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GAS PIPELINE DIAMETER SELECTION METHOD WITH REFERENCE TO THE PIPE MANUFACTURING STANDARDS

METODA DOBORU ŚREDNIC ODCINKÓW SIECI ROZDZIELCZYCH GAZU ZGODNYCH Z PROGRAMEM PRODUKCJI RUR

A method of the optimal selection of the gas distribution network component section diameters has been described in the present study. The definitions of the alternative values of such parameters as: diameter, length and flow discharge, have been described. In result of the diameter calculation, the disposable pressure drop, including both alternative diameter and gas flow discharge, are modified, in result of the successive elimination of the component row sections, for which the diameter was calculated. However, the diameter values calculated in such manner are not fully compliant with pipe manufacturing standards. Therefore, an optimal diameter selection method, with reference to the pipe manufacturing standards, has been developed. The proposed new methods can be implemented when the gas distribution networks are designed.

Key words: gas distribution networks, gas pipeline diameters, optimization procedures

W publikacji podano podstawy teoretyczne doboru optymalnych średnic odcinków sieci gazowych funkcjonujących w układzie szeregowym oraz zasady doboru średnic złożonych układów gazociągów rozgałęzionych lub pierścieniowych. Zasady doboru średnic opracowane zostały na potrzeby projektowych sieci rozdzielczych. Warunki funkcjonowania tych sieci w zasadniczym zakresie różnią się od warunków funkcjonowania sieci przesyłowych. W przypadku sieci rozdzielczych odbiorcy gazu rozmieszczeni są praktycznie wzdłuż wszystkich odcinków sieci, co w znacznym stopniu zmniejsza dokładność oszacowania obliczeniowych natężeń przepływu gazu określanych również jako projektowane.

Opracowane zasady doboru średnic uwzględniają również ten problem, szczególnie ważny, gdy ustala się średnice złożonych układów gazociągów.

W założeniu teoretycznym opracowanej metody doboru średnic minimalizuje się średnice szeregu odcinków, przy stałych prędkościach przepływu gazu w każdym z odcinków. Odcinki wchodzące w skład analizowanego szeregu różnią się natężeniami przepływu gazu i długościami. Wykorzystując

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wprowadzoną zależność oblicza się w pierwszym etapie stratę ciśnienia, a następnie teoretyczną optymalną średnicę odcinka sieci gazowej najbliższego od stacji gazowej. Średnica teoretyczna zależna jest w istotnym zakresie od dyspozycyjnej straty ciśnienia ΔP. Wielkość ΔP ustala się indywidualnie dla każdego szeregu odcinków.

Ważnym elementem opracowanej metody jest wprowadzenie nowych pojęć, takich jak zastępcza długość, zastępcze natężenie przepływu gazu oraz zastępcza średnica. Zastępczość w tym przypadku związana jest z możliwością obliczenia dla szeregu odcinków — różniących się długościami, natężeniami przepływu gazu i średnicami — straty ciśnienia równej sumie strat ciśnień obliczanych kolejno dla poszczególnych odcinków danego szeregu.

W opracowanej metodzie, wykorzystując wyprowadzoną zależność, kolejno oblicza się wszystkie średnice odcinków danego szeregu. W trakcie obliczeń średnic kolejnych odcinków szeregu, zmianie ulegają również odpowiednie dyspozycyjne straty ciśnienia oraz wielkości zastępcze długości i natężeń przepływu gazu. Kolejna dobrana średnica zmniejsza wielkość początkową ΔP ustaloną dla danego szeregu. Zmienność tej wielkości, jak również wielkości zastępczych, wynika z eliminowania kolejnych odcinków szeregu, dla których obliczona jest następna średnica.

Uwzględniając opracowane założenia teoretyczne doboru średnic, można obliczyć tylko optymalne teoretyczne średnice odcinków wchodzących w skład odpowiedniego szeregu. Obliczone teoretyczne średnice, praktycznie w żadnym przypadku nie są zgodne z tymi, które są produkowane. Aby umożliwić praktyczne wykorzystanie opisanej metody do celów projektowych, opracowano również zasady doboru średnic odcinków zgodnych z programami produkcji. Dobrana średnica zgodna z odpowiednim programem produkcji może być najbliższą większą lub najbliższą mniejszą od obliczonej optymalnej teoretycznej.

Dla ułatwienia doboru średnic z wykorzystaniem opracowanych założeń teoretycznych, każdą sieć gazową po jej uprzednim rozcięciu traktuje się jako układ połączonych szeregów odcinków. W takim układzie wyróżnia się szeregi o znaczeniu dominującym, dostarczające gaz od stacji gazowej do konturu zasilania, oraz pozostałe. Szeregi odcinków rozprowadzające gaz od stacji gazowych do konturu zasilania określono głównymi kierunkami. Liczba głównych szeregów zasilania jest zależna od wielkości sieci i liczby stacji gazowych zasilających daną sieć rozdzielczą. Pozostałe szeregi odcinków zawsze są funkcjonalnie podporządkowane odcinkom szeregów głównych. Podporządkowanie polega na tym, że szeregi te bezpośrednio lub pośrednio maja wspólne węzły zasilania z odcinkami głównego szeregu. Zgodnie z opracowanymi zasadami w pierwszej kolejności dobierane są średnice odcinków szeregów głównych.

W publikacji określono również szczegółowe zasady, które winny być spełnione, aby dobór średnic zgodnych z programami produkcji spełniał założone kryterium minimalizacji średnic. Opracowana metoda składająca się z założeń teoretycznych i zasad doboru średnic uwzględnia również istotne wymagania funkcjonalne. Do takich wymagań zalicza się minimalizację zniekształceń obliczeniowych natężeń przepływu gazu, które uznaje się za najbliższe rzeczywistym. Nadmierne zniekształcenie tych wielkości może być przyczyną, iż zaprojektowana sieć rozdzielcza po jej wykonaniu może nie spełniać w całości lub fragmentarycznie postawionych celów technologicznych.

Słowa kluczowe: sieci rozdzielcze, średnice gazociągów, optymalizacja

1. Introduction

Gas distribution network is developed in order to provide gas supply for potential consumers, due to assumed exploitation parameters. Selection of suitable diameters, with reference to pipe production standards, is a major factor needed to achieve that goal. Problems met in achieving proper exploitation parameters, at every point of the gas distribution network, are related to incorrect knowledge of the gas consumption volume, in every point of the gas distribution network, as well as within individual zones, regions and whole gas network, as well. Incorrect assessment of the gas flow discharge may result in the occurrence of local pressure depression, causing malfunction of local gas installations. Redimensioning of the gas network (oversized diameters of component network sections, too big flow capacity of gas stations), are also considered as incorrect solutions.

Elimination of such abnormalities calls for the implementation of the suitable diameter selection rules, depending on the on gas distribution mode, due to functional requirements, i.e. distribution from the gas station to the supply contour, including regionalization of the gas consumption. Regionalization problem calls for division of the supply network into individual regions, which are usually independently operated. Reasoning of such functional division of the gas distribution network results from the fact that individual groups of consumers have diversified gas consumption demand. In result of such assumptions, various functions can be assigned to individual sections of the gas network, what is related to the pipe diameter selection necessity.

While selecting diameters of the gas distribution network we tend to the optimal cost-reduction program, however realization of such ventures is accompanied with many problems, both of analytical and technical character. Analytical problems are related to the methodology, because the problem of gas network construction cost--reduction program is not connected with a number and distribution of the gas stations. Gas distribution networks are built in diversified field conditions, thus simple function relation between the pipeline diameter and its construction unit cost, is not observed. Thus the currently used cost-reduction criterion programs, limited only to gas distribution networks, are rarely used, and their practical value is limited. Gas distribution networks are commonly built irrespectively to the unit cost and diameter of given pipeline, thus the criterion, which can satisfy the general-purpose function, comprises the problem of the diameter minimization. Universal character of such criterion results from the fact that it gives consideration to the cost-minimization problem, including functional criterion.

The cost-minimization criterion comprise some faults and simplifications, such as:

- unit building costs of the pipeline sections of the same diameter, fixed dependently on their location, can be considerably diversified,
- partial construction costs of individual section (earth works, infrastructure, assembling works, material costs, repairs, and work arrangement) are changed very often, thus after some time, the assumed criterion may no longer be satisfied,
- as the calculated gas flow discharges, computed for individual network sections and gas stations, have to be considered as constant values, we have no possibility to consider the errors constituting individual components of each case.

The method of selection of the optimal gas network diameter (Ellis et al. 1998; Osiadacz 2000; Hansen et al. 1991), describes the cost-minimization criterion expressed as:

$$K(D)=\sum_{i=1}^{m} L_i \cdot S(D_i)$$

where:

K — construction cost of the distribution network, based on the planned localization of gas stations and the assumed gas distribution directions, for each component section of the pipeline,

$D_i = (D_1 \dots D_m)$ — diameters of component sections,

m — number of sections within the gas network,

$S(D_i)$ — function describing the unit cost, depending on the diameter,

L_i — length of the component section of given network.

The method is based on linearization of the function $K(D)$, using generalized pressure calculation formula, matrix record of the connection of individual sections, as well as on the condition, that the minimal pressure on supply contour can not be lower than defined P_{min}, should be satisfied. Initially assumed diameters of individual sections, which are changed in result of the interaction, are considered as the basis of the assumed solution. The calculations are made in the manner giving consideration to the change of individual network diameters into "nearby-smaller" or "nearby greater" of the pipe series of types, until minimum of the assumed function is achieved.

Implementation of the method causes modification of the initially assumed diameters. For the options where the assumed criterion is satisfied, diversified diameters of considered gas network are achieved. The obtained results depend on the initial values used in the optimization calculations. For similar cost of several options satisfying needs of the assumed minimum, a problem related to the decision which option should be implemented, is met.

The method gives consideration to the calculated values of the gas flow discharge, considered as constant values prescribed to given network section, including its length. Such assumption leads to solutions satisfying the diameter solution criterion, where only pressures on the contours are greater than the minimal permissible ones.

Within the gas distribution networks, depending on their size, 8 to 12 various diameters are used. Gas network construction unit cost increases non-linearly, depending on the diameter, thus when the diameter minimization criterion is used, the smaller diameters are preferred. Considering conditions of the gas distribution within given network, depending on its size and configuration, the problem comprises only 30 to 50% of the network sections. The other sections of the network have diameters equal to the technical minimum.

2. Gas network diameter selection method

Selection of the diameter of component section of given network constitutes major of the gas pipeline designing, including minimization of the construction cost and functional efficiency. Factors affecting diameter selection of individual section comprise:

- gas network configuration,
- function of given pipeline within the system,

- gas type,
- disposable pressure drop,
- section length,
- gas flow discharge within given section.

Analytic solution of the diameter selection problem, in first order calls for assumption of the proper criterion. Computational gas flow discharge is determined for given configuration of the gas network. Accuracy of assessment of the gas flow discharge of component network sections is a major factor of the diameter selection procedure, including technical requirements.

Gas networks are usually composed of several sections, and analysis of their operation, from supplying source to the contour, including diameter selection, is very essential for the network functionality. To facilitate the problem, the methods based on suitably selected alternative values, have been considered. Such alternative values comprise: length of individual sections, sectional gas flow discharges, and sectional diameters. These methods have been formerly described (Zajda 1994, 1996).

In a case of the gas distribution networks, we can assume (without essential error) that gas density, gas flow velocity, temperature and flow resistance coefficient, are not diversified within individual sections of given gas network. In a case of row of connected sections supplied from the same node, we can assume that the pressure drop volume is effected mostly by the length of individual sections, including gas flow discharges and diameters of these sections. Substitutivity of these values within a row of sections of diversified values of the mentioned parameters should be equivalent to the calculated pressure drops. This equivalence should satisfy conditions of the following equation (1).

$$K\frac{Q_z^2 L_z}{d_z^5}=K\frac{Q_1^2 L_1}{d_1^5}+K\frac{Q_2^2 L_2}{d_2^5}+K\frac{Q_{n-1}^2 L_{n-1}}{d_{n-1}^5}+K\frac{Q_n^2 L_n}{d_n^5} \tag{1}$$

where:

K — constant related to the gas density, flow resistance factor, unit conversion, etc.,
Q_z — alternative value of the gas flow discharge,
L_z — alternative length of component network sections,
d_z — alternative diameter of sections with parameters L_z and Q_z,
Q_1, Q_2 ... — gas flow discharge within individual sections,
L_1, L_2 ... — length of individual sections,
d_1, d_2 ... — diameters of individual sections.

Alternative value for a row of sections L_z is equal to a sum of lengths of the component sections of the gas pipeline. Length of the component row sections, i.e. their alternative length, influence the total pressure drop, independently on the gas flow discharge and diameter of individual sections.

Thus, alternative length L_z can be calculated from a formula (2):

$$L_z = L_1 + L_2 + \ldots + L_{n-1} + L_n \tag{2}$$

Alternative value of the gas flow discharge Q_z for a given row of sections depends not only on the gas flow discharges within individual sections but also on the total length of these sections. Thus, all mentioned values influence the total pressure drop.

To facilitate calculations, considering only two sections of the row, we can re-write formula (1), in form:

$$\frac{Q_z^2 L_z}{d_z^5} = \frac{Q_1^2 L_1}{d_1^5} + \frac{Q_2^2 L_2}{d_2^5} \tag{3}$$

When rearranged, the equation (3) takes a form:

$$Q_z = \sqrt{\frac{(Q_1^2 L_1 d_2^5 + Q_2^2 L_2 d_1^5) d_z^5}{d_1^5 d_2^5 (L_1 + L_2)}} \tag{4}$$

As Q_z is calculated from a formula (4), we must already know parameters: d_z, d_2 i d_3. If we consider particular case, where individual sections of given row have the same diameters, thus $d_1 = d_2 = d_z$, and consequently we receive formula (5).

$$Q_z \cong \sqrt{\frac{Q_1^2 L_1 + Q_2^2 L_2}{(L_1 + L_2)}} \tag{5}$$

Alternative diameter of individual sections is determined using the relation (3), which when rearranged, and substituted in place of Q_z in formula (5), takes a form:

$$d_z \cong d_1 d_2 \sqrt[5]{\frac{Q_1^2 L_1 + Q_2^2 L_2}{Q_1^2 L_1 d_2^5 + Q_2^2 L_2 d_1^5}} \tag{6}$$

For greater number of sections within given row, we can analogically determine generalized dependence allowing to assess parameters Q_z and d_z, from formulas (7) and (8)

$$Q_z \cong \sqrt{\frac{Q_1^2 L_1 + Q_2^2 L_2 + \ldots + Q_n^2 L_n}{L_1 + L_2 + \ldots + L_n}} \tag{7}$$

$$d_z \cong d_1 d_2 \ldots d_n \sqrt[5]{\frac{Q_1^2 L_1 + Q_2^2 L_2 + \ldots + Q_n^2 L_n}{Q_1^2 L_1 d_2^5 d_3^5 \ldots d_n^5 + Q_2^2 L_2 d_1^5 d_3^5 \ldots d_n^5 + \ldots + Q_n^2 L_n d_1^5 d_2^5 \ldots d_{n-1}^5}} \tag{8}$$

Thus Q_z, d_z and L_z comprise values of the gas flow discharge, diameter and length, which equilibrate total pressure drop of individual sections within given row, having gas flow discharges Q_1, Q_2, Q_3, ..., Q_n, diameters d_1, d_2, d_3, ..., d_n, and lengths L_1, L_2, L_3, ..., L_n.

Pressure drop calculations are usually made using one of a number of formulas, which are diversified only with indices of Q and d, thus formulas (7) and (8) should also take under consideration this feature. Final form of the formulas is following:

- alternative value of the gas flow discharge

$$Q_z = \sqrt[a]{\frac{Q_1^a L_1 + Q_2^a L_2 + \ldots + Q_n^a L_n}{L_1 + L_2 + \ldots + L_n}} \tag{9}$$

- alternative diameter of the gas pipeline

$$d_z \cong d_1 d_2 \ldots d_n \sqrt[b]{\frac{Q_1^a L_1 + Q_2^a L_2 + \ldots + Q_n^a L_n}{Q_1^a L_1 d_2^b d_3^b \ldots d_n^b + Q_2^a L_2 d_1^b d_3^b \ldots d_n^b + \ldots + Q_n^b L_n d_1^b d_2^b \ldots d_{n-1}^b}} \tag{10}$$

In the proposed diameter selection method, conditions of the diameter reduction criterion should be satisfied only with reference to a rows of sections, which have different lengths and gas flow discharges.

For the determined disposable pressure drop ΔP of all sections within given row, the system is considered as two row sections with given values of the flow discharge, diameter and length, where for the first section of the row we have values Q_1, d_1, L_1; for the second Q_z, d_z and L_z, according to formulas (1), (9) and (10).

In this case we have a generalized formula:

$$\Delta P = K \frac{Q_1^2 L_1}{d_1^5} + K \frac{Q_z^2 L_z}{d_z^5} \tag{11}$$

Substituting Q_1 and Q_z with

$$Q_1 = A d_1^2 \tag{12}$$

$$Q_z = A d_z^2$$

where:

$$A = \frac{\pi}{4} w$$

w — gas flow velocity; w = const for d_1 and d_z (as assumed)

as well as substituting to formula (11) the assumption (12) we receive:

$$\Delta P = K \frac{A^2 d_1^4 L_1}{d_1^5} + K \frac{A^2 d_z^4 L_z}{d_z^5}$$

and in result of further rearrangements, we receive:

$$d_z = \frac{L_z d_1}{\frac{\Delta P}{KA^2} d_1 - L_1}$$

Substituting $\frac{\Delta P}{KA^2} = B$, d_z takes a form:

$$d_z = \frac{L_z d_1}{B d_1 - L_1} \tag{13}$$

Alternative diameter of the first section having diameter d_1, and the next one in the row, having fixed diameter d_z, can be calculated from a formula:

$$D_z \cong \sqrt[5]{\frac{d_1^5 d_z^5 (Q_1^2 L_1 + Q_z^2 L_z)}{Q_1^2 L_1 d_z^5 + Q_z^2 L_z d_1^5}} \tag{14}$$

Substituting d_z to formerly determined formula (13), we receive:

$$D_z \cong \sqrt[5]{\frac{d_1^5 L_z^4 (Q_1^2 L_1 + Q_z^2 L_z)}{Q_1^2 L_1 L_z^4 + Q_z^2 (B d_1 - L_1)^5}}$$

and substituting

$$\sqrt[5]{L_z^4 (Q_1^2 L_1 + Q_z^2 L_z)} = a$$

and

$$Q_1^2 L_1 L_z^4 = b$$

we receive

$$D_z \cong \frac{a d_1}{\sqrt[5]{b + Q_z^2 (B d_1 - L_1)^5}} \tag{15}$$

The diameter reduction procedure calls for the selection of minimum of the formula (15), with respect to a variable d_1, finally:

$$\sqrt{\frac{Q_1}{Q_z}} \cdot L_z + L_1 = B d_1 \tag{16}$$

Using formula (12), for a section located nearby the gas station, the pressure drop ΔP_1 will occur.

As well as using the former substitution $\frac{\Delta P}{KA^2} = B$, we receive

$$d_1 = \frac{\Delta P \cdot L_1}{\Delta P_1 \cdot B}$$

Substituting this relation to formula (16) we receive:

$$\sqrt{\frac{Q_1}{Q_z} \frac{L_z}{L_1}} + 1 = \frac{\Delta P}{\Delta P_1} \tag{17}$$

Formula (17) determines relation between the disposable pressure drop ΔP of component sections of given row and the pressure drop for optimal diameter of a section located nearby supplying node, depending on the alternative values of: total gas flow discharge and length, as well as gas flow discharge and length of the first section of the row.

In the equation (17), only value ΔP_1 should be determined, whereas the other values result from intermediate calculations, as values Q_z, and L_z can be estimated formerly. When rearranged, we can obtain practical relation which can be used to calculate ΔP_1, for the first section of the row, counting from the supply source (gas station), having a form:

$$\Delta P_1 = \Delta P \frac{\sqrt{Q_z} L_1}{\sqrt{Q_1} L_z + \sqrt{Q_z} L_1} \tag{18}$$

or for arbitrary section of the row:

$$\Delta P_{ij} = \Delta P_i \frac{\sqrt{Q_{zi}} L_{ij}}{\sqrt{Q_{ij}} L_{zi} + \sqrt{Q_{zi}} L_{ij}} \tag{19}$$

However, if we consider the use of any of usually applied formulas of pressure drop calculation, formula (19) takes final form:

$$\Delta P_{ij} = \Delta P_i \frac{\sqrt[a]{Q_{zi}} L_{ij}}{\sqrt[a]{Q_{ij}} L_{zi} + \sqrt[a]{Q_{zi}} L_{ij}} \tag{20}$$

where:

- ΔP_{ij} — pressure drop of the section $(i\text{–}j)$, used to calculate its diameter,
- ΔP_i — disposable pressure drop of all sections of the row, including also section $(i\text{–}j)$,
- Q_{zi} — alternative gas flow discharge of the component row sections, without section $(i\text{–}j)$,
- L_{ij} — length of section $(i\text{–}j)$, for which the pressure drop ΔP_{ij} was calculated,
- Q_{ij} — gas flow discharge within section $(i\text{–}j)$,
- L_{zi} — alternative length of the component row sections, excluding section $(i\text{–}j)$,

i, j — numbers nodes of gas network,
a, b — index occurring in the formula, used in the pressure drop calculation

$$\Delta P = K \frac{Q_{ij}^{a} L_{ij}}{d_{ij}^{b}}; \qquad a = 1.8\text{–}2.25, \qquad b = 4.8\text{–}5.25$$

Estimation of the pressure drop of successive row sections is schematically shown in Fig. 1a, b and c. Scheme shown in the Fig. 1 refers only to calculation of the "theoretical" diameters, according to formula

$$d_{ij} = \sqrt[b]{\frac{K Q_{ij}^{a} L_{ij}}{\Delta P_{ij}}} \tag{21}$$

Such procedure of the diameter selection has no practical use, as the "real" diameters should be compliant with all pipe-manufacturing standards.

If the diameter of section (i–j) d_{ij} is calculated from the formula (21), using the pressure drop ΔP_{ij} determined by formula (20), where the selected diameter d_{ijR} is compliant with the assumed production program, the pressure drop estimated for this diameter equals to ΔP_{ijR}. In general, depending on the selected diameter d_{ijR}, greater or smaller than that calculated from formula (21), the following inequalities may occur:

$$\Delta P_{ij} > \Delta P_{ijR} \qquad \text{or} \qquad \Delta P_{ij} < \Delta P_{ijR}$$

A rare case, when $\Delta P_{ij} = \Delta P_{ijR}$, may be practically neglected. If an inequality $\Delta P_{ij} > \Delta P_{ijR}$ occurs, it means that network sectional diameters d_{ijR} will be selected, being the "nearby-bigger" to the manufactured pipe standards. Option of the selection of "real" diameters, i.e. the "nearby-bigger" diameters, is schematically illustrated in Fig. 2a, b and c. If a "real" diameter is selected — according to the "nearby-smaller" rule — the following inequality can be written:

$$\Delta P_{ij} < \Delta P_{ijR}$$

The first option of the diameter selection results in a fact that for all next sections of given row, the disposable pressure drop $\Delta P - \Delta P_{ijR}$ is adequately greater than in a case ΔP_{ij}, thus it leads to the selection of smaller diameters for the other sections of the row, as $\Delta P - \Delta P_{ij} < \Delta P - \Delta P_{ijR}$. However, if an inequality $\Delta P - \Delta P_{ij} > \Delta P - \Delta P_{ijR}$ is observed, the disposable pressure drop of the other component row sections will be smaller, i.e. diameters selected for the other sections will be greater. Each of the mentioned methods of the "real" diameter selection is accompanied with the occurrence of differences between diameters d_{ij} and d_{ijR}, particularly for the sections within the row. Selection of successive "real" diameters of given row is closely connected to the selection of downstream sections, i.e. with the disposable pressure drop. In the second option of the diameter selection, a reverse range of the disposable pressure drop, is observed.

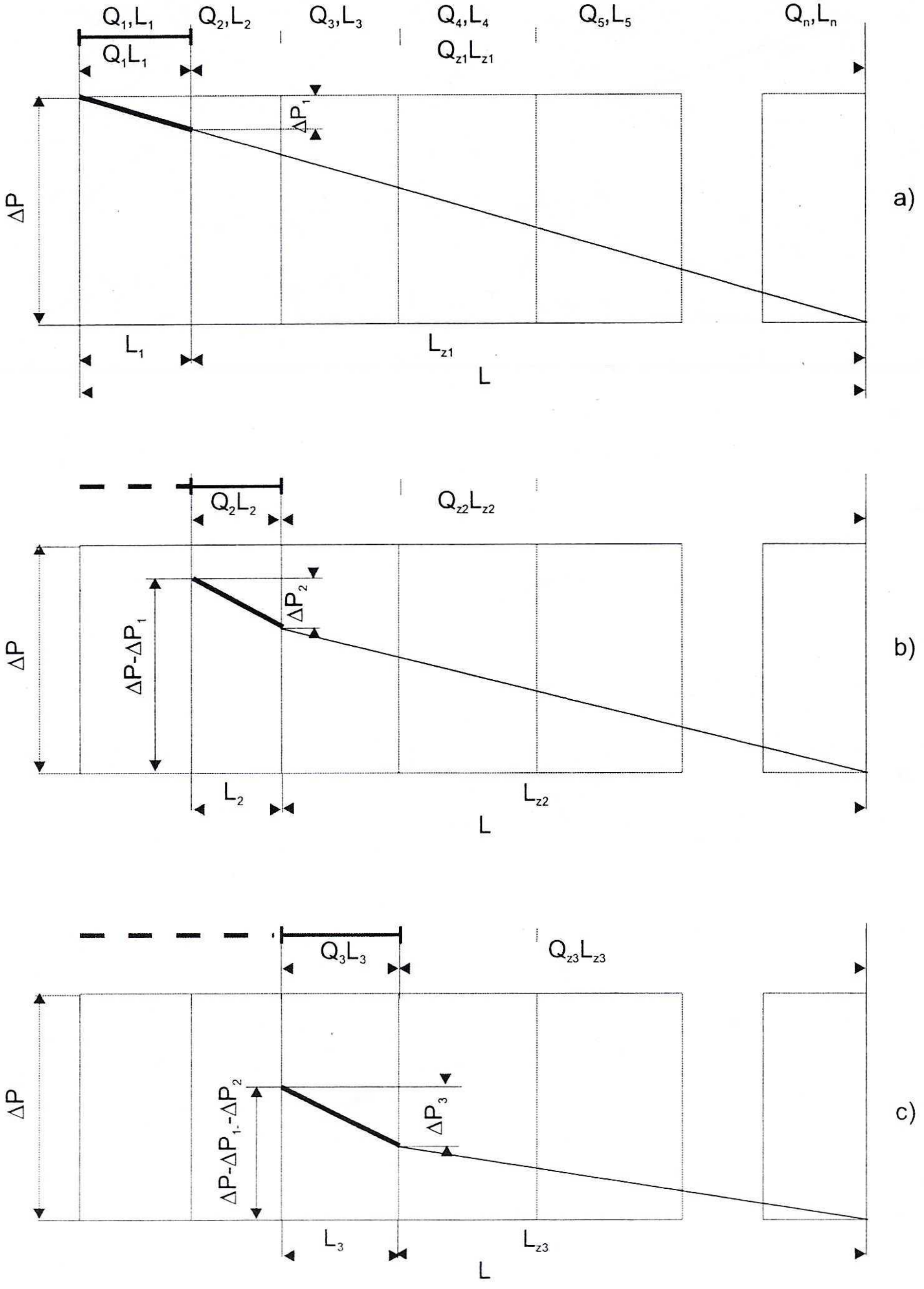


Fig. 1. Graphical scheme of the pressure drop calculation procedure used for the optimal diameter selection of the row component section, according to formula (19)

Rys. 1. Graficzna ilustracja obliczenia strat ciśnienia pozwalających na dobór optymalnych średnic dla kolejnych odcinków w szeregu, z wykorzystaniem zależności (19)

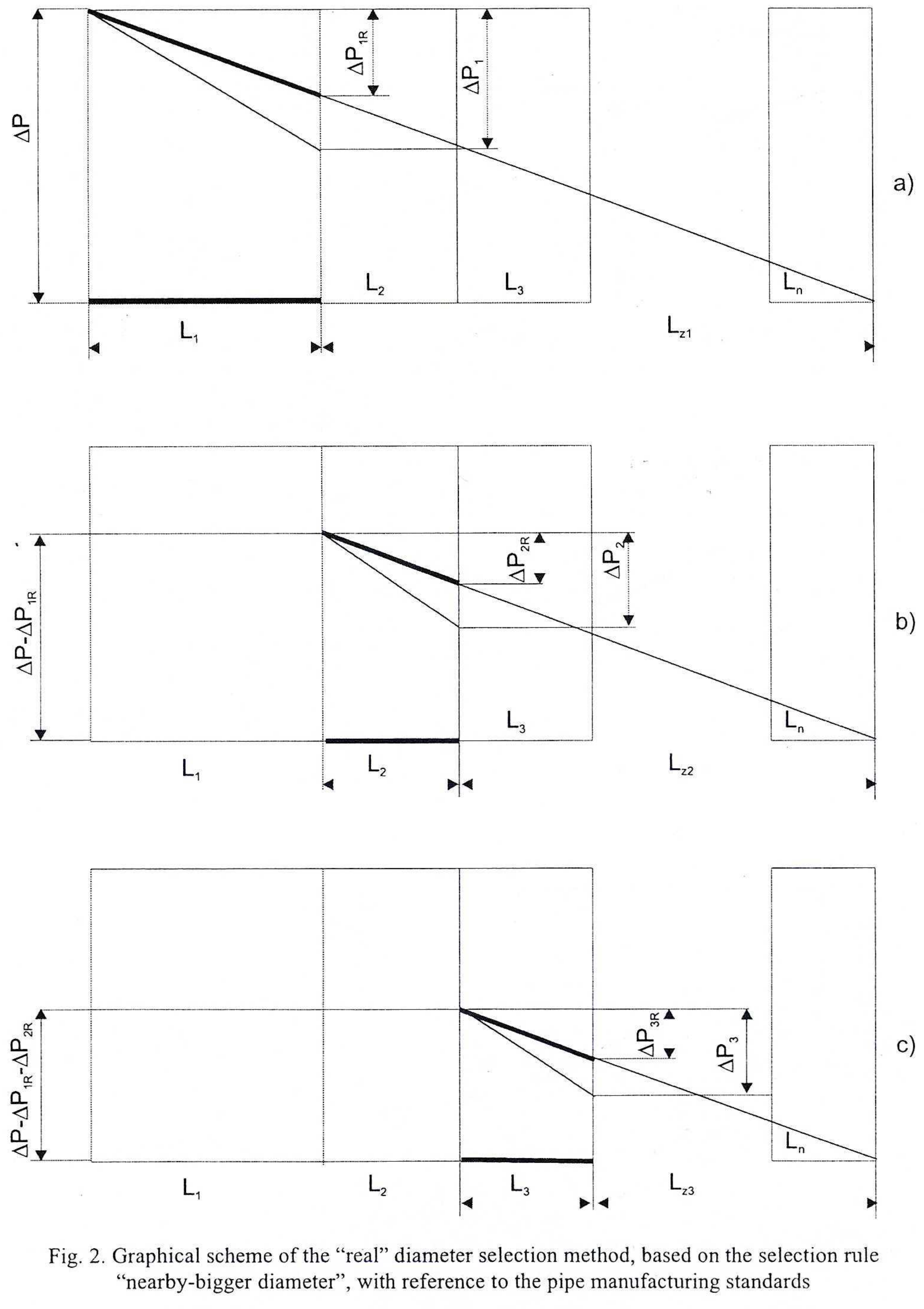


Fig. 2. Graphical scheme of the "real" diameter selection method, based on the selection rule "nearby-bigger diameter", with reference to the pipe manufacturing standards

Rys. 2. Graficzna ilustracja metody doboru „rzeczywistych" średnic przy zastosowaniu zasady doboru „najbliższa większa" z produkowanego szeregu wymiarowego

Problem of the diameter optimization comprise also necessity of the diameter selection, according to requirements of the production program.

A case, when the calculated pressure drops are compliant with the pipe manufacturing requirements is rather sporadic. Selection of "real" diameters is thus related with the necessity of the selection of the "nearby-smaller" or "nearby bigger" diameter. In each case of the selection of the "real" diameter d_{ijR}, a pressure drop ΔP_{ijR} will occur, being different from that which is calculated as ΔP_{ij}, using the method mentioned before. Selection of the "first-bigger" diameter of the manufactured pipe series leads to cumulation of the differences $\Delta P'_R$.

In a case of small number of sections within the row, including big differences in the section length and gas flow discharge, a diameter which is bigger than in cases of the preceding sections, may be selected for the last section. Occurrence of such problem confirm a rule that the proposed diameter selection method can be effectively used in cases when number of sections of the main row is not bigger than 10. Main supply direction of the gas distribution network serves the transit functions for the sections supplied by component sections, thus the diameter selection should be commenced from this row. Neutralization of such cases, for small number of the row component sections, calls for the diameter selection procedure which is based also on the rule "nearby the arithmetic mean", which satisfy conditions of the assumptions listed below. In a case of inequality:

$$d_{ij} > \frac{d_{jRW} - d_{jRN}}{2} + d_{jRN}\text{, a diameter } d_{jRW} \text{ is selected,} \tag{22}$$

however, in a case when:

$$d_{ij} < \frac{d_{jRW} - d_{jRN}}{2} + d_{jRN}\text{, a diameter } d_{jRN} \text{ is selected} \tag{23}$$

where:

d_{jRW} — "real" diameter, "nearby-bigger",
d_{jRN} — "real" diameter, "nearby-smaller".

As the described diameter selection method is considered with respect to the problems related to pipe manufacturing standards, we can conclude that selection of the diameter d_{ijR} from the manufactured pipe series, which is closest to the theoretically calculated optimal diameter d_{ij}. Thus we can consider only "nearby-bigger" and "nearby-smaller" diameters of the manufactured series of types. Finally, we can draw the following conclusions:

1. In the optimal diameter selection method, pressure drops within individual sections are determined as the priority. The calculated pressure drops are used to calculate diameters, in direction from the gas station toward the supply contour.

2. Depending on the predicted functional parameters of the gas distribution networks, we can define general rules of the diameter selection, i.e. "nearby-bigger"

(N–W), "nearby-smaller" (N–M), or in a case of their combination, "nearby-arithmetic mean" (N–$\acute{S}r$).

3. Selected "real" diameters of the component row sections influence the mean diameters, i.e. influence the degree in what the diameter reduction criterion will be satisfied, particularly for a case of small number of sections.

4. Procedure of the diameter selection method for the rows composed of the different number of sections, different gas flow discharges and different lengths, is based on optional calculations, where the diameters should satisfy functional requirements of the gas distribution network.

5. The rule "nearby-bigger" can be considered as the universal method of the diameter selection.

6. In case of the gas distribution networks, diameter minimization should not be considered as the only selective criterion.

7. Selection of the "real" diameters causes that the disposable pressure drop ΔP_D is not fully utilized. Such pressure drop differences are cumulated within the last sections of the row. Thus in some cases, selection of diameters which are smaller than those calculated from a formula (20), is recommended.

8. Diameter selection according to the rule "nearby-arithmetic mean" allows receiving the pressure drops which are closest to those calculated from formula (20).

The presented diameter selection methods, including the diameter minimization, comprise row of sections expanding from the supplying source to the contour. Thus the presented methods satisfy conditions of an important technological standard, related to small disturbances of the assumed gas flow discharge, including the diameter selection combined with optimal supply directions, extending from the gas station to the supply contour. Selection of diameters of the side row sections, which are supplied from the main row, create also very essential problem.

3. Procedure of selection of the component gas network sections

Diameter selection of the gas distribution network, with use of the developed theoretical solutions, should be preceded with dissection of the gas network (Fedorowicz et al. 2002). For each section of the dissected gas network, the gas flow discharge volume must be determined. Diameter selection is made properly if the estimated gas flow discharge is closest to the real discharge occurring within the gas distribution network. Gas is consumed practically along all sections of the network. Improper dissection of the gas network may result in incorrect diameter selection. In case of the gas distribution networks, most of their component sections may serve local, or local-transit functions. Number of dissection variants increase proportionally to the number of sections. Thus the same section of the network, in various variants of the dissection, may have different computational values of the gas flow discharge. Diameter selection satisfying conditions of the assumed cost and diameter reduction criterion depends on a variant of the network dissection. The mentioned problems, considered as problems of technological nature, should be taken into consideration, when the diameters which should be compliant with technological standards, are selected. Dissected gas network constitutes a tree, comprising sections playing different functions within the supply system. The most important are the rows expanding from the gas stations to the supply contours. As a rule, the lowest permissible pressures should be observed on the supply contours. Pressure differences, between the gas station pressure and the pressure assumed for the contour, are called as "gas network disposable pressure drop". In case of the main row diameter selection, the selection comprises also the disposable pressure drop within this row.

Depending on a number of sections and connections, each gas network may be composed of more than one main row. However, not every row should be classified as a main row. Practically, in calculations, such function can be assigned to a row, for which $\Sigma Q^{a}_{Zij} L_{Zij}$ will have the greatest value. In real operational conditions, some cases of arbitrary selection of the main row, related to the infrastructure planning requirements, may be met. Other sections of the dissected network, described as side rows, are supplied from the main row. Such system is called as "supply region", which is operated independently on the adjacent regions of the same network. The difference results from the minor transit capacity of the terminal sections of the side rows. Terminal sections of the gas distribution network have usually small diameters, which are equal to the technical minimum. Functional system composed of connected sections of the gas network can thus be considered as a set of rows with: different supply nodes, different terminal nodes, diversified number of row sections, and different products $Q^{a}_{ij} L_{ij}$.

Diameter selection rules determined for complex gas distribution systems should consider the described condition in such manner that the optional distribution network would supplement the assumed technological functions.

General diameter selection procedure of the branched and ring-type distribution networks, with reference to the pipe production standards, comprise the following procedural steps:

a) the network supply region, where we intend to select diameters of the component gas network sections, should be selected;

b) selection of diameters of chosen region should be commenced from the main row;

c) in a case, when in spite of the selected diameter of all sections of the main row, a reserve of the disposable pressure is observed, the suitable corrections should be made, beginning from a section located nearby the gas station. Reserve of the disposable pressure drop comprise the difference between parameter ΔP and total pressure drop, calculated after selection of the diameters which are compliant with production standards. While making corrections, we should follow the rule that the diameter of the successive row section can not be smaller than the diameter of the antecedent section.

d) diameters of side row component sections, supplied from the main row, should be selected. In the first order, diameters of the row having its terminal section located nearby the supply contour should be selected.

e) if needed, the selected diameters should be corrected. Diameter of the last section of the side row located nearby the supply contour should have "nearby-smaller" diameter, but not smaller than the technical minimum. The other terminal sections of the side rows should comprise "nearby-bigger" diameters;

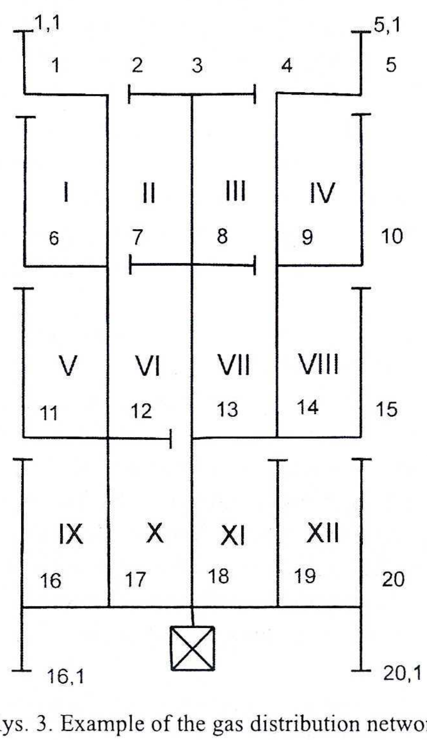
f) diameters of the other sections terminating the rings should be selected according to a rule "nearby-bigger diameter";

g) consecutive supply region should be selected, and the diameters should be selected according to the rules mentioned above. Chosen supply region join its nodes with a region for which the diameters have already been selected;

h) diameters of sections having jointed nodes with the sections of the adjacent regions should be selected.

Selection of the diameters satisfying the production standards is accompanied with other problems and requirements, which will be described by an example of the gas network shown in Fig. 3 and 4. In this example, main supply directions comprise rows extending between nodes:

18–17–16–16.1
18–17–12–7–2–1–1.1
18–13–14–9–4–5–5.1
18–19–20–20.1



Rys. 3. Example of the gas distribution network

Rys. 3. Przykładowy schemat sieci gazowej

Based on the described qualification criterion of given row, considered as the main supply row, we can assume, that in this example, rows terminated with nodes 1.1 and 5.1 play such role. According to the described procedure, diameters of the main row component sections, based on the main row with terminal node 1.1, are selected in the first order. When the diameters of all sections of this row, excluding terminal section, are selected, a diameter "nearby-bigger" should be selected for this section, in order to eliminate possibility of exceeding the assumed disposable value of the pressure drop ΔP. In practice, selection of the diameters compliant with production programs leads to the occurrence of the relation $\Delta P_R = \Delta P - \Sigma\Delta P_{ijR}$. This calculation procedure results from the occurrence of the value ΔP_R both within the main and side rows. In some circumstances, this value may be used for the correction of chosen real diameters of the row. Such correction helps to satisfy conditions of the preliminary assumed criterion of the diameter reduction. The calculations should be commenced from the sections located nearby the gas stations. However, such correction procedure is not advantageous from the point of view of functional conditions, because transit capacity of these sections is reduced. The correction procedure should give consideration to several technological requirements. The first requirement comprises a rule that the diameter of the preceding section should not be smaller than the diameter of the subsequent section, within given row. Correction of the diameter of the given section by doubled diameter is also inadmissible.

Next stage of the diameter selection procedure comprises selection of diameters of the reminding sections of given supply region. The selection should be commenced from the side rows, where the pressure within terminal nodes is equal to the pressure within a node of the main row section. In a case of the supply region, in the example shown in Fig. 4, based on the main row of the section 18–13–14–9–4–5–5.1, the diameters of the side rows with terminal nodes located nearby the supply contour, should be selected in the first order. Conditions of such requirements are satisfied within nodes 5 and 4. Node 5 can be considered as a terminal node of the side row comprising nodes 9–10–5. For this row, disposable pressure drop ΔP_i equals to a sum of the pressure drops, calculated for selected diameters of component sections of the region IV (9–4) and (4–5), i.e. $\Delta P_i = \Delta P_{9,4R} + \Delta P_{4,5R}$. The same diameter selection procedure may be used same both for side and main row, excluding terminal sections of these rows. Selection of the side row component sections should be commenced from the sections having their terminal nodes located within the supply contour, whereas, each of these terminal should have diameter close to "nearby-smaller diameter". Such method may be used because these sections have rather minor transit function. Priority rule of the side row diameter selection results from inability of determination of the disposable pressure drops for other side rows connected to given main row. In example shown in Fig. 4, the sections with nodes located on the supplying contour (9–4), and (6–1), constitute the terminal sections of the side rows. Such solution allows, to some extend, to reduce the value ΔP_R for component rows of given gas network, which satisfy the conditions of the assumed diameter reduction criterion, with small risk that the parameter ΔP will be exceeded.

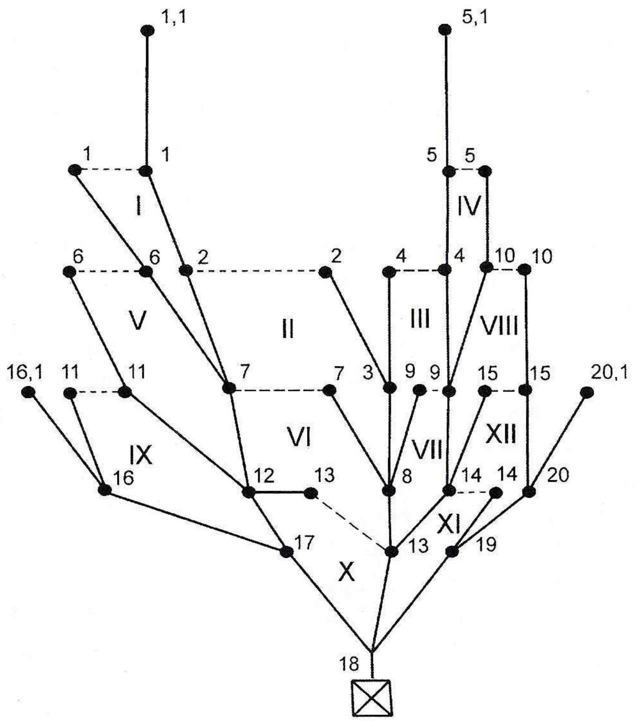


Fig. 4. Dissected graph of the gas network shown in Fig. 3

Rys. 4. Rozcięty graf sieci gazowej z rysunku 3

Thus within the example network, diameters of the side row 9–10–5 should be selected in the first order, however, row comprising the nodes 18–19–20–15–10 should be considered as a connected side row. Node 10 is a joint node of the mentioned side rows. The pressure within node 10 should be determined on the basis of formerly selected diameter of the section (9–10). When the component of the row 9–10–5 are already selected, diameters of the component sections of the mentioned row 18–19–20–15–10, should be selected. Disposable pressure within this row comprise a sum of the pressure drops resulting from the diameter selection of sections (18–13), (13–14), (14–9) and (9–10), i.e. component sections of main row, including component section of side row (9–10). Sections (14–15) and (13–14) terminating regions XII and XI, including free section (20–20.1), constitute also component element of given service zone. Disposable pressure drop needed for diameter selection of the sections (14–15) and (13–14), is determined on the basis of the pressure drop differences resulting from reverse gas flow directions within individual networks. Values of the disposable pressure drop are:

Section (14–15)

$$\Delta P_{i14,15} = \Delta P_{18,19} + \Delta P_{19,20} + \Delta P_{20,15} - \Delta P_{18,13} - \Delta P_{13,14}$$

Section (13–14)

$$\Delta P_{i13,14} = \Delta P_{18,13} + \Delta P_{13,14} - \Delta P_{18,19}$$

While selecting the diameter of terminal sections located behind the supply contour, the "nearby-bigger diameters" should be selected. Sections (14–15) and (13–14) shown in Fig. 4 constitute a right example. Such distributed terminal sections of the side rows, in some extent, play a transit function, and selection of the "nearby-smaller diameters" may result in exceeding the value of the assumed disposable pressure drop ΔP, within whole gas network. In case of such arbitrary diameter selection of the side row component section diameters, which satisfy the conditions of the diameter minimization criterion, is not reasonable without implementation of suitable diameter corrections. If needed, the corrections should be made also for the side rows.

In practice, the gas distribution systems do not comprise the networks in form of simple graphs. Groups of additional free sections and branched systems are commonly observed. In our example, such free section comprises a section (20–20.1), for which the disposable pressure drop, used for the diameter selection, is calculated from the formula $\Delta P_{i20,20.1} = \Delta P - \Delta P_{19,20} - \Delta P_{18,19}$. However, use of the mentioned criterion is not fully satisfactory for the diameter selection. In operational conditions, gas flow velocity should not exceed the assumed value, which in case of the low-pressure distribution networks, is defined as w_1 = 10 m/s, and w_2 = 15 m/s in case of the medium pressure networks. Additional condition, which also must be satisfied for all component sections of the gas distribution networks, comprises the necessity of the selection of diameters, which are not smaller than diameters defined as the technical minimum. In a case of the low-pressure distribution networks $d_{\min} \geq 80$ mm, whereas for the case of medium pressure distribution networks $d_{\min} \geq 25$ mm. The mentioned diameters should be considered as nominal diameters.

The same procedure is used for the diameter selection of component sections of a zone outlined by nodes 13, 8, 7, 2, 4, 9. Here, diameter selection of the sections (8–7) and (3–2) is problematical, because their terminal nodes occur also within the second supply region of the exampled network.

The second region of the considered example network comprises sections which are determined by nodes 18, 17, 16, 11, 6, 1, 2, 7, 13. The main row of this region comprises sections located between nodes 18–17–12–7–2–1–1.1. Using analogous selection rules as in the case of the first region, all other diameters are selected, excluding section (12–13), as a node 13 constitutes also a component of the first supply region. In order to select diameters of the sections (12–13), (8–7) and (3–2), disposable pressure drops should be determined in the first order:

Section (3–2)

$$\Delta P_{i3,2} = \Delta P_{18,17} + \Delta P_{17,12} + \Delta P_{12,7} + \Delta P_{7,2} - \Delta P_{18,13} - \Delta P_{13,8} - \Delta P_{8,3}$$

Section (8–7)

$$\Delta P_{i8,7} = \Delta P_{18,17} + \Delta P_{17,12} + \Delta P_{12,7} - \Delta P_{18,13} - \Delta P_{13,8}$$

Section (12–13)

$$\Delta P_{i12,13} = \Delta P_{18,17} + \Delta P_{17,12} - \Delta P_{18,13}$$

Diameter selection of the terminal sections of the unbalanced networks, where their component sections considerably differ with the length and the gas flow discharge, can be accompanied by the following problems:

- According to the assumed rules, diameter of the subsequent section of the side row should not be bigger than diameter of the preceding section,
- Disposable pressure drop ΔP_i may have too small numerical value, what forces necessity of selection of bigger diameters,
- Numerical value ΔP_i may also be negative, thus the section should constitute a component element of the other supply zone.

The problems listed above are related mostly to a great number of the terminal sections. The procedure based on the diameter selection of the side row terminal sections, including terminal sections, which are not bigger than the preceding section, constitute the best method related to the reduction of the number of sections.

The described rules of the diameter selection of complex network systems, in each case are accompanied by the occurrence of the small disposable pressure drop reserve, with reference to the diameter defined in the foredesign assumptions. Moreover, this reserve theoretically may be used for the correction of chosen diameters, however, implementation of such procedure may considerably disturb the assumed gas distribution, as the reserve in question concerns mostly the transit sections.

4. Summary

Fuel gas is delivered to the municipal consumers from the gas networks, which are only component parts of the global gas distribution system. The gas distribution systems, including factors which effect their operational performance, comprise:

- gas distribution networks,
- distribution pipelines,
- local gas stations,
- gas stations layout.

Errors erased during the estimation of the gas flow discharge computational values constitute essential problem disturbing the proper design of the gas distribution network. In case of the great population of the potential gas consumers, these errors may exceed ±20%. In case, when the potential consumers are supplied from a single section, the error may exceed even ±200%. Thus the technical optimization methods should consider the problems mentioned above. However, the methods in question not always satisfy the complex conditions of the building and town-planning requirements. In such situations, the problem is restricted only to the gas distribution pipelines and networks.

The cost-reduction program is commonly considered as a basic criterion used in the gas distribution network construction. The unit construction cost of a component section of given gas pipeline is commonly determined with use of empirical formulas. Using appropriate formulas, we can determine the unit construction cost as a function of the diameter. Accuracy of estimation of the gas pipeline construction unit cost considerably depends on the pipeline outline. However, the gas distribution pipelines are practically built irrespectively to the construction costs. Usually, the only criterion comprises the existence of the potential consumers, within given region. As the construction costs are not decisive, a criterion of the diameter minimization, has been proposed. Such criterion, in some extend, gives also consideration to both construction costs and technical requirements as well.

The proposed method is based on theoretical assumptions, which satisfy conditions of the assumed criterion of the diameter minimization. However, the calculated theoretical diameters are in none case compliant with the equivalent production programs. Use of the method in question should be supplemented by the development of the diameter selection rules, due to the pipe production standards. Thus the method can be implemented, when both theoretical assumptions and diameter selection rules, are combined together. The theoretical basis of the method in question has been determined with reference to the row component sections, which have different length and different computational gas flow discharges.

The developed rules of the diameter selection comprising production zones, expanding from the gas station to the supply contour, have essential functional function. Selection of each diameter of the subsequent section of given row depends on already selected diameters of the preceding sections. Such selection assures stable pressure distribution within the network, extending from the gas station to the supply contour. In such case, the estimation errors made during the gas flow discharge calculations, have smaller effect upon the gas network functionality. The assumed diameter selection rules can be used irrespective of a number of the gas stations. As dissected, each gas network can be considered as a set of interconnected supply regions. Each supply region comprises so-called "main row composed of the component pipeline sections". Side rows, which supply particular zones, are supplied from individual sections of the main row. The diameter selection rules, with few exceptions, are the same both for the main and side rows. Such attitude to the gas distribution network diameter selection procedure, assures the functional connection of the component sections of given gas network. Moreover, divergences between computational values of the real gas flow discharges and the discharges resulting from implementation of the proposed method, are considerably minimized.

The rules of the production-oriented diameter selection method described in the present study not fully satisfy the diameter minimization criterion. Most of the terminal section diameters, including terminal ring sections, are selected according to the rule "nearby-bigger diameter", according to the manufactured pipe series. Acceptation of such rule constitutes the major reason that the assumed criterion is not fully satisfied. In order to satisfy the diameter minimization criterion, the method proposed in the present study should be modified in the future. Such modification should comprise a correction of the formerly selected diameters of the component side row sections, including the ring terminal rows. Cost-effectiveness of such criterion is rather minor, however it can considerably change the local gas distribution conditions, within the component network sections. In each case, the diameter reduction is accompanied also with the decrease of the transit capacity, within the component sections. Finally we may conclude, that the modification of the diameter selection procedure, with use of the proposed method, has no practical meaning.

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