archives
of thermodynamics
Vol. **43**(2022), No. 3, 111–124
DOI: 10.24425/ather.2022.143174

Impact of hydrogen blended natural gas on linepack energy for existing high pressure pipelines

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Abstract The aim of this work is to examine the impact of the hydrogen blended natural gas on the linepack energy under emergency scenarios of the pipeline operation. Production of hydrogen from renewable energy sources through electrolysis and subsequently injecting it into the natural gas network, gives flexibility in power grid regulation and the energy storage. In this context, knowledge about the hydrogen percentage content, which can safely effect on materials in a long time steel pipeline service during transport of the hydrogen-natural gas mixture, is essential for operators of a transmission network. This paper first reviews the allowable content of hydrogen that can be blended with natural gas in existing pipeline systems, and then investigates the impact on linepack energy with both startup and shutdown of the compressors scenarios. In the latter case, an unsteady gas flow model is used. To avoid spurious oscillations in the solution domain, a flux limiter is applied for the numerical approximation. The GERG-2008 equation of state is used to calculate the physical properties. For the case study, a tree-topological high pressure gas network, which have been in-service for many years, is selected. The outcomes are valuable for pipeline operators to assess the security of supply.

Keywords: Existing steel pipeline; Hydrogen blended natural gas; Hydrogen percentage content; Linepack energy

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1 Introduction

1.1 Background

The green hydrogen generated from renewable energy sources, using electricity, is a promising way to satisfy H_2 demand on the large scale. Production of hydrogen from renewable energy sources, mainly from wind generation through electrolysis, provides flexibility in both the power grid regulation and the energy storage. In the transition period, to the moment of construction of pure hydrogen grids, injection of H_2 into the existing natural gas network and storage of the chemical energy in gaseous form are effective options called power-to-gas. The most commonly used electrolysis methods are alkaline, polymer membrane electrolyte (PEM) and solid oxide electrolysis. The efficiency of the latest constructions of PEM electrolysers available on the market is more that 75%. However, the overall efficiency of power-to-gas technology for hydrogen production and pressurization is between 34–51% [1]. When the hydrogen blended natural gas is used in gas fired power plants with gas turbines, the thermal efficiency of fuel chemical energy utilisation is between approximately 35% in a simple cycle and 70% in the combined heat and power production. State-of-the art of electrolysis technologies is low hydrogen output pressure, such as 10 kPa. To introduce hydrogen into a gas network, the additional compression using a certain amount of energy to gain the network pressure is required. For the abovementioned reasons, first of all, the injection of hydrogen into the natural gas network at medium pressure should be carried out.

In the current paper, the technical aspects of injection of hydrogen into the gas transmission network is considered as an option if no distribution grid is available in the neighbourhood of the green energy power plant.

The heating value of hydrogen is approximately 13 MJ/m^3, whereas the upper heating value of natural gas considered as pure methane is approximately 38 MJ/m^3, which is three times as much. For this reason, to deliver the same amount of energy to the customer, the volume of pure H_2, transported through the pipeline network, needs to be three times higher compared to CH_4. From energetic efficiency of fluid transport point of view, an increase in the hydrogen content in the natural gas mixture causes a decrease in the energy transported by pipelines [1,2]. Assuming the same level of tariffs, financial benefits for the operator of the transmission system of hydrogen blended natural gas would be lower due to a lower energy content of H_2/CH_4 mixture.

The physical parameters, such as a change of a compressibility factor as well as explosive limits for different hydrogen-natural gas mixtures, were investigated in [1,2]. For both the constant gas pressure and the temperature, the compressibility factor increases with an increase in hydrogen percentage in the blended natural gas. The compressibility factor reaches the value of 1 for the hydrogen blended natural gas of approximately 70% vol at the 8.4 MPa. For the devices applied by end users of natural gas group E, the maximum hydrogen content may be up to 45% if the Wobbe index acceptable range from approximately 48 to 52 is taken into account. If the lower value of Wobbe index is 47, as it has been agreed in the UK, the acceptable hydrogen content rises to 50% vol. However, regarding materials and the equipment applied in the high pressure pipelines utilized for many years, a hydrogen content needs to be significantly lower. The natural gas infrastructure, existing both in Poland and around the world, has not been designed for high H_2 concentrations.

While injecting hydrogen into a natural gas network, an additional risk is introduced since leakages are particularly hazardous. If hydrogen is expanded, e.g., on leakage, the Joule-Thomson effect increases the temperature of H_2; however, in the case of lots of gases, the temperature decreases during their extension. For this reason, to reduce the probability of failure, it is necessary to apply a modelling framework for integrity management of a pipeline system similar to that described in [3, 6].

In the context of hydrogen blended natural gas transmission, the following maintenance problems should be specified:

1) energetic aspects of burning of gas mixture containing hydrogen in both industrial and end users' appliances;
2) material aspects of a hydrogen content influencing the elements of transmission and distribution grids;
3) gas composition regarding capacity of transmission and distribution networks, e.g., performance of compressors, errors of measurements devices, others.

In the present paper, a technical review, in terms of the applied materials, taking into consideration a certain content of hydrogen in natural gas transported through the existing high pressure pipelines, are presented. The study focuses on mixtures, up to the volume of 10% and the working pressure ranging from 1.6 MPa to 8.4 MPa, applied on gas transmission networks in Poland. The low alloy steel grade applied in the current paper is L360 and two levels of a hydrogen blended volumetric content, 5%

and 10%, are provided as acceptable for the specific pipeline equipment, working at the maximum operating pressure of 5.5 MPa.

1.2 Literature review

Many publications in the recent time have dealt with the issues of transportation of hydrogen blended natural gas through the existing pipeline infrastructure designed a long time ago. For both technical and economic reasons, first of all the injection of hydrogen into the natural gas network at medium pressure should be carried out. Both maintenance problems in the distribution network and combustion disturbances in the end users' burners are not expected if application of hydrogen mixtures is limited up to 17% vol, according to the conclusions drawn in [4].

In a gas transmission grid, two types of compressors are mainly used: reciprocating (driven by gaseous piston engines) and centrifugal (driven by gas turbines). For gas turbines, in-service for many years, such manufacturers as Siemens confirmed that up to 10% of hydrogen blended natural gas, no changes in burners, combustion chambers, fuel supply system or a protection system are necessary [12]. In the case of other worldwide manufacturers of compressor units, such as Solar, the hydrogen content for in-service gas turbines, without modifications, is limited to 5% vol [13]. As turbomachinery manufacturers publicized [12, 13], the existing rotating compressors can be upgraded to be used for up to 40% vol of hydrogen in the transported gas mixture. A similar hydrogen volumetric content, up to 50%, is provided by manufactures of gas turbines as a limit of a hydrogen volumetric content in natural gas after modification of burners, combustion chambers, fuel supply system; however, it depends on a particular manufacturer and on the turbomachinery age. The compressors for both pure and rich hydrogen have used in the chemical and refinery industry for many years. By year 2023, the availability of the rotating equipment, including aero derivative and industrial gas turbines for applications on pipelines for transmission of pure H_2 or rich hydrogen content, is expected. The transportation of a rich hydrogen content in the gas is not problematic if thick low alloy carbon steels are used.

The possible hydrogen embrittlement of steel materials is complicated to predict. Hydrogen in H+ atomic form causes reduced bonding forces between metal atoms, which changes the steel fracture properties from ductile to brittle [5, 19]. Hydrogen cracking of metal pipes depends on a steel grade as well as on the stress of the pipe wall material and, therefore, the defects originated during maintenance and construction are crucial due to local stress concentrations. For this reason, only intensive inspections and testing of the existing steel pipelines including welds would provide a definite information about the accepted level of a hydrogen content in the specific high pressure gas grid [6–9].

Hydrogen not only can lead to initiation of cracks at high stress but also can reduce the yield strength by decreasing the energy required for dislocations [18,19]. The environmental hydrogen embrittlement of the high strength low-alloy steel was investigated in [11] and the conclusions from this paper are below. In the case of tensile tests of notched bars, 1% and 2% volumetric hydrogen has similar effects on the tensile strength results with the maximum difference of less than 2%. The content of hydrogen, up to 5%, significantly increases an influence on such mechanical properties of L555 steel grade as tensile strength and elongation after fracture which were obtained as 98% and 79%, respectively, compared to the pure natural gas. As morphology of a fracture specimen shows, higher proportions of hydrogen-natural gas mixture can increase degradation parameters and an impact of morphology of steels such as L555, which is the highest steel grade applied on the high pressure gas transmission grid in Poland [10]. The case study applied in the present paper is related to L360 low alloy steel grade pipeline working at the maximum operating pressure of 5.5 MPa, and two levels of a hydrogen blended volumetric content of 5% and 10% are provided as acceptable for the specific network equipment.

Research [20] investigates statistical assessment of hydrogen blending based on various models of gas distribution networks and different H_2 injection points. The paper focusses on the steady-state fluid flaws and gas quality compliance issues at increasing hydrogen admixture levels up to 75%. Unsteady analyses on looped networks characterized by mixtures of the natural gas and hydrogen are presented in [21], showing different pressure oscillations in transients when the networks supply customers with the hydrogen blended natural gas. The study [22] deals with a mathematical model developed to simulate transmission pipeline networks with distributed injection of green fuel gasses under the steady-state condition while adopting a non-isothermal flow. However, none of the above mentioned research [20–22] do not take into consideration dynamic issues in respect of the network linepack energy.

1.3 Motivation of this study

Due to fluid compressibility, a gas transmission network is used to store a certain amount of energy for the case when the supply is disturbed at the intake nodes. The aim and novelty of this work is to examine the impact of hydrogen blended natural gas on linepack energy under emergency scenarios of network operation, such as startup and shutdown of compressors. Instead of considering normal operation conditions, an emergency situation is examined for an existing high pressure pipeline. In this research, a hydraulic model is based on the work published, *inter alia*, in [14, 23]; however, a different numerical approximation is implemented because in this case study an emergency situation is investigated.

2 Unsteady flow model

In this section, a compressible flow model, numerical approximation and linepack energy equation are presented. To avoid undesired oscillations during the compressor emergency shutdown in the solution domain, the numerical approximation of the flow model is using a flux-limiter.

2.1 Compressible gas flow model

The gas flow model constitutes a nonhomogeneous hyperbolic system of partial differential equations derived from the conservation principles of mass, momentum, and energy. The set of equations can be written as follows [14, 23]:

$$
\begin{aligned}
\frac{\partial p}{\partial t} = {} & \frac{a_s^2}{c_p T}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right)\left(\frac{q}{A}+\frac{\dot{m}zRT}{pA^2}w\right) \\
& -\left[\frac{\dot{m}zRT}{pA}-\frac{a_s^2\dot{m}}{pA}\left(1-\frac{p}{z}\left(\frac{\partial z}{\partial p}\right)_T\right)\right]\frac{\partial p}{\partial x} \\
& -\frac{a_s^2\dot{m}}{TA}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right)\frac{\partial T}{\partial x}-\frac{a_s^2}{A}\frac{\partial \dot{m}}{\partial x}\,,
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\frac{\partial T}{\partial t} = {} & \frac{a_s^2}{c_p p}\left(1-\frac{p}{z}\left(\frac{\partial z}{\partial p}\right)_T\right)\left(\frac{q}{A}+w\frac{\dot{m}zRT}{pA^2}\right) \\
& -\frac{\dot{m}zRT}{pA}\frac{\partial T}{\partial x}-\frac{a_s^2}{c_p}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right) \\
& \times\left[\begin{array}{c}
\dfrac{\dot{m}zR}{pA}\left(1+\dfrac{T}{z}\left(\dfrac{\partial z}{\partial T}\right)_p\right)\dfrac{\partial T}{\partial x} \\
-\dfrac{\dot{m}TRz}{p^2A}\left(1-\dfrac{p}{z}\left(\dfrac{\partial z}{\partial p}\right)_T\right)\dfrac{\partial p}{\partial x}+\dfrac{zTR}{pA}\dfrac{\partial \dot{m}}{\partial x}
\end{array}\right],
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
\frac{\partial \dot{m}}{\partial t} = & -\frac{\dot{m}}{T}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right)\frac{\partial T}{\partial t} \\
& + \frac{\dot{m}}{p}\left(1-\frac{p}{z}\left(\frac{\partial z}{\partial p}\right)_T\right)\frac{\partial p}{\partial t} \\
& - \frac{\dot{m}^2 zR}{pA}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right)\frac{\partial T}{\partial x} \\
& + \left[\frac{\dot{m}^2 TRz}{p^2 A}\left(1-\frac{p}{z}\left(\frac{\partial z}{\partial p}\right)_T\right) - A\right]\frac{\partial p}{\partial x} \\
& - \frac{\dot{m} zTR}{pA}\frac{\partial \dot{m}}{\partial x} - w - \frac{pAg\sin(\theta)}{zTR}\,,
\end{aligned}
\tag{3}
$$

where: p – pressure, $\dot{m}$ – mass flow rate , T – temperature, A – cross-sectional area, w – frictional force, g – gravitational acceleration, θ – angle of inclination, q – heat flow, R – specific gas constant, z – compressibility factor, c_p – specific heat at constant pressure, t – time, x – Cartesian coordinate.

The isentropic wave speed $(\partial p/\partial \rho)_s^{1/2}$ is denoted as a_s and obtained from the expression

$$
\left(\frac{\partial p}{\partial \rho}\right)_s = \left[\frac{\rho}{p}\left(1-\frac{p}{z}\left(\frac{\partial z}{\partial p}\right)_T - \frac{p}{\rho c_p T}\left(1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_p\right)^2\right)\right]^{-1}, \tag{4}
$$

where ρ is the density. The frictional force per unit length is defined as

$$
w = \frac{1}{8} f_r \rho v|v|\pi D_i\,, \tag{5}
$$

where v is the velocity and D_i is the internal diameter. The friction factor f_r is obtained from the Colebrook–White equation. The heat transfer between the fluid and the soil per unit length and time is defined as

$$
\Omega = -\pi D_i dU\left(T - T_s\right), \tag{6}
$$

where U is the total heat transfer coefficient and T_s is the soil temperature. The physical properties are calculated from the Helmholtz-energy explicit mixture model (GERG-2008) [15].

2.2 Numerical approximation

Equations (1)–(3) are spatially discretized and converted into a system of ordinary differential equations. For the spatial discretization, a flux limiter is used due to steep gradients that might appear in the solution domain.

The following semi-discrete scheme is considered:

$$\frac{du_i}{dt} + \frac{1}{\Delta x_i}\left[F\left(u_{i+\frac{1}{2}}\right) - F\left(u_{i-\frac{1}{2}}\right)\right], \tag{7}$$

where u is the state vector containing pressure, temperature, and mass flow rate. Here $F\left(u_{i+1/2}\right)$ and $F\left(u_{i-1/2}\right)$ are the flux values on the grid points i represented by low- and high-resolution schemes. The flux limiter switches between these two, i.e.,

$$\begin{aligned} F\left(u_{i+\frac{1}{2}}\right) &= f^{\text{low}}_{i+\frac{1}{2}} - \phi\left(r_i\right)\left(f^{\text{low}}_{i+\frac{1}{2}} - f^{\text{high}}_{i+\frac{1}{2}}\right), \\ F\left(u_{i-\frac{1}{2}}\right) &= f^{\text{low}}_{i-\frac{1}{2}} - \phi\left(r_{i-1}\right)\left(f^{\text{low}}_{i-\frac{1}{2}} - f^{\text{high}}_{i-\frac{1}{2}}\right), \end{aligned} \tag{8}$$

where f^{low} and f^{high} denote the low- and high-resolution flux, respectively. The ratio of successive gradients is defined as

$$\begin{gathered} \phi(r) = \max\left\{0,\ \min\left[2r,\ 1,\ \min(r,2)\right]\right\}, \\ \lim_{r\to\infty}\phi(r) = 2\,. \end{gathered} \tag{9}$$

Roe's superbee flux limiter [16] is considered as a suitable compromise between accuracy and computational efficiency and is defined as

$$r_i = \frac{u_i - u_{i-1}}{u_{i+1} - u_i}\,,\ r\,. \tag{10}$$

For the time advancing, a variable-step, a variable-order solver based on the numerical differentiation formulas of orders 1 to 5 is used.

3 Linepack

The linepack, which refers to the volume of mass in the pipeline is defined as [17]

$$\frac{dL_p}{dt} = \frac{d}{dt}\int\limits_0^L \rho(x)A(x)dx\,, \tag{11}$$

where L is the pipeline length. It is assumed that no deformation occurs in the pipeline. The total amount of linepack energy is obtained by multiplying Eq. (11) with the net heating value on a weight basis. The total linepack can be obtained by integrating over the control period.

The linepack volume is calculated from Eq. (11). From the transient flow model, the pressure and temperature conditions in the pipeline are calculated. The compressibility factor is calculated from GERG-2008 and, as a consequence, the density of the mixture. After integration of Eq. (11), by means of the trapezoidal method, the linepack volume or linepack energy is determined.

4 Case study

For the case study, a real gas network transporting natural gas is considered. The applied topology of the network was selected due to availability of the detailed data for calculations. Other tree-structured topologies as well as loop-structured networks can be applied for the presented methodology without any limitations. The topology of the pipeline system is shown in Fig. 1. The length of the pipeline is 147.267 km with an outer pipe diameter of 711 mm and wall thickness of 11 mm. At the stations, two reciprocating compressors (CS-1, CS-2), are installed, as it is shown in Fig. 1, with a nominal flow rate of 1.19×10^5 m^3/h and suction pressure that lies within the range $p = 1.57{-}5.5$ MPa.

The flow rates required at node $n_9,\ldots,n_{14}$ are: 6×10^3, 2.5×10^4, 1×10^4, 8×10^3, 1.6×10^4, and 8×10^4 m^3/h. The minimum pressure at n_{14} is 3.8 MPa and at the remaining customer nodes it is equal to 3.0 MPa. The simulations are performed using $U = 3.61$ W/m^{2}K. For the case study, it is assumed that one compressor is shut down for 2 h of servicing. The shutdown time is 1 min while the startup time takes 15 min. As a result, the following boundary conditions are imposed:

$$p(Lt) = 3.77\ \text{MPa}, \qquad T(0,t) = 303.6\ \text{K}\,, \tag{12}$$

$$Q(0,t) = \begin{cases} 2.29\times10^5, & \text{if } \ t \le t_f\,, \\ a_1 t + b_1, & \text{if } \ t_f < t \le t_f + t_{\text{sd}}\,, \\ 1.145\times10^5, & \text{if } \ t_f + t_{\text{sd}} < t \le t_r\,, \\ a_2 t + b_2, & \text{if } \ t_r < t \le t_r + t_{\text{su}}\,, \\ 2.29\times10^5, & \text{otherwise,} \end{cases} \tag{13}$$

where Q is the flow rate, t_f is the moment at which the compressor is turned off for maintenance, t_r is the recovery time, t_{sd} is the shutdown time, t_{su} is the startup time, and a_1, a_2, b_1, b_2 are the slope-intercept coefficients. The shutdown and startup of the compressor is described by

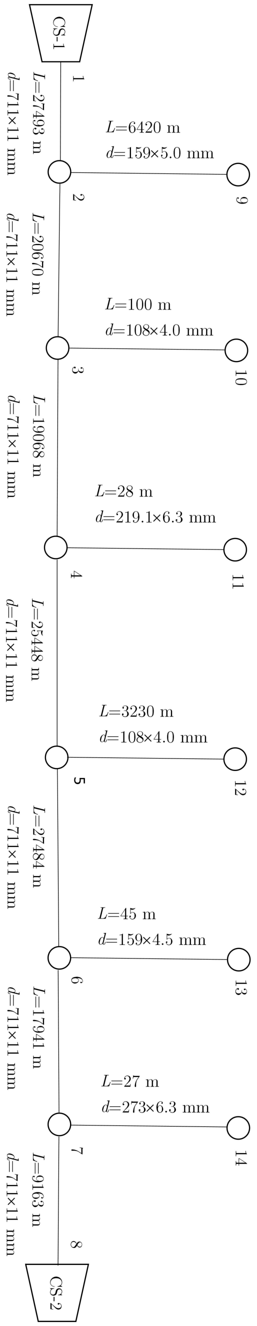

Figure 1: Topology of the gas network with reciprocating compressors CS-1, CS-2: L – pipeline length, d – internal pipe diameter.

boundary condition (13). If both compressors operate at CS-1, the flow rate in the normal conditions is equal to 2.29×10^5 m^3/h. The simulation time is $0 < t < 24$ h. Based on the allowable hydrogen content in pipeline systems, the linepack is computed for natural gas blended with 5% and 10% vol. hydrogen (see Table 1). A conventional normalization approach is applied, in which the sum of fractions is corrected to the unity by applying the same proportional correction to all natural gas components.

Table 1: Natural gas/H_2 compositions.

Gas component	NG % vol	NG/H_2 % vol	NG/H_2 % vol
Methane	96.833	91.991	87.150
Ethane	1.760	1.672	1.584
Propane	0.388	0.368	0.349
Butane	0.061	0.058	0.055
Isobutane	0.055	0.052	0.050
Pentane	0.009	0.009	0.008
Isopentane	0.007	0.006	0.006
Hexane	0.008	0.008	0.007
Nitrogen	0.115	0.110	0.104
Carbon-Dioxide	0.765	0.726	0.688
Hydrogen	–	5.000	10.000

Figure 2 shows the linepack for natural gas blended with 5% and 10% hydrogen. The total linepack in the case of hydrogen is added to the natural gas decreases by 0.21% for NG/H_2 (5% vol.) and 0.26% for NG/H_2 (10% vol.).

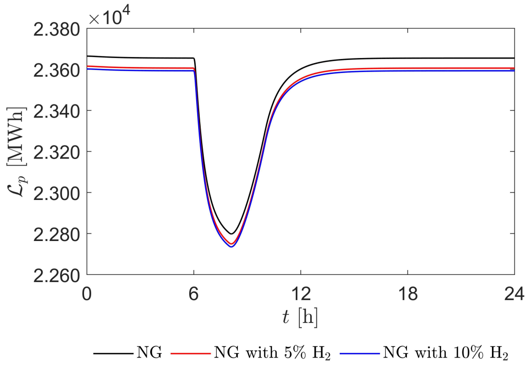

Figure 2: Linepack for NG, NG/H_2 (5% vol.) and NG/H_2 (10% vol.).

The difference in the linepack compared to the natural gas is shown in Fig. 3. The peaks appear at the moment the compressor is switched off and turned on. This nonlinear behavior is caused by the difference in downward and upward gradients that differ for each scenario. This is also illustrated in the zoom in the plot in Fig. 4 at the moment of switching off one compressor.

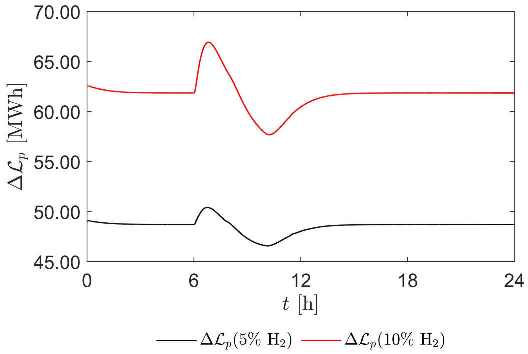

Figure 3: Difference in linepack compared to the natural gas.

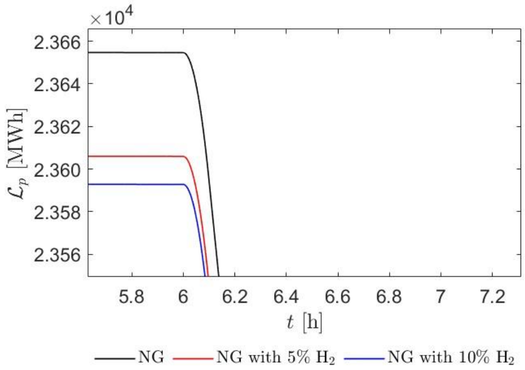

Figure 4: Difference in slopes at the moment of switching off one compressor.

5 Conclusions

Taking into consideration pipeline materials as well as the equipment of the compressor station of natural gas infrastructure utilized for many years, hydrogen blending volumes up to 5%, in specific cases up to 10%, seems to be acceptable. However, a limit of H_2 content depends on materials and compressor equipment used in the specific gas transmission network. In each case, a detailed study is required before admission of injection of hydrogen into the high pressure gas grid operated for many years. During the maintenance activities in later years, the inspections of a possible influence of a hydrogen content on the mechanical equipment need to be conducted.

The proposed nonisothermal flow model, numerical approximation and Helmholtz-energy explicit mixture model enable estimating accurately the flow transients and the linepack under emergency situations for the hydrogen blended natural gas in the pipelines. Simulations showed that mixing hydrogen with 5% and 10% natural gas lowered the linepack energy, however not significantly. At the moment when the compressor was switched off, the nonlinear linepack differences were observed. This was caused by the difference in downward and upward gradients. In the transition period for a hydrogen dedicated network, it is reasonable from technical and economic point of view to apply transport of a mixture of gases with a low content of hydrogen through the existing gas pipelines.

Received 20 February 2022

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