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A Gas Distribution Network Hydraulic Problem from Practice

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Abstract *The purpose of this is the determination of appropriate friction factor and selection of a representative equation for natural gas flow under the presented conditions in the network. Calculation of the presented looped gas pipeline network is done according to principles of Hardy Cross method. The final flows were calculated for known pipe diameters and nodes consumptions while the flow velocities through pipes have to stand below certain values. In optimization problems flows are treated as constant, and the diameters are variables.*

Keywords flow friction, gas distribution, hydraulic resistance, natural gas, pipeline network

1. Introduction

When a gas is forced to flow through pipes it expands to a lower pressure and changes its density. Flow rate, that is, pressure drop equations for the condition in gas distribution networks, assumes a constant density of a fluid within the pipes. This assumption applies only to incompressible fluids; that is, for liquids flows such as in water distribution systems for municipalities (or any other liquid, like crude oil, etc.). For the small pressure drops in typical gas distribution networks, gas density can be treated as constant, which means that gas can be treated as an incompressible fluid (Pretorius et al., 2008) but not as liquid flow. *Liquid flow* and *incompressible flow* are not synonymous. Under these circumstances, the flow equation for water or crude oil cannot be literally copied and applied for natural gas flow. This means that the original Darcy-Weisbach equation cannot be used without some modifications.

Each pipe is connected to two nodes at its ends. In a pipe network system, pipes are the channels used to convey fluid from one location to another. The physical characteristics of a pipe include the length, inside diameter, and roughness. The Darcy's coefficient of hydraulics resistance is associated with the pipe material and age but also with fluid flow rate and pipe diameter; that is, with relative roughness and Reynolds number. When fluid is conveyed through the pipe, hydraulic energy is lost due to the friction between the moving fluid and the stationary pipe surface. This friction loss is a major energy loss in pipe flow and is a function of relative roughness and Reynolds number, as mentioned before. In the case when the relative roughness is negligible, a typical flow regime is hydraulically smooth, where Darcy's coefficient of hydraulic resistance depends only on

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Reynolds number. This regime is typical for gas networks that are built using polyethylene pipes. For that regime Darcy's coefficient of hydraulic resistance can be calculated using so-called Blasius-type equations or so-called Prandtl-type equations. Prandtl equations, which are also known as Nikuradse-Prandtl-von Karman (NPK), are implicit in friction coefficient (Moody, 1944; Coelho and Pinho, 2007). For liquid flow where the liquid density has larger values compared to gas, the Reynolds number increases, and if it is accompanied with increased value of relative roughness, which is typical for steel pipes, a full turbulent regime is possible. For the fully turbulent regime the most convenient is the von Karman type of equation from Western practice, or the Shifrinson equation from Russian practice. For the fully turbulent flow regime, Darcy's coefficient of hydraulic resistance depends only on relative roughness.

In this article, new facts are provided in comparison to previous calculation of a gas distribution network in Kragujevac, Serbian, which was done in 1994. After the implementation, measurements were performed in situ and real measured values deviated from calculated values. Previously published results are available and hence comparisons are possible (Manojlović et al., 1994).

This article addresses the problem of hydraulic resistance in pipes used for construction of networks for distribution of natural gas in cities and subject to all the practical requirements for engineers charged with design and/or analysis of such systems (Mathews and Köhler, 1995). This article is especially addressed to those engineers willing to understand and interpret the results of calculation properly and to make good engineering decisions based on this subject.

2. On the Darcy's Coefficient of Flow Friction

To predict whether flow will be laminar, hydraulically smooth, partially turbulent, or fully turbulent, it is necessary to explore the characteristics of flow (Figure 1). A hydraulically smooth regime is also sort of turbulent regime. One has to be very careful in these considerations because some authors use Darcy's friction factor, whereas the others use Fanning's factor (Brkić, 2009b). Darcy's friction coefficient is four times larger than Fanning's though the physical meaning is equal. Graphically, the friction factor for a known Reynolds number and relative roughness can be determined using the well-known Moody diagram (Moody, 1944). The Darcy friction factor and the Moody friction factor are synonymous. Note also that relative roughness is variously defined using pipe diameter and using pipe radius, which can be source of error in the case of inappropriate use (Chen, 1979, 1980; Schorle et al., 1980; Brkić, 2009b).

Note that the Darcy friction factor is defined in theory as $\lambda = (8 \cdot \tau) / (\rho \cdot v^2)$.

As mentioned in introduction, for polyethylene pipes absolute roughness k is very small compared to the pipe diameter D_{in} ; that is, relative roughness is negligible ($k/D_{in} \rightarrow 0$), and Darcy's friction coefficient depends only on Reynolds number. For the low value of Reynolds number, but above 2,320, the flow regime is hydraulically smooth (there is no effect of roughness). For the Reynolds number below 2,320 the regime is laminar. The upper limit for a hydraulically smooth regime is $\zeta = 16$. A typical partially turbulent regime occurs for $16 < \zeta < 200$, and for $\zeta > 200$ a fully turbulent regime is possible. Parameter ζ can be found using:

$$\zeta = \frac{k \cdot \text{Re} \cdot \sqrt{\lambda}}{D_{in}} \quad (1)$$

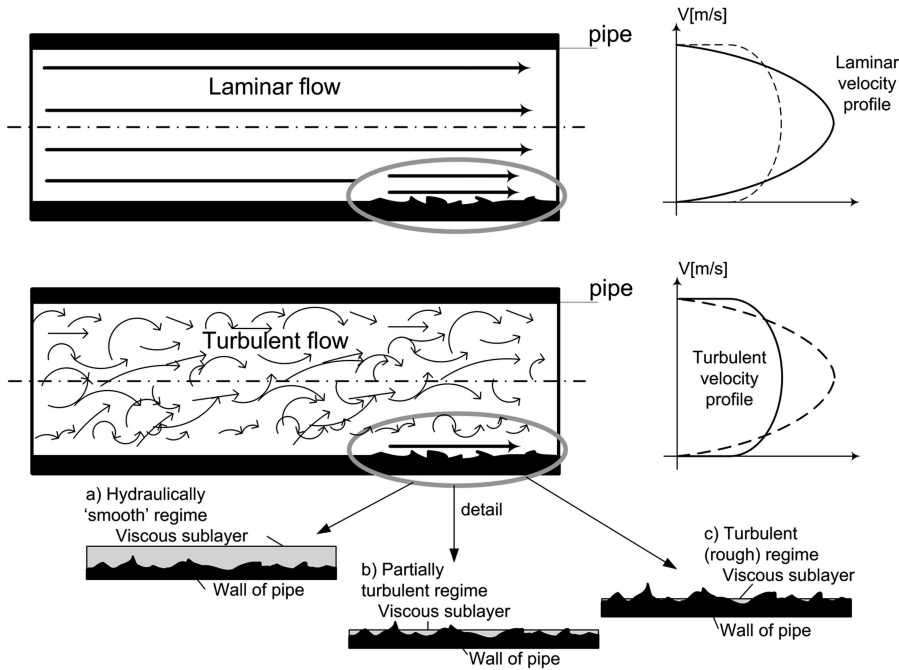


Figure 1. Physical description of flow regimes.

So, as Reynolds number increases, the flow becomes transitionally rough; that is, the flow regime is partially turbulent in which the friction factor rises above the smooth value and is a function of both relative roughness and Reynolds number. As Reynolds number continues to increase, the flow reaches a fully turbulent or so-called rough regime, in which Darcy's friction coefficient is independent of Reynolds number and depends only on relative roughness. In a hydraulically smooth pipe flow, the viscous sublayer completely submerges the effect of roughness on the flow. For turbulent flow in smooth pipes, friction losses are completely determined by Reynolds number. In rough pipes, however, the value of friction coefficient depends for large values of Reynolds number also on the roughness of the inside pipe surface. The important point is not so much the absolute roughness size because for the same absolute roughness, the flow resistance in large pipes is considerably smaller than the resistance in small pipes.

Darcy' friction factor for a hydraulically smooth regime can be determined after Renouard (1952):

$$\lambda = \frac{0.172}{\text{Re}^{1.8}} \quad (2)$$

This equation belongs to the so-called Blasius type of equations for a hydraulically smooth regime.

For a fully turbulent regime, the following Shifrinson equation is available from the Russian literature (Nekrasov, 1969; Sukharev et al., 2005):

$$\lambda = 0.11 \cdot \left(\frac{k}{D_{in}} \right)^{\frac{1}{4}} \quad (3)$$

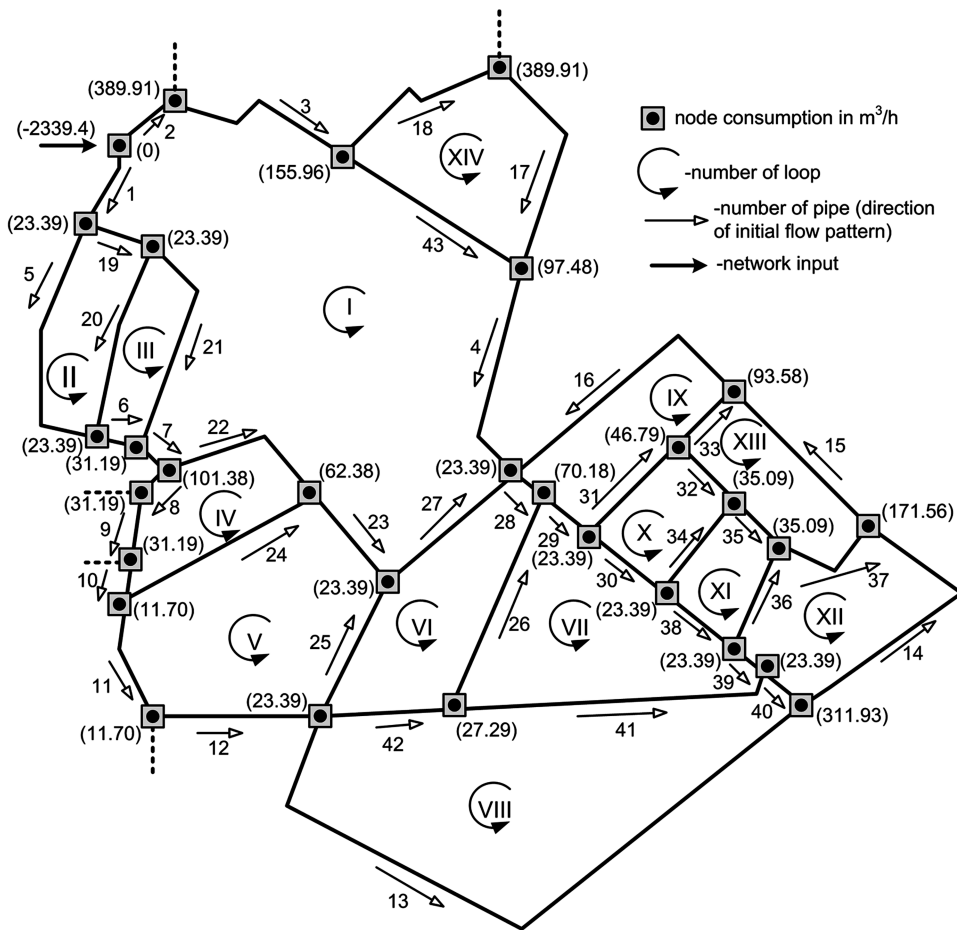


Figure 2. Gas pipeline network in Kragujevac, Serbia.

The Shifrinson Eq. (3) was used for calculation of a gas network in Kragujevac in 1994. In our case for the Kragujevac gas network, gas dynamic viscosity is $\eta = 1.0758 \times 10^{-5}$ Pas, which is typical for natural gas, density of natural gas is 0.84 kg/m^3 (that implies that relative density is 0.64). The value of absolute roughness is $0.007 \times 10^{-3} \text{ m}$ for the polyethylene pipes in Kragujevac as reported in Manojlović et al. (1994), which is even smaller compared to the value reported in Sukharev et al. (2005). Sukharev et al. (2005) found that the absolute roughness of inner surface of polyethylene pipes is $0.002 \times 10^{-2} \text{ m}$. To find which flow regime occurred in a network it is necessary to find parameter ζ , and hence every tenth pipe from the network shown in Figure 2 was examined and results are listed in Table 1.

Results of a random samples of pipes shown in Table 1 proved the assumption that flow in the presented gas network is in a hydraulically smooth regime because $\zeta < 16$, and hence the Renouard Eq. (2) is more suitable for this calculation. The Shifrinson Eq. (3) used in Kragujevac in 1994, which is suitable for rough pipes, cannot be used. In some pipes such as 21 (see Figure 2), the regime is not even smooth, it is rather laminar. The velocity of gaseous fluids depends on the pressure in the pipe because they

Table 1
Determination of flow friction regime

Pipe	D_{in} , mm	Q , m ³ /sec	Velocity, m/sec		Re	Friction coefficient λ		Criterion ζ^d	
			Liquid	Gas ^a		Renouard ^b	Shifrinson ^c	Renouard	Shifrinson
1	220.4	0.295497222	7.75	1.94	20,391.6	0.028828830	0.008258	0.11	0.06
11	158.6	0.126230556	6.39	1.60	12,105.2	0.031666022	0.008966	0.10	0.05
21	15.4	0.000383333	2.06	0.51	378.6	0.05908245	0.016062	0.04	0.02
31	96.8	0.040133333	5.45	1.36	6,305.8	0.035610262	0.010144	0.09	0.05
41	96.8	0.059622222	8.10	2.03	9,367.9	0.033161384	0.010144	0.12	0.07
51	109.8	0.086647222	9.15	2.29	12,002.3	0.031714738	0.009829	0.14	0.08
61	79.2	0.021661111	4.40	1.10	4,159.7	0.038379256	0.010666	0.07	0.04

^aFor 4 bar abs; see Eq. (4).

^bSee Eq. (2).

^cSee Eq. (3).

^dSee Eq. (1); Renouard equation can be used if $\zeta < 16$, and Shifrinson if $\zeta > 200$, but in both cases only if $Re > 2,320$.

are compressible:

$$v = \frac{4 \cdot p_{st} \cdot Q_{st}}{p \cdot D_{in}^2 \cdot \pi} = \frac{4 \cdot Q}{D_{in}^2 \cdot \pi} \quad (4)$$

Assumption of gas compressibility means that it is compressed and forced to convey through pipes, but inside the pipeline system the pressure drop of already compressed gas is small and hence further changes in gas density can be neglected. This is the main difference between liquid and incompressible flow. According to this, water flow in pipelines is liquid incompressible flow, whereas the gas flow is gaseous incompressible flow.

The calculated Darcy's friction factor using the Shifrinson relation (3) in Kragujevac in 1994 is more than three times smaller in comparison to the results obtained using the recommended Renouard Eq. (2) (Figure 3).

Previous results (Manojlović et al., 1994) are not in correlation with the Moody diagram (1944). One can conclude that below a laminar and smooth regime, or below the lines in the Moody diagram, which represent these regimes exist some other regimes (Figure 3). Of course, regimes such as sublaminal or some kinds of turbulent regimes below the hydraulically smooth regime cannot exist (Figure 1).

3. General Equation for Fluid Flow

Loss of energy, or head (pressure) loss, depends on the shape, size, and roughness of a channel and the velocity and viscosity of a fluid, and it does not depend on the absolute pressure of the fluid. For gaseous fluids some laws of thermodynamics also have to be included.

3.1. General Equation for Liquid Flow

Experiments show that in many cases pressure drop is approximately proportional to the square of the velocity (5). Equation (5) is called the Darcy-Weisbach equation, named

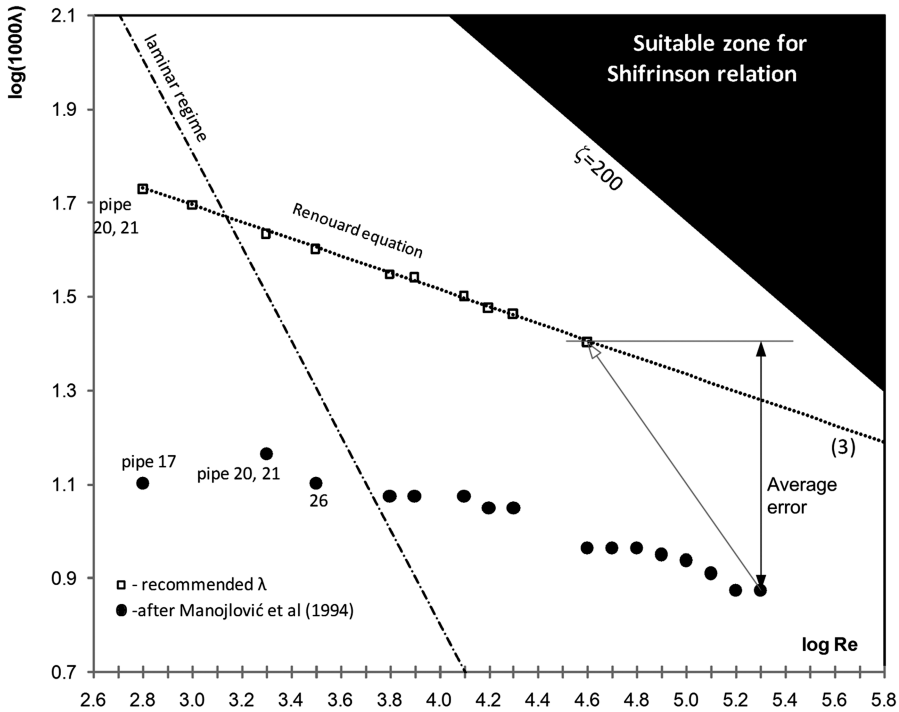


Figure 3. Identification of the problem in a characteristic diagram.

after Henry Darcy, a French engineer of the 19th century, and Julius Weisbach, a German mining engineer and scientist of the same era.

$$p_1 - p_2 = \lambda \cdot \frac{L}{D_{in}} \cdot \frac{v^2}{2} \cdot \rho \quad (5)$$

In the previous equation velocity and gas density must be correlated, because the gas is incompressible fluid, and hence for gas an equation in the following form is more suitable because $Q \cdot \rho = Q_{st} \cdot \rho_{st}$.

$$p_1 - p_2 = \lambda \cdot \frac{L}{D_{in}^5} \cdot \frac{8 \cdot Q^2}{\pi^2} \cdot \rho = \lambda \cdot \frac{L}{D_{in}^5} \cdot \frac{8 \cdot Q_{st}^2}{\pi^2} \cdot \rho_{st} \quad (6)$$

For example, pressure drop using the Darcy-Weisbach equation for liquid flow (6) in a random set of pipes chosen from gas network from Kragujevac is shown in Table 2.

In (6), if flow rate Q is given for pressure in a gas pipeline, that is, for 4×10^5 Pa abs, and not for normal conditions, density also has to be adjusted for this existing value of pressure in the pipeline (volume of gas is four times smaller in 4×10^5 than Pa in 1×10^5 Pa).

3.2. General Equation for Steady-State Flow of Gas

Density of gas can be noted as:

$$\rho = \frac{p \cdot M}{z \cdot R \cdot T} \quad (7)$$

Table 2
Pressure drop using the Darcy-Weisbach
equation for liquid flow

Pipe	L, m	Pressure drop, ^a Pa	
		Renouard	Shiffrinson
1	84	276.84	79.30
11	119	407.40	115.35
21	212	1,446.82	393.32
31	115	528.42	150.52
41	278	2,625.35	803.07
51	78	792.36	245.57
61	383	1,506.96	418.78

^aUsing (5) or (6) and values from Table 1; gas density is $\sim 0.84 \text{ kg/m}^3$.

Considering the momentum equation applied to a portion of the pipe length, inside which flows a compressible fluid with an average velocity, for example, natural gas, and assuming steady-state conditions, a general equation for gas flow can be written as:

$$\int_1^2 dp + \int_1^2 \lambda \frac{dL}{D_{in}} \frac{v^2}{2} \rho = \int_1^2 \rho dp + \int_1^2 \lambda \frac{dL}{D_{in}} \frac{v^2}{2} \rho^2$$

$$= \frac{M}{z_{avr} \cdot R \cdot T_{avr}} \frac{p_1^2 - p_2^2}{2} + \lambda \frac{\Delta L}{D_{in}} \frac{v^2}{2} \rho^2 = 0 \quad (8)$$

In (9) flow can be used instead of velocity (8) and, combined with (7), gives:

$$(v\rho)^2 = \frac{Q^2}{A^2} \rho^2 = \frac{Q_{st}^2}{A^2} \rho_{st}^2 = \frac{16 \cdot Q_{st}^2}{D_{in}^4 \cdot \pi^2} \frac{p_{st}^2 \cdot M^2}{z_{st}^2 \cdot R^2 \cdot T_{st}^2} \quad (9)$$

Considering that gas density (see Eq. (7)) at standard pressure conditions is equal as in average pressure in pipeline ($\rho_{st} = \rho_{avr}$), and finally assuming that for perfect gas $M = M_{air} \cdot \rho_r$, a general equation for steady-state flow of gas can be written as:

$$p_1^2 - p_2^2 = \lambda \frac{16 \cdot \Delta L \cdot Q_{st}^2}{D_{in}^5 \cdot \pi^2} \frac{p_{st}^2 \cdot M_{air} \cdot \rho_{st}}{z_{st} \cdot R \cdot T_{st}} \quad (10)$$

This equation was rearranged by Renouard (1952) in the well-known equation:

$$C = p_1^2 - p_2^2 = \frac{4810 \cdot Q_{st}^{1.82} \cdot L \cdot \rho_r}{D_{in}^{4.82}} \quad (11)$$

The previous equation is correlated with Renouard's equation used for calculation of Darcy's friction factor for a hydraulically smooth regime (2), but with the only difference that Darcy's factor does not need to be calculated as for Eq. (10) because it is already incorporated by setting of appropriate coefficients and exponents in Eq. (11). Renouard (1952) assumed that dynamic viscosity of natural gas is $\eta = 1.0757 \times 10^{-5}$

Pas, factor of compressibility is $z = 1$, and that pressure and temperature in a pipeline are actually standard ($T_{st} = T_{avg} = 288.15$ K, $P_{st} = 1.01325 \times 10^5$ Pa). This means that by fixing the value of gas kinematic viscosity, the density is also kept fixed, which is physically inaccurate when considering compressible gas flow at medium or high pressure, because the kinematic viscosity of gases is highly dependent upon pressure. According to this, gas flow in a city distribution network can be treated as incompressible, as in Kragujevac where pressure drop was minor, and hence the Renouard Eq. (11) can be used.

Some other transformations of a general equation for steady-state flow of gas are available in Coelho and Pinho (2007).

4. Comparison of the Actual and Previous Results

In Figure 2 a ring-like part of the gas distribution network from one municipality of the Serbian town of Kragujevac (Manojlović et al., 1994) is shown. There are 29 independent nodes in the ring-like network, 43 branches belonging to rings with 25 branches mutual to the two rings. The total network gas supply input in node 1 is 2,339.4 m³/hr.

The Hardy Cross method can give good results in design of a looped gas pipeline network of composite structure (Cross, 1936; Corfield et al., 1974; Brkić, 2009a). Results in Table 3 are calculated for locked up diameters from previous calculation available in Manojlović et al. (1994), and flows are treated as variables. In last two columns in Table 3, an optimization problem take place where flows are treated as constant and diameters are variables. Gas consumption per nodes is presented in Figure 2 in brackets and computation results using Renouard's equation adjusted for gas pipelines (11) are shown in Table 3.

The flow direction in branches 15 and 16 is opposite to the flow direction shown in Figure 2.

The velocity limits are 6 m/sec for small diameter (up to 90 mm) pipes and 12 m/sec for large diameter pipes (up to 225 mm) according to the original project (Manojlović et al., 1994). But calculated velocities in each of the pipes do not reach even 3 m/sec. For example, velocity in some of the pipes is higher than proposed only with the assumption that gas is actually a liquid. In previous calculations the fact that gas is actually compressed and hence that volume of gas is decreased is neglected. Hence, the mass of gas is constant, but the volume is decreased when gas density is increased. According to this gas network is not nearly optimized and for gas network with input pressure 4×10^5 Pa abs; that is, 3×10^5 Pa gauge all values of velocities are in the ranges of proposed limits. It is much different with liquid. For example, gas velocity in pipe 1 from Table 1 is only 1.94 m/sec, but in the case of water or crude oil equivalent an volume of fluid cannot be initially compressed and hence this observed liquid is forced to convey with increased velocity. For pipe 1 from Table 1 this velocity for liquid flow is 7.75 m/sec.

5. Optimized Design of a Gas Distribution Pipeline Network

In the problem of optimization of pipe diameters, flow rates calculated previously and shown in Table 3 are not treated as variables. Results of optimization problem are shown in the last two columns of Table 3. These flow rates in the next calculation will be treated

Table 3
Computational results for gas network in Kragujevac

Pipe number	Pipe diameter, mm	Pipe length, m	Flows, m ³ /hr	Velocity, m/sec	Optimized design	
					Pipe diameter, ^a mm	Velocity, m/sec
1	220.4	84	1,035.86	1.89	104.28	8.42
2	220.4	72	1,303.54	2.37	109.77	9.57
3	198.2	170	913.63	2.06	91.34	9.68
4	109.8	206	270.28	1.98	48.13	10.32
5	198.2	224	987.13	2.22	94.14	9.85
6	198.2	37	964.70	2.17	96.85	9.09
7	198.2	30	934.50	2.10	99.21	8.39
8	176.2	35	544.21	1.55	82.23	7.12
9	176.2	64	513.02	1.46	80.10	7.07
10	158.6	34	481.83	1.69	77.91	7.02
11	158.6	119	434.48	1.53	69.71	7.91
12	158.6	154	422.78	1.49	68.83	7.89
13	44.0	639	21.40	0.98	19.24	5.11
14	35.2	268	6.85	0.49	11.01	5.00
15	35.2	164	-7.52	-0.54	10.77	5.73
16	44.0	276	-25.35	-1.16	19.23	6.06
17	27.4	363	0.52	0.06	5.59	1.47
18	123.4	175	390.43	2.27	65.26	8.11
19	44.0	52	25.34	1.16	23.52	4.05
20	15.4	177	0.96	0.36	6.91	1.78
21	15.4	212	0.99	0.37	7.02	1.78
22	109.8	161	288.91	2.12	47.57	11.29
23	123.4	108	262.18	1.52	49.77	9.36
24	55.4	194	35.65	1.03	23.44	5.74
25	96.8	135	147.75	1.39	38.42	8.85
26	27.4	215	2.69	0.32	9.02	2.92
27	141.0	155	386.54	1.72	60.96	9.20
28	158.6	34	608.08	2.14	69.78	11.04
29	158.6	48	540.58	1.90	69.25	9.97
30	123.4	86	376.63	2.19	57.16	10.19
31	96.8	115	140.56	1.33	37.21	8.98
32	35.2	75	18.02	1.29	14.63	7.44
33	55.4	70	75.75	2.18	26.00	9.91
34	96.8	102	196.90	1.86	36.38	13.15
35	96.8	52	179.83	1.70	35.76	12.43
36	35.2	104	12.45	0.89	12.35	7.22
37	96.8	101	157.18	1.48	34.32	11.80
38	96.8	86	156.35	1.48	43.11	7.44
39	96.8	37	120.51	1.14	37.04	7.77
40	96.8	30	297.39	2.81	52.12	9.68
41	96.8	278	200.27	1.89	39.79	11.18
42	96.8	115	230.24	2.17	46.88	9.26
43	123.4	199	367.24	2.13	53.34	11.41

^aFirst larger or smaller standard diameter has to be chosen.

as constant while the pipe diameters will be treated as variables:

$$\frac{\partial(p_1^2 - p_2^2)}{\partial D_{in}} = \frac{\partial C}{\partial D_{in}} = \frac{\partial \left(\frac{4810 \cdot Q_{st}^{1.82} \cdot L \cdot \rho_r}{D_{in}^{4.82}} \right)}{\partial D_{in}} = \frac{-4.82 \cdot 4810 \cdot Q_{st}^{1.82} \cdot L \cdot \rho_r}{D_{in}^{5.82}} \quad (12)$$

For example, for loop XIV from the network shown in Figure 2, the previous so-called loop equation can be written as:

$$\begin{aligned} \frac{\partial C_{XIV}(D)}{\partial D_{\{XIV\}}} &= \frac{\partial(|-C_{17}(D_{17})| + |-C_{18}(D_{18})| + |C_{43}(D_{43})|)}{\partial D_{\{XIV\}}} \\ &= -4.82 \cdot 4810 \cdot \rho_r \\ &\quad \cdot \left(\left| -\frac{(Q_{17}^{1.82})_{st} \cdot L_{17}}{(D_{17}^{5.82})_{in}} \right| + \left| -\frac{(Q_{18}^{1.82})_{st} \cdot L_{18}}{(D_{18}^{5.82})_{in}} \right| + \left| \frac{(Q_{43}^{1.82})_{st} \cdot L_{43}}{(D_{43}^{5.82})_{in}} \right| \right) \end{aligned} \quad (13)$$

An optimized design of a gas distribution pipeline network for the Kragujevac gas network is shown in last two columns in Table 3. This optimization is for average velocity of gas in a network of 9 m/sec. Some pipes have very small diameters after optimization and hence after adoption of a larger standard diameter, calculation of flow distribution for these new standard diameters has to be repeated.

According to the principles of the Hardy Cross method, loop equations, that is, the condition after Kirchhoff's second law has to be fulfilled at the end of calculation. These equations represent energy continuity, and Kirchhoff's first law represents mass continuity for nodes. Mass continuity has to be fulfilled in all iterations for all nodes without exception. Diameter corrections are calculated using:

$$\Delta D_{\{i\}} = \frac{C_i(D)}{\left| \frac{\partial C_i(D)}{\partial D_{\{i\}}} \right|} \quad (14)$$

These corrections calculated for all particular loops from the Kragujevac gas network have to be added to the previous value of diameter according to the algebraic scheme available in the literature (Corfield et al., 1974; Brkić, 2009a). Of course, many more efficient methods than the original Cross (1936) method exist, but this is not the main subject of this article. For example, calculated flows presented in the fourth column in Table 3 are obtained using the node-loop method (Boulos et al., 2006) and the result for the optimization problem from the last two columns in Table 3 is obtained using an improved Hardy Cross method (Boulos et al., 2006; Brkić, 2009a). In both methods matrix formulations are used that can be easily solved using MS Excel.

6. Conclusions

The Hardy Cross method procedure or a similar improved procedure can provide good results in the design of a looped gas pipeline network of composite structure. According to the price and velocity limits, the optimal design can be predicted. But all parameters, such as friction factor and relation for calculation of pressure drop in pipes, that is, equation for calculation of gas flow, must be chosen in a very careful way. Today, a distributive gas network is usually calculated using the Renouard equation for determination of gas flow

and pressure drop value. The inner surface of polyethylene pipes, which are almost always used in gas distribution networks, are practically smooth and hence the flow regime in the typical network is hydraulically smooth. Using an inappropriate friction factor can lead to a paradoxical result; that is, the calculated Darcy's friction factor can belong to nonexistent regimes such as a sublaminar or turbulent regime that is below hydraulically smooth. This means that the calculated Darcy's friction factor is highly underestimated. Further, using the Darcy-Weisbach equation for liquid flow instead of a modified version for gaseous flow, pressure drop is overestimated. This leads to pseudo-accurate final results. After all, visible error occurred in numerical values of some parameters, like velocity in this case. According to previous results, the velocities in the network are significantly larger than expected. A consequence is that the pipe diameters are too large for the required amount of gas and hence the network is not optimal.

In the 1994 gas pipeline project in Kragujevac, Serbia, the Darcy-Weisbach equation for liquid flow was used instead of the modified Darcy-Weisbach equation for gaseous flow, accompanied by inappropriate usage of the Shifrinson equation for a fully turbulent regime, which is typical for liquid flow in a steel pipes, instead of some sort of Blasius or Prandtl form of equations, which are typical for gas flow through polyethylene pipes, as used for the Kragujevac gas network.

The Hazen-Williams relation is frequently used for waterworks or sewerage systems (Boulos et al., 2006) but it is not only inaccurate, or accurate within limits, the Hazen-Williams equation is conceptually incorrect (Liou, 1998). Even assuming that gas flow is incompressible in municipal pipelines, this relation cannot be used for such systems as gas distribution networks.

References

- Boulos, P. F., Lansey, K. E., and Karney, B. W. (2006). *Comprehensive Water Distribution Systems Analysis Handbook for Engineers and Planners*. MWH Soft Inc.
- Brkić, D. (2009a). An improvement of Hardy Cross method applied on looped spatial natural gas distribution networks. *Appl. Energ.* 86:1290–1300.
- Brkić, D. (2009b). Comments on "Settling Velocities of Particulate Systems 15: Velocities in Turbulent Newtonian Flows." *Int. J. Miner. Process.* 92:201–202.
- Chen, N. H. (1979). An explicit equation for friction factor in pipe. *Ind. Eng. Chem. Fund.* 18:296–297.
- Chen, N. H. (1980). Comments on "An Explicit Equation for Friction Factor in Pipes." *Ind. Eng. Chem. Fund.* 19:229–230.
- Coelho, P. M., and Pinho, C. (2007). Considerations about equations for steady state flow in natural gas pipelines. *J. Braz. Soc. Mech. Sci. Eng.* 29:262–273.
- Corfield, G., Hunt, B. E., Ott, R. J., Binder, G. P., and Vandaveer, F. E. (1974). Distribution design for increased demand. In: *Gas Engineers Handbook*, Segeler, C. G. (Ed.). New York: Industrial Press, pp. 63–83.
- Cross, H. (1936). Analysis of flow in networks of conduits or conductors. *University of Illinois Engineering Experiment Station Bulletin* 286:3–29.
- Liou, C. P. (1998). Limitation and proper use of the Hazen-Williams equation. *J. Hydraul. Eng.* 124:951–954.
- Manojlović, V., Arsenović, M., and Pajović, V. (1994). Optimized design of a gas-distribution pipeline network. *Appl. Energ.* 48:217–224.
- Mathews, E. H., and Köhler, P. A. J. (1995). A numerical optimization procedure for complex pipe and duct network design. *Int. J. Numer. Meth. Heat Fluid Flow* 5:445–457.
- Moody, L. F. (1944). Friction factors for pipe flow. *Trans. ASME* 66:671–684.
- Nekrasov, B. (1969). *Hydraulics for Aeronautical Engineers*. Moscow: Mir Publishers.

- Pretorius, J. J., Malan, A. G., and Visser, J. A. (2008). A flow network formulation for compressible and incompressible flow. *Int. J. Numer. Meth. Heat Fluid Flow* 18:185–201.
- Renouard, P. (1952). Nouvelle méthode pour le calcul des réseaux maillés de conduites de gaz. Communication au Congrès du Graz.
- Schorle, B. J., Churchill, S. W., and Shacham, M. (1980). Comments on “An Explicit Equation for Friction Factor in Pipes.” *Ind. Eng. Chem. Fund.* 19:228–229.
- Sukharev, M. G., Karasevich, A. M., Samoilov, R. V., and Tverskoi, I. V. (2005). Investigation of the hydraulic resistance in polyethylene pipelines. *J. Eng. Phys. Thermophys.* 78:350–359.

Nomenclature

C	$p_1^2 - p_2^2$
D	diameter of pipe, m
k	inside pipe wall roughness, m
L	length of pipe, m
M	relative molecular mass
p	pressure, Pa
Q	flow, m ³ /sec
R	universal gas constant = 8,314.41 J/(kmol · K)
Re	Reynolds number
T	temperature, K
v	velocity, m/sec
z	gas compressibility factor

Greek

ζ	parameter for existing of different turbulent regimes ($\zeta < 16$, smooth turbulent regime; $16 < \zeta < 200$, partially turbulent regime; $\zeta > 200$ fully turbulent regime)
η	gas dynamic viscosity, Pa · s
λ	Darcy friction factor or coefficient
π	Ludolph's number (3.14159)
ρ	density, kg/m ³
τ	shear stress, Pa

Subscripts

avr	average
i	counter
in	inner
r	relative
st	at standard condition ($T_{st} = 288.15$ K, $p_{st} = 1.01325 \times 10^5$ Pa)
1	beginning of pipe (accompanied with p)
2	end of pipe (accompanied with p)
{}	mark loop or contour

Other

∂	partial differential
d	infinitesimally small change of value
Δ	definitive change of value

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Erratum

In volume 29, issue 4 of *Petroleum Science and Technology*, the incorrect author name appeared in A Gas Distribution Network Hydraulic Problem from Practice by Brkić, pages 366–377. The correct name is shown below.

D. Brkić

The publisher apologizes for any inconvenience caused.