1} = \left[1 - 2.\left(\Delta Fo_r + \Delta Fo_\varphi + \Delta Fo_z\right)\right].T_{i,n,m,k} + \Delta Fo_r.\left(1 - \frac{\Delta r}{2r_i}\right).T_{i-1,n,m,k} + $$
$$+ \Delta Fo_r.\left(1 + \frac{\Delta r}{2r_i}\right).T_{i+1,n,m,k} + \Delta Fo_\varphi.\left(T_{i,n-1,m,k} + T_{i,n+1,m,k}\right) + \Delta Fo_z.\left(T_{i,n,m-1,k} + T_{i,n,m+1,k}\right) \quad (21)$$

and:

$$\Delta Fo_r = \frac{a.\Delta\tau}{\Delta r^2}; \Delta Fo_\varphi = \frac{a.\Delta\tau}{r_i^2.\Delta\varphi^2}; \Delta Fo_z = \frac{a.\Delta\tau}{\Delta z^2} \quad (21)$$

The stability condition of systemu, which is the basis for determining of the temperature field in the layer cylinder. [3]

$$0\langle\left[1 - 2.\left(\Delta Fo_r + \Delta Fo_\varphi + \Delta Fo_z\right)\right]\langle 1 \quad (22)$$

The equation shows that, when the temperature at the point 0 is known, as well as in neighbouring points that surround this point in time τ_k temperature field in the layer of the cylinder at the moment of time τ_{k+1} is counted.[3,4]

3. RESULTS

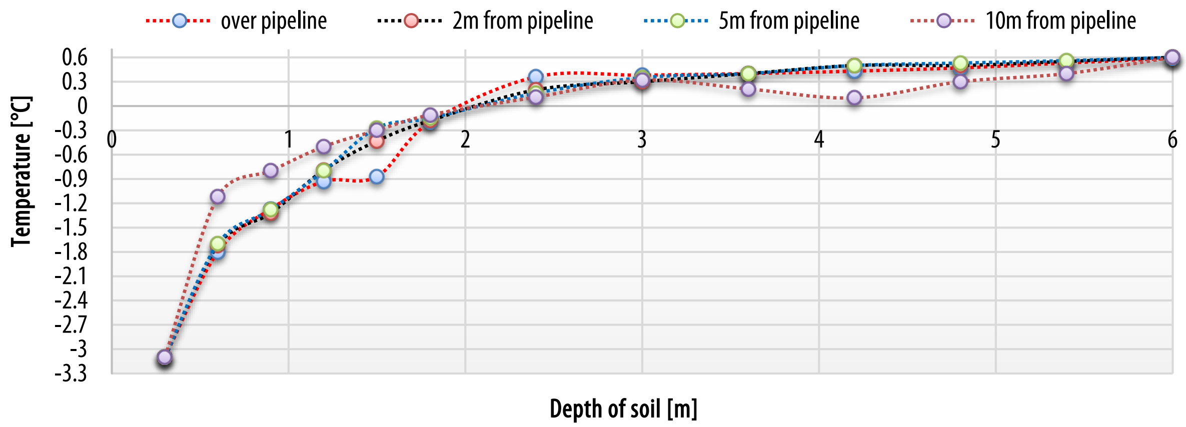

Figure 10. Temperature course in soil, air temperature: -3,5°C

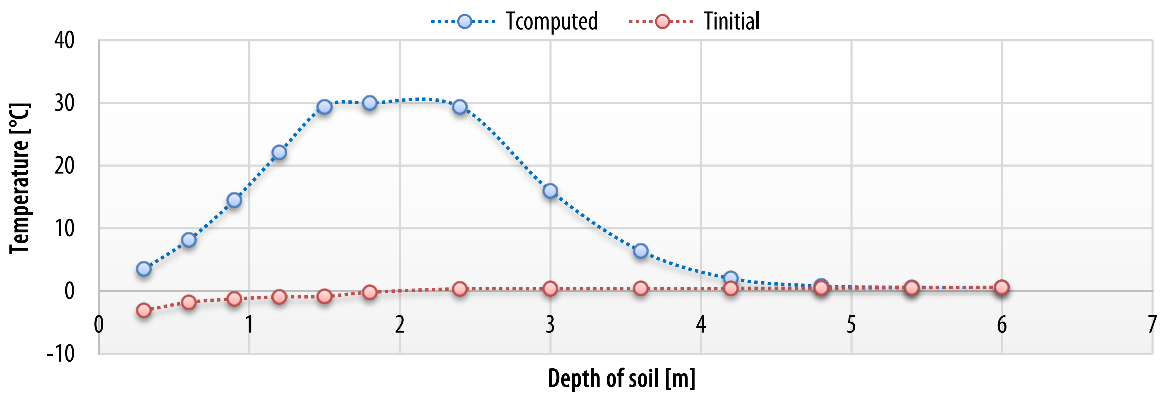

Figure 11. Temperature course over pipeline in the case of affecting (blue line) and not affecting (orange line) the temperature of natural gas

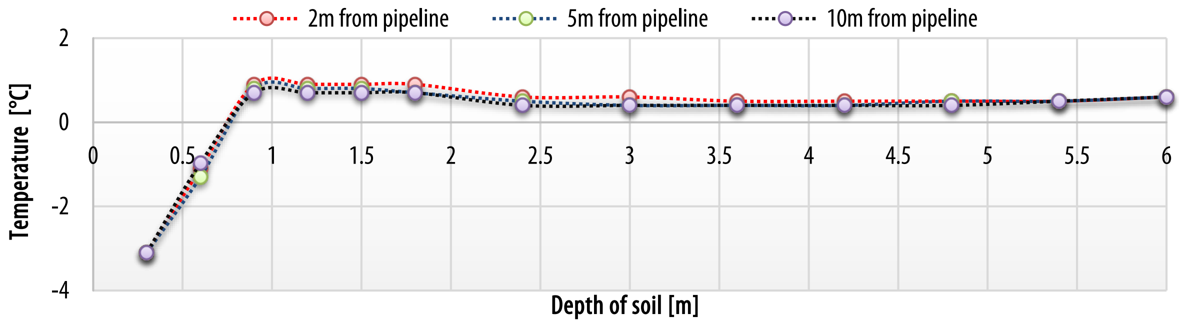

Figure 12. Course of calculating temperature in distance 2 m, 5 m and 10 m from pipeline

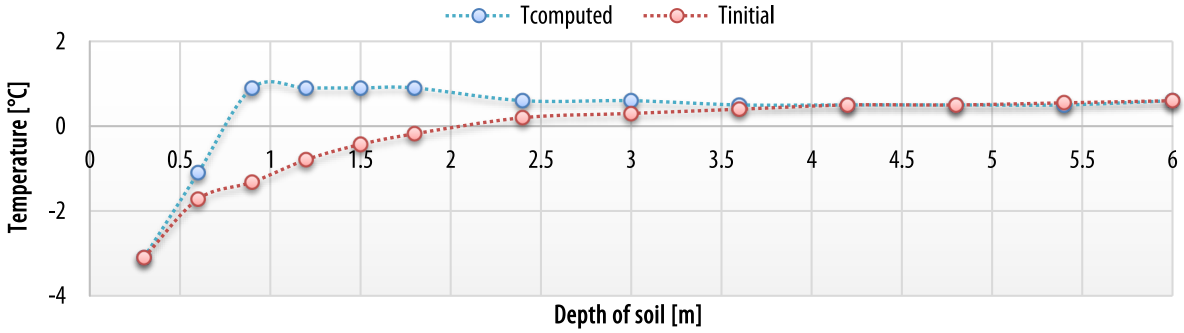

Figure 13. Temperature course in distance 2 m from pipeline in the case of affecting (blue line) and not affecting (orange line) the temperature of natural gas

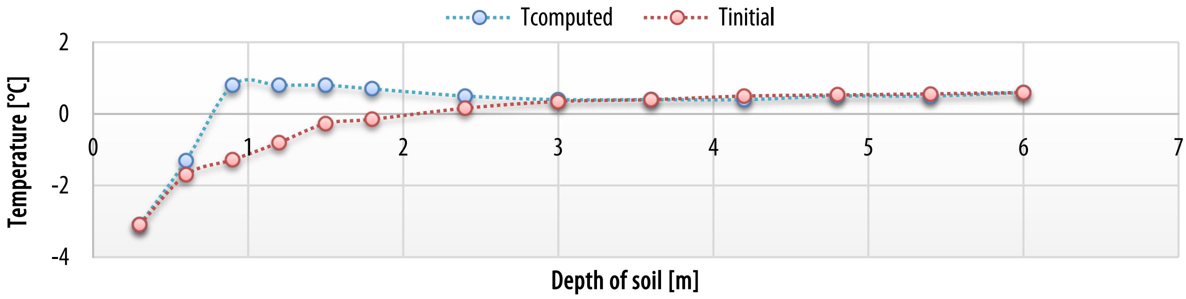

Figure 14. Temperature course in distance 5 m from pipeline in the case of affecting (blue line) and not affecting (orange line) the temperature of natural gas

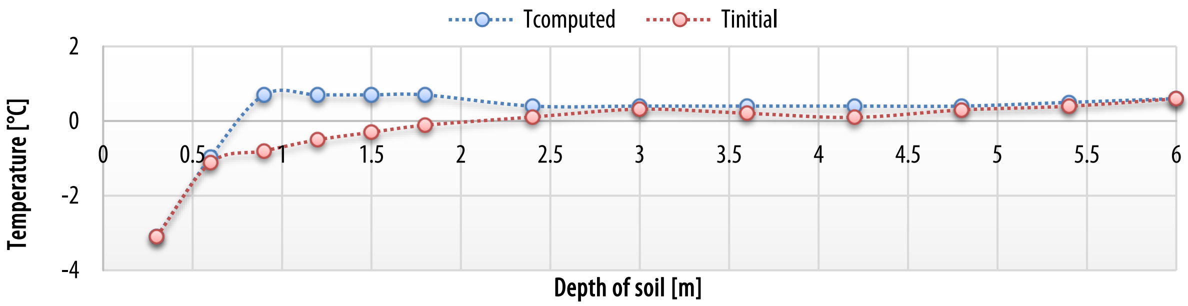

Figure 15. Temperature course in distance 10 m from pipeline in the case of affecrting (blue line) and not affecting (orange line) the temperature of natural gas

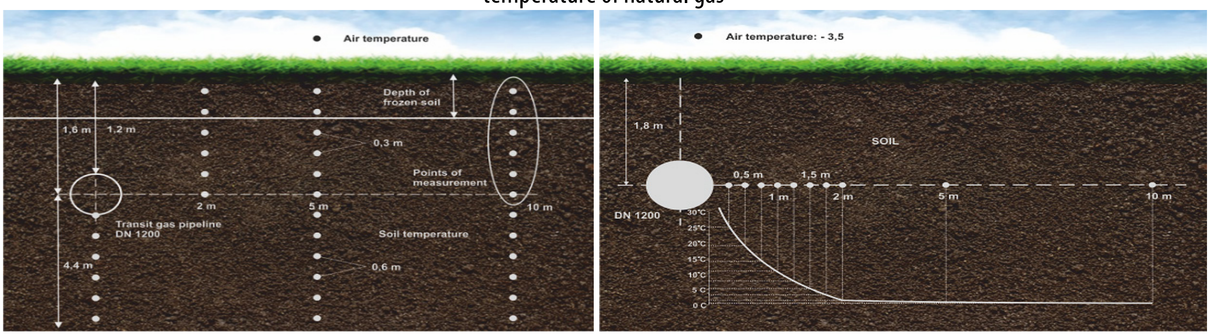

Figure 16. Deposit of pipeline in depth 1,8 m and location measurement points in soil (left figure), cross temperature gradient from pipeline (right figure)

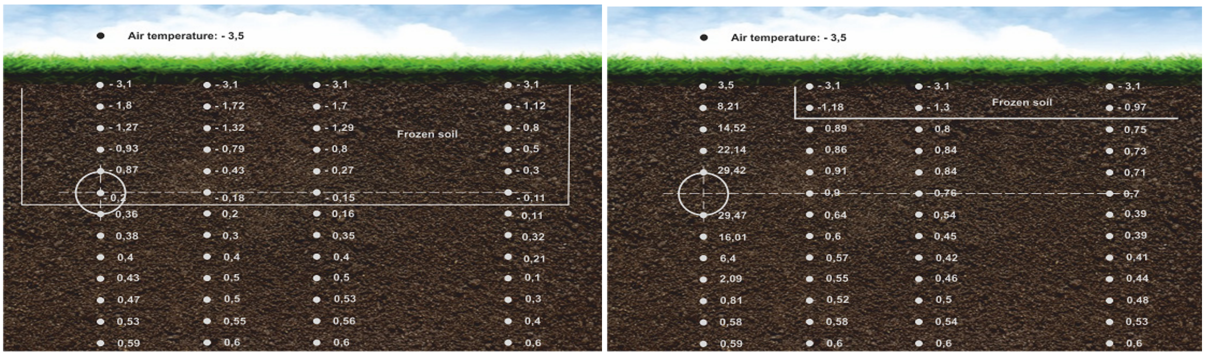

Figure 17. Temperature course in soil in the case not affecting (left figure) and affectint (right figure) the temperature of natural gas and displayer depth of frozen soil for both cases

4. SUMMARY

The paper aimed to create a computer program that is able to calculate the temperature in all the coordinates with respect to time. The program remains of several modules, which launched in the main program. This program can be used in calculations of the pressure and the temperature fields of natural gas and the temperature fields of the entire transit pipeline. Drop of the pressure and the temperature course was logarithmic and decrease of temperature between the two compressor stations was about 15°C. Calculations were applied to the soil, which was frozen in depth approx. 2 m (Figure 18). At the gas temperature of about 30°C overheating of soil occurs and as follows:

- above the line of the pipe there is a heat build-up to the ground surface, that means also the heat exchange with the environment, because the surface temperature reached the value 3,5 ºC in air temperature -3,5 ° C
- from 2 m to 10 m of pipe is layer of the frozen soil decreased from 2 m to 0,6 m
- greater distance is not taken into account, because the gas lines are one from another at the distance about 30 m, isothermal surfaces will touch at a distance about 15 m from the line pipe

It can be concluded that the gas temperature significantly affect the thermal processes in the soil, although it has been frozen in a depth of 2 m (the plot in Figure 11 - 16). Simulations for the summer period were also carried out, the gas temperature influenced the soil layers at the distance about 1 m from the pipeline. Soil layer below ground were affected of air temperature. In the winter period soil temperature is affected only by the natural temperature gas. Good heat transfer from the gas to the surrounding ground is influenced by several factors such as temperature of transported natural gas, gas flow, flow rate and laying depth pipeline.

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