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ANALYSIS OF THE PARTICIPATION OF VARIOUS COMPONENTS IN NATURAL GAS TRANSPORT

1. INTRODUCTION

Nowadays hydrocarbon energy carriers such as coal, oil and natural gas are the major energy materials [7]. Owing to its low level of waste gas emissions, high calorific value and large documented reserves across the world, natural gas is an important element of any domestic energy balance. In recent years, its consumption has systematically increased. Intensive works are being conducted on the development of the domestic gas network, thanks to which the directions and sources of blue gas can be diversified. Natural gas is a gaseous mixture of many different components. The basic element of natural gas is methane and its content totals about 90%. The remaining natural gas components are ethane, propane, butane, nitrogen, carbon dioxide and others. The natural gas composition depends on, amongst others, the field where it has been extracted and type of transport to which it has been designed: pipeline or LNG. Depending on the source, natural gas composition has a decisive influence on its thermodynamic and hydraulic properties. Heavy hydrocarbon components in natural gas increase the calorific value of gaseous fuel. If natural gas is high in inorganic gases, the energy obtained from the combustion of natural gas decreases, and at the same time chemical compounds which negatively affect the pipeline and environment are formed.

In recent years, with the intensive development of use of renewable energy sources, the *Power to gas* technology is observed to be more frequently used. The excess of electric energy from renewable energy sources is applied in the production of hydrogen, which may be directed to the existing natural gas network. Such a mixture containing hydrogen is transported through the network. Presently, a network of pipelines transmitting nitrided gas (Ls and Lw) exists in Poland. The purpose of this paper is to analyze the influence of admixtures in natural gas on the change of production parameters in transmission pipelines. The influence of various admixtures on the transmission of natural gas through the pipelines has been analyzed in the paper.

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Description of calculation model

Model of pressure drop calculation

The steady flow of gas through the pipeline can be described with a Bernoulli equation:

$$\frac{dp}{\rho} + g \cdot dh + \alpha d\left(\frac{w^2}{2}\right) + dl_r = 0 \tag{1}$$

where:

P – pressure [Pa],
w – gas flow rate [m/s],
ρ – density of gas [kg/m^3],
α – Coriolis coefficient,
h – height above sea level [m],
l_r – friction loss.

Friction losses are calculated with the Darcy–Weisbach formula:

$$dl_r = \lambda \cdot \frac{w^2}{2 \cdot D} dx \tag{2}$$

where:

λ – linear flow resistance coefficient,
D – diameter of pipeline [m],
x – coefficient in the gas flow direction [m].

Continuity equation for gas:

$$w = \frac{M}{F \cdot \rho} \tag{3}$$

where:

M – mass intensity of flow [kg/s],
F – cross-section of pipe [m^2].

State equation of real gas:

$$\rho = \frac{p}{Z \cdot R_i \cdot T} \tag{4}$$

where:

R_i – individual gas constant [J/(kg·K)],
T – average temperature of gas [K],
Z – pseudo compressibility of gas.

If we assume that the pipeline is placed in a flat area and the influence of the kinetic energy of gas has not been accounted for, the mass intensity of gas flow in the pipeline is calculated with the formula, integrating pressures P_2 to P_1:

$$M = \frac{\pi \cdot D^{2,5}}{4} \cdot \sqrt{\frac{P_1^2 - P_2^2}{\lambda \cdot R_i \cdot Z \cdot T \cdot L}} \tag{5}$$

In practice, the intensity of gas flow in the pipeline is calculated on the basis of volumetric units calculated for normal conditions: $Q_n = M/\rho_n$ here $\rho_n = \mu/22.41$. At the same time, the individual gas constant may be expressed in the equation by relative density of gas: $R_i = 8314.51/\mu$, $d = \rho_n/1.293$. After accounting for this condition, the below formula for flow intensity expressed in cubic meter per second is obtained:

$$Q_n = 0.035841 \cdot D^{2.5} \cdot \sqrt{\frac{P_1^2 - P_2^2}{\lambda \cdot d \cdot Z \cdot T \cdot L}} \tag{6}$$

Equation (6) is frequently transformed to a form in which the capacity of the pipeline section can be calculated in cubic meter per day.

$$Q_n = 3096.66 \cdot D^{2.5} \cdot \sqrt{\frac{P_1^2 - P_2^2}{\lambda \cdot d \cdot Z \cdot T \cdot L'}} \tag{7}$$

Equation (7) is treated as General Flow Equation for high pressure gas pipelines [4].

Model of calculating gas temperature changes

The change of gas temperature can be calculated from the heat balance [8], [2]:

$$C_p \cdot \rho_n \cdot Q_n \cdot dT = -k \cdot \pi \cdot D \cdot (T - T_0) dx \tag{8}$$

where:

C_p – specific heat of gas at constant pressure [J/(kg·K)],
ρ_n – density of gas in normal conditions [kg/m^3],
Q_n – gas flow intensity in normal conditions [m^3/s],
k – heat transfer coefficient [W/(m^2·K)],
D – diameter of pipeline [m],
T – temperature of gas [K],
T_0 – temperature of ground [K].

After transforming equation (8) we have:

$$\frac{dT}{(T - T_0)} = \frac{k \cdot \pi \cdot D}{C_p \cdot \rho_n \cdot Q_n} dx \tag{9}$$

Integrating the right side of equation (9) for T_1 to T and left side for 0 to L, we get:

$$\ln\frac{T-T_0}{T_1-T_0}=\frac{k\cdot\pi\cdot D}{C_p\cdot\rho_n\cdot Q_n}\cdot L \tag{10}$$

Solving equation (10) for T we obtain:

$$T=T_0+(T_1-T_0)\cdot e^{-\alpha L} \tag{11}$$

where:

$$\alpha=\frac{k\cdot\pi\cdot D}{C_p\cdot\rho_n\cdot Q_n} \tag{12}$$

Calculation of compressibility coefficient with virial equation GERG 88

Owing to a broad range of admixtures in the analyzed natural gas, the compressibility coefficient will be calculated with the virial equation GERG88, which has a broad range of applicability [6]:

– Absolute pressure	0 MPa	$\le P \le$	12 MPa
– Temperature	263 K	$\le T \le$	338 K
– Methane	0.7	$\le x_{\mathrm{CH_4}} \le$	1
– Nitrogen	0	$\le x_{\mathrm{N_2}} \le$	0.2
– Hydrogen	0	$\le x_{\mathrm{H_2}} \le$	0.1
– Carbon dioxide	0	$\le x_{\mathrm{CO_2}} \le$	0.2
– Combustion heat	30 MJ/m^3	$\le Q_S \le$	45 MJ/m^3
– Relative density	0.55	$\le d \le$	0.8

The virial EOS is a straightforward way to describe the behavior of a real gas. This equation, truncated after the third term, has the form [1]:

$$Z=1+B_m(T)\cdot\rho_m+C_m(T)\cdot\rho_m^2 \tag{13}$$

where:

$B_m(T)$ – second virial coefficient [m^3/kmol],
$C_m(T)$ – third virial coefficient [m^6/kmol^2].

Virial coefficients are calculated from formulae,

$$B_m(T)=\sum_{i=1}^{n}\sum_{j=1}^{n}x_i\cdot x_j\cdot B_{ij}(T) \tag{14}$$

$$C_m(T)=\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}x_i\cdot x_j\cdot x_k\cdot C_{ijk}(T) \tag{15}$$

where:

x_i, x_j, x_k – the mole fractions of the i-th, j-th, and k-th component, respectively,
$B_{ij}(T)$, $C_{ijk}(T)$ – unlike-interaction virial coefficients

$$B_{ij}(T) = b_{ij}^{(0)} + b_{ij}^{(1)} \cdot T + b_{ij}^{(2)} \cdot T^2 \tag{16}$$

$$C_{ijk}(T) = c_{ijk}^{(0)} + c_{ijk}^{(1)} \cdot T + c_{ijk}^{(2)} \cdot T^2 \tag{17}$$

where $b_{ij}^{(0)}, b_{ij}^{(1)}, b_{ij}^{(2)}, c_{ijk}^{(0)}, c_{ijk}^{(1)}, c_{ijk}^{(2)}$ – temperature expansion coefficients.

Entry data

Calculations were performed for a pipeline, the basic characteristics of which are presented in Table 1.

Table 1

Characteristic of gas transmission pipeline

Initial pressure, P_1 [MPa]	Initial temperature of gas, T_1 [K]	Temperature of ground, T_0 [K]	Inner diameter of pipeline, D [m]	Length of pipeline, L [km]	Gas flow intensity (w.n.), Q_n [m^3/d]	Absolute roughness of pipeline, k [mm]
6	313	287	0.7	120	$15.5 \cdot 10^6$	0.02

Three sets of gas composition were analyzed and in each of them the participation of a given component was changed. Ten gas compositions were obtained in each set. In the first set, nitrogen content was changed from 1% to 10%, and at the same time the participation of methane decreased from 94% to 85%. The participation of carbon dioxide in the first set totaled 0.5%, and the share of hydrogen equaled 0.1%. The results for the first set of natural gas are presented in Table 2.

Table 2

Gas composition – first set

No. of sample	Volumetric participation									
	1	2	3	4	5	6	7	8	9	10
Methane	0.94	0.93	0.92	0.91	0.9	0.89	0.88	0.87	0.86	0.85
Ethane	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
Propane	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Butane	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
Nitrogen	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Carbon dioxide	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Hydrogen	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Carbon oxide	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

In the second set, the carbon dioxide content increased from 1% to 10%, and the participation of methane decreased from 94% to 85%. The nitrogen content totaled 0.5%, and hydrogen content 0.1%. The data for the second set are presented in Table 3.

Table 3

Gas composition – second set

No. of sample	Volumetric participation									
	11	12	13	14	15	16	17	18	19	20
Methane	0.94	0.93	0.92	0.91	0.9	0.89	0.88	0.87	0.86	0.85
Ethane	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
Propane	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Butane	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
Nitrogen	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Carbon dioxide	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Hydrogen	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Carbon oxide	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

In the third set, the participation of hydrogen ranged from 1% to 10%, with the correspondingly decreasing share of methane from 94% to 85%. The participation of nitrogen totaled 0.5% and carbon dioxide 0.1%. The third set of natural gas is presented in Table 4.

Table 4

Natural gas composition – third set

No. of sample	Volumetric participation									
	21	22	23	24	25	26	27	28	29	30
Methane	0.95	0.94	0.93	0.92	0.91	0.9	0.89	0.88	0.87	0.86
Ethane	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
Propane	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Butane	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Nitrogen	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Carbon dioxide	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Hydrogen	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Carbon oxide	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

2. ANALYSIS OF RESULTS

Transport of natural gas with pipelines over long distances is associated with a considerable drop in gas pressure. The quantitative expression of pressure drop depends on a number of factors, i.e. length, diameter and profile of the pipeline route, intensity and character of natural gas flow, as well as the physical properties of the transmitted medium, which in turn, depend on the composition of the transmitted gas [3, 5].

The first analyzed parameter is a drop of pressure in the transmission pipeline, depending on the change in the composition of the transmitted medium.

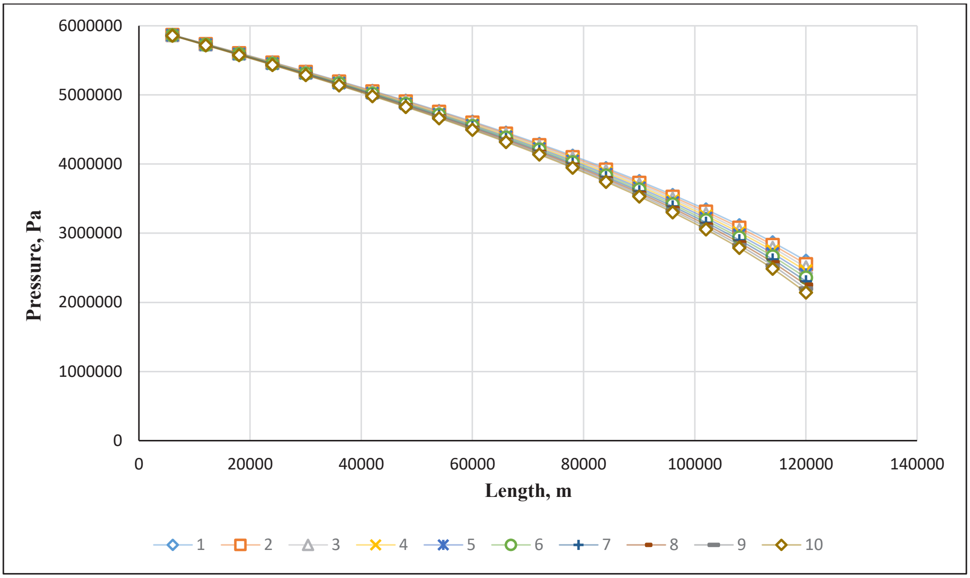

Fig. 1. Change of pressure in pipeline for analyzed gas – first set

The analysis of the figure reveals that the participation of nitrogen with the corresponding decrease of methane content results in the lowering of gas pressure at the end of the transmission pipeline. Nitrogen is heavier than methane, therefore the increase of nitrogen content and lowering of the share of methane means that the medium becomes heavier and additional pressure losses are observed during the transmission through the pipelines. Owing to a small difference in their molar masses (methane 16.04 kg/kmol, nitrogen 28.01 kg/kmol), the change in the end section of the pipeline is not big – for 94% of methane and 1% of nitrogen the end pressure totals 2.6008 MPa, and for natural gas containing 85% methane and 10% nitrogen, the end pressure equals 2.145 MPa.

Carbon dioxide is many times heavier than methane (molar mass of CO_2 equals 44.01 kg/kmol) therefore its higher content in gas causes a drop of pressure in the pipeline section as presented in Figure 2. At the same time, carbon dioxide is a very undesirable component because it is aggressive and corrosive. The Instructions of Transmission Grid's Operation and Maintenance does not allow higher CO_2 content in natural gas than 3%. In view of this restriction, the case study presented in Figure 2 should be treated only as a theoretical consideration. On the other hand, the expertise in carbon dioxide transmission through the pipelines is considerable on the global scale.

For natural gas containing 94% methane and 1% $CO_{2,}$ the end pressure in the pipeline totals 2.581 MPa. For natural gas containing 85% methane and 10% $CO_{2,}$ the end pressure is equal to 1.635 MPa. The analysis of the plot shows that the participation of CO_2 considerably affects the drop of pressure in the transmission pipeline.

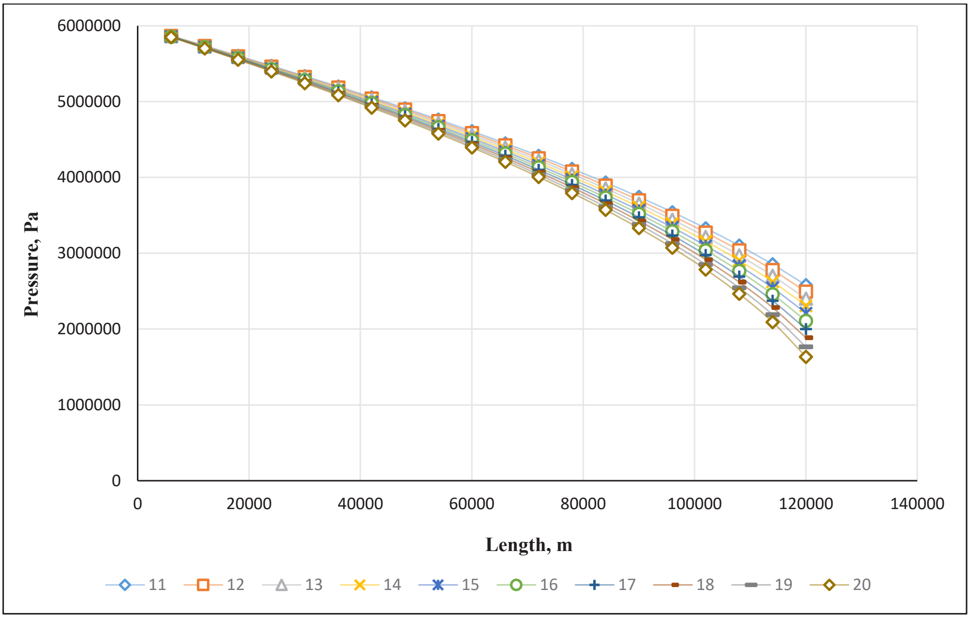

Fig. 2. Change of pressure in pipeline for analyzed gas – second set

A plot of pressure changes in a transmission pipeline and change of hydrogen and methane content in transmitted gas is presented in Figure 3. Hydrogen is the lightest component of the gaseous mixture; it is almost eight times lighter than methane (molar weight of hydrogen is 2.016 kg/kmol).

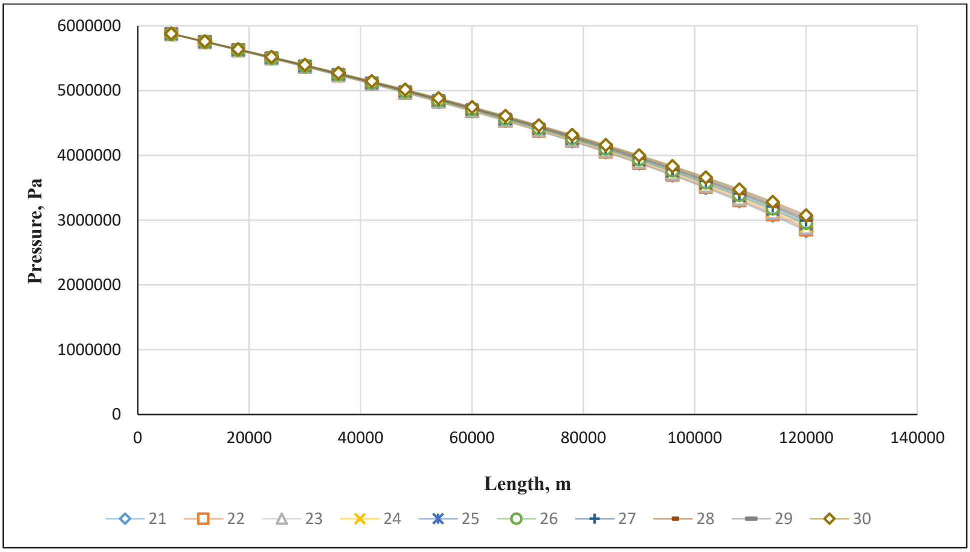

Fig. 3. Change of pressure in pipeline for analyzed gas – third set

For this reason, the participation of hydrogen in natural gas with the decreasing methane content causes a decrease of natural gas density and thus higher end pressure in the transmission pipeline. This phenomenon is illustrated in Figure 3.

For natural gas with 1% hydrogen and 94% methane content, the final pressure in the pipeline totals 2.836 MPa. When the hydrogen content increases to 10% and methane content decreases to 85%, the final pressure increases to 3.077 MPa.

The collective plot of changes of end pressure in the transmission pipeline section, depending on the changing participation of nitrogen, carbon dioxide and hydrogen is presented in Figure 4.

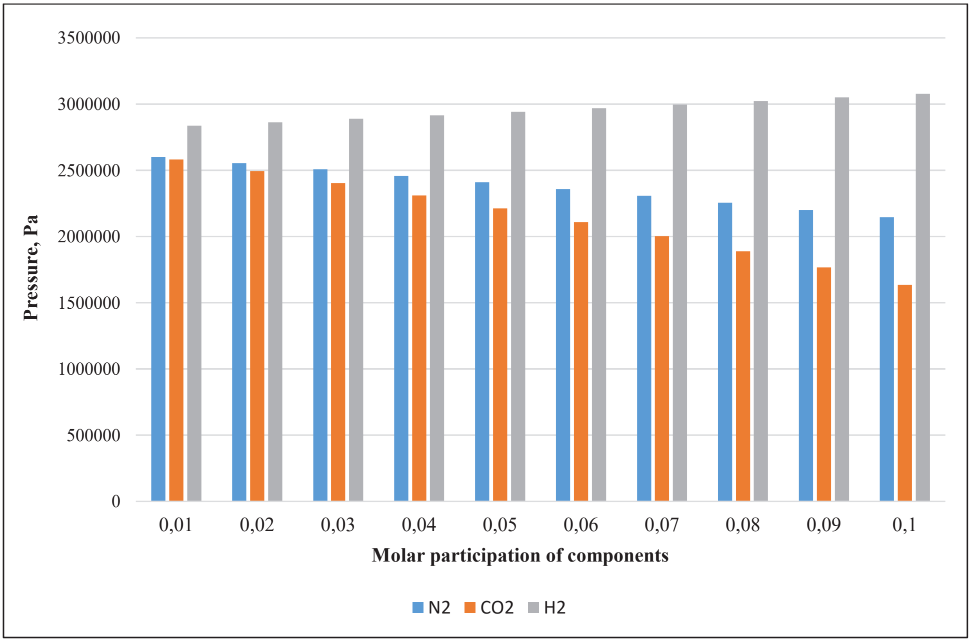

Fig. 4. Change of final pressure in transmission pipeline depending on the change of participation of nitrogen, carbon dioxide and hydrogen

The influence of natural gas composition on heat transfer was also analyzed. In natural gas compression stations, the gas pressure is increased and consequently also its temperature increases even up to 60–70°C. After leaving compressor aggregates, natural gas is cooled in special air heat exchangers. The temperature of cooled gas cannot exceed 40°C. Cooled gas is directed to underground transmission pipelines, where during transmission the temperature changes under the influence of the soil temperature; the latter is considerably stable over the whole length of the pipeline route.

The plots illustrating the changes of temperature along the pipeline in a function of gas composition is presented in Figures 5 and 6.

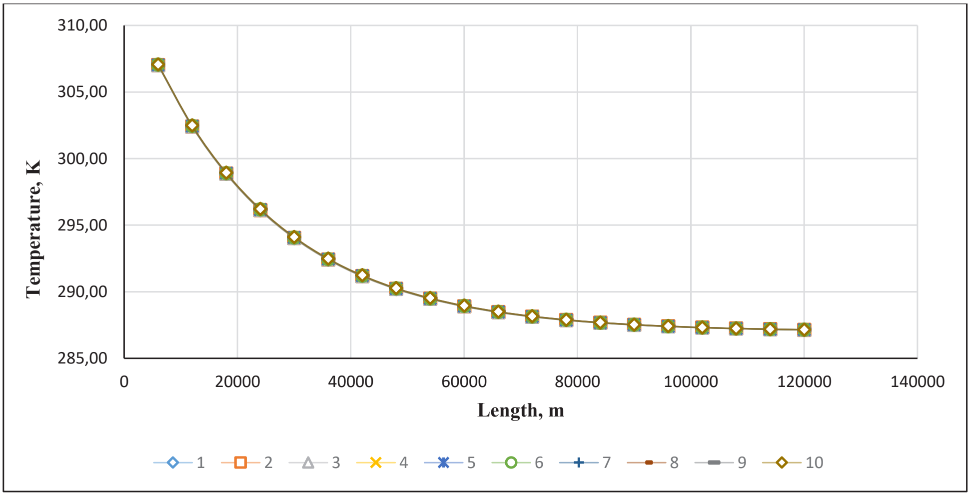

Fig. 5. Gas temperature changes over the pipeline route in a function of varying participation of nitrogen and methane

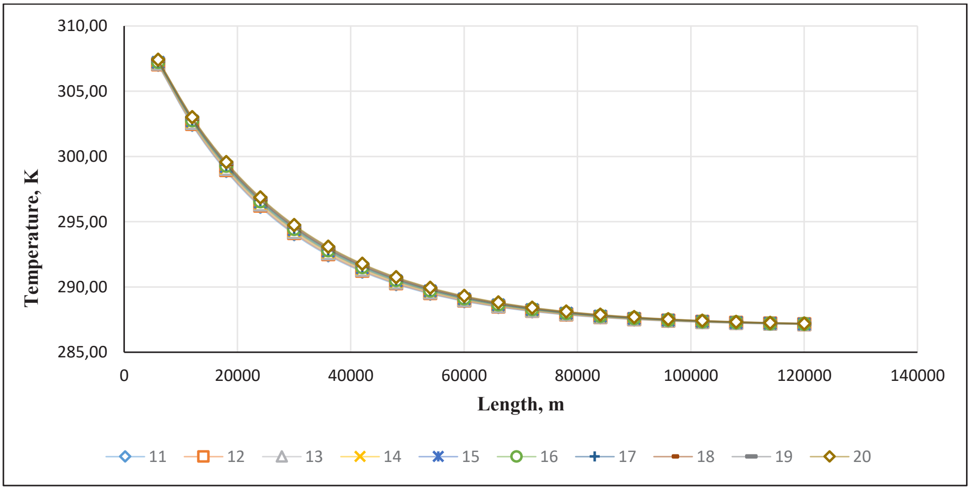

Fig. 6. Gas temperature changes over the pipeline route in a function of varying participation of carbon dioxide and methane

The analysis of the above plots reveals that a change in the participation of nitrogen, carbon dioxide and methane does not have any significant influence on the change of temperature of the gas transmitted with the pipeline, unlike hydrogen, the content of which has a visible impact on the heat transfer, as shown in Figure 7.

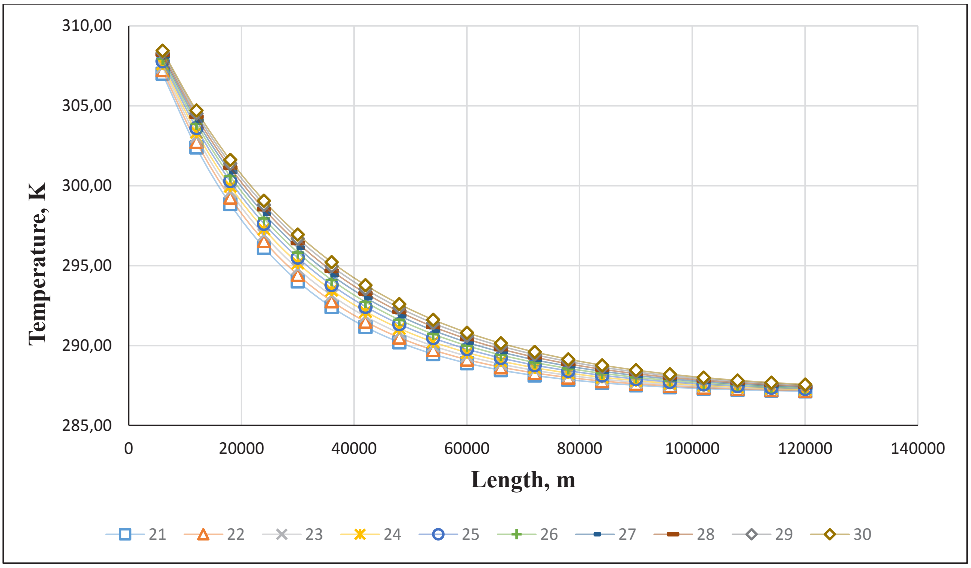

Fig. 7. Gas temperature along the pipeline vs. hydrogen and methane contents

Despite a very small difference over the pipeline length (maximum about 3 K), the temperature at the end of the pipeline asymptotically approaches ambient temperature. For this reason, the presented change of temperature does not have a significant influence on the basic operational parameter of transmission pipelines, i.e. pressure.

3. CONCLUSIONS

Gas composition has a significant influence on the change of pressure along the gas transmission pipeline and pressure at the end of the pipeline. For 94% methane and 1% nitrogen content, the end pressure totals 2.6008 MPa. For natural gas containing 85% methane and 10% nitrogen the end pressure totals 2.145 MPa. The increase of nitrogen participation from 1% to 10%, with the lowering of methane content from 94% to 85% causes a drop of end pressure by 17.53%. For natural gas containing 94% methane and 1% $CO_{2,}$ the end pressure is 2.581 MPa. For natural gas containing 85% methane and 10% CO_2 the end pressure totals to 1.635 MPa, and the described change of composition results in a drop of end pressure in the pipeline of 36.65%. For natural gas with the participation of 1% hydrogen and 94% methane, the end pressure in the pipeline is 2.836 MPa, and with the increase of hydrogen content to 10% and lowering of methane content to 85%, the end pressure increases to 3.077 MPa. The described change of natural gas composition results in the increase of the end pressure by 8.5%. No significant influence of changes in the natural gas composition on the heat transfer was observed in the tests.

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