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Changes in gas flow in the pipeline depending on the network foundation in the area

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A B S T R A C T

The article presents an analysis of the results of overpressure distribution, velocity and gas streams obtained during the simulation of gas flow in the low pressure pipeline network. The calculations were made for the section of an existing gas network and the actual data describing gas consumption from the network by municipal customers and actual weather data characteristic to the specific city. Minimum and maximum overpressure of gas stream entering the network was determined, depending on the size of the network load and the difference in height between the gas station supplying the network and the most distant network connection (parameter ΔH). It was demonstrated that taking into account in the calculation the differences in the height of particular pipelines location in the network affects the selection of overpressure limit values of gas stream supplying the network. Moreover, gas overpressure distributions were compared in particular pipelines in the network for different cases of pipeline location in the area.

1. Introduction

Natural gas is defined as an ecologically clean fuel (Lueken et al., 2016; Faramawy et al., 2016), which use as an energy carrier or raw materials in the industry gradually increases (Al-Sobhi and Elkamel, 2015). Natural gas may be transported in a number of ways (Thomas and Dawe, 2003), but over long distances it is the most often realized using the tankers or pipelines. Various kinds of methods and computer-aided techniques are increasingly used in gas pipelines design, construction and operation, and in gas transport through the networks monitoring, so that many errors can be detected at an early stage of the work. Moreover, flow modeling is one of the main methods to obtain the information about the changes occurring in the flow and distribution of parameters characterizing the stream. The results obtained during gas flow simulation in complex network systems of pipelines can be used, inter alia, to predict fuel demand and in pipelines capacity planning (Amani et al., 2016; Reddy et al., 2006; Szoplik, 2015), in an increase of pipelines capacity and transport gas improvement (Monforti and Szikszai, 2010; Lochner, 2011; Voropai et al., 2012; Szoplik, 2010, 2012, 2016), fault detection and gas leaks from the network locating (Reddy et al., 2006; Sun, 2012; Kostowski and Skorek, 2012; Ebrahimi-Moghadam et al., 2016). In turn, the results of numerical studies performed in order to optimize the gas network structure (Nguyen and Chan, 2006; Űster and Dilaveroğlu, 2014) may be used to reduce the costs of gas transport (Wu et al., 2000; El-Mahdy et al., 2010; Najibi and Taghavi, 2011; Steinbach, 2007; Sanaye and Nasab, 2012; Ruan et al., 2009).

However, a number of assumptions and simplifications that significantly affect the results of calculations are adopted in the models of flow in the networks of pipelines and methods of model equations solving. The general model of fluid flow in complex network systems is based on the classic laws of mass, momentum and energy conservation. In turn, the detailed form of the flow model largely depends on the purpose of modeling. Therefore, different forms of model equations are often used in various scientific papers, which were achieved due to the use of certain simplifications or adding specific members. One of the criteria for the selection of the type of gas flow model in the pipeline may be the size of gas overpressure in the pipe. In this case, it was usually assumed that an unsteady state model should be used for the pipelines which send the gas under the high pressure (40 bar or more), since due to the transport of large gas streams the flow changes are slow. An effect of the model type (steady-state thermal model or unsteady thermal model) on a decrease in gas pressure in the high-pressure pipeline was confirmed by Osiadacz and Chaczykowski (2001). According to the authors, higher decrease

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in gas pressure is observed in the case of an adoption of the assumption of non-isothermal flow in the calculation. Also Chaczykowski (2010) points to the better results of numerical calculations for an unsteady heat transfer compared to the steady-state thermal model. Matko et al. (2000), on the basis of a comparison of experimental data concerning the stream size, and the gas pressure at the end of high pressure pipeline with the results of simulation in the non-steady state, demonstrated that higher consistency of the results is achieved in case of nonlinear distributed parameter and linear distributed parameter model using in the calculation compared to linear lumped parameter model. Chaczykowski (2009) in turn, did not observe any clear effect of the state equation on the quality of the results of simulation of basic dynamic flow parameters, when unsteady-state nonisothermal model was used in the calculations. To analyze transient flow in gas pipeline network, Alamian et al. (2012) used the state space equation, which was obtained using a transfer function equation. However, slow changes in the flow of high pressure gas pipeline can be sometimes accompanied by rapid changes in velocity or pressure caused, for example, by the sudden closure of the valve or damage to the pipeline. As demonstrated by Gato and Henriques (2005), untypical flow changes mainly depend on the dynamic characteristics of the control and safety valve, as well as pipeline capacity adopted in simulation calculations. Amani et al. (2016) analyzed the results of gas flow modeling in the transient state in the pipeline of serial, parallel and loop structure obtained on the basis of the steady state Weymouth equation. The author points out that due to the changes in stream volume at the inlet and outlet of the pipeline, a steady flow in the pipeline is rare, and steady state model adoption in the calculations can lead to calculation errors. The steady flow model was, however, used in the study by Fasihizadeh et al. (2014) for the optimization aimed at the reduction of operating costs of gas transport in high pressure network containing gas compressor stations. In the modeling of the flow of gas with different thermodynamic properties in high pressure network containing both the pipelines and non-pipe components, Li et al. (2014) applied the steady state model being the combination of hydrodynamic and thermodynamic models. In turn, Brkić (2009) used an improvement of Hardy Cross method to optimize the loop structure of the high pressure network. Based on the comparison of the results of gas flow modeling, assuming isothermal or nonisothermal model in the steady or unsteady state in the high pressure pipeline network, Osiadacz and Chaczykowski (2001) found that the choice of flow model should also take into account the structure and complexity of gas network. Herrán-González et al. (2009) also indicate that the decrease in gas pressure during the flow through the pipeline is significantly affected by the location of the pipeline in the area. Such relationship was confirmed by the calculations made for a straight section of high pressure pipeline, the end of which was located above ($\Delta H < 0$) or below ($\Delta H > 0$) than the entrance to the pipeline.

In case of gas flow modeling in low pressure pipelines, it is sufficient to use the steady-state model in order to obtain a satisfactory quality of the results, since flow changes are fast, and the time to reach the steady state is very short. Model equations can be solved using the methods based, for example, on an analogy to the current flow in electrical circuits (Tao and Ti, 1998; Sun, 2012). An example of practical use of flow modeling in low pressure network to control an overpressure of the gas stream entering the network, depending on the magnitude of the stream, is presented in the study by Szoplik (2016). In addition to knowledge of the network structure, flow modeling in low pressure networks with a complex structure requires the knowledge about all the streams collected from the network and the size of an intake pressure. Other parameters in the form of overpressure distribution, gas flow and velocity in all pipelines of the network can be determined during the simulation conducted in an appropriate computer program.

Models of gas flow in the pipeline network can be developed for individual pipelines or may include other network components, such as compression stations (Ríos-Mercado et al., 2006; Najibi and Taghavi, 2011), valves and other fittings used for closing the flow (Gato and Henriques, 2005), material or roughness of the pipe wall (Abdolahi et al., 2007; Ruan et al., 2009), or take into account the complexity of the network structure (Brkić, 2009; Amani et al., 2016) and its positioning in the area (Herrán-González et al., 2009). All of these parameters can affect the quality of the results of gas flow modeling in the network.

The results of flow modelling presented in the literature mainly relate to the flow of gas in high pressure pipeline networks, in which gas pressure drop in the pipeline mainly depends on the length of the pipeline, and it is virtually impossible to obtain a gas pressure too high for this type of network. The main problem is to provide the pressure higher than the minimum one, which is achieved installing gas pressure compressors on high pressure pipeline networks within a specified spacing, which task is gas stream compression. In turn, in the low pressure networks, in which smaller volumes of gas are transported and stream parameter changes are fast, omitting the differences in individual pipelines height in the network in the calculations may lead to large errors in the results of gas pressure in the network nodes. In this case, it is easy to lead to a situation of an exceeding the maximum, or default to maintain the minimum gas pressure in the network, which will result in an improper functioning of the equipment installed at the gas consumers. Therefore, experimental determination of limit values of overpressure in the low pressure network is so important, taking into account the actual data on the uneven load on the network and the ordinate of network position in the area.

The aim of the study is a comparative analysis of basic parameters characterizing the dynamics of gas flow in the pipeline network, depending on network location in the area. On the basis of simulation calculations performed in the GasNet software, the size of minimum and maximum overpressure of gas stream feeding the network of low pressure pipelines supplying the gas to municipal customers, was selected empirically depending on pipelines inclination in the network. Five ways of network foundation were examined: one case of horizontally positioned network ($\Delta H = 0$), and two cases, when the supply gas reduction station is located lower than the rest of the network ($\Delta H < 0$), and two examples of the networks in which the supply station is arranged above with respect to the rest of the network ($\Delta H > 0$). The limit overpressure of gas stream feeding the network was selected individually for each case, depending on the network load, i.e., the size of gas stream entering the network in order to cover the demand for gas by the consumers. The study was conducted for the fragment of the actual gas network in one of Polish cities, and actual data about gas consumption from the network by individual customers connected to that network and the actual weather data. Moreover, the unevenness in gas consumption by the customers depending on the temperature and hour of the day was taken into account in the calculations. The results of the calculations of overpressure feeding the network, obtained for the real network, which is characterized by the horizontal arrangement of all the pipelines, were previously verified using the data acquired from the network operation. Based on the analysis of the results of gas overpressure distribution in the network, an effect of taking into account in the calculations of the difference in heights of each of pipelines location in the network on proper network operation and safe gas transport was demonstrated. It was additionally demonstrated that the use of the dynamic system of overpressure adjustment to the volume of gas stream feeding the network, or suitable location of the gas reduction station in relation to the rest of the gas network, allowed to reduce the amount of gas entering the network and can be used to reduce gas transport costs.

2. Methods of the study

2.1. Pipeline networks characteristics

Gas flow modeling was performed for the fragment of the existing network of low pressure gas pipelines supplying gas to a group of municipal customers consuming gas to prepare meals, hot water and home heating. Table 1 presents the nominal and inner diameters of the pipes and the corresponding combined length of all the pipelines in the network. All pipelines of the networks are made of polyethylene PE of the absolute roughness ratio of 0.05 mm. The network is supplied by one of the gas stations (Z), in which the reduction in gas stream overpressure from the value of 4.5 bar to the value in the range from 1700 to 2500 Pa is performed. High-methane gas (methane content > 95%) is collected from the network by the customers at 108 gas connections. Fig. 1, presenting the scheme illustrating the analyzed network, also includes 12 nodes within the network, in which flow changes were analyzed. Among 347 nodes within the network, the node A147 is the most distant from the supply station (Z). Depending on the size of the network load (summary gas collected from the network in 108 connections), the streams fed to the left and right sides of the network meet in the node A147. Additionally, the dashed line in Fig. 1 indicates the pathway 1 of gas transport from the station Z to the node A147 via the left side of the network, while the dotted line indicates the pathway 2 of gas transport from the supply station Z to the node A147 via the right side network.

The study on the changes of parameters characterizing the dynamics of gas flow in the network was carried out of the five variants of network foundation in the area. The differences between adopted variants included the assumption of various differences between the height of supply station Z location, and node A147 which is the most distant from it. Table 2 summarizes the differences in height $H_z - H_k$, where k – means subsequent node A2, …, A147 distinguished in the network from Fig. 1. The statement contains the data for both the left and the right pathway of gas transport via the network (pathway 1 and pathway 2). Five options for the network location in the area were analyzed in the study. Reduction station Z situated at the same height as the node A147 ($\Delta H = 0$), the supply station situated 20 or 35 m higher than the node A147 ($\Delta H = 20$ m or 35 m), the supply station situated 20 or 35 m below with respect to node A147 ($\Delta H = -20$ m and -35 m). The changes in the localization of subsequent nodes distinguished in the network depending on the maximum height difference ΔH, and the distance L of the node to the reduction station Z, are

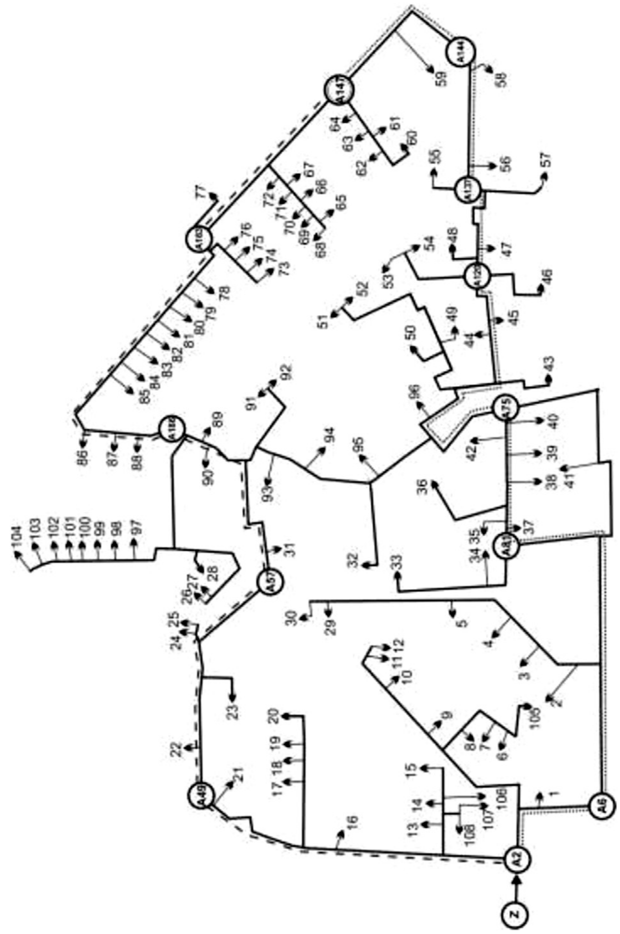

Fig. 1. Scheme of pipeline network for gas transport; Z – supply gas reduction station, A2, … A147 - selected network nodes.

Table 1
List of parameters of the pipelines of the network from Fig. 1; nominal diameter D_{nom}, inner diameter D_{in}, and total length of pipelines L.

No	D_{nom} 10^3 [m]	D_{in} 10^3 [m]	L [m]
1	250	204.6	18.7
2	225	184.0	687.6
3	180	147.2	1280.7
4	160	130.8	80.2
5	125	102.2	517.1
6	90	73.6	813.5
7	63	51.4	735.8
8	50	40.8	17.8

Table 2
List of selected nodes in the network from Fig. 1; node distance from the supply gas reduction station L; height difference between the supply station and the selected node ΔH.

Node k	L [m]	$\Delta H = H_Z - H_k$ [m]				
		0	−20	−35	35	20
Pathway 1						
Z	0	0	0	0	35	20
A2	31	0	−2	−3	32	18
A49	230	0	−3	−5	30	17
A57	329	0	−6	−11	24	14
A186	475	0	−8	−15	20	12
A163	652	0	−15	−25	10	5
A147	763	0	−20	−35	0	0
Pathway 2						
Z	0	0	0	0	35	20
A2	31	0	−2	−3	32	18
A6	90	0	−2	−6	29	18
A81	256	0	−6	−12	23	14
A75	419	0	−8	−18	17	12
A120	613	0	−15	−30	8	5
A137	676	0	−19	−33	2	1
A144	764	0	−20	−35	0	0
A147	863	0	−20	−35	0	0

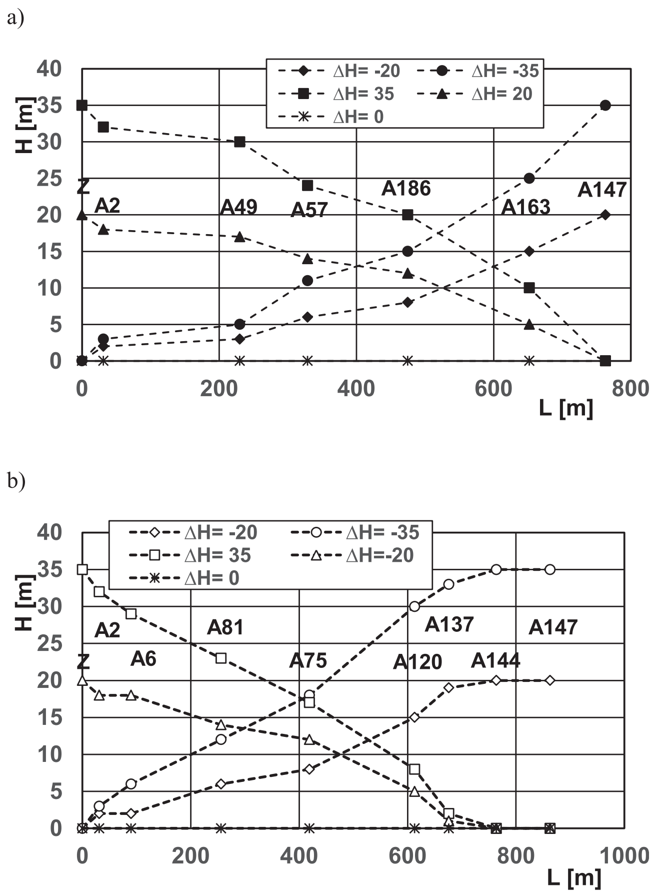

Fig. 2. Relationship of the height of selected network nodes on the distance from the supply gas reduction station; a) pathway 1; b) pathway 2.

illustrated in Fig. 2a (pathway 1) and Fig. 2b (pathway 2), respectively.

2.2. Variability in gas pipeline network load

Gas to municipal customers who use gas for home heating, water heating and food preparation is transported via the network. The flow of gas in the network is thus characterized by a variability that is observed in seasonal and daily cycles and depends on the air temperature and hour of the day. Variability of gas consumption depending on the temperature was developed in the form of the following relationship:

$$Q = a * Sd + b \tag{1}$$

where: Q - daily gas demand [m^3/day], a and b - experimentally determined equations parameters, Sd - number of heating degree days [°C day], depending on the base temperature T_b (T_b = 18 °C was assumed in the study) and daily average air temperature T_m [°C]. Number of heating degree days Sd was defined as a quantitative indicator used to estimate the requirements for energy needed to heat the rooms from the average daily temperature T_m to the assumed base temperature T_b, and depending on the average air temperature was calculated using equation (2) or (3):

$$Sd = \sum [T_b - T_m(i)], \text{ for } T_m(i) \le T_b, \text{ or} \tag{2}$$

$$Sd = 0, \text{ for } T_m(i) > T_b \tag{3}$$

Gas demand variability was determined individually for each group of customers collecting the gas from each of the 108 connections. In total, 108 relationships of gas demand on the number of heating degree days Sd were developed based on the data on actual gas consumption by the customers in 2006. The methodology for equation (1) parameters determination is described in detail in (Szoplik, 2016). Fig. 3 presents the results in the form of summary gas demand by all customers collecting gas from the network, and the average daily air temperature T_m in the subsequent days of 2006. The analysis of the results presented in Fig. 3 shows that there is a clear relationship between the average air temperature and daily demand for gas. In winter, when the air temperature is low, the demand for gas is higher compared to gas consumption in summer, when the air temperature is higher than in winter. Fig. 4 presents the relationship of gas demand as a function of the number of heating degree days Sd. In this case, demand for gas increases linearly with an increasing number Sd, as the number of degree days Sd is greater when the air temperature is lower.

Equation (1) allows to estimate of the daily gas stream dependent on the average temperature, presented as Sd. In turn, the daily variability in gas demand depending on the hour of the day was based on the characteristics obtained from the medium pressure reduction station. The percentage distribution of daily gas consumption in the subsequent hours of the day was determined on this basis. Fig. 5 presents the relationship between hourly gas consumption, in total in all the network connections in the subsequent hours of sample day in the winter season (Fig. 5a), and a sample day in the summer season (Fig. 5b). It can be noticed when comparing these results, that the volume of hourly gas stream depends both on air temperature and time of the day. Clearly higher demand for gas is observed in daylight hours (especially in the so-called morning and afternoon peak) than at night. Moreover, higher differences between the demand for gas in the hours of day and night are characteristic for the summer days compared to winter, but total gas consumption in these days is much lower than in the days of the winter season.

2.3. Modeling of gas flow in the pipeline network

The mathematical model of gas flow in the network presents a set of partial differential equations describing one-dimensional and isothermal flow of compressible fluid (Kralik et al., 1998), and describes the relationship between pressure drop, flow velocity, diameter and inclination of the pipeline and gas physical

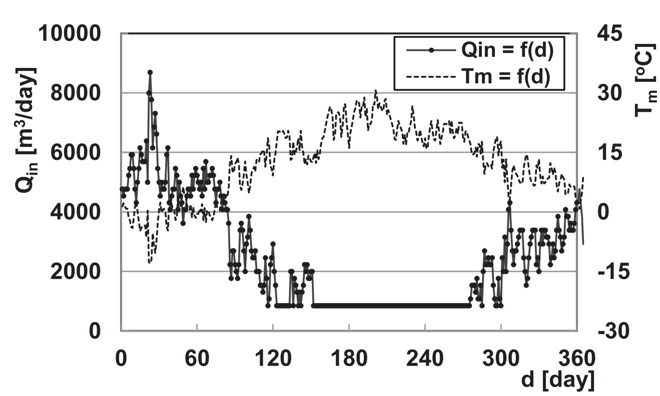

Fig. 3. Variability of gas demand Q_{in} in the network from Fig. 1, and the average air temperature T_m in the subsequent days of 2006.

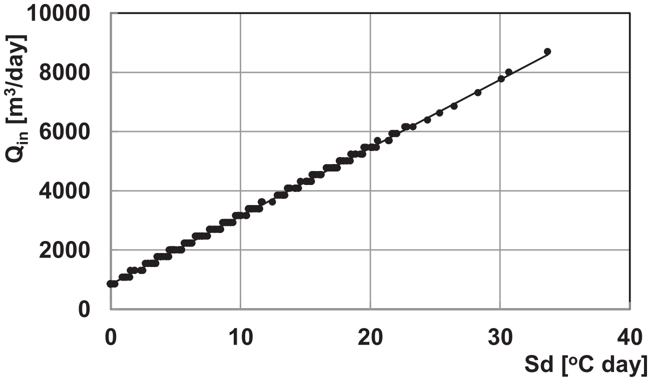

Fig. 4. Relationship of daily gas stream Q_{in} on the number of heating degree days Sd.

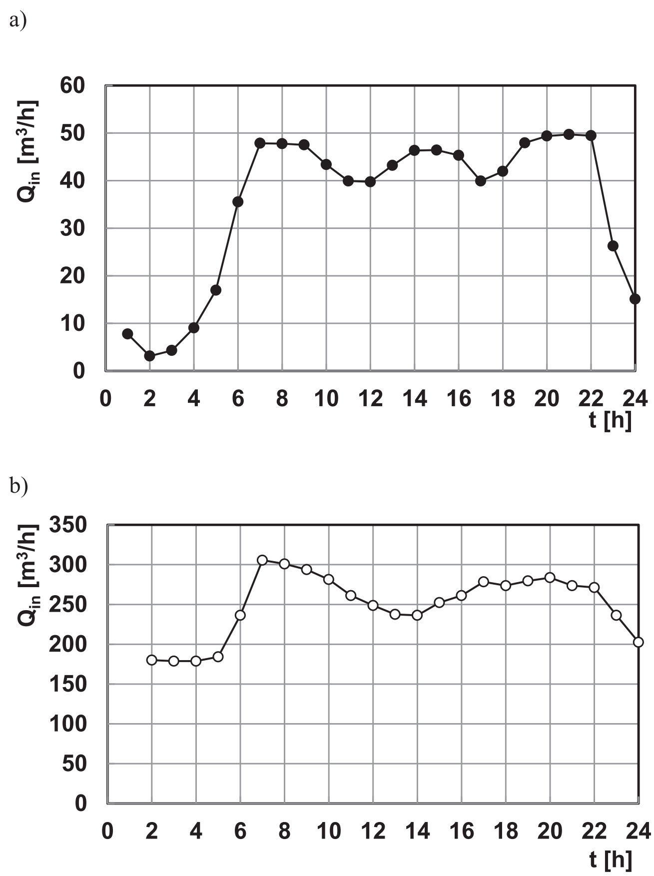

Fig. 5. Variability of gas demand Q_{in} in the subsequent hours of the day; a) data for the 15th June 2006; b) data for the 21st January 2006.

properties.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho w)}{\partial x} = 0 \quad (4)$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho w^2 + P)}{\partial x} = \frac{\rho w|w|}{2D} f - g\rho \sin\alpha \quad (5)$$

$$P = \rho ZRT \quad (6)$$

where: ρ is the density of gas, w is the gas flow velocity, λ is the Finning friction coefficient, D is the inner diameter of the pipeline, α is the angle between the horizon and the direction x, P is the pressure, g is the gravitational acceleration, Z is the gas compressibility factor, R is the individual gas constant and T is the gas temperature.

Steady flow model was accepted for the calculations, and it was assumed that the changes in gas pressure in the network pipelines are very quick at constant network load, hence the size of gas stream pressure is a function of only localization and does not depend on time. The mathematical model of flow in the network and the methodology of equations solving are described in (Szoplik, 2012, 2016). The calculations in a steady state were performed using commercial GasNet software, and the model equations were solved using the loop method based on the analogy of gas flow in the network to current flow in electrical circuits. The initial sizes of the streams in all the pipelines of network are assumed in the start point of the calculations, so that the first Kirchhoff's law was fulfilled. In turn, such pressures in the network nodes are determined in subsequent iterations, so that also the second Kirchhoff's law was also met in each circle of network. The result of the simulation is the distribution of flows in pipelines and overpressure in the nodes that meet the first and second Kirchhoff's law, and flow equation which is a relationship of stream size on pressure drop. The network node was defined as the point in the network in which the change in the pipeline diameter is observed, streams are combined or separated, or other non-pipe element is present on the network (valve, gate). As a result of the simulations, the distributions of streams and pressure, and gas velocity in all pipelines of the network satisfying the 1st and the 2nd Kirchhoff's law and flow equation, were obtained.

Simulations of gas flow in the network were performed for seven different air temperatures (ranging from −13 to 35 °C) which demonstrated a clear impact on the size of network load, while the volume of gas stream feeding the network varied in the range from 50 to 402 m^3/h. A total of 35 series of simulations of gas flow in the network were performed for each set of input data in a form of hourly gas streams collected in each of 108 connections for the five cases of network localization in the area.

3. Results of the study

3.1. Distribution of gas streams, velocity and overpressure in the network pipelines

Examples of the results of the calculations in the form of gas streams distribution in all pipelines of the network for the lowest and the highest load of the network horizontally positioned in the area ($\Delta H = 0$) are presented in Fig. 6. The network load is defined as the volume of gas feeding the whole network, and is determined as the total stream of gas collected in 108 gas connections. The distribution of volumetric gas streams in the low pressure network does not depend on the height of particular nodes localization in the area and the size of overpressure of gas stream feeding the network, and therefore, Fig. 6 presents only the results for the case where the supply station and node A147 are localized at the same height. Analysis of these results demonstrated that the size of gas stream flowing through consecutive pipelines depends on the network load and decreases with the distance from the supply station. The lowest gas streams are observed at the terminals supplying gas to municipal customers. In turn, the distribution of gas velocity in particular pipelines of the network for the two selected days with different load are illustrated in Fig. 7. Gas velocity in the pipe depends mainly on the size of the volumetric gas stream and the pipe cross-section, and therefore higher gas velocities are observed in the pipelines close to the supply station, and the lowest in the pipelines and connections the most distant from

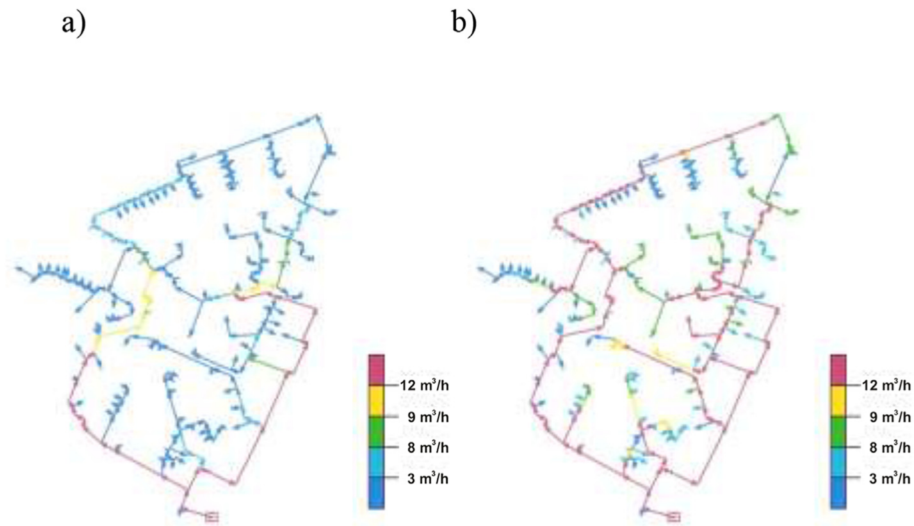

Fig. 6. Distribution of gas streams in the network pipeline; $\Delta H = 0$; $P_z = 1800$ Pa; a) Sd = 0, $Q_{in} = 50$ m^3/h b) Sd = 31, $Q_{in} = 402$ m^3/h.

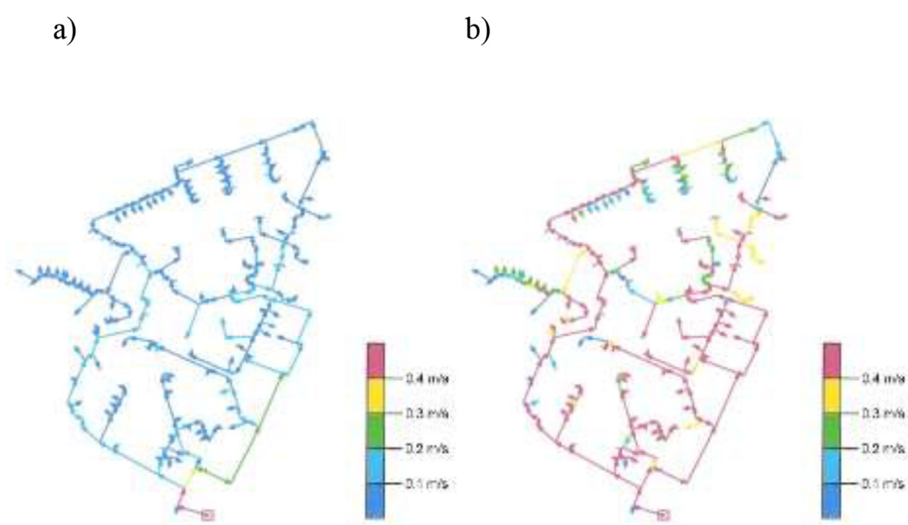

Fig. 7. Distribution of gas velocity in the network pipeline; $\Delta H = 0$; $P_z = 1800$ Pa; a) Sd = 0, $Q_{in} = 50$ m^3/h b) Sd = 31, $Q_{in} = 402$ m^3/h.

the supply station. However, it is easy to notice that gas velocity in all pipelines of the network is clearly lower than 5 m/s, which means that this network has the potential to expand and transport much larger quantities of gas.

One of the parameters determining the correct operation of the network and secure pipeline gas transport is the size of gas stream overpressure. According to the national regulations, it is assumed for low pressure gas networks that gas overpressure in each network connection should be in the range from 1700 Pa to 2500 Pa. Both too low and too high gas overpressure in the receiver may result in damage or improper functioning of equipment powered by gas. Therefore, proper selection of the overpressure of gas stream feeding the network is such an important issue, it can increase or decrease its size as a result of the resistance and due to the differences in heights between particular network elements. Gas stream pressure in a horizontal pipeline is mainly dependent on stream volume, diameter and length of the pipe and decreases with distance, while in the case of the network where with significant differences in heights between the start and end point of the network, an increase or decrease in gas overpressure must also be taken into account. Fig. 8 presents the results as a distribution of gas stream overpressure in all pipelines of the network for the sample day of the summer season (Sd = 0, $Q_{in} = 5$ m^3/h) and the input stream overpressure $P_z = 1800$ Pa and three cases of different location of network nodes ΔH in the area. It can be seen comparing these results, that in the summer season, despite the decrease in gas overpressure in the pipelines with the distance from the station, supply overpressure of 1800 Pa is sufficient to supply gas at a suitable overpressure to all connections of the network (in each point of the network the overpressure is slightly higher than minimum 1700 Pa). However, it was observed that in the case of a network in which the supply station is localized lower than the other part of the pipelines of the network ($\Delta H = -35$ m), gas stream overpressure increases with an increasing distance from the supply station. In turn, in the network in which the supply station is localized higher than the rest of the network ($\Delta H = 35$ m), an increase in gas overpressure in the pipelines closest to the supply station is observed, and then gas stream overpressure is reduced.

Analogical results of gas overpressure distribution in network pipelines, but characteristic for a typical winter day when the air

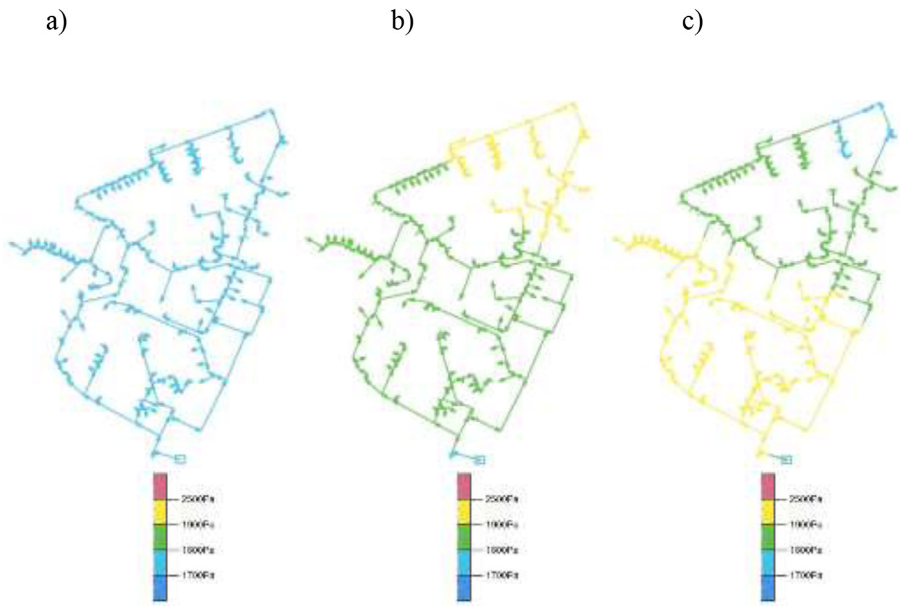

Fig. 8. Distribution of gas overpressure in the network pipeline; Sd = 0; Q_{in} = 50 m^3/h; P_z = 1800 Pa; a) ΔH = 0; b) ΔH = −35 m; c) ΔH = 35 m.

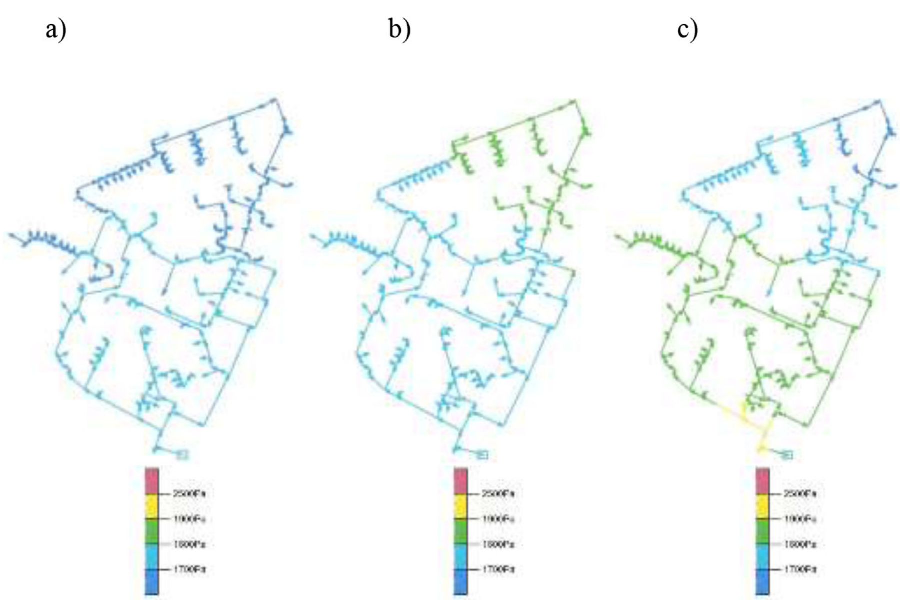

Fig. 9. Distribution of gas overpressure in the network pipeline; Sd = 31; Q_{in} = 402 m^3/h; P_z = 1800 Pa; a) ΔH = 0; b) ΔH = −35 m; c) ΔH = 35 m.

temperature is low and the demand for gas is high, are presented in Fig. 9. Overall relationship of gas overpressure drop in the horizontal gas network (ΔH = 0) and partially in the network with a positive difference in height (ΔH = 35 m), and an increase in gas overpressure with an increasing distance from the supply station in the network with a negative difference in height (ΔH = −35 m) is similar as for the data presented in Fig. 8. However, higher network load (higher value of the feeding stream Q_{in}) causes that for the same size of feeding stream overpressure, gas overpressure in particular pipelines of the network is sufficiently smaller than in case of lower network load (Fig. 8). Moreover, comparison of the results presented in Figs. 8a and 9a, as well as in Figs. 8c and 9c, demonstrates the results of network supplying with gas stream of too low overpressure. Inlet pressure of gas stream feeding the network in the summer season can be maintained at possibly low level, since the network load is low, while network supplying with the stream of an overpressure of 1800 Pa in the winter season also means that in horizontally situated network (ΔH = 0), or in the network, in which the supply station is situated 35 m higher than the most distinct nodes of the network, gas at an overpressure lower than the minimum 1700 Pa will be supplied to a significant part of the customers. Analysis of the results presented in Figs. 8 and 9 allowed to identify one of the major problems associated with gas transport through the network arranged at different heights of its particular elements (ΔH ≠ 0), and consisting of the selection of overpressure suitable for the correct network operation and gas transport.

It can be concluded on the basis of the results of gas overpressure distribution in the network, presented in Figs. 8 and 9, that the highest decrease in gas overpressure is characteristic for the

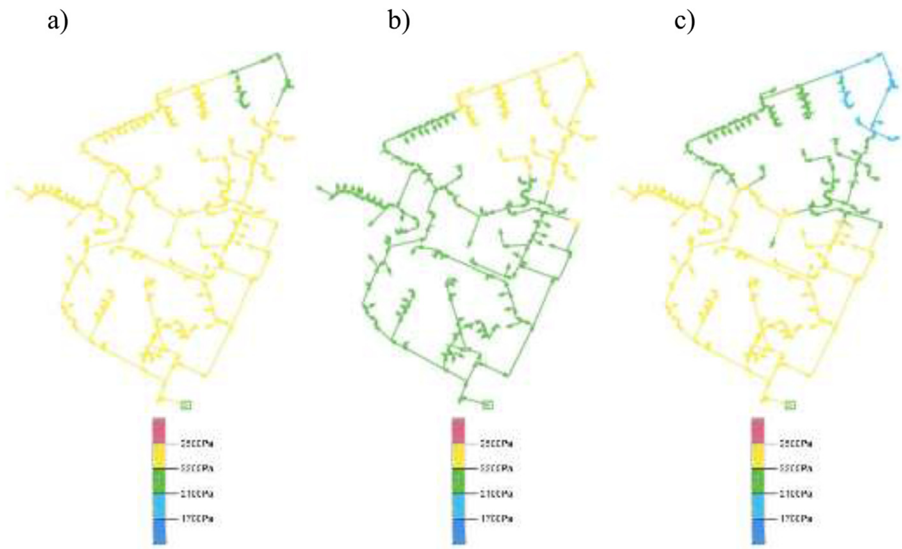

Fig. 10. Distribution of gas overpressure in the network pipeline; Sd = 31; Q_{in} = 402 m^3/h; P_z = 2200 Pa; a) ΔH = 0; b) ΔH = −35 m; c) ΔH = 35 m.

network horizontally positioned in the area (ΔH = 0), and proper selection of the minimum overpressure of gas entering the network depending on the network load is essential in this case. Fig. 10 contains the results of calculations in the form of a gas overpressure distribution in the network supplied with the stream of an input overpressure P_Z = 2200 Pa for the maximum (Q_{in} = 402 m^3/h) network load and various differences in the height of each of its components location ΔH. It can be noticed based on a comparison of these results, that such size of the overpressure of the stream supplying the network will assure gas supply to all the network connections at an overpressure higher than the minimum 1700 Pa. The differences in gas overpressure distribution depending on the network location in the area (parameter ΔH) are also observed in this case. A clear drop in gas overpressure with an increasing distance from the supply station is characteristic for the horizontally localized network (ΔH = 0). However, in the network, where the supply station is located lower than the rest of the network (ΔH < 0), an increase in gas overpressure with an increasing distance from the supply station is observed, and the network, in which the supply station is higher than the other pipelines (ΔH > 0), an increase in gas overpressure in the vicinity of the station can be noticed, and then gas overpressure drop as it moves away from the station.

3.2. Selection of minimum and maximum overpressure of gas stream supplying the network

Knowledge of the value of maximum and minimum overpressure of the stream supplying the network is necessary for proper network operation. An introduction of gas stream to the network with an overpressure higher than $P_{z(max)}$ will cause that the overpressure in some network connections will be higher than the allowable 2500 Pa. In turn, network feeding with gas stream with an overpressure lower than $P_{z(min)}$ will cause that gas overpressure in the selected network connections will be lower than the permissible 1700 Pa.

Based on the simulations of gas flow in the network performed for different sizes of the overpressure supplying the network, the maximum $P_{z(max)}$ and minimum $P_{z(min)}$ pressures were selected depending on network load Q_{in} and the network location in the area $\Delta H = H_z - H_k$. Table 3 summarizes all minimum and maximum pressures determined by simulation. In the summer, when the air temperature is high and network load is the smallest, regardless of network location in the area, calculated minimum overpressure of the feeding stream necessary for the proper operation of the network is 1710 Pa. In turn, the maximum overpressure of gas leaving the reduction station clearly depends on network location in the area $\Delta H = H_z - H_k$. In this case, the lowest maximum gas pressure $P_{z(max)}$ is characteristic for the network in which the supply station is situated 35 m higher than the most distant from it point (node A147; ΔH = 35 m). However, when the network load is the highest (winter season, low air temperature), the lowest minimum overpressure of supplying gas is characteristic for the network in which the supply station is situated about 35 or 20 m lower with respect to the most distant from it node on the network (ΔH = −35 m or −20 m). In turn, the lowest maximum overpressure of the supplying gas stream is observed in the network in which the supply station is situated 35 m higher than the most distant from is point in the network (ΔH = 35 m). Analysis of the results presented in Table 3 also demonstrated that the higher is the network load Q_{in} (lower air temperature T_m), the higher must be the minimum overpressure $P_{z(min)}$ of gas stream entering the network. Such a relationship is particularly clear in the case where the supply station and the most distant node in the network are arranged at the same height relative to sea level (ΔH = 0), or supply station is situated higher than the rest of the gas network (ΔH = 20 or 35 m). In turn, in the case of maximum overpressure $P_{z(max)}$, the highest effect of network load is observed when the supply station is situated about 35 or 20 m below the node most distant from it ΔH = −35 or −20 m.

Fig. 11 graphically presents the variation of the maximum and minimum supplying overpressure depending on the size of gas streams entering the network for three cases of network location in the area (ΔH = 0, 35 or −35 m). Comparing the results presented in Fig. 11, it can be seen that the highest differences between overpressure $P_{max} - P_{min}$ of gas supplying the network occur when the supply station and the node the most distant of it are at the same height above sea level (ΔH = 0), and network load is the lowest. In this case (Fig. 11a), the minimum overpressure of the stream should be increased with an increase in the gas stream entering the network, due to the partial gas pressure drop during the flow through the network. In turn, the maximum overpressure of gas

Table 3
Calculated values of maximum $P_{z(max)}$ and minimum $P_{z(min)}$ overpressure depending on the size of the stream feeding the network Q_{in} and network location in the area ΔH.

Q_{in} [m^3/h]	T_m [°C]	Sd	$P_{z(min)}$ [Pa]					$P_{z(max)}$ [Pa]				
			$\Delta H = H_z - H_{A147}$ [m]					$\Delta H = H_z - H_{A147}$ [m]				
			0	−20	−35	35	20	0	−20	−35	35	20
50	>18	0	1710	1710	1710	1710	1710	2500	2410	2340	2330	2400
135	10	8	1720	1710	1710	1720	1720	2500	2420	2350	2330	2400
195	5	13	1740	1710	1710	1740	1740	2500	2430	2360	2330	2400
254	0	18	1760	1730	1710	1760	1760	2500	2450	2380	2340	2410
301	−4	22	1780	1750	1720	1770	1770	2500	2470	2400	2340	2410
348	−8	26	1800	1760	1740	1790	1800	2500	2490	2420	2340	2410
402	−13	31	1830	1790	1770	1820	1820	2500	2500	2440	2340	2410

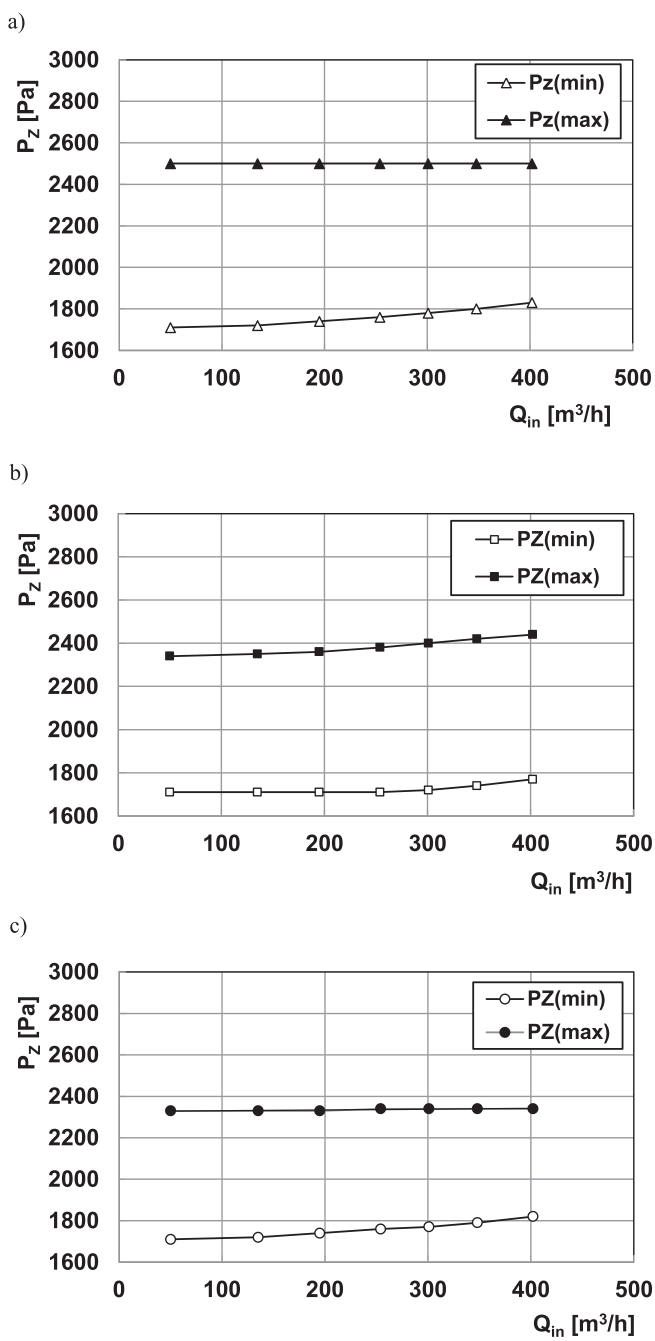

Fig. 11. Relationship of maximum $P_{z(max)}$ and minimum $P_{z(min)}$ overpressure of gas stream supplying the network and the size of network load Q_{in}; a) ΔH = 0; b) ΔH = −35; c) ΔH = 35.

supplying the network remains stable and there is practically no possibility of maximum pressure exceeding at any network node. However, when the station supplying the network is localized 35 m below (Fig. 11b) with respect to the network node A147 (ΔH = −35 m), the overpressure of gas stream supplying the network should be sufficiently lower (for Q_{in} = const) when compared to the data for network ΔH = 0 (Fig. 11a). This can be explained by the fact that, since the main component of natural gas is methane with a density less than the density of air, the gas transport through the network that is located on an increasing height from the starting point is supported by the nature of the gas. Gas pressure drop during the flow is partially compensated by natural and free movement of gas in the flow direction, hence the lower minimum overpressure (for Q_{in} = const) compared to the network ΔH = 0. Quite other relationship of maximum overpressure depending on the flow is observed with when the station supplying the network is situated 35 m higher than the most distant from is network point (Fig. 11c). Maximum overpressure practically does not depend on the network load and is clearly lower compared to the values determined for the network located at the same level ΔH = 0. This effect can be explained by the fact, that the decrease in the height of network localization in the direction of the flow of gas with a density lower than the density of air causes a retraction of gas in the pipelines, which can affect the local (especially near the reduction station) exceeding of the maximum permissible gas overpressure in low pressure networks (P_{max} = 2500 Pa). In turn, the relationship of minimum overpressure from the stream volume is growing and is similar to the horizontal network when ΔH = 0.

The following relationships were developed on the basis of the maximum and minimum overpressure selected during the simulation depending on the size of the volumetric stream of gas supplying the network (Q_{in}, m^3/h):

$$P_{z(\min)} = aQ_{in}^2 + bQ_{in} + c \tag{7}$$

$$P_{z(\max)} = a_1 Q_{in}^2 + b_1 Q_{in} + c_1 \tag{8}$$

which allow to select the optimum overpressure of the input stream in any size of the input stream. The coefficients of equations (7) and (8) were determined on the basis of the data presented in Table 3, separately for each network location in the area (parameter ΔH) and summarized in Table 4.

Fig. 12 presents the results of gas overpressure variability in selected nodes of the network from the reduction station Z to most distant from node A147 depending on particular network nodes location in the area, obtained for the maximum network load (Q_{in} = 402 m^3/h) and the maximum $P_{z(max)}$ or minimum $P_{z(min)}$ overpressure of gas stream supplying the network. The list of nodes and their calculated distance L calculated from the supplying node

Table 4
Parameters of equations (7) and (8).

$\Delta H = H_z - H_{A147}$ [m]	$P_{z(min)}$ [Pa]				$P_{z(max)}$ [Pa]			
	$a \cdot 10^4$	$b \cdot 10^2$	c	R^2	$a_1 \cdot 10^4$	$b_1 \cdot 10^2$	c_1	R^2
0	7	4.7	1705	0.9986	0	0	2500	–
−20	9	−18.12	1716	0.9860	4	7.63	2403	0.9839
−35	10	−30.6	1727	0.9551	6	1.6	2337	0.9957
35	5	6.16	1705	0.9942	−0.1	4.21	2326	0.7512
20	6	6.66	1704	0.9926	−0.1	4.21	2396	0.7512

Z for the five cases the network location in the area are presented in Table 2. Comparison of the results presented in Fig. 12a and b shows that the nature of gas overpressure changes in the subsequent network nodes, with an increasing distance from the reduction station, mainly depends on the network location in the area $\Delta H = H_z - H_k$. Additionally, it can be observed that with an increasing distance from the supply station, gas stream overpressure is reduced in the network in which the supply station is localized at the same level or higher than the node the most distant from it ($\Delta H = 0, 20, 35$ m), and the pressure drop is higher with greater the difference in the height between the supply station and node A147. In turn, a clear increase in gas pressure with an increasing distance from the supply station is noted in the network, where the supply

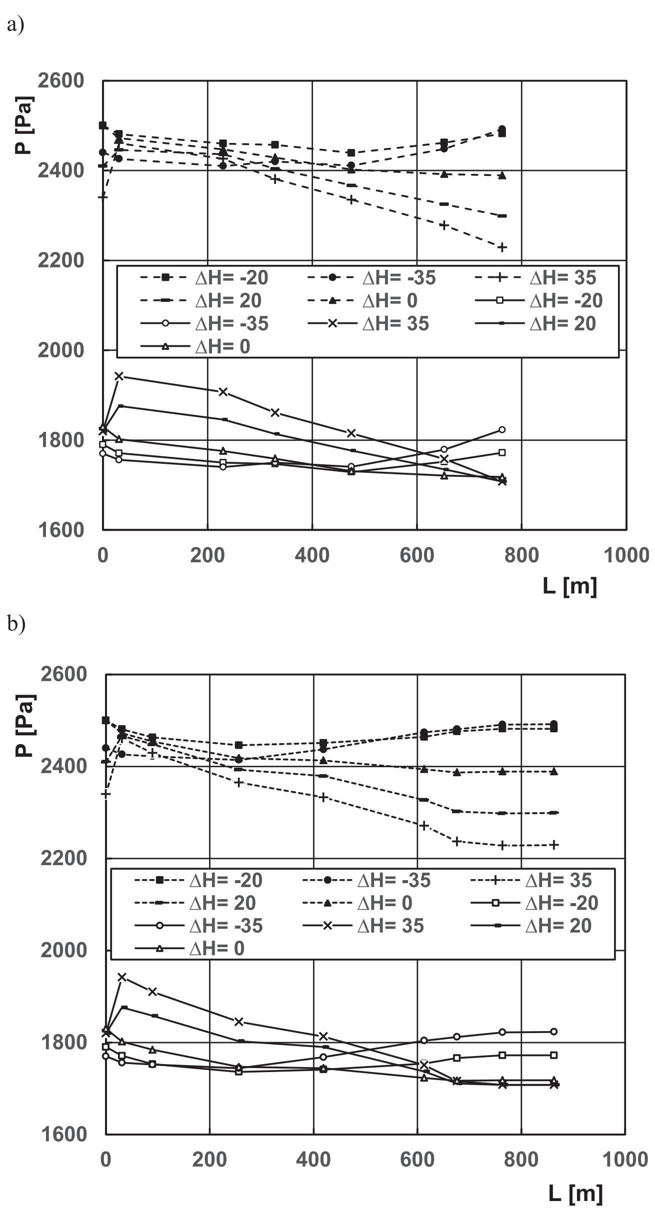

Fig. 12. Variability of gas overpressure in selected network nodes; $Q_{in} = 402$ m^3/h; a) the results for pathway 1; b) the results for pathway 2.

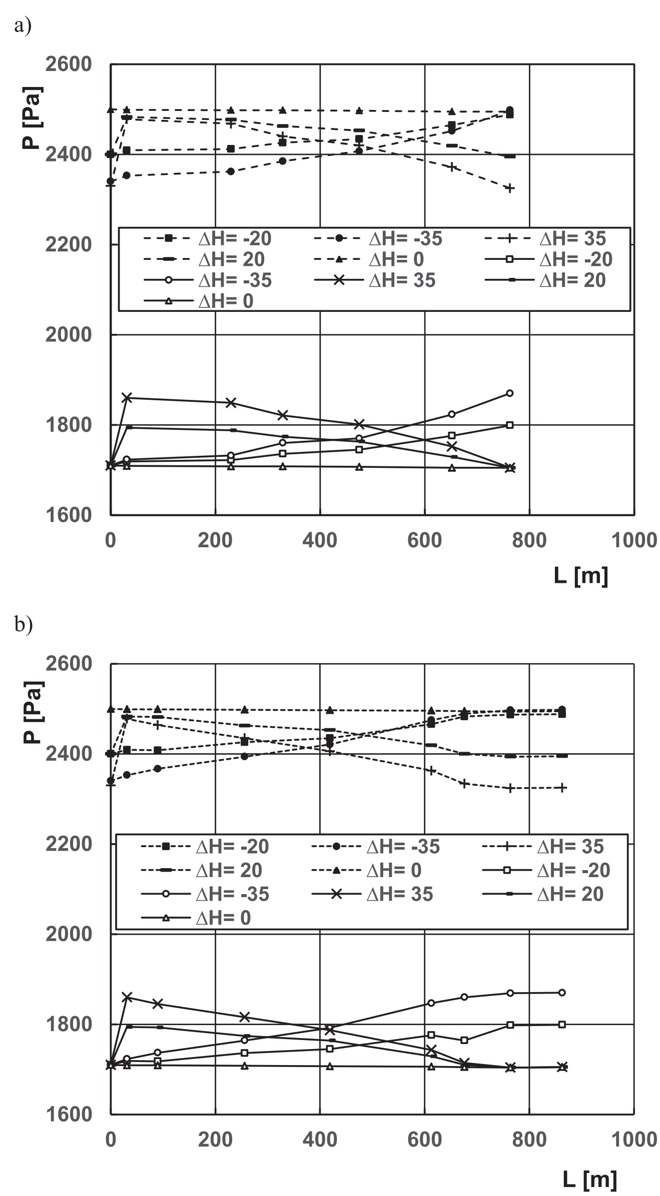

Fig. 13. Variability of gas overpressure in selected network nodes; $Q_{in} = 50$ m^3/h; a) the results for pathway 1; b) the results for pathway 2.

station is located lower than the other network nodes ($\Delta H = -20$ or -35 m). Such relationships are observed regardless of the size of the overpressure supplying the network ($P_{z(max)}$ or $P_{z(min)}$).

Analogical results of gas overpressure in the selected nodes of the network, but obtained for typical summer day when air temperature is high, and gas network load is the lowest ($Q_{in} = 50$ m^3/h), are presented in Fig. 13. In the case of a small load of the network, a decrease in gas overpressure (for $\Delta H = 0$, 20 or 35 m) or an increase in gas overpressure (for $\Delta H = -20$ or -35 m) with an increasing distance from the supply station L are also observed, however, not as clear as in the network with a maximum load (Fig. 12). Also in this case, the maximum gas overpressure in the node A147 does not exceed the maximum value of 2500 Pa, and the minimum value of overpressure 1700 Pa, which indicates the correct selection of the maximum supplying pressure $P_{z(max)}$ and the minimum supplying pressure $P_{z(min)}$.

3.3. *Variability in the input stream depending on the input overpressure and the network location in the area*

Experimentally determined maximum and minimum overpressure of gas stream entering the network, developed in the form of equations (7) and (8), allow to determine the scope of changes in stream overpressure for any pipelines load and network location in the area. From an economic point of view, maintaining possible the lowest gas overpressure in all network connections reduces the cost of gas transport and significantly reduces gas losses as a result of leakages or network failure, since lower mass flow (G_{in}, kg/h) of gas is transported through the network. Maintenance of the lowest gas overpressure in the network can be performed automatically using the devices installed at the reduction stations supplying the gas network (Szoplik, 2016). Table 5 presents the results of sample calculations of an annual mass stream of gas supplying the network for the minimum and maximum overpressure of gas entering the network, for different cases of network location in the area ΔH. It was assumed in the calculations that the maximum mass gas stream is the product of the volumetric gas stream and gas density in the condition of maximum pressure and the temperature of 281 K, while the minimum mass gas stream is the product of the volumetric gas stream and gas density in case of minimum overpressure and the temperature of 281 K. Then, for each hour of the day in 2006, depending on the size of gas stream entering the network and the corresponding minimum and maximum stream overpressure (calculated from equations (4) and (5)), the size of mass gas stream was calculated. The difference between annual summary maximum and minimum gas stream supplying the network, relative to the annual minimum mass gas stream, indicates the percentage by which the gas stream supplying the network may be lower in case of minimum gas pressure maintaining at the input to the network. Additionally, the calculations performed for different cases of network location in the area indicate that the larger difference in the height between the location of the supply station and the most distant from it node A147, the smaller are the differences between the summary mass stream calculated for the minimum and maximum input overpressure. An annual amount of gas entering the network can be decreased about 0.9% in a horizontally arranged pipeline network, maintaining the minimum stream overpressure the network entrance. However, when the supply station is situated 35 m higher or lower than the most distant from it point of gas consumption, the annual gas savings due to the maintenance of minimum overpressure in the network are approximately 0.6%. This can be explained by the fact, that in the case of gas transport through the horizontal pipeline network, the difference between the maximum and minimum overpressure of the supplying stream is significantly higher than in the case of overpressure values characteristic for the network located in differentiated area ($\Delta H \neq 0$).

Table 5
Results of the calculation of annual mass gas stream for minimum G_{min} and maximum G_{max} input stream overpressure for different cases of network location in the area ΔH.

$\Delta H = H_Z - H_{A147}$ [m]	G_{min} [kg/year]	G_{max} [kg/year]	$G_{max}-G_{min}$ [kg/year]	$(G_{max}-G_{min})/G_{min}$ %
0	31999	32278	279	0.9
−20	31992	32209	217	0.7
−35	31989	32191	202	0.6
35	31997	32182	185	0.5
20	31997	32204	207	0.7

However, when it is not possible to use at the supply station of the system for automatic stream overpressure adjustment to its size, it is worth to consider the possibility of reduction station location lower than other pipelines of the network ($\Delta H < 0$) for the newly designed or modernized networks. Such designed network will allow to transport gas at a higher overpressure in the network without the need of the input stream overpressure increase. It was also demonstrated that the network for which the difference in height between the supply station and node A147 is negative, can operate under the overpressure of the supplying stream lower than 1800 Pa practically through the entire year (regardless of network load). This overpressure is lower (in terms of the study conducted) than in case of horizontally arranged network ($\Delta H = 0$), or when the supply station is localized higher than node A147 ($\Delta H > 0$). The differences in streams size will be higher with greater network capacity and load, and the difference in height between the supply station and the node most distant from it.

4. Conclusions

The simulation of gas flow in the network allowed to obtain the distributions of gas overpressure in all pipelines and connections of the network, and to select minimum and maximum overpressure of gas stream entering the network, depending on the size of network load and the difference in height between the supply station and the most distant node in the network. The study demonstrated that gas transport through the network, in which the difference in height between the supply station and the most distant from it node in the network is $\Delta H < 0$, requires lower maximum overpressure of the input gas stream than in the case of horizontal network ($\Delta H = 0$), or when the height difference is positive ($\Delta H > 0$). In this case, gas transport is supported by the nature of the fluid itself, that due to the density lower that air density automatically moves in the direction of gas flow in the network. In the overpressure range (1700–2500 Pa), the average density of the air is 1.322 kg/m^3, and the average density of the natural gas is 0.729 kg/m^3. In turn, in the network with a negative height difference $\Delta H < 0$, an input overpressure of gas stream is slightly higher than in the network with positive height difference, and clearly lower than in horizontal network $\Delta H = 0$, since in order to deliver gas to the most distant connections of the network under the right overpressure, it must defeat the forces responsible for gas flow in the pipelines in the direction opposite to the direction of gas transport. An effect of the height of particular nodes location in the network significantly affects the parameters of network performance and safe gas transportation through the network. In horizontal network $\Delta H = 0$, it is easy to estimate the size of gas overpressure in particular networks connections, while in the networks in which the supply station is localized higher or lower than the other nodes in the network, the permissible value of maximum overpressure of the supplying stream must be determined experimentally due to the possibility of maximum gas overpressure exceeding in the network. In case of the network where $\Delta H < 0$, the nodes most distant from the supply station are particularly vulnerable to exceed the maximum gas overpressure, while for network where $\Delta H > 0$, an exceeding of the maximum overpressure may occur in the connections near the supply station.

In order to determine the maximum and the minimum value of pressure of feed gas stream of network it is necessary to conduct additional studies, taking into account the impact of gas composition (gas density), length and diameter of pipeline networks (network capacity) and the location of the selected nodes within the network relative to the power station. In the study was analyzed only a case where subsequent nodes of the network were located at a height systematically larger or smaller in relation to the position of the power station. However, it is worth to consider an example of accidental location of internal nodes in the network, since in some parts of the network, in the area of nodes situated clearly above or below with respect to the power station, local increases or decreases of the gas pressure will be observed. In addition, depending on the accuracy of measuring devices used to measure the size of the gas streams collected by the customers and the feed gas stream supporting the network, one should also take into account an element associated with the uncertainty of measurements. In the studies conducted, in order to measure the size of gas streams received by the customers, very accurate measuring devices were used for which the maximum measurement error of the stream (provided by the manufacturer) is below 0.5%, therefore it was assumed that uncertainty associated with the measurement of gas streams collected from the network by the consumers does not significantly affect the size of the pressure of feed gas supporting the network.

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