AGH DRILLING, OIL, GAS • Vol. 32 • No. 3 • 2015

http://dx.doi.org/10.7494/drill.2015.32.3.525

Piotr Janusz*, Krystian Liszka*, Mariusz Łaciak*, Rafał Smulski*, Andrii Oliinyk, Oleksandr Susak*****

APPLICABILITY OF EQUATIONS FOR PRESSURE LOSSES IN TRANSMISSION GAS PIPELINES

1. INTRODUCTION

Judging from the gas consumption forecasts presented in *Energy Policy by the year 2030* assumed by the Cabinet in 2009 and predictions presented in the project of *Energy Policy by the year 2050* we have faced a dynamic development of national transmission pipelines [1, 2].

The developing network helps the Polish natural gas market integrate with Europe's market liquidating narrow throats and increasing access to gas infrastructure [5]. As a consequence of recent changes in the gas sector the annual technical import capacity of Poland from the west and south has increased to the level of 10.2 billion m^3/year. It should be noted that this constitutes about 90% of gas demand in Poland [4].

Presently, the Operator of Gas Transmission Pipelines GAZ-SYSTEM S.A. implements an investment program for the years 2014 to 2023, mainly focusing on the development of the high-pressure pipelines in the western, southern and eastern part of Poland. According to the investment plan, about 2000 km of new transmission pipelines are to be built by the year 2023.

This will enable long-term development and functioning of companies using the transmission system and will create a competitive gas market in Poland [3]. The division of gas pipelines managed by the operator of the transmission system according to the life structure in the year 2009 and 2014 is presented in Table 1.

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

** AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland – doctoral student

*** Ivano-Frankivsk National Technical University of Oil and Gas, Faculty of Oil and Gas Engineering, Ukraine

Table 1
Life structure of gas pipelines administered by the operator in the years 2009 and 2014

Life	2009		2014	
	Pipeline length [km]	Participation [%]	Pipeline length [km]	Participation [%]
Under 5 years	221	2.27%	2,006	19.43%
6–10 years	224	2.30%	503	4.87%
11–15 years	1 081	11.12%	453	4.39%
16–20 years	1 691	17.40%	1,102	10.68%
21–25 years	726	7.47%	1,561	15.12%
over 26 years	5 776	59.43%		
26–30 years			712	6.90%
31–35 years			711	6.89%
36–40 years			1,641	15.90%
Over 40 years			1,634	15.83%
Total	9 719		10,323	

Source: own materials after [2] and [3]

2. DESCRIPTION OF THE CALCULATION MODEL

Long-distance transport of natural gas through the transmission pipelines is connected with considerable pressure losses. The quantitative representation of pressure drops depends on a number of factors, e.g. length, diameter and full-length profile of the pipeline, physical properties of transported medium, intensity and character of flow of natural gas. The technical condition of the pipeline, especially its roughness inside, which is proportional to the exploitation life of the pipeline, importantly influences the pressure losses.

The analysis of Table 1 reveals that the Polish transmission network considerably varies as far as the life of the pipelines is concerned. Recently, a number of new elements of the gas transport infrastructure have been built. Out of the total, 19.5% pipelines have been exploited for less than 5 years, which is quite a number. On the other hand almost 45% of all gas pipelines have been exploited for over 25 years, in that almost 15% are operational for over 40 years. Obviously, the drops of pressure will be quite different in two pipelines transmitting natural gas of identical physicochemical parameters, having the same length and the same diameter but differing in their activity time. However the end pressure in the older pipeline will be lower than in its newer equivalent.

There are many mathematical models for calculating drops of pressure in a given pipeline section. The paper is focused on the analysis of the applicability of selected, most commonly used in world practice equations for pressure drops in a given pipeline section:

1. Mass Flow Equation,
2. General Flow Equation,
3. Weymouth Equation,

4. Panhandle A,
5. Panhandle B,
6. Institute of Gas Technology IGT,
7. Renuard Equation,
8. Walden Equation,
9. WNIIGAZ I.

These equations are used in the IV flow zone (transient zone) where hydraulic resistance is a function of gas flow parameters and its relative roughness $\lambda = f(Re, \varepsilon)$ which corresponds with the selected scope of the calculations.

All these equations account for the intensity of flow, initial pressure and temperature of natural gas, length and outer diameter of the pipeline, and relative density of gas. All equations, except for equation 6, take into account the gas compressibility factor. In equation 6 it is substituted with the dynamic viscosity coefficient. Equations 1 and 2 account for the coefficient of linear pressure losses whereas equations 8 and 10 include the relative roughness coefficient. In the remaining cases the real condition of the inner surface of the pipeline is not included.

The analyses of applicability of selected equations were based on measurement data obtained from the exploitation of three transmission gas pipelines, the technical and technological parameters of which are presented in Table 2.

Table 2

Technical and technological parameters of analyzed pipelines

Parameter	Pipeline no. 1	Pipeline no. 2	Pipeline no. 3
Beginning of exploitation [year]	1987	1967	1967
Length [km]	69.687	7.64	15.92
Inner diameter D_w [mm]	311.3	492	492
Outer diameter D_w [mm]	323.9	508	508
Height difference of beginning and end [m]	166	101	71
Initial pressure P_1 [MPa]	5.3	4.128	3.956
Final pressure P_2 [MPa]	2.33	3.956	3.616
Flow intensity Q [thousand m^3/h]	90.38	162.981	161.851

Source: data provided by the Operator of Transmission Gas Pipelines GAZ-SYSTEM S.A.

Three gas pipelines were analyzed, whereas pipelines 2 and 3 are sections of one gas pipeline. They were so selected as to present the dependence of height difference at the beginning and the end of the pipeline on the accuracy of pressure losses calculations. Selected gas pipelines differ in their life (year in which they started to be operational), length, diameter (1 with 2, 3), as well as technical and exploitation parameters (flow intensity, pressure, temperature of gas).

The composition and parameters of gas transmitted by the analyzed pipelines are presented in Tables 3 and 4.

Table 3

Composition and parameters of natural gas transmitted with pipeline no. 1

Component	Mole fraction, [%]	Molar mass [kg/kmol]	Dynamic viscosity at normal conditions [Pa·s]	Critical pressure [MPa]	Critical temperature [K]
Methane	97.286	16.043	10.43	4.6	191
Ethane	1.263	30.07	8.62	4.88	306
Propane	0.34	44.097	7.47	4.25	370
i-butane	0.058	58.123	6.8	3.65	408
n-butane	0.056	58.123	6.59	3.78	425
i-pentane	0.017	72.15	6.05	3.38	460
n-pentane	0.032	72.15	5.87	3.36	470
Nitrogen	0.808	28.014	17.15	3.39	126
CO_2	0.14	44.01	13.27	7.39	304

Source: data provided by the Operator of Transmission Gas Pipelines GAZ-SYSTEM S.A.

Table 4

Composition and parameters of natural gas transmitted with pipelines nos 2 and 3

Component	Mole fraction, [%]	Molar mass [kg/kmol]	Dynamic viscosity at normal conditions [Pa·s]	Critical pressure [MPa]	Critical temperature [K]
Methane	97.259	16.043	10.43	4.6	191
Ethane	1.3	30.07	8.62	4.88	306
Propane	0.348	44.097	7.47	4.25	370
i-butane	0.061	58.123	6.8	3.65	408
n-butane	0.059	58.123	6.59	3.78	425
i-pentane	0.017	72.15	6.05	3.38	460
n-pentane	0.026	72.15	5.87	3.36	470
Nitrogen	0.753	28.014	17.15	3.39	126
CO_2	0.177	44.01	13.27	7.39	304

Source: data provided by the Operator of Transmission Gas Pipelines GAZ-SYSTEM S.A.

3. ANALYSIS OF SIMULATION RESULTS

The applicability range of selected equations was determined on the basis of chosen equations, calculating end pressure on particular sections of a given pipeline. Then the obtained end pressure values were compared with the actual ones, thanks to which the error of the mathematical model could be assessed.

Several analyses were performed for pipeline no. 1. The end pressure calculated for momentary input data, most typical of the analyzed period (2012–2013), was determined in the first analysis making use of various mathematical models. These calculations accounted for the change in the full-length profile of the pipeline. The height difference between the beginning and the end part of the analyzed pipeline section was 166 m, whereas the highest point (37 km of the pipeline) was located 344 m higher than the lowermost point – in the analyzed case from the beginning of the pipeline.

Pressure drop plots (Fig. 1) are based on calculations with the use of mentioned equations as well as technical and technological parameters of pipeline and composition of gas.

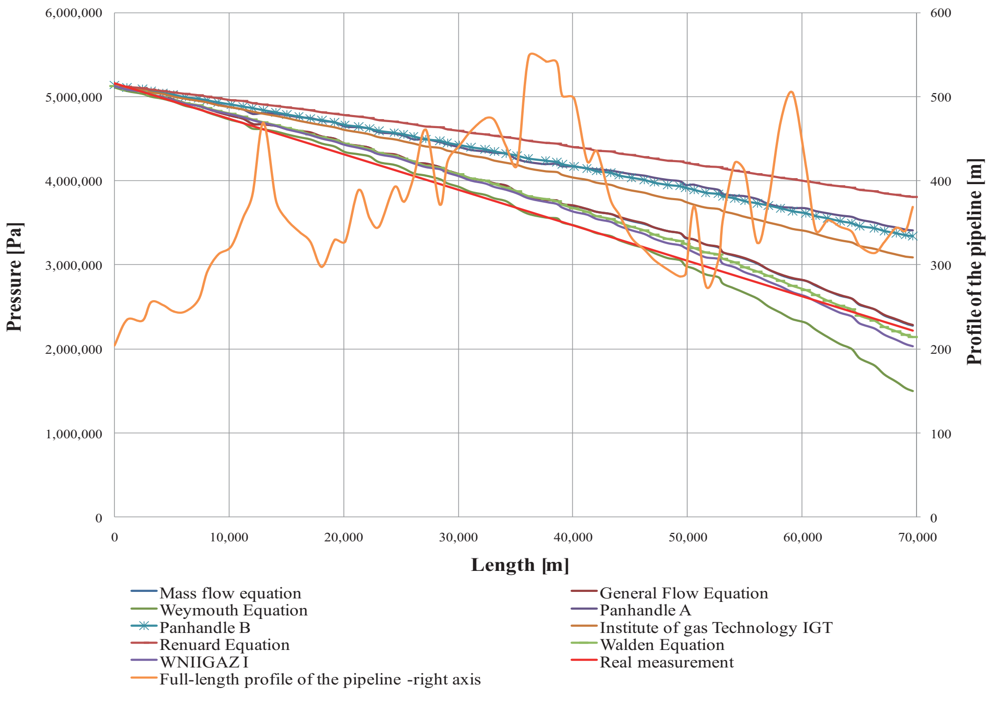

Fig. 1. Pressure drop curves full-length profile of the pipeline obtained from calculations – pipeline no. 1

Source: own calculations

Attention should be paid to considerable discrepancies between the results of the calculations and the real measurements at the end of the pipeline. The biggest differences of the results were observed for equations: Renuard – higher by over 73% as compared to the actual measurement, Panhandle A and Panhandle B – higher by 55% and 52%, respectively, IGT – higher by over 40%. The results obtained with the Weymouth Equation were lower than the real data by about 30%.

The smallest error in these exploitation conditions noted for pipeline no. 1 was obtained with the Mass Flow Equation and General Flow Equation, i.e. 0.96%.

The results of pressure drop calculations in pipeline no. 1 are presented in Table 5.

Table 5

Results of calculations of pressure drop on pipeline no. 1

Pipeline length	Real measure-ment	Mass flow equation	General Flow Equation	Weymouth Equation	Panhandle A	Panhandle B	Institute of Gas Technology	Renuard Equation	Walden Equation	WNIIGAZ I
[km]	[MPa]									
0	5.16	5.12	5.12	5.12	5.13	5.14	5.14	5.14	5.13	5.13
5	4.95	4.97	4.97	4.94	5.02	5.02	5.01	5.05	4.96	4.96
10	4.74	4.77	4.77	4.73	4.88	4.91	4.87	4.96	4.79	4.79
15	4.53	4.62	4.63	4.55	4.78	4.79	4.74	4.87	4.63	4.62
20	4.32	4.44	4.44	4.34	4.65	4.67	4.60	4.78	4.44	4.43
25	4.11	4.27	4.27	4.15	4.54	4.55	4.47	4.69	4.27	4.25
30	3.90	4.08	4.08	3.92	4.40	4.43	4.33	4.60	4.08	4.05
35	3.69	3.87	3.87	3.68	4.26	4.30	4.19	4.50	3.88	3.85
40	3.47	3.70	3.70	3.47	4.17	4.17	4.04	4.40	3.67	3.63
45	3.26	3.53	3.53	3.24	4.08	4.04	3.89	4.31	3.45	3.41
50	3.05	3.32	3.32	2.99	3.95	3.92	3.75	4.22	3.25	3.20
55	2.84	3.11	3.11	2.72	3.83	3.79	3.61	4.13	3.03	2.97
60	2.63	2.84	2.84	2.36	3.68	3.64	3.43	4.02	2.75	2.68
65	2.42	2.60	2.60	2.00	3.57	3.50	3.27	3.92	2.47	2.38
70	2.21	2.30	2.31	1.54	3.42	3.36	3.10	3.82	2.16	2.06

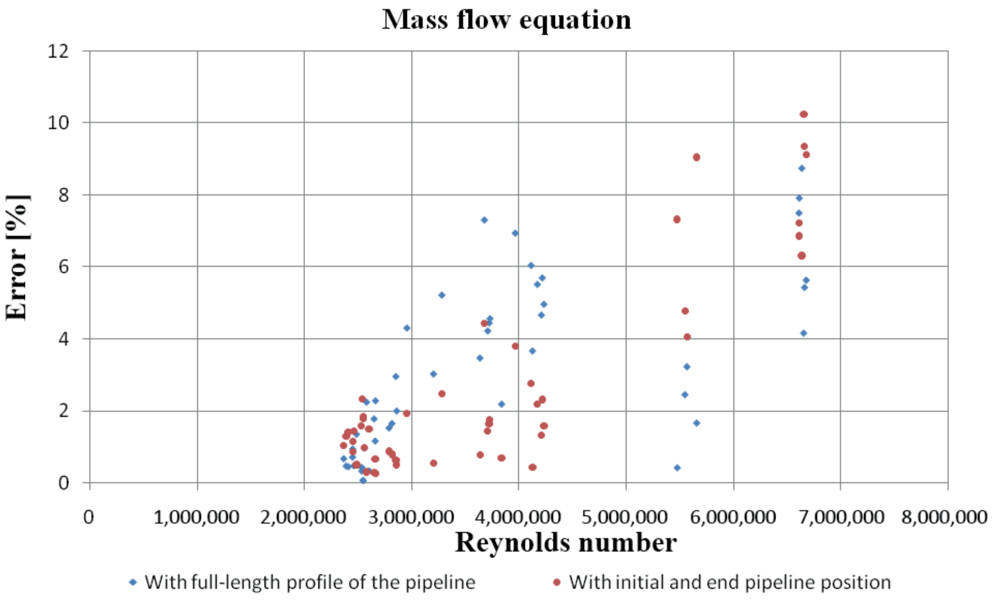

Fig. 2. Error of calculations performed with mass flow equation vs. real measurement – pipeline no. 1

Source: own calculations

50 momentary measurements representing different exploitation ranges of a given pipeline are presented in the next analysis. The end pressure was calculated on the basis of the location of the beginning and end pipeline section as well as for the entire profile, analogous to the previous analysis. The obtained end pressure values were compared with the real ones, and calculation error was assessed for each of these equations. The measurement error obtained when calculating the pressure drop with the analyzed equations was presented in Figures 2–10. For a better visual effect the plots were presented as a dependence of error and Reynolds number.

In the case of equations 1 and 2 (Mass Flow Equation, General Flow Equation) the obtained results are similar. Attention should be paid to the fact that when the Reynolds number equals to 5,000,000, the calculations including the full-length profile of the pipeline are burdened with bigger error than for calculations accounting for only the location of the beginning and end of the pipeline, whereas for higher Reynolds numbers ($> 5 \cdot 10^5$) the situation changes. Equations 1 and 2 give relatively good results in the entire scope of calculations and only in one case the error exceeded 10%, which is the best result among the analyzed equations.

The analysis of the plots presented in Figures 4–8 reveals that the calculation error is basically influenced by the gas flow intensity expressed by Reynolds number. The magnitude of this error rapidly increases when the flow intensity is higher than 60,000 m^3/h, which corresponds to Reynolds number of $4.3 \cdot 10^6$. For lower values of Reynolds number than $4.3 \cdot 10^6$ the calculation error does not exceed 10%, except Renuard equation. This equation generates the biggest calculation error for maximum Reynolds number equal to about 70–80%.

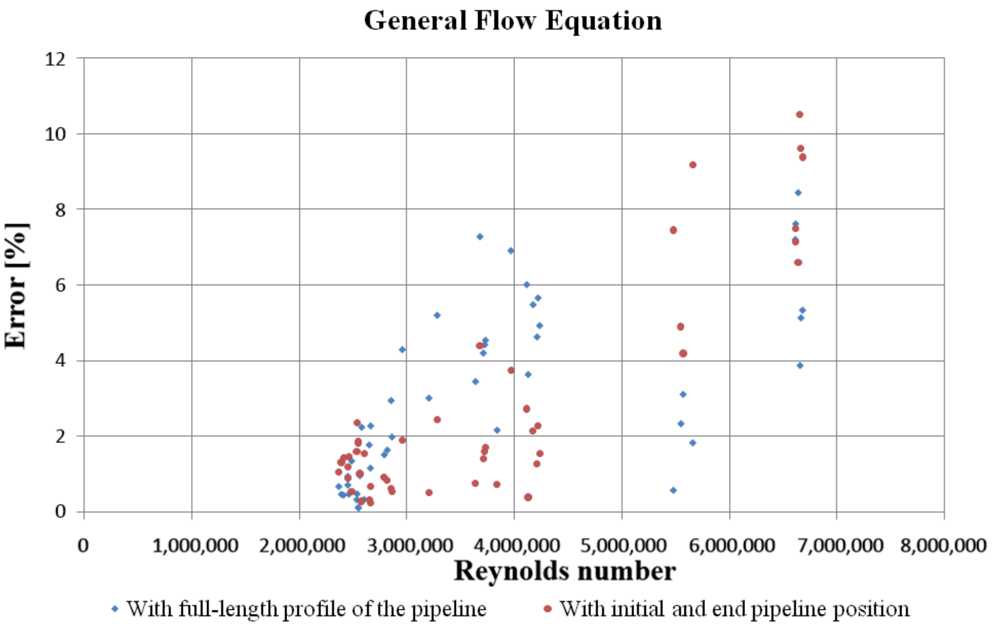

Fig. 3. Error of calculations performed with General Flow Equation vs. real measurement – pipeline no. 1

Source: own calculations

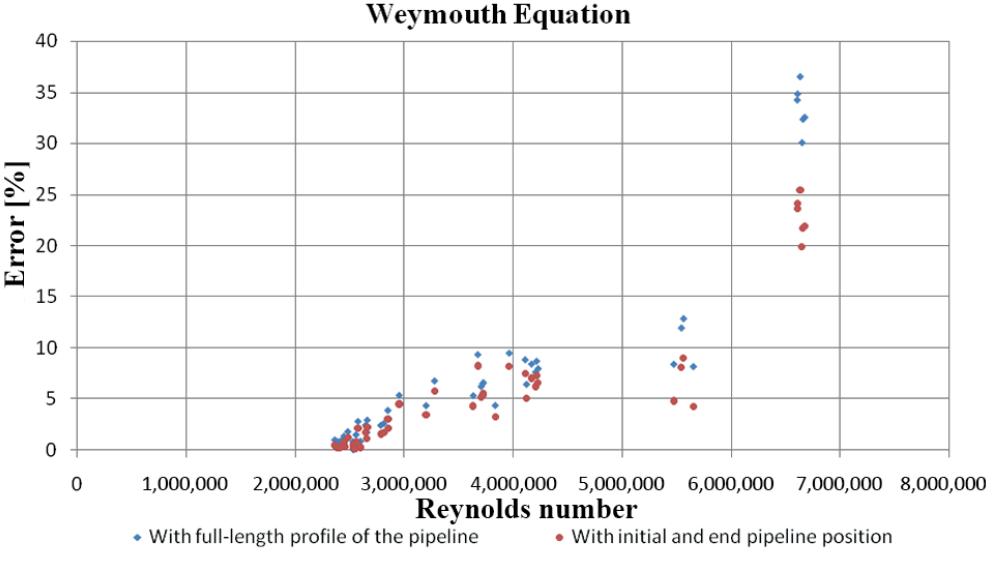

Fig. 4. Error of calculations performed with Weymounth equation vs. real measurement – pipeline no. 1

Source: own calculations

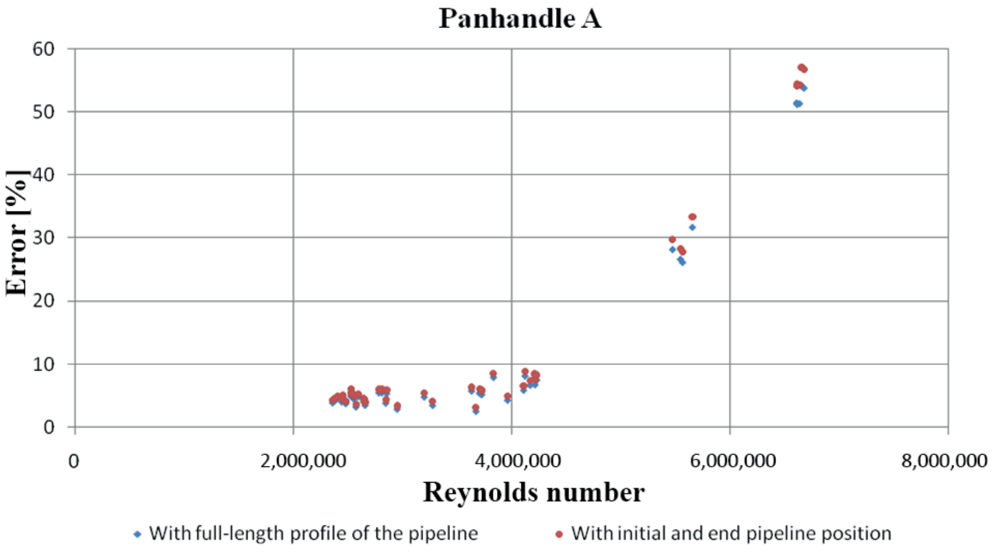

Fig. 5. Error of calculations performed with Panhandle A equation vs. real measurement – pipeline no. 1

Source: own calculations

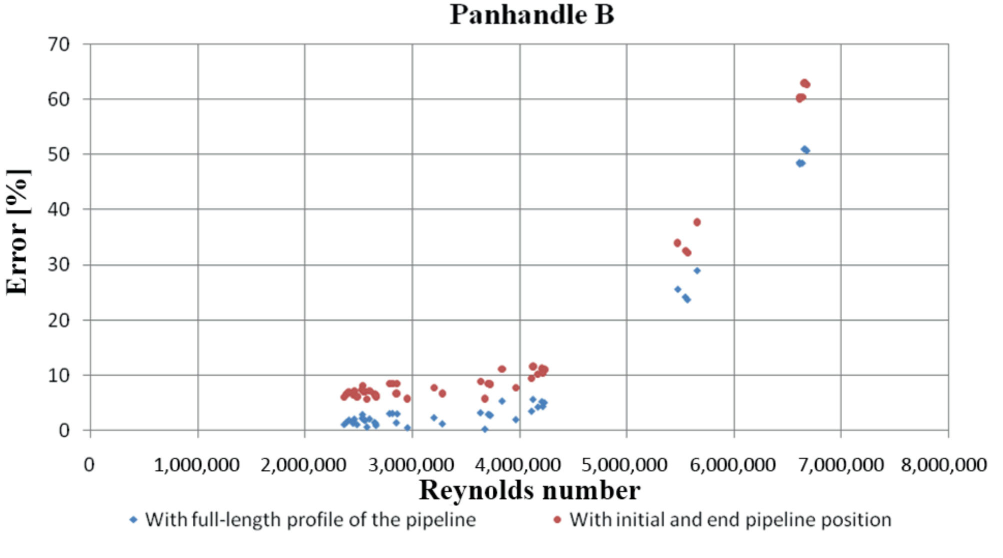

Fig. 6. Error of calculations performed with Panhandle B equation vs. real measurement – pipeline no. 1

Source: own calculations

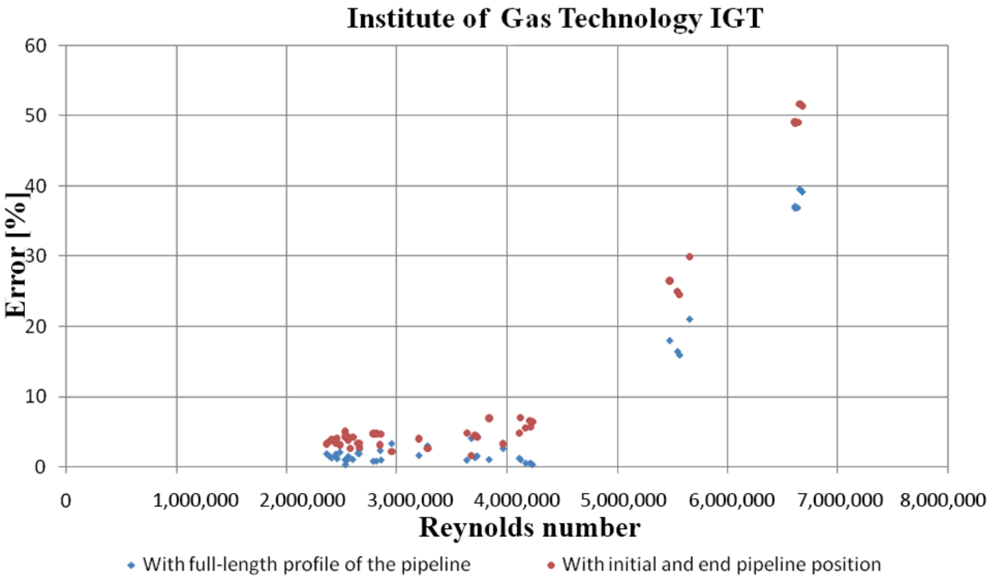

Fig. 7. Error of calculations performed with Institute of Gas Technology equation vs. real measurement – pipeline no. 1

Source: own calculations

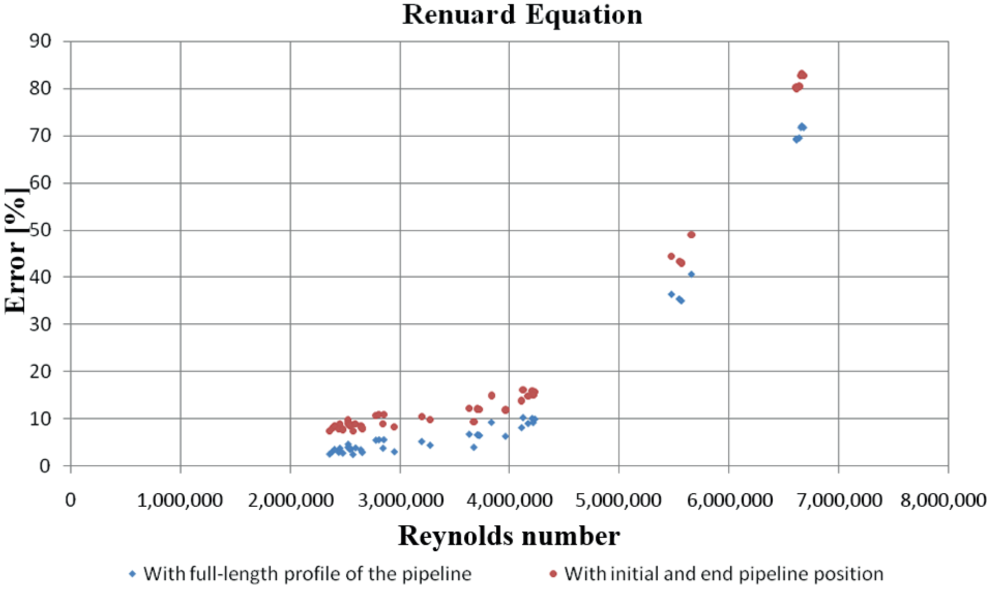

Fig. 8. Error of calculations performed with Renuard equation vs. real measurement – pipeline no. 1

Source: own calculations

Unlike the Weymouth equation, which accounts for the full-length profile of the pipeline and where the error value decreases, the remaining equations (3–7) have an opposite tendency. This can be explained by the fact that in the first analysis the Weymouth equation generated a very underestimated value of end pressure, therefore the error will have a lower value when comparing the results of the calculations from the full-length profile of the pipeline, where the pressure drop values were obviously higher, with the results of calculations encompassing only height differences of the placement of the initial and end pipeline section.

The dependence of error on Reynolds number in Walden equation turns out to be analogous to the dependence for equations 1 and 2. For $Re < 4.3 \cdot 10^6$ the results of calculations, in which the full-length profile of the pipeline was considered, generate a bigger error than in the calculations based on the initial and end pipeline parameters. However for $Re > 4.3 \cdot 10^6$ this dependence changes (Fig. 9).

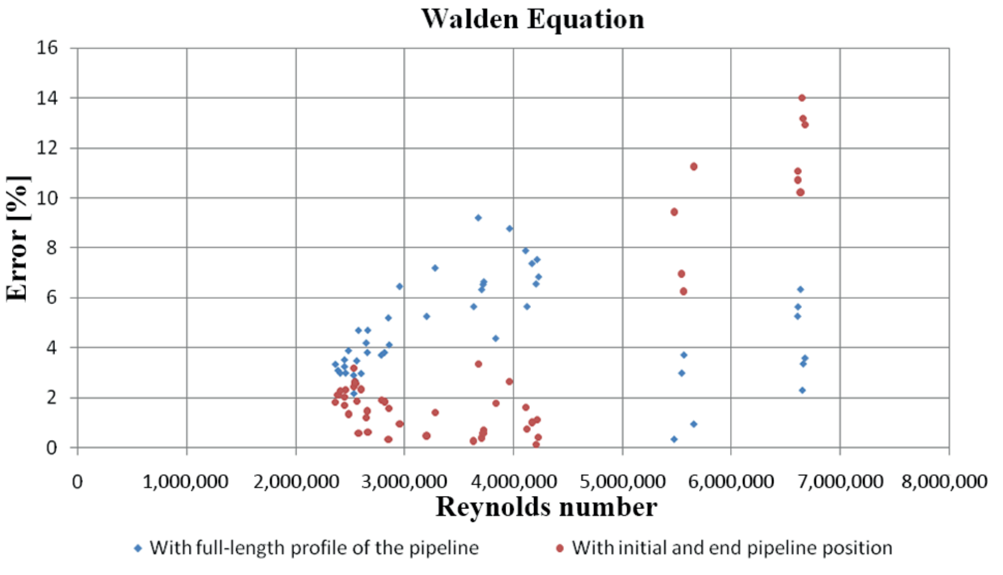

Fig. 9. Error of calculations performed with Walden equation vs. real measurement – pipeline no. 1

Source: own calculations

The least standard behavior can be observed for equation WNIIGAZ 1. Only in this case the error for $Re < 4.3 \cdot 10^6$ is higher than for $Re > 4.3 \cdot 10^6$.

The calculation error for pipelines nos 2 and 3 is presented in Figures 10 and 11. Attention should be paid to the fact that when accounting for the height difference between the beginning and the end pipeline section, the calculation error is smaller than in calculations which does not make such an assumption. Interestingly, the value of error increases by the same value in all analyzed equations. This dependence can be observed for pipeline no. 2 and also no. 3, though in the former case the dependence is more visible. This is a consequence of the fact that pipeline no. 2 is shorter than pipeline no. 3, though on the other hand the height difference between the beginning and end section of pipeline no. 2 is bigger.

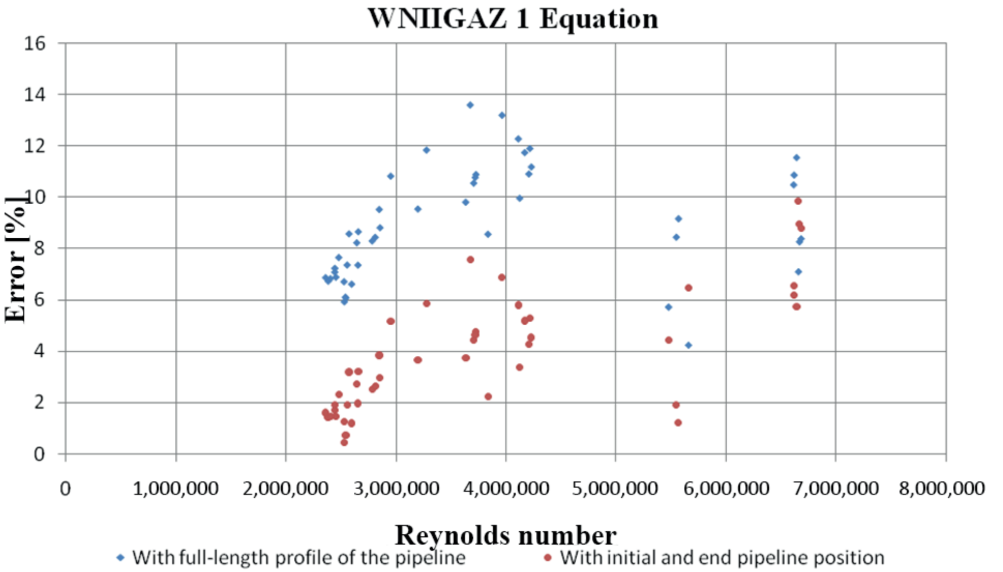

Fig. 10. Error of calculations performed with WNIIGAZ I equation vs. real measurement – pipeline no. 1

Source: own calculations

It can be assumed from the analysis of plots nos. 11 and 12 that the influence of height difference will decrease with the increasing length of the pipeline, unless it proportionally increases with the growing length.

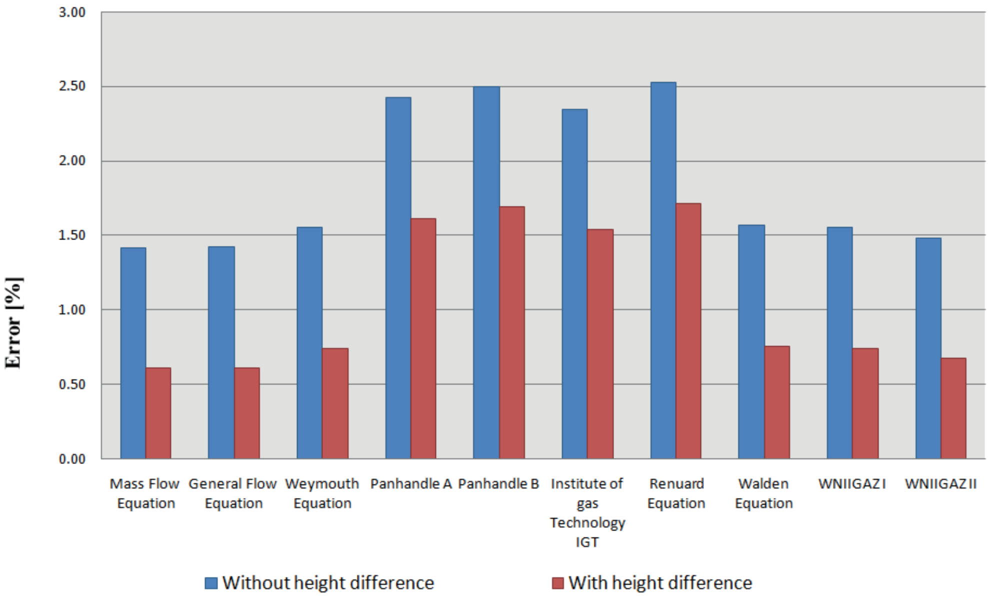

Fig. 11. Error of calculations performed for gas pipeline no. 2

Source: own calculations

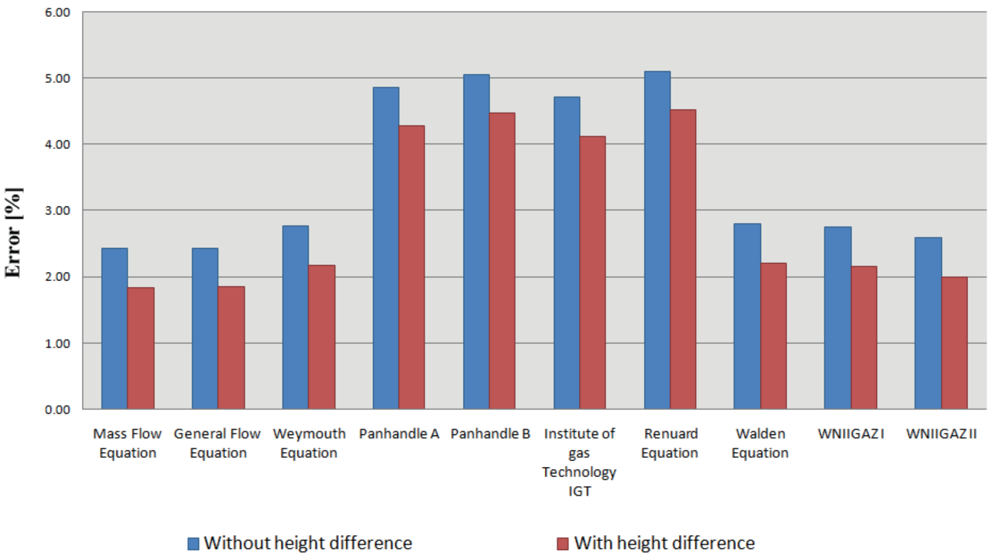

Fig. 12. Error of calculations performed for gas pipeline no. 3

Source: own calculations

4. CONCLUDING REMARKS

Considerable discrepancies between calculation results and actual pressure data at the end of the pipeline were observed while making calculations for pipeline no. 1. The biggest differences were noted for equations: Renuard – higher by over 73% with respect to the measurement, Panhandle A and Panhandle B – higher by 55% and 52%, respectively, Institute of Gas Technology IGT – higher by over 40%. The results obtained with the Weymouth equation were lower than the actual measurement by about 30%.

Accordingly, the full-length profile of the pipeline should be accounted for in the calculations, not only the height difference between the beginning and end sections.

The analysis of the calculations reveals that the smallest error was observed in the case of equations incorporating coefficients representing the actual condition of the inner surface of the pipeline, i.e. linear coefficient of pressure losses in equations 1 and 2, or relative roughness coefficient in equations 8 and 10.

This is the case in the case of older pipelines, which have been exploited for over 25 years (pipeline no. 1 for 28 years, and pipelines 2 and 3 for 45 years), and in this case the technical state of the inner surface has a decisive influence on the pressure losses in the gas transport situations.

The remaining equations give relatively accurate results to a certain extent. In the case of analyzed pipeline no. 1 this range is below the Reynolds number equal to $4.3 \cdot 10^6$. Weymouth, Panhandle A, Panhandle B, Institute of Gas Technology IGT, Renuard, WNIIGAZ I equations are not recommended for higher values because of the increasing inaccuracy of calculation results.

REFERENCES

[1] Projekt *Polityki energetycznej Polski do 2050 r.* przedstawiony do konsultacji społecznych w sierpniu 2015 r.

[2] *Polityka energetyczna Polski do 2030 roku.* Dokument rządowy przyjęty przez Radę Ministrów dnia 10.11.2009 r.

[3] Plan rozwoju Operatora Gazociągów Przesyłowych GAZ-SYSTEM S.A. w zakresie zaspokojenia obecnego i przyszłego zapotrzebowania na paliwa gazowe na lata 2014–2023 [wyciąg].

[4] Łoś M., Biały R., Janusz P., Szurlej A.: *The influence on the national gas infrastructure development on Polish energy security* [in print].

[5] Kaliski M., Janusz P., Szurlej A.: *Wpływ infrastruktury przesyłowej gazu ziemnego na wielkość jego zużycia w Polsce*. Konferencja Naukowo-Techniczna FORGAZ 2010 „Pomiar ilości i jakości gazu", Prace Naukowe INIG, no. 173.

[6] Łaciak M.: *Ocena niepewności wyników statycznej symulacji sieci gazowych.* Wiertnictwo, Nafta, Gaz, vol. 26, no. 4, 2009, pp. 661–669.

[7] Łaciak M.: *Wpływ zmian wysokości położenia na wyniki obliczeń hydraulicznych gazociągów*. Wiertnictwo, Nafta, Gaz, vol. 26, no. 3, 2009, pp. 547–553.

[8] Łaciak M., Gniewek-Grzybczyk B., Siuciak M., Grela I.: *Energetyka gazowa.* Wydawnictwo Tarbonus, Kraków – Tarnobrzeg 2011.

[9] Ikoku Chi U.: *Natural Gas Production Engineering*. John Wiley & Sons Inc., New York 1984.