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Analysis of Pressure Drop Characteristics in Natural Gas Networks

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***Abstract* – In this work, new friction factor equations were developed for the steady state natural gas pipeline network system. Different equations were developed and verified for different pressure range. For each case study, the corresponding equation is verified in the specific pressure range to check the achieved enhancement in prediction. The prediction was compared with the result obtained from Synergee Gas simulator tool, where different gas flow equation were used. For a specific pressure range, the predictions were validated using filed data for 3 different study cases in order to determine the equation that can best predict the pressure in the natural gas pipeline network. The newly developed equations were compared with the other flow equations for the 3 case studies to ensure the affectivity of these newly developed equations. The outlet pressure was calculated and compared with the experimental data.**

Keywords— Gas pipeline; Natural Gas; Friction Factor; Gas Networks.

I. INTRODUCTION

Pipelines network systems consist of a large number of facilities which are used for the conveyance of water, gas, or petroleum products. They are generally the safest, the most efficient, and the most economical way to transport these fluids. These systems vary from the very simple ones to very large and quite complex ones.

Natural gas pipeline are made of steel or plastic tubes, which are usually buried in the ground. Compressors stations move the natural through the pipelines. [1]

Since the natural gas major discoveries in Egypt in the 1990s, it importance as a source of energy increased. At 2005, the estimated reservoir of natural gas in Egypt is 66 trillion cubic feet, which is the third largest in Africa. Since 1990s, natural gas has been discovered in the Western Desert, in the Nile Delta, and offshore from the Nile Delta.

Within the first half of year 2014, 24.3 billion standard cubic meters (BSCM) of natural gas were distributed to the local market. The transmission capacity has reached 210 million standard cubic meters per day (MSCMD) compared to 37 MSCMD in 1997. This is due to increasing the length of the grid to 7075 km of trucking lines compared to 2800 km in 1997. The distribution of natural gas to the local market by the end of 2014 is: 56% for power generation, 22% for domestic, commercial, industrial sectors, and for Compressed Natural Gas (CNG) stations, as a vehicular fuel, 10% for 384 industrial factories (iron and steel, fertilizers, cements, ceramics, and others), and 12% to natural gas processing plants to extract gas derivatives and valuable components for the petrochemical industry, in addition to using the natural gas as a fuel for petroleum refineries. [2]

The present work objective is to identify the best equation that could be used to predict the pressure drop in natural gas pipelines, therefore, a hydraulic analysis of the natural gas pipelines was carried out and the predictions with different gas flow equations as well as the field data were compared, in addition, a new gas flow equation of the friction factor was development. The new equation gave better predictions compared to the existing ones.

II. NATURAL GAS GOVERNING FLOW EQUATIONS IN CIRCULAR PIPES

A. *Natural Gas Governing Flow Equations*

The natural gas governing equations consist of: the continuity equation, the momentum equation, the conversation of energy equation, and the Bernoulli's equation.

B. *Assumptions to Calculate the Pressure and the Flow Rate*

The general flow equation can be derived from the total momentum balance around an element of fluid through a differential length of the pipe under the following assumptions:

- Isothermal flow
- Steady state flow
- Single phase flow
- No heat transfer from and to the gas to the surroundings
- No mechanical work done on: or by the fluid.
- Newtonian fluid.

C. *The Flow Equations*

There are several equations available that relate the gas flow rate with gas properties, pipe diameter, length and upstream and downstream pressures. These equations are [3]:

1. General flow equation
2. Colebrook – white equation
3. Modified Colebrook – white equation
4. AGA equation
5. Weymouth equation
6. Panhandle A equation
7. Panhandle B equation
8. IGT equation

9. Spitzglass equation
10. Mueller equation
11. Fritzsche equation

D. *The Feneral Flow Equations*

The general flow equation is the basic equation relating the flow rate to the pressure drop. It is also called the fundamental flow equation for the steady-state isothermal flow in gas pipelines. This equation applies over all pressure ranges and it is the basis for many of the flow equations used in the analysis of gas transmission and distribution networks [4], (in SI units):

$$Q = 5.747 \times 10^{-4} F \left(\frac{T_b}{P_b} \right) \left[\frac{\left(P_1^2 - e^s P_2^2 \right)}{G T_f L_e Z} \right]^{0.5} D^{2.5} \qquad (1)$$

Where, Q is the gas flow rate at standard condition (m^3/day)
F is the transmission factor (dimensionless)
P_b is the base pressure (kPa)
T_b is the base temperature (K)
P_1 is the upstream pressure (kPa)
P_2 is the downstream pressure (kPa)
G is the gas gravity (air = 1.00)
T_f is the average gas flowing temperature (K)
L_e is the equivalent length of pipe segment (km)
Z is the gas compressibility factor at the flowing temperature, dimensionless
D is the pipe inside diameter, mm

$$L_e = \frac{L\left(e^S - 1\right)}{S} \qquad (2)$$

Where, S is the dimensionless elevation adjustment parameter,
E is the pipe roughness (mm),
L is the pipe length (km)

$$S = 0.0684 G \left(\frac{H_2 - H_1}{T_f Z} \right) \qquad (3)$$

Where, H is the pipe elevation (m)

E. *Diffuculties to Solve the General Gas Flow Equation*

The general gas flow equation is difficult to be solved. The main difficulties are described as follows:

1- When the flow is unknown; the solution of the equation is obtained by iterative method.

2- The smooth pipe equation is also a non-explicit relationship between the Reynolds number and the friction factor. Therefore, further iterations are needed.

To solve this problem: several equations as Blasius-type equation (Blasius, Muller, Fritch, Polyflow, Panhandle, etc), are introduced to get a more simple form to calculate the friction factor. [4]

III. ANALYSIS

A. *Assumptions*

- The gas viscosity is constant where (CP = 0.01107).
- Elevation change between upstream and downstream of gas pipeline calculated through (GPS, Google Earth or elevation file from United States geological survey by using global mapper or GIS program).
- No temperature change between upstream and downstream temperature of the gas.
- The standard pressure condition is 1 atmosphere which is equal to 14.73 psia.
- The standard temperature condition is 15.56 °C (60 °F).
- Using modified Benedict- Webb-Rubin equation to calculate the gas compressibility factor.
- The results of the different gas flow equations are calculated by using Synergee Gas program version (4.3.0).

B. *First Case*

The medium pressure natural gas pipeline is feeding Warak area, Giza, Egypt. It serves about 200,000 customers. The pipeline data: length is 2619 m long, outer diameter (O.D.) is 355 mm, inner diameter (I.D.) is 290.6 mm, the gas specific gravity is 0.6090, the efficiency is 95%, the pipe roughness is 0.0152 mm, the pipe elevation is 2 m, the gas flow range is (7900-9100) standard cubic meters per hour (SCMH), the Reynolds number range is (0.64E6 – 0.73E6), the operating year is 2011.

TABLE 1. The Composition of natural gas for first case.

COMPONENT	MOLE %	COMPONENT	MOLE %
C1	91.5610	I-C5	0.0010
C2	5.0690	N-C5	0.0
C3	0.3090	C6+	0.0
I-C4	0.0100	N2	0.3860
N-C4	0.0100	CO2	2.6540

TABLE 2. The field data of natural gas pipeline for first case.

NO.	INLET PRESSURE P1 (BARG)	OUTLET PRESSURE P2 (BARG)	GAS FLOW RATE (SCMH)	Tg (K)
1	7.05	6.9334	9032.24	295.25
2	7.05	6.9375	9016	293.35
3	7.05	6.9316	9192.4	292.35
4	7.05	6.9285	9368.8	293.65
5	7.05	6.9290	9352	294.95
6	7.05	6.9369	9318.4	292.65
7	7.05	6.9400	9100	292.35
8	7.05	6.9416	9044	294.45
9	7.05	6.9440	8988	294.95
10	7.05	6.9551	8775.2	292.35
11	7.05	6.9543	8764	293.45
12	7.05	6.9466	8713.6	295.25
13	7.05	6.9508	8640.8	298.45
14	7.05	6.9503	8400	299.15
15	7.05	6.9618	7980	301.05

C. *Second Case*

The low pressure natural gas pipeline is feeding Medicine Factory, Giza, Egypt. The pipeline data: length is 113 m long, O.D. is 90 mm, I.D. is 80 mm, the gas specific gravity is 0.6090, the efficiency is 95%, the pipe roughness is 0.0152 mm, the pipe elevation is -1 m, the gas flow range is (5-80)

SCMH, the Reynolds number range is (1400 – 25000), the operating year is 2014. The natural gas composition is the same as first case.

TABLE 3. The field data of natural gas pipeline for second case.

NO.	INLET PRESSURE P1 (MBARG)	OUTLET PRESSURE P2 (MBARG)	GAS FLOW RATE (SCMH)	Tg (K)
1	298	297.68	21	304.15
2	303	302.22	13.2	304.15
3	301	300.02	16.8	304.15
4	316	315	3.6	304.15
5	295	285.45	75	304.15
6	294	291.24	42	304.15
7	297	296.03	27	304.15
8	290	282.08	90	304.15
9	290	285.21	78	304.15
10	292	288.04	72	304.15

D. *Third Case*

The high pressure natural gas pipeline is feeding the power station, Giza, Egypt. The pipeline data: 5000 m long, 711.2 mm O.D., 682.651 mm I.D., 0.5806 gas specific gravity, 90% efficiency, 0.0254mm pipe roughness, the gas flow range is (3.5-8) million metric standard cubic meters per hour (MMSCMH), the Reynolds number range is (5.3E6 – 11.5E6), the operating year is 1985.

TABLE 4. The Composition of natural gas for third case.

COMPONENT	MOLE %	COMPONENT	MOLE %
C1	96.133	I-C5	0.044
C2	2.569	N-C5	0.014
C3	0.477	C6+	0.03
I-C4	0.128	N2	0.075
N-C4	0.075	CO2	0.451

TABLE 5. The field data of natural gas pipeline for third case.

NO.	INLET PRESSURE P1 (BARG)	OUTLET PRESSURE P2 (BARG)	GAS FLOW RATE (SCMH)	Tg (K)
1	32.28	32.12	154.47	299.68
2	32.63	32.49	160.96	292.47
3	32.46	32.29	162.99	292.82
4	32.55	32.35	177.08	292.7
5	32.01	31.82	186.93	295.41
6	32.1	31.79	206.89	298.5
7	32.08	31.77	230.48	299.34
8	32.32	31.99	236.69	292.88
9	32.7	32.35	241.11	290.55
10	31.42	30.91	249.79	299.05
11	32.74	32.34	254.82	289.28
12	32.98	32.39	295.11	286.85
13	32.39	31.75	302.94	289.67
14	30.72	29.97	312.02	299.07
15	31.04	30.21	332.77	298.72

IV. RESULTS

A. *First Case*

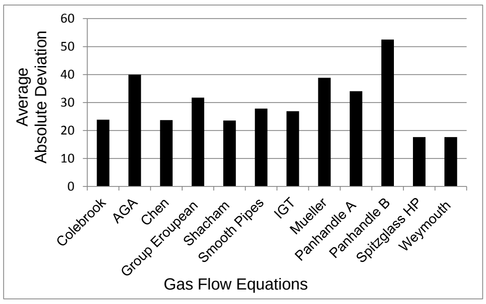

Fig. 1. Comparison between average absolute deviations for different flow equations for first case.

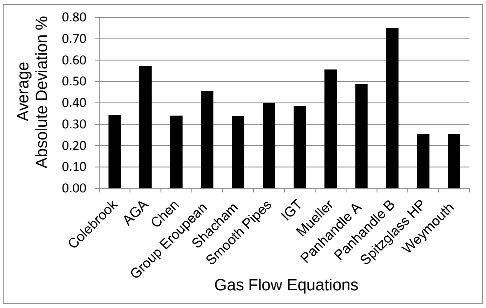

Fig. 2. Comparison between average absolute deviation percentages for different flow equations for first case.

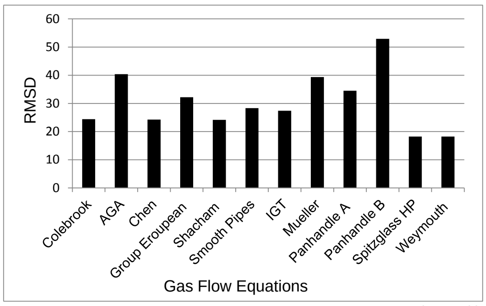

Fig. 3. Comparison between Root Mean Square Deviation for different flow equations for first case.

The Spitzglass HP gives the Minimum Average Deviation Percentage between the calculated and reading pressures (0.25%), and Root Mean Squared Deviation (18.21) comparing to the other equations. Spitzglass HP followed by Weymouth gives the best results followed by Shacham, Chen and Colebrook in ordered. Spitzglass LP give the worst results followed by Panhandle B, AGA and Mueller.

B. *Second Case*

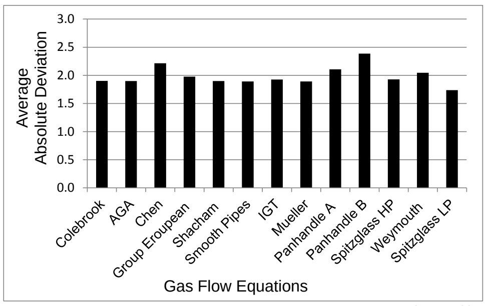

Fig. 4. Comparison between average absolute deviations for different flow equations for second case.

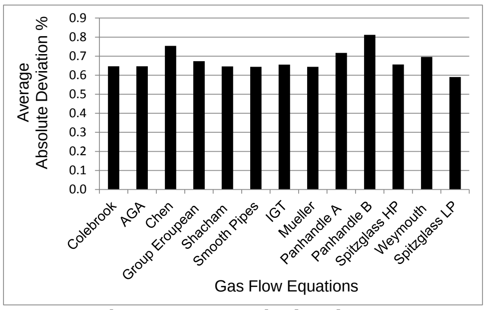

Fig. 5. Comparison between average absolute deviation percentages for different flow equations for first case.

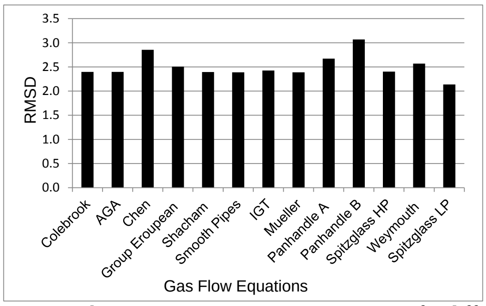

Fig. 6. Comparison between Root Mean Square Deviation for different flow equations for second case.

The Spitzglass LP gives the Minimum Average Deviation Percentage between the calculated and reading pressures (0.588%), the minimum Average Deviation between the calculated and reading pressures (1.714), and Root Mean Squared Deviation (2.184) comparing to the other equations. Spitzglass LP gives the best results followed by Smooth Pipes, Mueller, Shacham, AGA and Colebrook in ordered. Panhandle B gives the worst results followed by Chen, Panhandle A and Weymouth in ordered.

C. *Third Case*

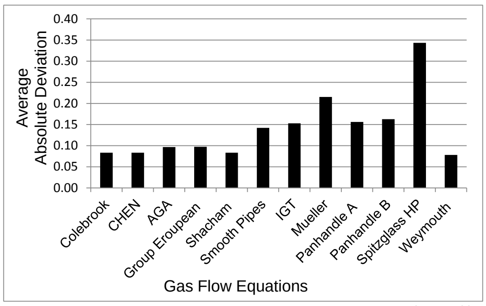

Fig. 7. Comparison between average absolute deviations for different flow equations for third case.

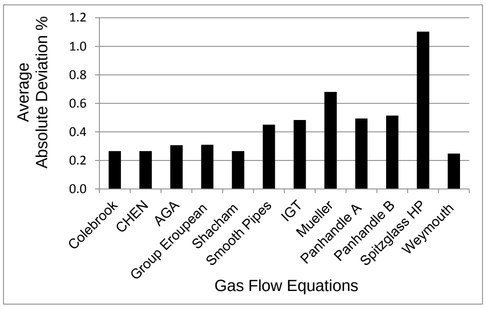

Fig. 8. Comparison between average absolute deviation percentages for different flow equations for third case.

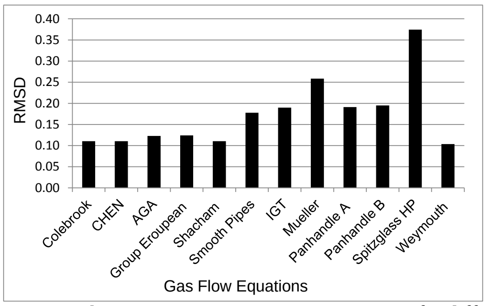

Fig. 9. Comparison between Root Mean Square Deviation for different flow equations for third case.

The Weymouth gives the Minimum Average Deviation Percentage between the calculated and reading pressures (0.25%), and Root Mean Squared Deviation (0.1) comparing to the other equations. Weymouth gives the best results followed by Colebrook, Chen, Shacham, AGA and Group European in ordered. Spitzglass HP gives the worst results followed by Mueller and Panhandle B.

D. *The Development of a New Gas Flow Equation*

Most of the friction factor equations for the gas flow equation have the Blasius form or power law relationships and can be expressed as the following:

$$\frac{1}{\sqrt{f}} = A\,\mathrm{Re}^{B} \tag{4}$$

For all the previous three cases studies, since most of the friction factor equations gives good results with some deviation between the calculated and the experimental reading pressures. Therefore, the development of a new friction factor equation is essentially to get better match and decrease the deviation between the calculated and the experimental reading pressures for minimizing the errors.

MATLAB program was used to develop the new friction equations for each case study.

- For first model, the equation's constants were found to be as A of 0.6314, and B of 0.1832. With the root mean square of the errors of ±0.0431. So the first new equation can be expressed as the following:

$$\frac{1}{\sqrt{f}} = 0.6314\,\mathrm{Re}^{0.1832} \tag{5}$$

The equation is valid for medium pressure range, for {0.64E6<Re<0.73E6}.

- For second model, the equation's constants were found to be as A of 0.05134, and B is 0.4151. With the root mean square of the errors of ± 0.1775. So the third new equation can be expressed as the following:

$$\frac{1}{\sqrt{f}} = 0.05134\,\mathrm{Re}^{0.4151} \tag{6}$$

The equation is valid for low pressure range, for {$1400 < Re < 25000$}.

- For third model, the equation's constants were found to be as A=1.311, and B is 0.1165. With the root mean square of the errors = ±0.08836. So the Fourth new equation can be expressed as the following:

$$\frac{1}{\sqrt{f}} = 1.311\,\mathrm{Re}^{0.1165} \tag{7}$$

The equation is valid for high pressure range, for {5.3E6 < *Re* < 11.5E6}.

E. *Verification of the New Gas Flow Equations*

- First case

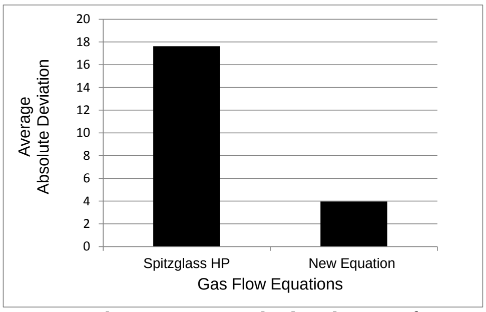

Fig. 10. Comparison between average absolute deviation for Spitzglass HP and new equation for first case.

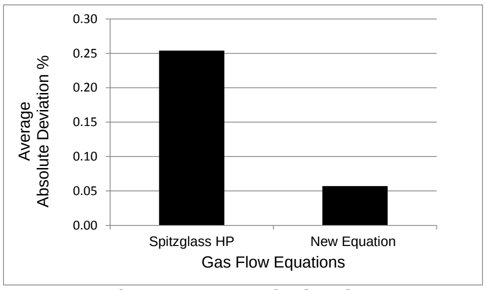

Fig. 11. Comparison between average absolute deviation percentage for Spitzglass HP and new equation for first case.

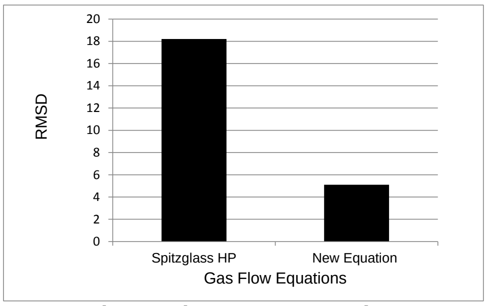

Fig. 12. Comparison between the root mean square deviation For Spitzglass HP and new equation for first case.

- Second case

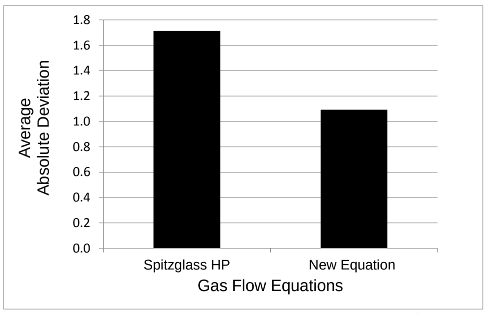

Fig. 13. Comparison between average absolute deviation for Spitzglass LP and new equation for second case.

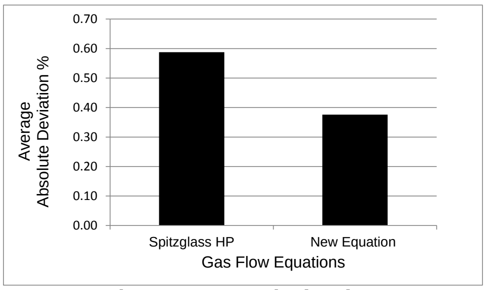

Fig. 14. Comparison between average absolute deviation percentage for Spitzglass LP and new equation for second case.

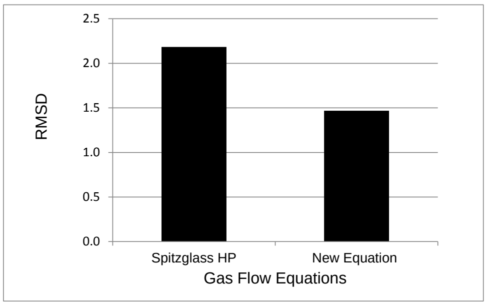

Fig. 15. Comparison between the root mean square deviation For Spitzglass LP and new equation for second case.

- Third case

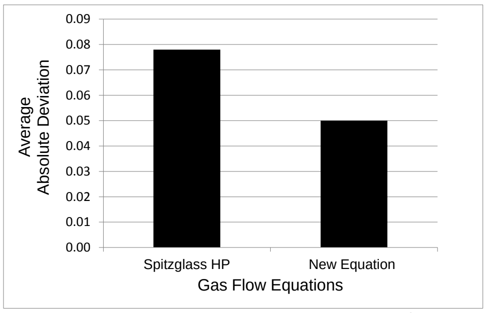

Fig. 16. Comparison between average absolute deviation for Weymouth and new equation for third case.

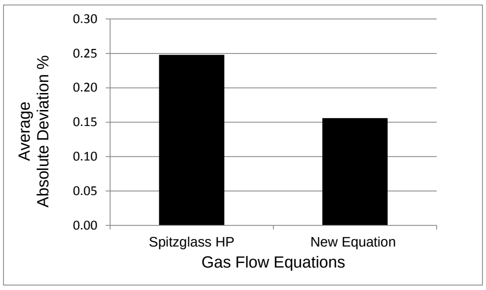

Fig. 17. Comparison between average absolute deviation percentage for Weymouth and new equation for third case.

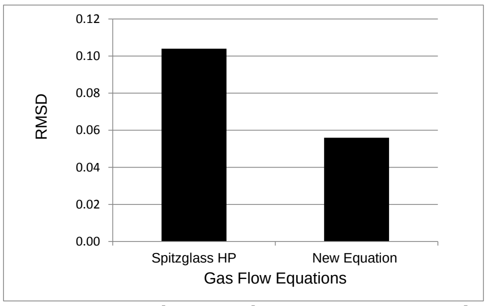

Fig. 18. Comparison between the root mean square deviation for Weymouth and new equation for third case.

F. *Discussions of the Results*

From the results of the three cases, the new equations gives the best results with the minimum value of absolute average deviation, absolute average deviation percentage, and root mean square deviation.

A very small deviation between the calculated pressures by using the new equations with the reading pressures from field. From the previous comparisons between the new equations and the other flow equations for the three case studies,

- New equation (Equation 5) is recommended for Reynolds number in the range of 0.64E6 to 0.73E6 for pipe diameter 355 mm for medium pressure range.
- New equation (Equation 6) is recommended for Reynolds number in the range of 1400 to 25000 for pipe diameter 90 mm for low pressure range.
- New equation (Equation 7) is recommended for Reynolds number in the range of 5.3E6 to 11.5E6 for pipe diameter 711.2 mm for high pressure range.

G. *Comparing and Checking the Validation of the New Gas Flow Equation*

TABLE 6. The field data of natural gas pipeline for forth case.

NO.	INLET PRESSURE P1 (BARG)	OUTLET PRESSURE P2 (BARG)	GAS FLOW RATE (SCMH)	Tg (K)
1	7.05	7.0058	5649.16	300.65
2	7.05	7.0061	5627.6	300.25
3	7.05	7.0067	5455.56	303.35
4	7.05	7.0059	5609.12	301.25
5	7.05	7.0171	5149.32	296.35
6	7.05	7.0198	5126	297.95
7	7.06	7.0193	5120.72	296.75
8	7.06	7.0250	5102.24	295.95
9	7.07	7.0262	4807.44	298.55
10	7.07	7.0303	4792.92	296.65
11	7.07	7.0263	4919.2	296.35
12	7.07	7.0293	4898.52	298.75
13	7.07	7.0333	4628.36	298.95
14	7.08	7.0385	4646.4	296.45
15	7.07	7.0341	4673.68	298.65

- Fourth case

The Medium pressure natural gas pipeline is feeding Bolaq area, Giza, Egypt. It serves about 170,000 customers. The pipeline data: length is 2315 m long, O.D. is 355 mm, I.D. is 290.6 mm, the gas specific gravity is 0.6090, the efficiency is 95%, the pipe roughness is 0.0152 mm, the pipe elevation is 5m, the gas flow range is (4600-5700) SCMH, the Reynolds number range is (0.37E6 – 0.46E6), the operating year is 2011. The natural gas composition is the same as first case.

The new developed equation gives the Minimum Average Deviation Percentage (0.058%), Average Absolute Deviation (4.103) and Root Mean Squared Deviation (4.980) comparing to the other equations. The new equation gives the best results followed by Spitzglass HP, Weymouth, Shacham, Chen and Colebrook in ordered. Spitzglass LP gives the worst results followed by Panhandle B, AGA and Mueller in ordered.

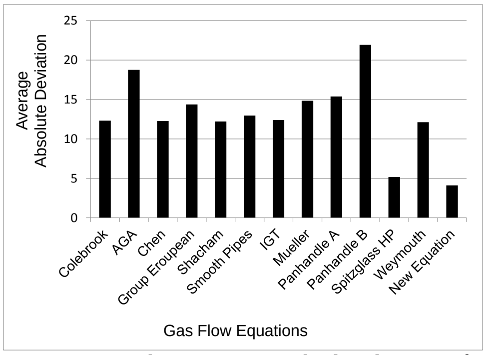

Fig. 19. Comparison between average absolute deviations for different flow equations for fourth case.

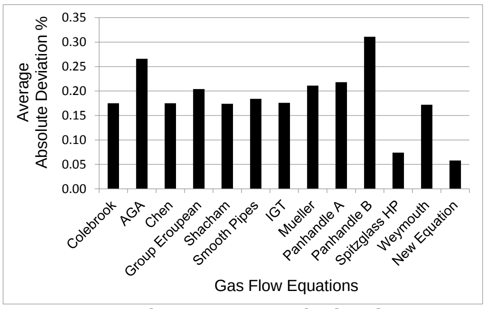

Fig. 20. Comparison between average absolute deviations percentages for different flow equations for fourth case.

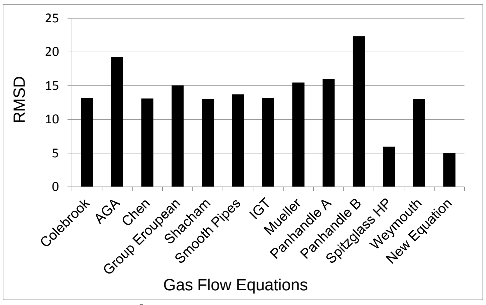

Fig. 21. Comparison between Root Mean Square Deviation For different flow equations for fourth case.

- Fifth case

The low pressure natural gas pipeline is feeding medicine factory, Giza, Egypt.It has the same data as case (2).

TABLE 7. The field data of natural gas pipeline for fifth case.

NO.	INLET PRESSURE P1 (MBARG)	OUTLET PRESSURE P2 (MBARG)	GAS FLOW RATE (SCMH)	Tg (K)
1	308	306.41	5.4	304.15
2	294	289.93	44.4	304.15
3	304	303.15	12	304.15
4	298	294.92	28.8	304.15
5	300	299.1	18	304.15
6	292	288.04	72	304.15
7	292	286.08	74	304.15

The new developed equation gives the Minimum Average Deviation Percentage (0.353%), Average Absolute Deviation (1.032) and Root Mean Squared Deviation (1.407) comparing to the other equations. The new equation gives the best results followed by Spitzglass LP, Smooth pipe, Mueller, Chen, Shacham, and Colebrook, in ordered. Panhandle B gives the worst results followed by AGA and Panhandle A in ordered.

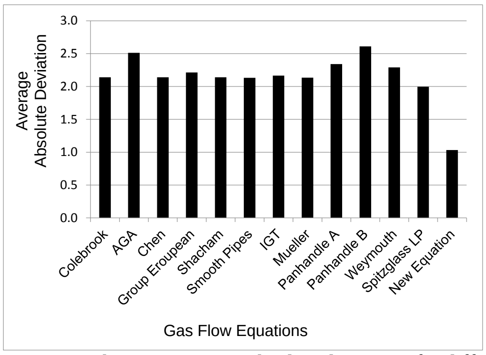

Fig. 22. Comparison between average absolute deviations for different flow equations for fifth case.

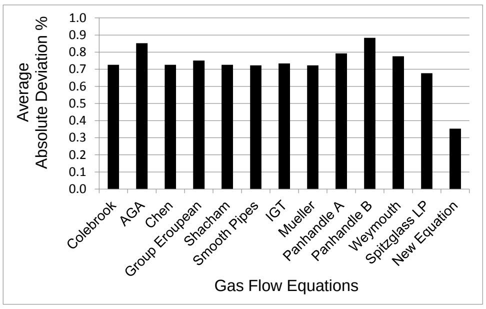

Fig. 23. Comparison between average absolute deviation percentages for different flow equations for fifth case.

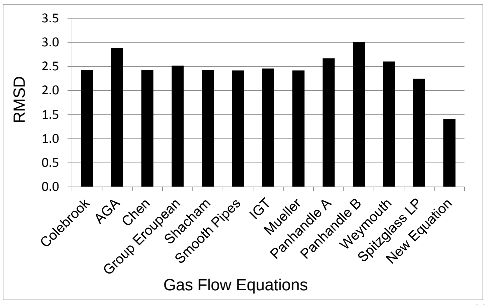

Fig. 24. Comparison between Root Mean Square Deviation For different flow equations for fifth case.

- Sixth case

The High pressure natural gas pipeline is feeding fertilizer factory, Giza, Egypt. It serves about 170,000 customers. The pipeline data: length is 5800 m long, O.D. is 406.4 mm, I.D. is 384.15 mm, the gas specific gravity is 0.5848, the efficiency is 92%, the pipe roughness is 0.02032 mm, the gas flow range is (2.3-3.9) SCMH, the Reynolds number range is (6.1E6 – 9.1E6), the operating year is 1997. The natural gas composition is the following:

TABLE 8. The field data of natural gas pipeline for six case.

COMPONENT	MOLE %	COMPONENT	MOLE %
C1	97.351	I-C5	0.047
C2	2.103	N-C5	0.011
C3	0.137	C6+	0.026
I-C4	0.041	N2	0.07
N-C4	0.021	CO2	0.0193

TABLE 9. The field data of natural gas pipeline for six case.

NO.	INLET PRESSURE P1 (BARG)	OUTLET PRESSURE P2 (BARG)	GAS FLOW RATE (KSCMH)	Tg (K)
1	44.29	43.06	100.76	313
2	44.29	43.01	105.43	313
3	44.19	42.9	108.9	313
4	44.19	42.8	113.36	313
5	44.24	42.74	116.98	313
6	44.34	42.32	138.35	313
7	44.23	42.37	133.35	313
8	44.29	43.16	95.35	313

The new developed equation gives the Minimum Average Deviation Percentage (0.373%), Average Absolute Deviation (0.159) and Root Mean Squared Deviation (0.177) comparing to the other equations. The new equation gives the best results followed by Weymouth, Colebrook, AGA, Shacham, Chen and Group European in ordered. Mueller gives the worst results followed by Spitzglass HP, Panhandle B and Panhandle A in ordered.

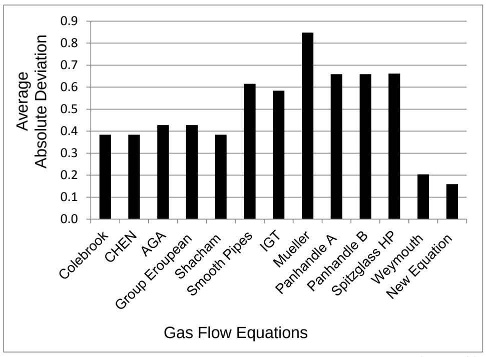

Fig. 25. Comparison between average absolute deviations for different flow equations for six case.

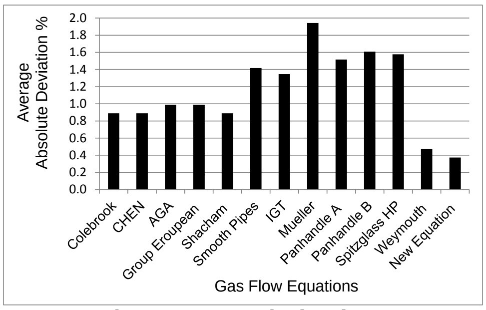

Fig. 26. Comparison between average absolute deviation percentages for different flow equations for six case.

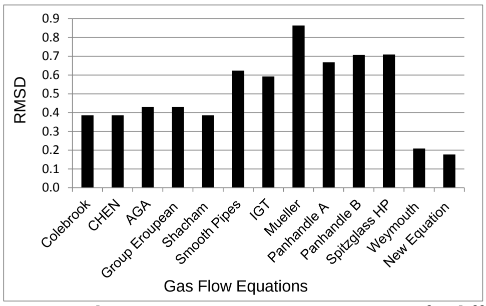

Fig. 27. Comparison between Root Mean Square Deviation for different flow equations for six case.

V. CONCLUSIONS

The newly developed friction equation (Equation 5) when used in the general flow equation, it gives the best results for medium pressure network comparing to the other gas flow equations, the equation is recommended for Reynolds number in the range of 0.37E6 to 0.73E6 for pipe diameter 355 mm.

The newly developed friction equation (Equation 6), when used in the general flow equation, it gives the best results for low pressure network comparing to the other gas flow equations, the equation is recommended for Reynolds number in the range of 1400 to 25000 for pipe diameter 90 mm.

The newly developed friction equation (Equation 7), when used in the general flow equation, it gives the best results for high pressure network comparing to the other gas flow equations, the equation is recommended for Reynolds number in the range of (5.3E6 to 11.5E6 for pipe diameter 711.2 mm) and in the range of (6.1E6 to 9.1E6 for pipe diameter 406.4 mm).

The newly developed equations can be used in the design of natural gas pipelines for predicting the pressure drop in the Reynolds number range specified that will allow the appropriate choice of the correct pipeline diameter for a given length.

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