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THERMODYNAMIC ANALYSIS OF HYDROGEN PIPELINE TRANSPORTATION – SELECTED ASPECTS***

1. INTRODUCTION

Nowadays the hydrogen is considered by industry as a fuel of the future, which may successfully replace conventional, non-renewable fuels. Because of this fact hydrogen is perceived as an efficient source of environmental-friendly energy.

Presenting the idea of using the hydrogen as a substitute of hydrocarbons is a forward thinking, because there are no large scale hydrogen production methods, which would be effective, economically justified and less time consuming to produce amounts required by industry. Actually the hydrogen is obtained from thermo-chemical processes, which main source of power is a combustion of coal, natural gas or oil. Unfortunately the resources of hydrocarbons are limited, this is why the industry should focus on diversified types of fuels.

The way of obtaining the hydrogen is not the only one issue that should be faced by industry, because there is a necessity of development effective methods of its transportation and storage. This type of fuel can be stored as a gas under the pressure or a liquid (hydrides, carbonaceous materials) which is not a leading issue, because those methods are used today and all action needed to be taken is to adapt them to store bigger amounts

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of hydrogen. A not effective truck transportation is more problematic issue, because can provide a limited fuel volume on a relative short distances. This is the main reason why the industry should focus on a hydrogen pipeline transportation. For transportation of hydrogen the special dedicated pipeline network can be developed. Furthermore using the natural gas pipelines for hydrogen transport should be considered as a component of natural gas. Industry practice in the USA shows that effective pipeline transport of hydrogen is possible also as a natural gas mixture component. Natural gas pipelines are long distance pipelines with high maximum operating pressure. The most important advantage of pipeline networks is their availability. Nowadays this type of transport is expensive and used for a short distances only. Despite this fact some countries (e.g. USA) are considering a conversion of their natural gas pipelines for hydrogen transportation. Using existing infrastructure the transportation of hydrogen would be definitely cheaper than building special dedicated pipelines. However there are some disadvantages of using natural gas pipelines. Hydrogen has a higher ability to penetrate through construction materials of gas pipelines than natural gas. Moreover, hydrogen is highly corrosive. This fact requires that additional material research for pipeline steel should be performed. Those issues would require some special improvements that will protect pipelines from negative influence of hydrogen.

This article is focused on thermodynamic analysis of hydrogen transportation by dedicated pipelines or natural gas pipelines. The flow of the pure hydrogen and bi-component mixtures of methane and hydrogen was analyzed especially for a pressure drops during the transportation in the pipeline. Increasing interest in hydrogen as a new medium of storage an excess energy is the main issue why pipeline transportation (for long distances in short time) becomes a challenge for scientists and engineers.

2. TECHNICAL AND THERMODYNAMIC ASSUMPTIONS

The obtained calculations assume a gas transportation by pipeline which is 200 kilometres long and divided for 10 segments (equal length of 20 km). A scheme of modelled pipeline is presented in the Figure 1. As shown in the Table 1 – the pipeline transportation in four variant scenarios depending on diameter and gas flow rate was considered. Furthermore, four composition variants: pure hydrogen, pure methane and two bi-component mixtures of methane and hydrogen in appropriate proportions were considered (Tab. 2).

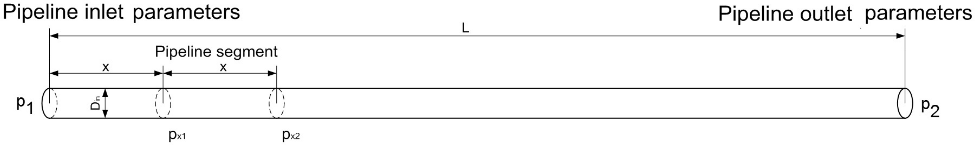

Fig. 1. Modeled pipeline scheme

Table 1

Technical parameters of pipeline

Overall pipeline length	L [km]	200
Pipeline segment length	x [km]	20
Inlet pressure	P_1 [MPa]	5
Pipeline inner diameter	D_1 [mm]	200
	D_2 [mm]	250
Flow rate	Q_1 [m^3/h]	20 000
	Q_2 [m^3/h]	30 000

Table 2

Exemplary bi-component hydrogen/methane compositions for pipeline flow modeling

Composition	I		II		III		IV	
Component	Hydrogen	Methane	Hydrogen	Methane	Hydrogen	Methane	Hydrogen	Methane
Symbol	H_2	CH_4	H_2	CH_4	H_2	CH_4	H_2	CH_4
Molar fraction [%]	100	0	20	80	10	90	0	100

Critical parameters of hydrogen are as follows – the critical temperature is 32.94 K and the critical pressure is 1.2838 MPa. Under those conditions a hydrogen specific volume is $3.18879 \cdot 10^{-2}$ m^3/kg. From a thermodynamics point of view low values of hydrogen critical parameters and low molar mass have a large impact on its pipeline transportation parameters.

3. THERMODYNAMIC PARAMETERS ANALYSIS

The analysis of the pure hydrogen or bi-component mixture of hydrogen and methane flow assumes calculations of transportation parameters changes (pressure drop, outlet pressure, compressibility factor, density and velocity of transported gas). Inlet pressure was assumed for each section of the pipeline. In the first stage of calculations compressibility factor was calculated using equation of state.

For the purposes of this paper the Peng–Robinson equation of state (EOS) was used. It is one of the most known real gas equation of state for phase equilibrium and thermodynamic parameters calculations in oil and gas industry.

Classic cubic Peng–Robinson EOS has the following form:

$$p=\frac{RT}{v-b}-\frac{a}{v^2+2bv-b^2} \tag{1}$$

Parametres of the Peng–Robinson EOS are described in equations (2)–(5):

$$a=\Omega_a\frac{R^2{T_{pc}}^2}{P_{pc}} \tag{2}$$

$$b=\Omega_b\frac{RT_{pc}}{P_{pc}} \tag{3}$$

$$m_i=d_0+d_1\omega_i+d_2\omega_i^2 \tag{4}$$

$$\alpha_i=\left[1+m_i\left(1-\sqrt{\frac{T_{pc}}{T}}\right)\right]^2 \tag{5}$$

Dimensionless Peng–Robinson EOS parameters have the form:

$$A=\frac{ap}{R^2T^2} \tag{6}$$

$$B=\frac{bp}{RT} \tag{7}$$

Values of the numeric factors in equations (2)–(4):

$$\Omega_a = 0.457240,\ \Omega_b = 0.07780,$$

$$d_0 = 0.37464,\ d_1 = 1.54226,\ d_2 = -0.22992.$$

The Peng–Robinson EOS in its iterative form allows to calculate the compressibility factor Z:

$$Z=\frac{Z}{Z-B}-\frac{AZ}{Z^2+2BZ-B^2} \tag{8}$$

To calculate the pressure drop in each pipelines section the Renouard hydraulic equation was used. It is a one of the most popular hydraulic equations in natural gas transportation industry:

$$p_1^2-p_2^2=18.872\cdot Z\cdot T\cdot L\cdot d\cdot\frac{{Q_n}^{1.82}}{D^{4.82}} \tag{9}$$

Obviously to define a value of the pressure drop it is possible to use different widely available hydraulic equations (e.g. Panhandle, Gas Technology Institute hydraulic equations).

Average gas temperature in pipeline was calculated using the following formula (10):

$$T = T_0 + \frac{T_1 - T_2}{\ln\left(\frac{T_1 - T_0}{T_2 - T_0}\right)} \tag{10}$$

Additionally, aside from the pressure drops calculation – (based on inlet or outlet pressures and compressibility factor) a density (11) and velocity (12) of the gas was calculated in each section of the pipeline.

$$\rho = \frac{p}{z \cdot R_i \cdot T} \tag{11}$$

$$w = \frac{4 \cdot Q_r}{\pi \cdot D^2} \tag{12}$$

4. CALCULATIONS ALGORITHM

Pipeline hydraulic calculations were made using algorithm presented in the Figure 2. In the first stage of presented algorithm values of several input parameters should be entered e.g. inlet pressure, pipeline length, pipeline segment length, inner diameter, ground (ambient) temperature, inlet and outlet gas temperature, gas composition, thermodynamic individual parameters for each component in mixture and flow rate.

In the second stage the algorithm calculates an average gas temperature and some gas parameters in pipeline (relative density, mixture parameters). Results of those preliminary calculations are required for calculation of compressibility factor Z with chosen equation of state. In the next stage an outlet pressure (in the end of each pipeline segment) and the rest of gas parameters like a density and velocity are calculated. All computational process is repeated till the last section of pipeline, then results obtained for the last pipeline segment are identical with results for the whole pipeline.

The algorithm can be modified or enhanced by additional parameters or dependences e.g. temperature changes in every section of pipeline:

$$T_x = T_0 + (T_1 - T_0) \cdot \exp\left(-\frac{k \cdot \pi \cdot D}{C_{p\cdot} \cdot \rho \cdot Q_n} \cdot x \right) \tag{13}$$

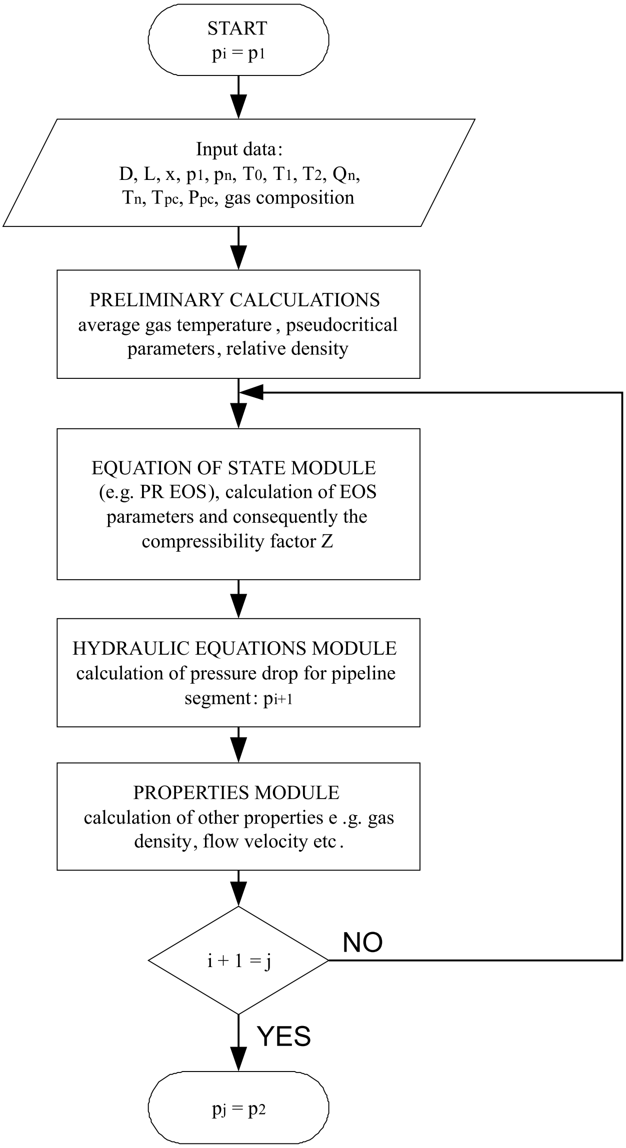

Fig. 2. Calculation algorithm

Using of constant, average temperature for whole pipeline is main assumption given by industrial practice (equation number (10)).

Accuracy of the presented algorithm can be improved by increasing of pipeline segments amount. Furthermore, by considering more parameters (e.g. terrain elevation) the applicability of algorithm can be extended. There is also possibility of using other hydraulic equations for pressure drop calculations.

It is possible to use numerical integration to calculate pressure drops and other parameters of transported gas as alternative calculation method. Example is shown for Darcy–Weisbach pressure drop equation:

$$-dp = \lambda \frac{w^2 \rho}{2D} dL \tag{14}$$

It can be assumed from reducing equations that:

$$\frac{pwF}{ZT} = \frac{p_x w_x F_x}{Z_x T_x} \tag{15}$$

$$\frac{\rho TZ}{p} = \frac{\rho_x T_x Z_x}{p_x} \tag{16}$$

After substituting w and ρ from the equations (15) and (16), assuming a constant pipeline cross-section and isothermal flow we obtain:

$$-pdp = \lambda \frac{{w_x}^2 \rho_x p_x}{2D} dL \tag{17}$$

Making separation of variables and integrating the equation (17) from p_1 to p_2, and from 0 to L we obtain:

$$-\int_{p_1}^{p_2} pdp = \int_0^L \frac{{w_x}^2 \rho_x p_x}{2D} dL \tag{18}$$

$$p_1^2 - p_2^2 = \lambda \frac{{w_x}^2 \rho_x p_x}{2D} L \tag{19}$$

Values of velocity and density of the fluid at given point of pipeline can be calculated with use the equation of state. Equation (19) can be used for numerical integration using the method of rectangles (left endpoint (20a), right endpoint (20b), or midpoint (20c)) or trapezoidal method (21):

$$\begin{aligned}\int_0^L f(x)dx &\approx f(x_0)(x_1 - x_0) + f(x_1)(x_2 - x_1) + \ldots + f(x_{n-1})(x_n - x_{n-1}) = \\ &= \sum_{i=1}^{n} f(x_{i-1}) \cdot (x_i - x_{i-1})\end{aligned} \tag{20a}$$

$$\int_0^L f(x)dx \approx f(x_1)(x_1 - x_0) + f(x_2)(x_2 - x_1) + \ldots + f(x_n)(x_n - x_{n-1}) = \\ = \sum_{i=1}^{n} f(x_i) \cdot (x_i - x_{i-1}) \tag{20b}$$

$$\int_0^L f(x)dx \approx \sum_{i=1}^{n} f\left(\frac{x_i - x_{i-1}}{2}\right) \cdot (x_i - x_{i-1}) \tag{20c}$$

$$\int_0^L f(x)dx \approx \sum_{i=1}^{n} \frac{f(x_{i-1}) - f(x_i)}{2}(x_i - x_{i-1}) \tag{21}$$

5. CALCULATION RESULTS

Pressure drop

In Figures 3–5 the pressure drop in exemplary pipeline is shown for pure hydrogen, pure methane and bi-component mixture of methane and hydrogen transportation:

a) Figure 3 for case with flow rate: Q_n = 20 000 m^3/h and inner pipeline diameter: D = 200 mm;
b) Figure 4 for case with flow rate: Q_n = 30 000 m^3/h and inner pipeline diameter: D = 200 mm;
c) Figure 5 for case with flow rate: Q_n = 30 000 m^3/h and inner pipeline diameter: D = 250 mm.

The analysis of pressure drop calculated with use the Renouard hydraulic equation shows low pressure drops for transported pure hydrogen. For flow rate of 30 000 m^3/h and 200 mm inner diameter case the value of pressure drop is 0.9 MPa and for 250 mm diameter case is only 0.3 MPa. The pressure drop for mixtures of methane and hydrogen with 30 000 m^3/h flow rate and 250 mm pipeline diameter is 2.2 MPa including 20% molar fraction of hydrogen, 2.5 MPa including 10% molar fraction of hydrogen and 2.75 MPa for pure methane. For pipeline diameter 200 mm and flow rate 30 000 m^3/h bi-component hydrogen-methane mixtures, and pure methane can be transported only for 80 km distance because of high pressure drops.

For the variant of flow rate 20 000 m^3/h and 200 mm diameter the pressure drop for pure hydrogen is 0.6 MPa and for mixture of methane and 20% of hydrogen is until 4.2 MPa. In these conditions, the mixture containing 10% of hydrogen can be transported only for 180 km distance and pure methane can be transmitted for 160 km distance. Obtained results show the clear dependence between increasing of molar fraction of hydrogen in mixture with methane and changes of pipeline transportation parameters of the whole mixture, which has a significant influence on pipeline transport conditions. The key point is decreasing the molar mass of whole mixture along with increasing the molar fraction of hydrogen.

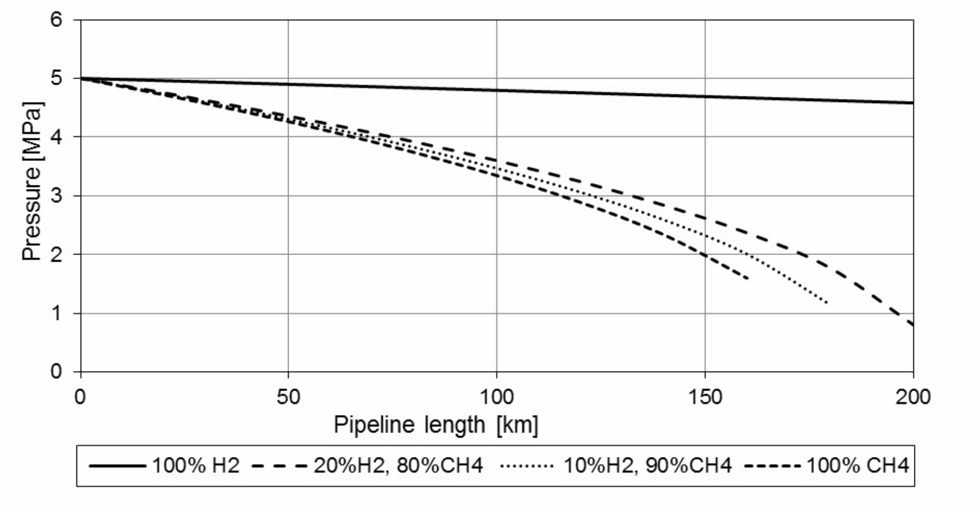

Fig. 3. Pressure drop for modeled pipeline (Q_n = 20 000 m^3/h, D = 200 mm) (see note)

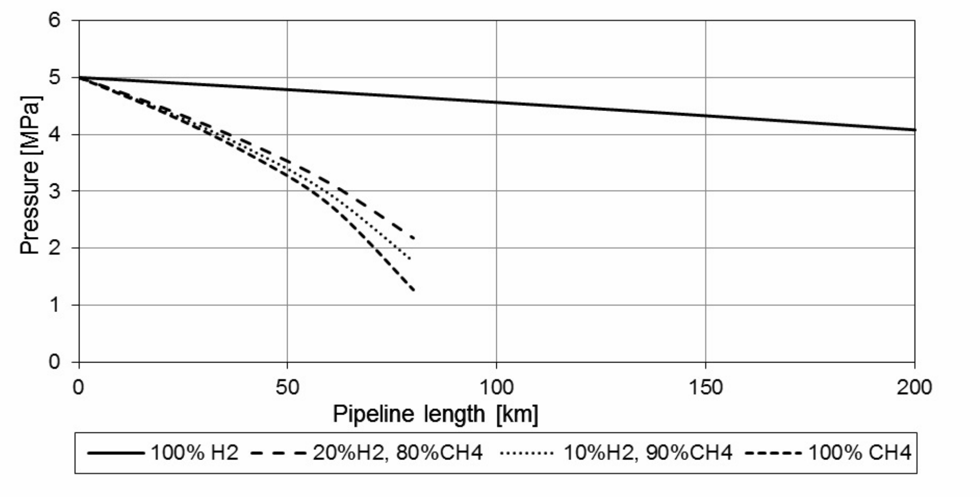

Fig. 4. Pressure drop for modeled pipeline (Q_n = 30 000 m^3/h, D = 200 mm) (see note)

Important Note: Considering only parameters of pipeline transportation (pressure drops, flow velocity or density) of pure hydrogen it is obtained an incomplete picture of the energy transportation possibilities, because the energy per unit volume for hydrogen is much lower than for natural gas. Pipeline transportation of hydrogen has low energy efficiency. Energy analysis for assumed cases is presented in Chapter 7.

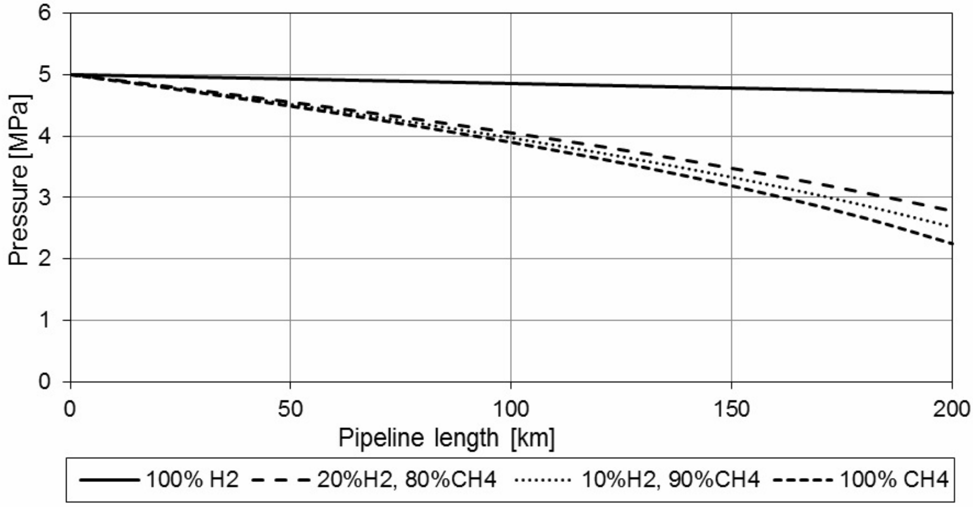

Fig. 5. Pressure drop for modeled pipeline (Q_n = 30 000 m^3/h, D = 250 mm) (see note)

Changes of compressibility factor *Z*

In Figures 6 and 7 the variability of compressibility factor Z in function of the pipeline length is shown for exemplary variants:

a) Figure 6 for case with flow rate: Q_n = 20 000 m^3/h and inner pipeline diameter: D = 200 mm;

b) Figure 7 for case with flow rate: Q_n = 30 000 m^3/h and inner pipeline diameter: D = 250 mm.

Compressibility factor Z in thermodynamics is defined as deviation of the real gas behaviour in relation to the ideal gas. Due to physical and chemical properties of the hydrogen the value of compressibility factor is higher than 1. For defined exemplary pipeline cases Z factor decreases slightly with increasing of pressure drop. For assumed conditions and bi-component mixtures of methane and hydrogen, and also pure methane the Z-factor increase in function of the pipeline length and molar fraction of hydrogen in the mixture.

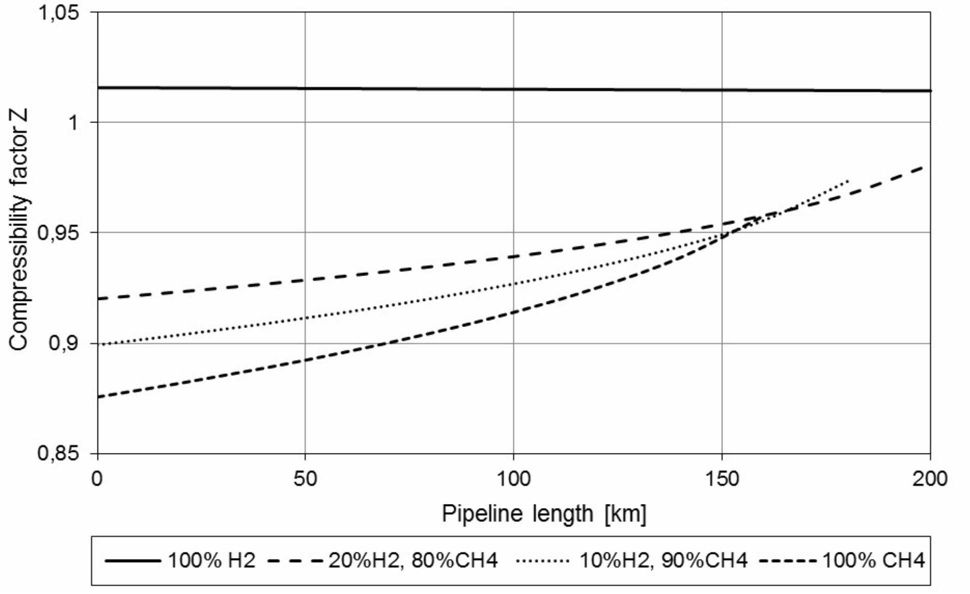

Fig. 6. Compressibility factor changes versus pipeline length
(Q_n = 20 000 m^3/h, D = 200 mm)

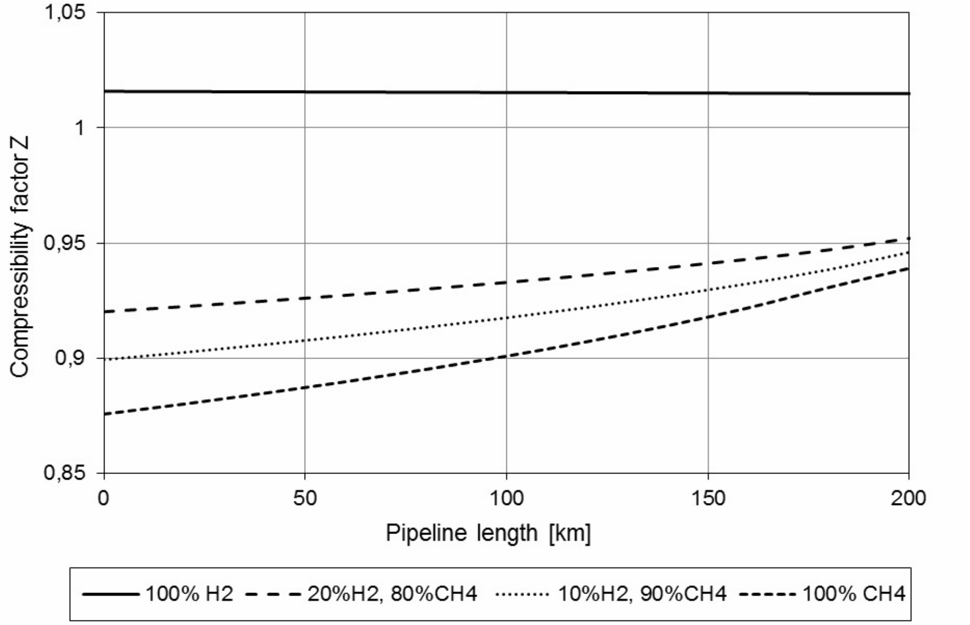

Fig. 7. Compressibility factor changes versus pipeline length
(Q_n = 30 000 m^3/h, D = 250 mm)

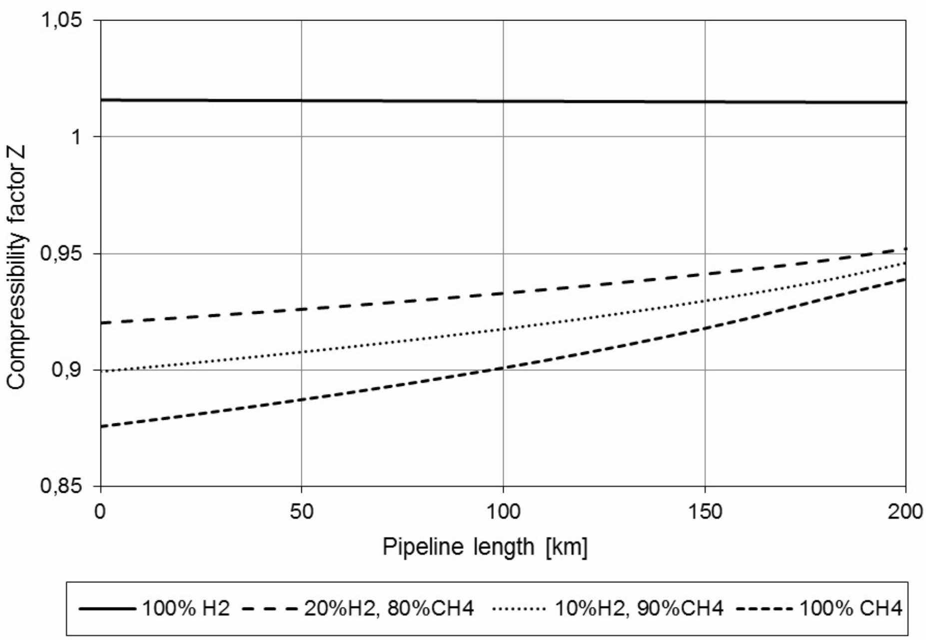

Fig. 8. Density changes versus pipeline length ($Q_n = 20\,000$ m^3/h, $D = 200$ mm) (see note)

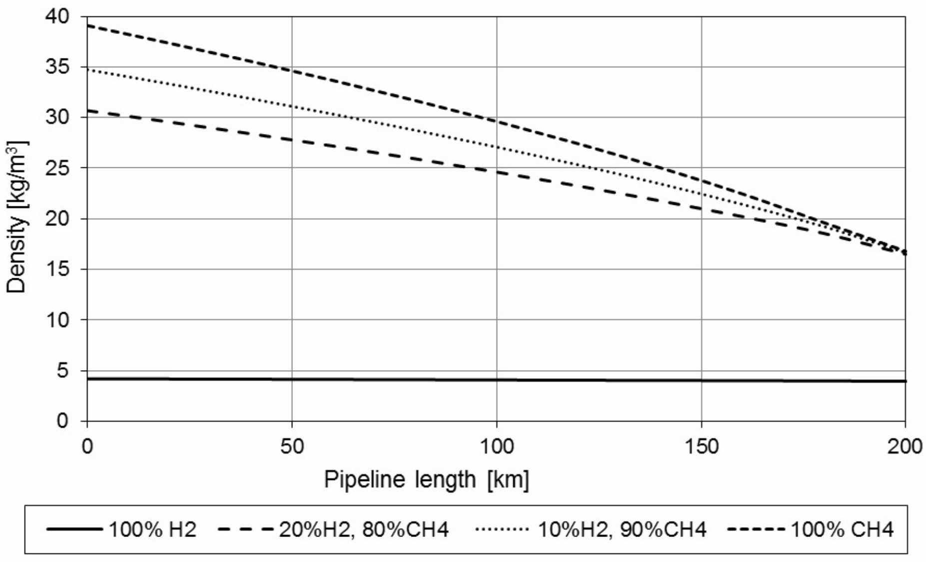

Fig. 9. Density changes versus pipeline length ($Q_n = 30\,000$ m^3/h, $D = 250$ mm) (see note)

Density changes analysis

In Figures 8 and 9 changes of gas density in function of pipeline length are shown for exemplary variants:

a) Figure 8 for case with flow rate: $Q_n = 20\,000$ m^3/h and inner pipeline diameter: $D = 200$ mm.
b) Figure 9 for case with flow rate: $Q_n = 30\,000$ m^3/h and inner pipeline diameter: $D = 250$ mm.

The gas density is strictly related to pressure, temperature and compressibility factor. In the algorithm temperature was assumed with a constant value, therefore the density depends on the first two parameters.

Hydrogen flow with assumed flow rate is characterised by a slight decrease of density due to low pressure drops. Density of transported hydrogen in assumed conditions is about 4 kg/m^3. For bi-component methane-hydrogen mixtures and pure methane the density drop is much higher because of higher pressure drop.

Flow velocity analysis

In Figure 10 the variability of gas flow velocity depending on pipeline length is shown for exemplary case of flow rate $Q_n = 20\,000$ m^3/h and diameter $D = 200$ mm.

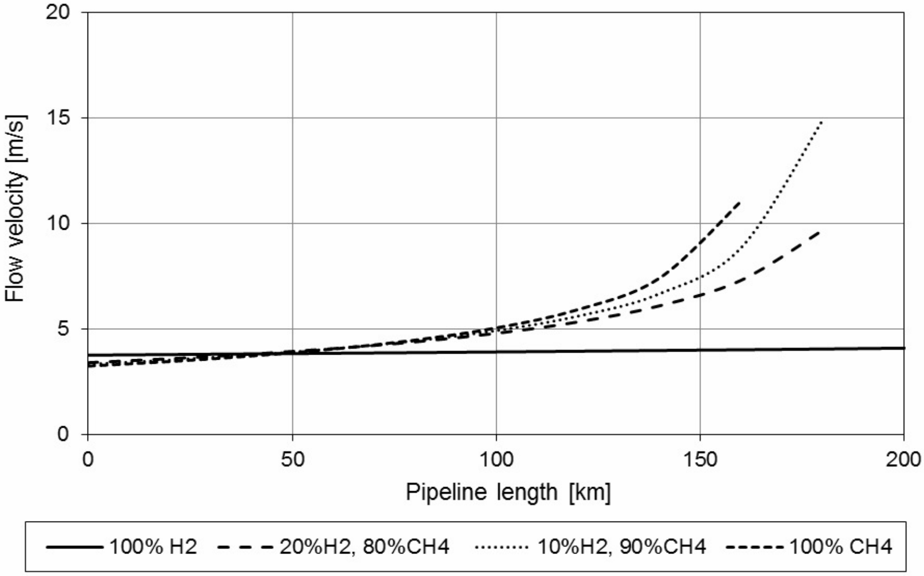

Fig. 10. Flow velocity versus pipeline length ($Q_n = 20\,000$ m^3/h, $D = 200$ mm) (see note)

For assumed case the flow velocity of pure methane and bi-component methane-hydrogen mixtures is lower in the pipeline inlet (about 3.5 m/s) than velocity of pure hydrogen (about 4 m/s). The flow velocity for assumed methane-hydrogen and for pure methane increase rapidly in function of pipeline length. Because of low pressure drop the flow velocity changes of pure hydrogen are not significant. The increase of the flow velocity is higher for mixtures with lower hydrogen molar fraction. The highest value of flow velocity has a pure methane but in assumed conditions it can be transported only for 160 km distance. For the mixture with 20% molar fraction of hydrogen the value of velocity has increased by 6 m/s and for mixture with 10% hydrogen molar fraction by 11 m/s. Double increase of the hydrogen molar fraction in the mixture causes 30% flow velocity value drop of its velocity at a 180 km distance.

6. FRICTION FACTOR COEFFICIENT CALCULATIONS

Linear friction coefficient is one of the most important issues of pipeline transportation of hydrocarbons or other substances. Determination of this coefficient for calculations of pressure drop along the pipeline with different hydraulic equations is key element to determine flow conditions. In this paper calculations of linear friction coefficient were considered for two variants of flow rates and inner pipeline diameters and for all assumed compositions of gas. Many empirical or semi-empirical formulas are available to determine this coefficient, most known are Colebrook–White equation for transitional flow in rough pipelines (hydraulic zone IV) (22):

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left(\frac{2.51}{\mathrm{Re}\cdot\sqrt{\lambda}} + \frac{\varepsilon}{3.71}\right) \tag{22}$$

and Prandtl–Nikuradse equation for flow with full influence of roughness (hydraulic zone V) (23):

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left(\frac{\varepsilon}{3.71}\right) \tag{23}$$

For transitional flow in rough pipelines (Reynolds number impact) the most important flow parameters are flow rate, density and viscosity determining Reynolds number and relative roughness. Under these conditions linear friction coefficient is highest for pure hydrogen and decreases with an increase of molar fraction of methane (Tab. 3).

Table 3

Linear friction coefficient at pipeline inlet (for Q_n = 20 000 m^3/h, D = 200 mm)

Composition	Linear friction coefficient
100% H_2	0.018281
80% CH_4, 20% H_2	0.017058
90% CH_4, 10% H_2	0.017027
100% CH_4	0.017001

Linear friction coefficient is a constant value depending on diameter and absolute roughness of pipeline for full roughness impact flow zone.

7. ENERGY TRANSPORTATION

Another issue of hydrogen pipeline transportation is energy transport. It has low molar mass and consequently low density. Due to these two facts higher amount of energy is required for its compression process. On the other hand low pressure drops allow to minimize the number of compression stations used for hydrogen transport. Hydrogen, as additive in natural gas, has positive impact on pipeline transportation of natural gas which can be transported for longer distances. The important issue for hydrogen pipeline transportation is its energy value. Combustion heat of hydrogen per mass unit is much higher (141.9 MJ/kg) than methane (54 MJ/kg). Because of lower density hydrogen has lower heat of combustion (12.67 MJ/m_n^3) per volume unit in normal conditions than methane (38.55 MJ/m_n^3). Changes of combustion heat as function of molar fraction of hydrogen are shown in Figure 11. Figure 11 shows that the amount of energy transmitted by pipeline decreases with the increase of hydrogen molar fraction in the mixture. Thus, in spite of better conditions for pipeline transportation, increased molar fraction of hydrogen reduces the energy efficiency of natural gas transmission. Despite of the low pressure drops pure hydrogen transportation is less energy efficient than transmission methane or natural gas (Tab. 4).

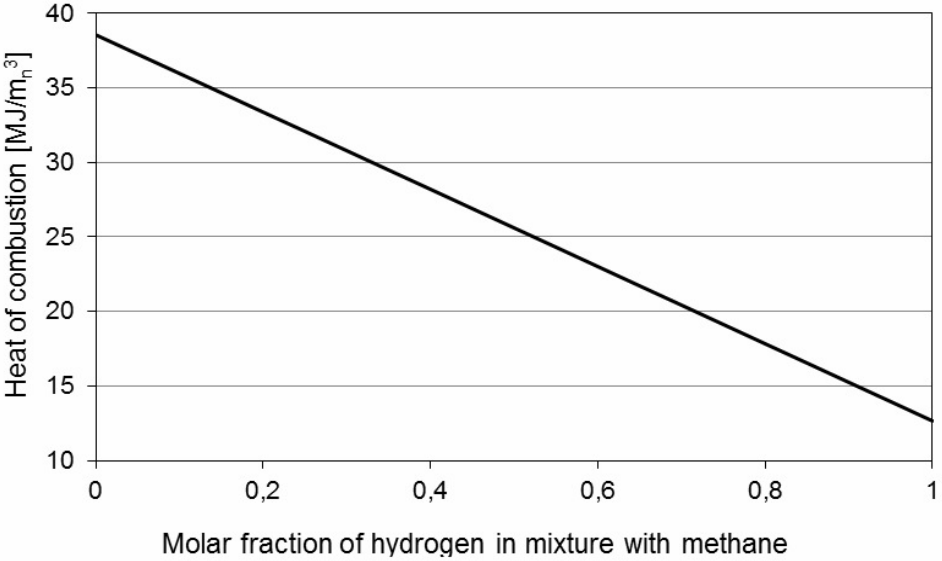

Fig. 11. Methane/hydrogen mixture heat of combustion

Table 4

Energy value of proposed flow rates for different compositions

Flow rate	Energy stream $[10^5$ MJ/h]			
	100% CH_4	90% CH_4, 10% H_2	80% CH_4, 20% H_2	100% H_2
20 000 m_n^3/h	7.71	7.19	6.67	2.53
30 000 m_n^3/h	11.5	10.8	10.0	3.8

8. CONCLUDING REMARKS

The developed by authors calculation algorithm for pipeline hydrogen transportation is a simple tool to determine basics thermodynamics parameters of transported gas in function of pipeline length. It is useful especially for pressure drop calculations. Presented algorithm can be improved or modified by implementing some other additional elements which have an impact on hydrogen or mixture of methane and hydrogen pipeline transportation. Those improvements might increase precision of the calculations and let to compute other important parameters for gas transportation.

Hydrogen molar fraction in mixture with methane causes smaller pressure drops during pipeline transportation than transmission of pure methane which leads to lower increase of gas flow velocity.

Transportation of hydrogen by pipelines is possible. It can be efficient and economically justified because of short time of transmission and large amounts that can be transported. Technical issues and assumptions were confirmed by calculations were made using developed algorithm. Pipeline inlet pressure (5 MPa) for hydrogen would require a lot of energy for compression process. According to calculation results and because of low pressure drop inlet pressure for pure hydrogen can be decreased to 2–3 MPa for presented case. Energy efficiency of hydrogen transportation is another important issue. Considering only parameters of hydrogen pipeline transportation it is obtained an incomplete picture of the energy transportation. Hydrogen has low heating value and heat of combustion per volume unit, therefore its transportation is less energy efficient than transmission methane or natural gas.

In the world (especially in the USA) natural gas transportation pipelines are widely used for efficient hydrogen transportation. Further technical research of hydrogen corrosion and penetration in a construction materials (pipeline steel) are required. Those issues should be solved to make a pipeline hydrogen transportation safe, more efficient and profitable.

NOMENCLATURE

a, b – Peng–Robinson EOS parameters
A, B – dimensionless PR EOS parameters
D – inner pipeline diameter [m]
d – relative gas density [–]
j – number of pipeline segments [–]
k – heat transfer coefficient [W/(m^2·K)]
L – overall pipeline length [m]
m – PR EOS parameter
p_1 – inlet pressure [Pa]
p_2 – outlet pressure [Pa]
p_{pc} – pseudocritical pressure [Pa]
R – universal gas constant [J/(mol·K)]
R_i – individual gas constant [J/(kg·K)]
Re – Reynolds number
T – average gas temperature [K]
T_1 – inlet gas temperature [K]
T_2 – outlet gas temperature [K]
T_0 – soil (ambient) temperature [K]
T_{pc} – pseudocritical temperature [K]
Q_n – flow rate [m^3/s]
w – flow velocity [m/s]
x – pipeline segment length [m]
Z – compressibility factor
α – PR EOS parameter
ε – relative roughness
λ – linear friction coefficient
ρ – gas density [kg/m^3]
ω – acentric factor

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