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RESEARCH NOTE

Steady Flow Analysis and Modeling of the Gas Distribution Network using the Electrical Analogy

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ABSTRACT

The mathematical modeling of a gas network is a powerful tool for identifying the behavior of system under different conditions. The modeling can be performed both for the steady state and unsteady state conditions. It is possible to use the fluid flow basic governing equations or the electrical analogy concept for developing the model. The second approach provides a simpler and more robust model, especially in large networks with different and numerous components. In this study, this approach has been used for studying the steady state behavior of a sample gas distribution network. The model is verified by comparing its results with some existing experimental and numerical data. The comparison shows a very good agreement between the two results.

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NOMENCLATURE

D	pipe diameter (m)
E	potential energy term, (Pa^2)
E'	constant electric potential source (Pressure drop due to potential energy effects) (Pa)
f	Darcy friction factor, dimensionless
G	gas specific gravity, dimensionless
g	gravitational acceleration (m/s^2)
H	height of points 1 and 2 (m)
I	electrical element current (standard gas volumetric flow rate of pipe element)(m^3/s)
L	pipe Length (m)
M	molecular weight (kg/kmol)
P	absolute pressure (Pa)
P_1	absolute pressure at pipe entrance (Pa)
P_2	absolute pressure at pipe exit (Pa)
P_{avg}	flow average pressure (Pa)
P_{st}	standard pressure 1.01325×10^5 (Pa)
Q_{st}	volumetric gas flow rate at standard conditions (m^3/s)
R	electrical pipe resistance (Pa.s.m^{-3})
$\overline{R}$	universal gas constant 8314.41 (J/kmol.K)
Re	Reynolds number, dimensionless

T	absolute gas temperature (K)
T_{avg}	flow average temperature (K)
T_{st}	standard temperature, 288.15 (K)
V	electric potential difference of element (total pressure drop) (Pa)
z_{avg}	gas compressibility factor, dimensionless
z_{st}	compressibility factor at standard conditions, $z_{st} \approx 1$

Greek Symbols

ΔP	pressure drop due to gas flow (Pa)
ε	surface roughness (m)
η	efficiency factor, dimensionless
μ	gas dynamic viscosity (Pa.s)
ρ	gas density (kg/m^3)

Subscripts

air	Air
avg	Average
cr	Critical
st	at standard pressure and temperature
1	relative to the generic point 1
2	relative to the generic point 2

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1. INTRODUCTION

Due to the increasing need for energy, especially energy produced by natural gas, distribution systems and related processes are becoming more complex. Mathematical modeling is one of the most important tools in the design and control of gas pipeline distribution systems. Simulation allows us to predict the behavior of gas network systems under different conditions. Such predictions can then be used to guide decisions regarding the design and operation of the real system.

For modeling flow in pipelines, two types of steady and unsteady flow can be considered. Steady state flow refers to the condition where the gas properties at a point in the system do not change over time; otherwise, flow is unsteady. However, most of the time, the network is in an unsteady flow regime because of imposed changes to the gas network, but the attitude of steady analysis, for simplicity of analysis and the beneficial results, still is faced with widespread acceptance and a lot of investigators are using it.

Rios-Mercado et al. [1] presented a reduction technique for solving natural gas transmission network optimization problems. Their results are valid for steady-state compressible flow through a network pipeline. Abdolahi et al. [2] analyzed steady state flow over pipeline analytically and numerically and they used their developed numerical approach to evaluate the influence of model parameters such as pipe roughness, soil thermal conductivity and velocity profile correction factor on pipeline pressure and temperature profiles. Cheboubaa et al. [3] proposed an ant colony optimization (ACO) algorithm for operations of steady flow gas pipeline. Chaczykowski et al. [4] used nonisothermal, steady state gas flow model with exergy-based analysis for modeling and comparing the performance of the gas transmission system under different cooler operating set points. Woldeyohannes and Abd Majid [5] developed a simulation model for the steady state analysis of transmission pipeline network system (TPNS) with detailed characteristics of compressor stations. Brikic [6] solved a looped gas pipeline network according to principles of Hardy Cross method for determination of appropriate friction factor and selection of a representative equation for natural gas flow.

Furthermore, in some other works, steady state analysis is used in natural gas network for other purpose, for example for leak detection [7], network optimization [8-10], and even transient modeling using quasi-steady state approximation which all the transient variables just act on the boundary conditions [11]. The objective of this study is to model steady flow through a gas pipeline, which is the predominant component of natural gas transmission and distribution networks, with electrical analogy approach. In such conditions for compressible real gas flow, modeling pipeline distribution network by implementing analogy between fluid behaviour and electrical elements, very little work has been done; and we have also done it by several pipeline resistance models. Using the electrical analogy by applying the simple changes in the flow equation, natural gas network simulates in the form of the electrical circuit which leads the simplicity and rapidity, especially in distribution networks with high intricacy and a lot of components in modeling gas transmission and distribution networks.

2. ELECTRICAL ANALOGY

The main goal to simulate gas pipeline as the most effective dynamic component of natural gas transmission and distribution networks is to illuminate and predict flow rate and pressure distribution along the pipe. Pressure as the driving factor of gas flow, in electrical analogy approach is to be considered as electric potential which is the factor of electricity transformation. Clearly, the gas flow is also in similarity with electrical current. A simple element of pipe as electric element which the flow rate and pressure values are stored in the beginning and the end is considered. In order to create a physical association between the electric potential difference (pressure drop) and the electrical current through this element (flow rate), a model that represents the physics of gas transmission through the pipeline should be provided. Accordingly in the following sections, to introduce appropriate electrical element model, steady flow of gas in pipeline is analyzed.

3. GOVERNING EQUATION FOR STEADY FLOW IN GAS PIPELINES

3. 1. Flow Regime

At first, before discussing the equations, since final form of equations will vary with the type of flow regime, it is important to know about natural gas flow regime. Considering the definition of the Reynolds number, the relation between the gas average velocity and its volume flow rate, and knowing that $r Q = r_{st} Q_{st} = \dot{m}$ for steady state conditions:

$$\mathrm{Re} = \frac{4 r_{st} Q_{st}}{m p D} \tag{1}$$

As, $r_{st} = M P_{st} / (z_{st} \bar{R} T_{st})$ where $z_{st} \approx 1$ and $M = M_{air} \times G \approx 29 G$:

$$\mathrm{Re} = \frac{4 Q_{st} 29 G P_{st}}{m p D \bar{R} T_{st}} \tag{2}$$

Knowing the constants $\bar{R}$, T_{st} and P_{st} and by assuming a gas dynamic viscosity of 1.0758×10^{-5} Pa.s as typical value for natural gas [12], the Reynolds number equation can be further simplified:

$$\mathrm{Re} = \frac{4\,Q_{st}\,29\,G\,P_{st}}{m\,p\,D\,\bar{R}\,T_{st}} \tag{3}$$

As known, for Re smaller than 2100 the flow is laminar, whereas for Re above 2100 the flow is considered turbulent. For typical transmission lines with high pressure gas and moderate to high gas flow rates, one of the two following situations is usually observed:

- Fully turbulent flow (rough pipe flow)
- Partially turbulent flow (smooth pipe flow)

According to the definition for critical Reynolds number (Re_{cr}), the Reynolds at which value there is an abrupt change from turbulent flow in smooth pipes towards turbulent flow in rough pipes, Equation (4) is presented which shows the border between these two flow regimes:

$$\mathrm{Re}_{cr} = 35.235(e\ /\ D)^{-1.1039} \tag{4}$$

Based on previous studies [13], in most of the pipes used in gas transmission industry like steel pipes, critical Reynolds is below the operational Reynolds. In fact, under typical operating conditions, the pipe gas flow is in fully turbulent regime. Only in pipes with low surface roughness like copper and polyethylene pipes with absolute roughness of about 0.0191 mm, the flow can be partially turbulent.

3. 2. General Steady Flow Governing Equation

Considering the momentum equation applied to a portion of pipe of length dx inside which flows a compressible fluid with an average velocity u (for example natural gas), assuming steady state conditions, the resultant differential equation is:

$$u\,du + \frac{dP}{r} + g\,dH + f\,\frac{dx}{D}\frac{u^2}{2} = 0 \tag{5}$$

Equation (5) consists of four parts of kinetic energy term, pressure force work term, potential energy term and energy dissipation by viscous friction. After the integration of each one of the terms, the steady flow equation in pipeline is obtained as follows ([13, 14]):

$$Q_{st} = 13.2986\,\frac{T_{st}}{P_{st}}\left[\frac{\left(P_1^2-P_2^2\right)-E}{L\,G\,T_{avg}\,z_{avg}}\right]^{1/2}\frac{D^{2.5}}{\sqrt{f}}\,h \tag{6}$$

where E that represents the potential energy effects is determined as:

$$E = 0.06843\,G\left(H_2 - H_1\right)\frac{P_{avg}^2}{T_{avg}\,z_{avg}} \tag{7}$$

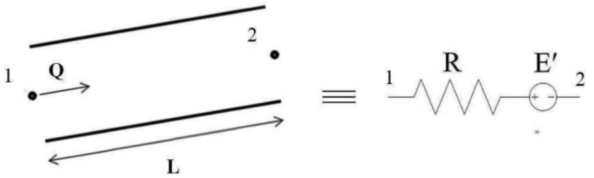

Figure 1. Analogy of pipe element with electrical element in steady state flow.

According to [15], the real gas flow in a pipe is inferior to that calculated by means of the flow equation, namely Equation (6) when $\eta = 1$, because of additional friction imposed by fittings like bends, tees, valves and also by other effects like corrosion, fouling and dust/rust deposition. To account for such extra flow reductions in a simple and effective way, it is a common practice to use a corrective multiplying factor, the efficiency factor η, which usually takes values between 0.8 and 1. Mohitpour et al. [12] suggest η values between 0.92 and 0.97, although experience recommends that for old piping it can be as low as 0.7 [15].

4. RESISTANCE AND CONSTANT ELECTRIC POTENTIAL SOURCE MODEL

In steady flow, an element of pipe with length L is simulated with electrical resistance and the constant electric potential source. The electric element of pipe is as Figure 1. R that is shown in Fig. 1 is an electrical resistance which represents the resistance of flow in gas transmission and E' is a constant electric potential source which imports effects of pipe element inclination (potential energy) into the electrical analogy. Specifically, in the horizontal pipe the E' should be zero. Now, by deriving appropriate values for R and E', a pipeline element can be simulated with an electrical element; thus, a natural gas distribution network which consists of several loops and branches is modeled by solving an electrical circuit.

In electrical circuits, the relationship between resistance, pressure drop and flow rate are governed by the Ohm's law which can be represented by:

$$V = R\,I \tag{8}$$

With the electrical analogy presented based on resistance model, the physical properties of flow have relationships with described electrical characteristics as:

$$V = \Delta P - E' = P_1 - P_2 - E' \tag{9}$$

$$I = Q_{st} \tag{10}$$

$$V = \Delta P = P_1 - P_2 \text{ (for horizontal pipe)} \tag{11}$$

To derive R and E', governing equation on steady state flow is used. From Equation (6) we have:

$$Q_{st}^{\ 2} = (13.2986h\,\frac{T_{st}}{P_{st}})^2 \left(\frac{\left(P_1^2 - P_2^2\right) - E}{L\,G\,T_{avg}\ z_{avg}}\right)\frac{D^5}{f} \tag{12}$$

Then:

$$P_1^{\ 2} - P_2^{\ 2} - E = \frac{L\,G\,T_{avg}\ z_{avg}}{\left(13.2986h\,\frac{T_{st}}{P_{st}}\right)^2}\frac{f}{D^5}Q_{st}^{\ 2} \tag{13}$$

And finally, Equation (6) is reformed as new style:

$$P_1 - P_2 - \frac{E}{P_1+P_2} = \left[5.65442\times10^{-3}(\frac{P_{st}}{T_{st}})^2 \frac{L\,G\,T_{avg}\ z_{avg}\ f\,Q_{st}}{h^2\,(P_1+P_2)\,D^5}\right]Q_{st} \tag{14}$$

With the similarity between Equations (8), (9), (10) and (14), resistance and constant electric potential source of pipe element can be concluded as:

$$R = 5.65442\times10^{-3}(\frac{P_{st}}{T_{st}})^2 \times \frac{LGT_{avg}z_{avg}f\,Q_{st}}{h^2(P_1+P_2)D^5} \tag{15}$$

$$E' = \frac{E}{P_1+P_2} \tag{16}$$

where E, depending on the height of the upstream and downstream of the pipe element, is obtained from Equation (7). With Equation (15) as it was predictable, resistance estimation of pipe is directly proportional to friction factor coefficient f. Since in application of gas transmission, flow regime is often fully turbulent, here we present several prevalent equations in the fully turbulent flow regime to estimate Darcy friction factor [13] and thus we have several resistance models as:

$$R_{Panhandle\ B} = 6.452892\times\frac{LG^{0.9608}\,T_{avg}\,z_{avg}\,Q_{st}^{\ 0.9608}}{h^2(P_1+P_2)D^{4.9608}} \tag{17}$$

$$R_{Weymouth} = 6.565358\times\frac{L\,G\,T_{avg}\ z_{avg}\ Q_{st}}{h^2\left(P_1+P_2\right)D^{16/3}} \tag{18}$$

$$R_{AGA\ Fully\ Turbulent} = 699.172165\times\frac{L\,G\,T_{avg}\ z_{avg}\ Q_{st}}{h^2\left(P_1+P_2\right)D^5} \times\left[-2\ \log_{10}\left(\frac{e/D}{3.7}\right)\right]^{-2} \tag{19}$$

$$R_{Modified\ Colebrook-White} = 699.172165\times\frac{L\,G\,T_{avg}\ z_{avg}\ Q_{st}}{h^2\left(P_1+P_2\right)D^5} \times\left[-2\ \log_{10}\left(\frac{e/D}{3.7}+\frac{2.825}{Re\sqrt{f}}\right)\right]^{-2} \tag{20}$$

$$R_{Gersten\ et\ al.} = 699.172165\times\frac{L\,G\,T_{avg}\ z_{avg}\ Q_{st}}{h^2\left(P_1+P_2\right)D^5} \times\left\{-\frac{2}{n}\log_{10}\left[\left(\frac{e/D}{3.71}\right)^n+\left(\frac{1.499}{t\,Re\sqrt{f}}\right)^{0.942.n.t}\right]\right\}^{-2} \tag{21}$$

where ε is pipe roughness (m) and is effective in last three equations. The parameter t in Equation (21) is equivalent to the efficiency factor η present in Equation (6) and similarly, it is equal to unity in the absence of localized pressure drops. Furthermore, experimental natural gas data shows for Gersten et al. friction factor that physics is well described for $n = 10$.

5. RESULTS AND DISCUSSION

In this section in order to verify the accuracy and efficiency of the proposed electrical analogy approach, two case studies with practical and experimental data are analyzed.

5. 1. Case Study 1: BHP Prediction

Considering Prediction of Bottom hole pressure (BHP) can be done by steady state flow analysis. In practice, because the depth profile measurements of gas wells have its own problems and complexities, surface gas properties (pressure and temperature at the well surface) is used to estimate BHP by flow analysis. Tables 1-4 show the comparisons among prediction of BHPs in gas wells by the present authors, field data and Zhou and Adewumi [17] results. Zhou and Adewumi derived an algebraic analytical equation from the steady state continuity and momentum equations, without neglecting any terms in the momentum equation and predicted BHPs using the Newton-Raphson method. In this study, a pipeline is divided into 50 segments (50 electrical elements). At first, the whole well is assumed at constant pressure. Knowing the gas flow rate, the height difference of two sides of element and pressures, the constant electric potential source is calculated from Equation (16) and electrical resistance from one of the Equations (17) to (21) for each pipe element. To obtain the electric potential sources and resistances in a network, we will be facing a simple circuit problem which is solved by Equations (8), (9) and (10). The new pressure distribution can be used as initial pressure guess for the next iteration until the pressure distribution becomes changeless. In addition, results take place for different resistance models.

As can be seen, in some of the presented resistance models, relative roughness (ε / D) must be considered since it has an impressive impact on estimations. According to the majority of measurements from wells flow, the regime reported in transient region is between partially and fully turbulent flow. On this basis in present work, relative roughness is evaluated from Equation (4) which leads to the flow in the mentioned region. Also, in order to be closer to the physical reality, the efficiency factor of 0.95 is used. The temperature used in the present calculation (isothermal consideration) is the average of the reservoir and surface temperatures.

As seen in Tables 1 and 2, the deviation of all models (except Weymouth RM) from the real value is acceptable and insignificant. Generally, Weymouth equation overestimates the friction coefficient and this overestimation is more obvious when the pipe diameter is small- like the case here (2.441 in). This is why the noticeable difference can be seen between Weymouth RM results and others while this equation is very common in many industrial applications with higher diameters. As can be seen in the results in Tables 1 and 2, Modified Colebrook-White RM has the best prediction for reservoir pressure. Thus in Tables 3 and 4, only this model is used to propone the results.

TABLE 1. Comparison of measured and predicted BHP

	BHP (kPa)	**Deviation %**
Actual	22721.5935	-------
Zhou	22657.4724	-0.28
Weymouth Resistance Model	24483.3781	7.75
Panhandle B Resistance Model	22255.0381	-2.05
AGA Fully Turbulent Resistance Model	22379.9043	-1.50
Mod. Colebrook-White Resistance Model	22547.7229	-0.77
Gersten et al. Resistance Model	22379.2835	-1.51

Well operator: Amoco Canada Co. Ltd.; Field: Bigstone; well: Pan American HB,C-1; tubing ID: 2.992 in.; reservoir temperature: 243˚F; surface temperature: 155˚F; gas specific gravity: 0.702; pseudocritical pressure: 798.3 psia; well depth: 10,965 ft.; pseudocritical temperature: 409.5˚R; q: 15.606 MMscf/D(*); outlet pressure: 2314.5 psia;

(*)Million Standard Cubic Foot per Day

TABLE 2. Comparison of measured and predicted BHP

	BHP (kPa)	**Deviation %**
Actual	25444.3236	-------
Zhou	25431.9131	-0.05
Weymouth Resistance Model	27383.5977	7.62
Panhandle B Resistance Model	24851.9098	-2.33
AGA Fully Turbulent Resistance Model	24975.3528	-1.84
Mod. Colebrook-White Resistance Model	25160.0423	-1.12
Gersten et al. Resistance Model	24974.6661	-1.85

Well operator: Amoco Canada Co. Ltd.; Field: Bigstone; well: Pan American HB, G-2; tubing ID: 2.992 in.; reservoir temperature: 243˚F; surface temperature: 170˚F; gas specific gravity: 0.702; pseudocritical pressure: 798.3 psia; well depth: 11,029 ft.; pseudocritical temperature: 409.5˚R; q: 17.359 MMscf/D; outlet pressure: 2599.5 psia;

TABLE 3. Comparison of measured and predicted BHP

Q (scm/s$^{(*)}$)	**Outlet Pres . (kPa)**	**Surface Temp. (K)**	**Actual BHP (kPa)**	**Zhou BHP (kPa)**	**Zhou Deviation %**	**Calculated BHP (kPa)**	**Calculated Deviation %**
2.1392	22403.75	328.71	29299.86	29548.07	0.85	29347.17	0.16
3.1457	21845.27	333.15	28997.87	29059.23	0.21	28902.88	-0.33
3.9486	21224.75	340.37	28704.15	28489.03	-0.75	28377.29	-1.14
4.6792	20618.01	343.15	28428.36	28065.01	-1.28	27960.26	-1.65

Well operator: Amoco Canada Co. Ltd.; Field: Bigstone; well: Pan American HB, G-2; tubing ID: 2.992 in.; reservoir temperature: 243˚F; gas specific gravity: 0.6997; pseudocritical pressure: 801.2 psia; pseudocritical temperature: 410.9˚R; well depth: 11,029 ft;.

(*)Standard Cubic Meter per Second

TABLE 4. Comparison of measured and predicted BHP

Q (scm/s)	Outlet Pres. (kPa)	Surface Temp. (K)	Actual BHP (kPa)	Zhou BHP (kPa)	Zhou Deviation %	Calculated BHP (kPa)	Calculated Deviation %
0.2730	11445.26	281.48	13297.87	13137.22	-1.21	13205.54	-0.69
0.5264	10797.15	284.82	12468.43	12398.80	-0.56	12451.51	-0.14
0.7164	10155.94	287.04	11733.46	11690.71	-0.36	11719.39	-0.12
0.9537	9376.84	287.59	10807.49	10877.82	0.65	10863.87	0.52

Well operator: Anderson Exploration Ltd.; Field: Dunvegan; well: Dunvegan 6-29; tubing ID: 2.441 in.; reservoir temperature: 115°F; gas specific gravity: 0.6402; pseudocritical pressure: 669.9 psia; pseudocritical temperature: 367.2°R; well depth: 4753 ft.;

TABLE 5. Pipe data of the sample network

Pipe	From	To	Diameter(m)	Length(km)
1	1	3	0.6	80
2	1	2	0.6	90
3	2	3	0.6	100

$r = 0.7165 kg / m^3; G = 0.6; T = 278 K.$

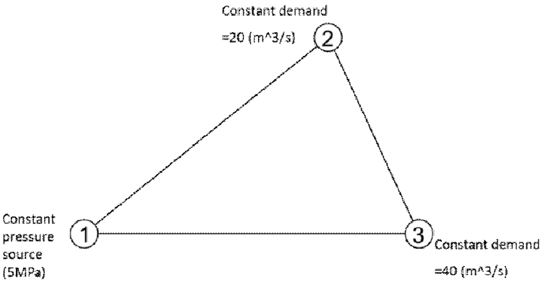

Figure 2. Sample network (case study 2).

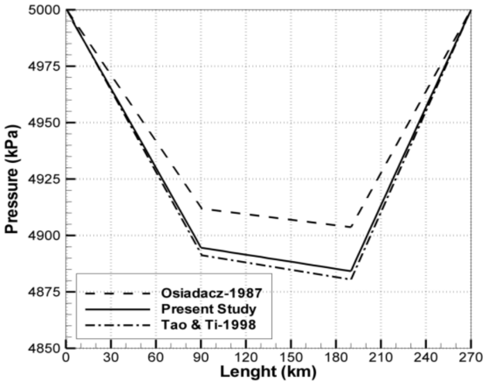

Figure 3. Pressure distribution in the direction of 1231.

5. 2. Case Study 2: A Sample Loop Steady Analysis

In this case, a sample network (Figure 2 and Table 5) which has been studied by Osiadacz [15], Tao and Ti [18] and Behbahani-Nejad and Bagheri [19] is considered and simulated with the presented approach considering isothermal condition without knowing pipelines flow rate. By dividing a pipeline into a number of electrical elements like Figure 1 until the pressure distribution becomes independent of the number of elements, we can assume the network as a circuit and solve it. In the sample network shown in Figure 2, node 1 is the pressure source with a constant pressure of 5 MPa. Furthermore, at nodes 2 and 3, constant standard volumetric flow rate (flow rate at standard pressure and temperature) of 20 and 40 (m^3/s) are leaving from network, respectively. Here like an electrical circuit, a clockwise current for loop is considered and by writing KVL and KCL in circuit, electric potential distribution or pressure distribution and the value of flow rate in pipelines can be obtained.

To provide the comparison with results of other researchers ([15, 18]), Weymouth RM is used. Since they analyzed this sample network at unsteady state conditions, their steady state results which is the pressure of their initial conditions, are used here. Figure 3 compares the pressure distribution of presented approach with some other works in the direction of 1231 at sample network of Figure 2. Analyzing the pressure values at maximum point of differences (nodes 2 and 3) indicates the deviation of less than 1 percent.

6. CONCLUSION

With increasing natural gas consumers and consequently growing gas networks, a simple and comprehensively accurate model to represent the gas pipeline networks behavior is inevitable. In this study, steady flow analysis of natural gas network pipeline has been simulated using electrical analogy to have simpler modeling procedure in solving complex distribution networks. To achieve this goal, the similarity between pipeline and an electrical element has been established. By applying some simple change in the form of steady flow equation, which is obtained from momentum equation, appropriate relationships for describing electrical resistance and constant electric potential source of electrical element have been derived.

Two case studies have been analyzed to see the effects of the algorithm procedure and electrical resistance models. The first case study (BHP prediction) which contains analysis of four wells under totally 10 different conditions, shows the overestimation of Weymouth RM in small pipe diameters and also Modified Colebrook-White RM powerful predictions with deviations of under 2 percent from field data. The second case study which is a classical common case in this field, shows the simplicity of proposed approach in solving a loop by means of simple electrical circuit's rules. Comparing the results with experimental data, and also with other researcher's classic works, shows the acceptable agreement.

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Electrical Element Pipe
Line Resistance Model

چکیده

مدل‌سازی ریاضی شبکه گاز ابزاری قدرتمند به منظور شناخت رفتار سیستم در شرایط مختلف می‌باشد. این مدل‌سازی می تواند در دو حالت پایا و ناپایا انجام پذیرد. به منظور توسعه مدل مناسب، می‌توان از معادلات پایه حاکم بر جریان سیال و یا از مفهوم تشابه الکتریکی استفاده نمود. دیدگاه دوم در مدل‌سازی شرایط به‌مراتب ساده‌تری را به خصوص در مواجهه با شبکه های بزرگ با اجزاء فراوان فراهم می‌کند. در این مقاله، مدل‌سازی رفتار پایای شبکه توزیع گاز با استفاده از نگرش تشابه الکتریکی صورت گرفته است. همچنین، نتایج این مدل‌سازی با نتایج برخی کارهای موجود تجربی و عددی مقایسه شده است. مقایسه صورت گرفته توافق خوبی را بین نتایج نشان می‌دهد

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