Journal of Scientific Research & Reports

26(6): 76-88, 2020; Article no.JSRR.58790
ISSN: 2320-0227

A New Analytical Model for Predicting Natural Gas Transportation Compressor Power

V. J. Aimikhe[1*] and N. E. Ezendiokwere[1]

[1]Department of Petroleum and Gas Engineering, University of Port Harcourt, Nigeria.

Authors' contributions

This work was carried out in collaboration between both authors. Author VJA designed the study, managed the analyses of the study, wrote the protocol and wrote the final draft of the manuscript. Author NEE managed the literature searches, wrote the first draft of the study and the analyses of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2020/v26i630273
Editor(s):
(1) Dr. Prinya Chindaprasirt, Professor, Khon Kaen University, Thailand.
Reviewers:
(1) Ranjan Kumar Behera, Veer Surendra Sai University of Technology, India.
(2) Navdha Natvarlal Soni, Gujarat Technological University, India.
Complete Peer review History: http://www.sdiarticle4.com/review-history/58790

Original Research Article

Received 01 May 2020
Accepted 07 July 2020
Published 20 July 2020

ABSTRACT

The compressor power requirement for gas pipelines is critical to the efficient delivery of natural gas over long distances. Existing models for predicting compressor power using pipeline length and gas throughput as input parameters are limited. This study focused on developing a new analytical model using the general energy equation to capture better interrelationships between compressor power and other parameters affecting compressor power requirements of horizontal natural gas pipelines. The developed model was validated using Bryan Research and Engineering (BRE) ProMax 2.0 process simulation software. The results indicated that the developed model was reliably consistent and accurate when compared with ProMax results. In other to improve the efficiency of the developed model, correction factors for both pipe length and gas throughput were developed. The percentage average absolute deviation (% AAD) was 4.37 for the fixed pipe length with variable throughput and 0.68 for the fixed throughput with variable length, scenarios.

Keywords: Natural gas compression; compressor power; gas pipeline; gas transportation.

**Corresponding author: E-mail: victor.aimikhe@uniport.edu.ng;*

1. INTRODUCTION

Natural gas is usually found in vast deposits in reservoirs around the world, mainly as associated, non-associated gas or unconventional sources like Coal Bed Methane, Shale Gas, and Tight gas. In its natural form, natural gas is barely useful. It has to be processed into various forms like liquefied petroleum gas (LPG), liquefied natural gas (LNG), pipeline gas, compressed natural gas (CNG), and transported to potential customers safely. The transportation of the processed gas is usually by pipelines and specialized containments or vessels (LNG, CNG and LPG).

The global population growth accompanied by a corresponding increase in demand for sustainable energy, environmental benefits, and the quest for energy security, has led to the growth in demand for natural gas, compared to other fossil fuels. The global market for natural gas is expected to grow at a rate of 1.6% year on year, with consumption projected to reach 150 Trillion Cubic Feet (TCF) by 2025, up from 136 TCF in the year 2018. This growth is expected to be more prominent in the Asia- Pacific region, especially in China and India, which has been projected to experience a rapid economic development increasing the total gas pipelines in these countries, to 123 000 km and 28,000 km, respectively by 2025 [1]. Due to the demand for natural gas, there has been an increase in the total length of pipelines dedicated to natural gas transmission and distribution. In 2019, gas pipelines accounted for 64% of the global length of pipelines with North America and the Former Soviet Union, accounting for 38% and 23% of total global gas pipelines, respectively. Fig. 1 shows the entire length of gas, crude oil, petroleum products, and natural gas liquids pipelines globally [2].

According to Statista, 2016 [3], Africa and the Middle East had the least length of gas pipelines of about 41,000 km each. Fig. 2 shows the total gas pipeline by Country in Africa. As more nations adopt natural gas as a feasible alternative to other fossil fuels, the demand for natural gas will result in the expansion of the total length of gas pipelines. Therefore, the increasing demand for natural gas will, in no doubt, result in the expansion of gas pipeline infrastructure.

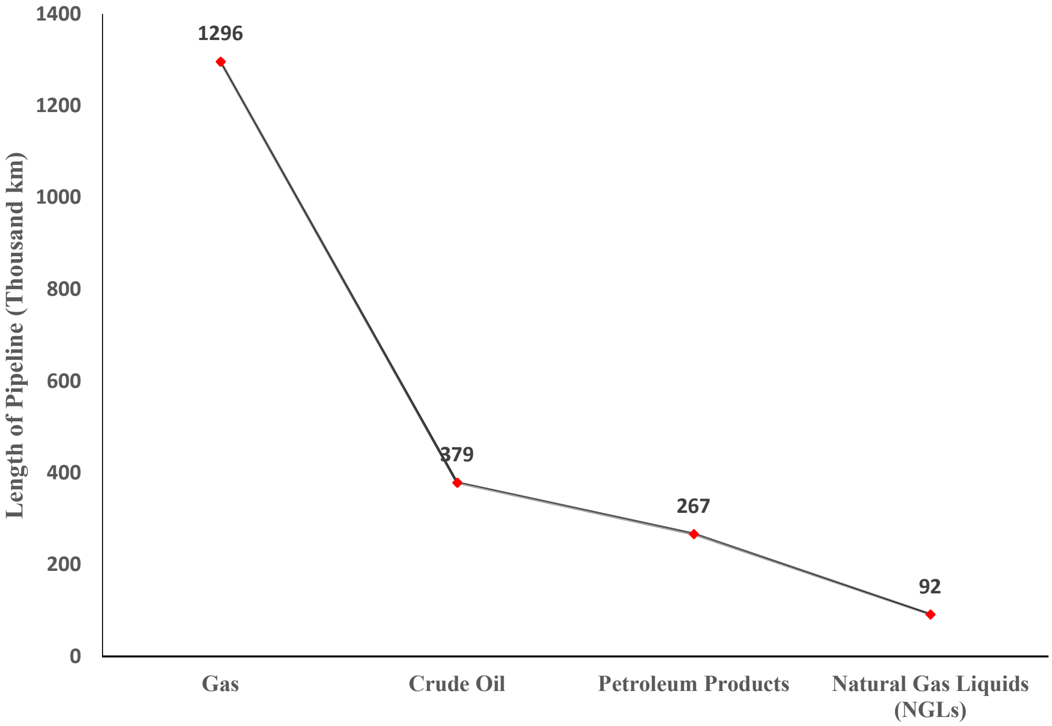

Fig. 1. Global pipeline length by commodity [2]

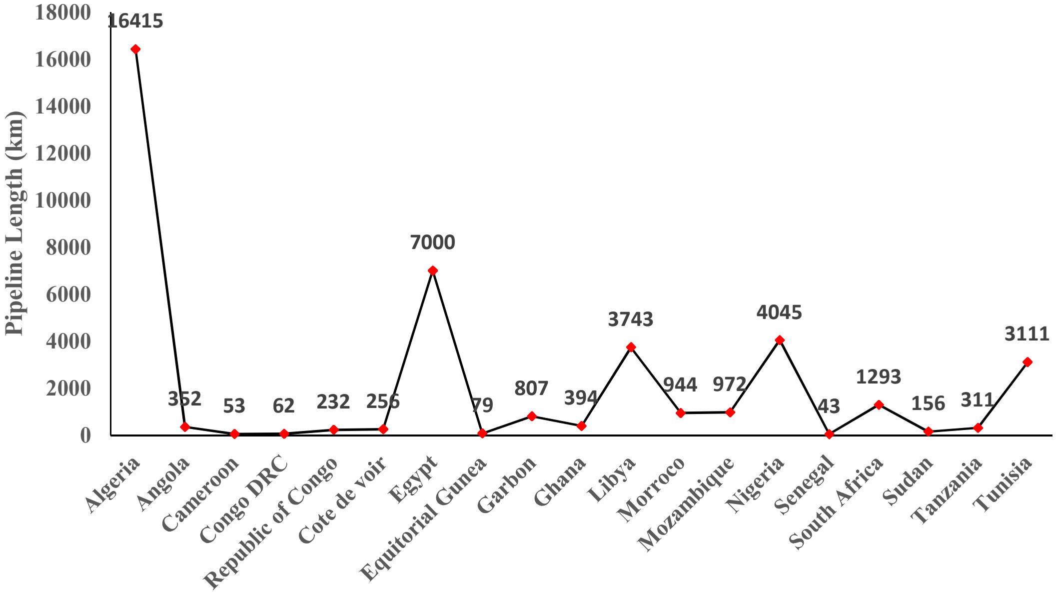

Fig. 2. Total length of gas pipelines by country in Africa [4]

1.1 Natural Gas Pipeline Transportation

Gas transportation is usually a critical task requiring specialized transportation systems. Different transport solutions are suitable for various conditions. However, pipeline gas is typically the transport system of choice for over relatively long distances, so long as the economics is favorable. Pipelines are usually a network of pipes that can be categorized as;

- Gathering systems, which are no more than 18 inches in diameter and about 700 psi, working pressure.
- Transmission systems, which are about 3 to 48 inches in diameter and 200 to 1500 psi, working pressure.
- Distribution systems, which are about 2 to 20 inches in diameter and 0.5 to 200 psi, working pressures [5].

The main differences between these categories of pipelines are the physical properties of the pipes used, such as diameter, stiffness, material, etc., and the maximum and minimum upstream and downstream operating pressures. Pipelines are usually buried underground, with a standard depth requirement of 2 to 4 feet to top of the pipe [6]. They are mostly installed by either the open trench method or the horizontal directional drilling technique (HDD), which allows the pipelines to traverse urban settlements, rivers and road crossings, without disturbing the physical environment. Gathering systems help to aggregate untreated gas from different wellheads for processing. Transmission systems take the processed gas from process plants to customers over long distances. In contrast, distribution systems bring gas to the doorsteps of customers like households, power plants and other end-users.

In most cases, one can determine whether a pipeline is inter- or intrastate by finding out if it transcends the borders of a single state. If it leaves the state, it should be interstate; if it stays within one state, it should be intrastate. This definition of inter and Intra- State pipeline, is usually subject to pipeline ownership jurisdiction and fiscal policies. At the point of distribution, various layout optimization models like the Graph theory, Dynamic programming, Neural Network Method, Genetic Algorithm, Complex method [7,8]. Minimum Spanning Tree Method, and the Dominance Degree Model Technique [9], are used to select the best gas pipeline layout, based on pipeline network topography and several other considerations. The advantages and disadvantages of the various pipeline layout optimization models have been well documented in the literature [9]. Fig. 3 shows a typical gas pipeline transportation system from production to consumption.

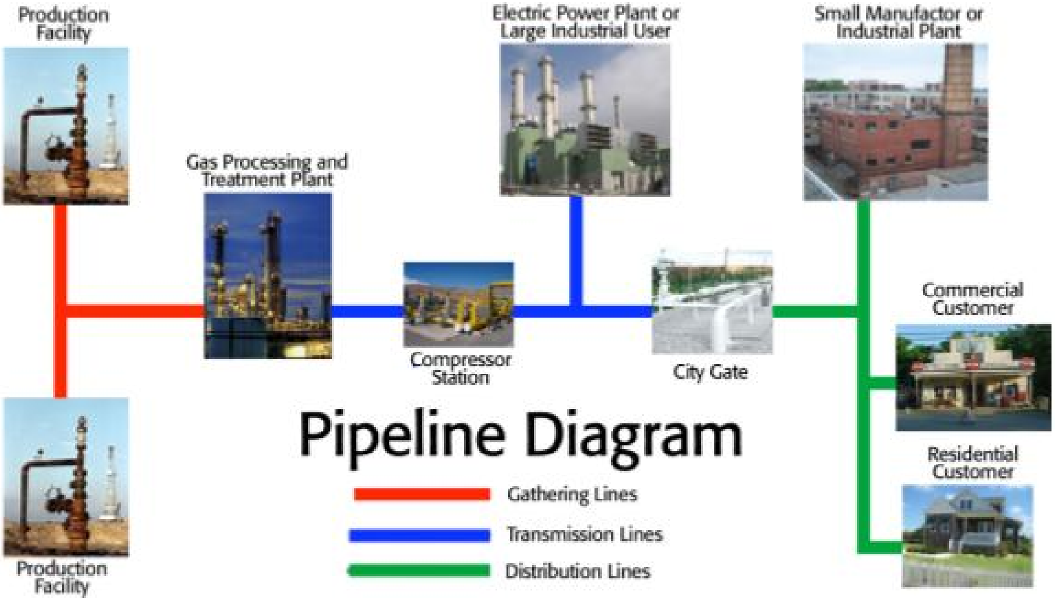

Fig. 3. Gas pipeline transportation system [10]

1.2 Natural Gas Compression

Gas transportation requires much energy, mainly in the form of pressure energy. This high amount of energy is because, as natural gas flows through both gas gathering and processing plant equipment and pipelines, its pressure decreases. A critical component of the gas transportation value chain is gas compression. A compressor is a device used to increase the pressure of natural gas by reducing its volume, thus providing the required force or energy to move the gas over long distances in the pipeline. They are placed or installed along the gas pipeline for the provision of sufficient energy to natural gas for its transmission [5]. Therefore, compression of the gas is required to augment the pressure energy within a pipeline system to ensure natural gas gets to its destination. For gas transmission lines, compression stations are strategically placed at 40-100 miles intervals along the lines to compensate for lost energy in the system and maintain pipeline pressures. Compressor stations consist of large-scale compressors, whose primary work is to compress or increase gas pressure to some specific ratio, relative to suction pressures. The energy needed for compression is usually provided by an electric motor, internal combustion, or a turbine engine [5]. There are five types of compressor stations [11]. The specific functions of these stations have been reported in the literature. Fig. 4 shows the various types of compressor stations. In cases where the gas pressure is sufficient enough to deliver the gas to its destination, gas compressors may not be required. This is usually the case for high-pressure gas wells.

Transporting natural gas is energy-intensive, and energy is expensive. The operating costs of Compression stations could range from 25-50% of the pipeline operating budget [12]. Hence, the objective of a transmission network is to minimize compression stations operating costs to the lowest value possible and simultaneously satisfy agreed delivery flow rates and minimum pressure requirements at delivery terminals. Common types of compressors used in the natural gas industry are the Centrifugal and Reciprocating compressors. Fig. 5 shows the various kinds of industrial gas compressors.

1.3 Compressor Power Determination

The ability to size and predict the compressor horsepower requirements for gas transportation is useful to pipeline design engineers. Various models have been developed over the years for estimating the compressor power required for transporting natural gas to desired destinations. Analytical models are commonly used to calculate the horsepower for each compression stage from the isentropic work formula. The basis of the derivation of all analytical expressions for calculating theoretical work required to compress a quantity of gas is the general energy equation [11]. In developing these models, some assumptions are usually made to make the models mathematically tractable. These models require parameters like the isentropic factor, which is either read from charts or outrightly assumed to be 1.28. Most of these models form the basis of some commercial software used for this purpose. The Enthalpy- Entropy chart is also used to calculate compressor power, based on isentropic compression and isobaric cooling.

Most models that describe gas compression in literature are mainly optimization models developed using operations research. They were usually designed to address the minimum fuel cost problem of compression stations in gas transmission systems. In developing these models, steady-state flow is typically assumed. Objective functions are then solved using different computer algorithms, but subject to some physical constraints, one of which is a gas compression analytical equation. Some of the algorithms include linearization computer programs, generalized reduced gradient (GRG), dynamic programming, and mixed-integer linear programming.

Krishnaswami et al. [14] studied compression stations, fuel consumption minimization for several compressor units in gas compressor stations using optimization methods. Still, their study investigated the line-packing phenomenon during seasons of low gas demand. They presented an approach for using gas compression stations to meet specific line-pack profile with excellent results.

Chebouba et al. [15] presented an ant colony optimization (ACO) algorithm for solving the issue of reduction in fuel cost with different numbers of compressor units in a compressor station. They validated their method with the Hassi R'Mel-Arzew pipeline network in Algeria consisting of 5 pipes, six nodes, five compressor stations, and three units in each compressor.

Jin and Wojtanowocz [16] presented a study that looked at optimizing an extensive network in China. The results obtained showed that increasing gas throughput substantially reduced costs.

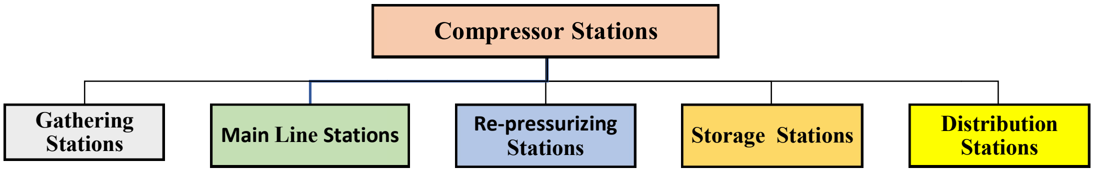

Fig. 4. Types of compressor stations

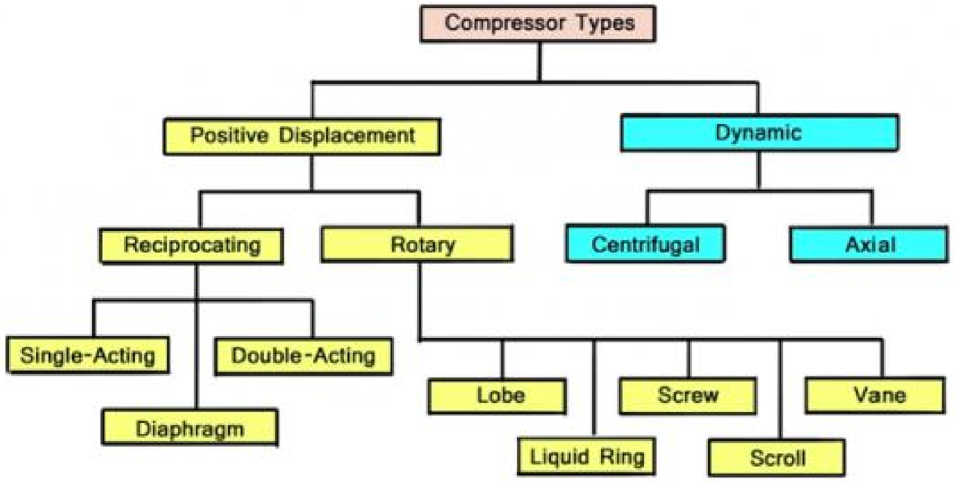

Fig. 5. Types of industrial gas compressors [13]

Wu et al. [17] presented a hybrid model with compressor toggling constraints that aimed at increasing revenue plus throughput, at the same time putting into consideration a weighting value to cater for two optimization problems. The model's solution was gotten by employing a particle swarm optimization (PSO) algorithm that includes a responsive inertia weight adjusting procedure to overcome premature convergence issues.

Agwu et al. [18] studied reducing fuel costs at gas compressor stations. As case studies, they considered two 24-inch natural gas lines in Nigeria: 198-km long Oben-Ajaokuta and 460-km long Ajaokuta-Abuja-Kaduna lines. They presented a simple relationship between total compressor power requirements and the entire length of a gas pipeline while considering local operating conditions.

Ezendiokwere et al. [19] studied natural gas transmission lines of varying lengths using commercial software. They were able to establish strong relationships between compressor power requirements and variables like pipeline pressure drop, length, gas throughput, and compression station suction pressure.

Analytical models for estimating compressor power using variables like pipeline length and gas throughput are very limited in the literature. Where they exist, the knowledge of the pipeline length and gas throughput is unknown. In this study, an analytical model for predicting compressor power requirements of horizontal gas transmission lines that do not require an isentropic factor is presented.

2. MATERIALS AND METHODS

The analytical model for predicting compressor horsepower is presented in this section. All the assumptions made for model reliability are also stated.

2.1 Model Development

Considering an open steady-state system in Fig. 6, the energy balance on the whole system between points 1 and 3 may be written as:

$$U_3 + P_3V_3 + \frac{mu_3^2}{2g_c} + \frac{mgZ_3}{g_c} = U_1 + P_1V_1 + \frac{mu_1^2}{2g_c} + \frac{mgZ_1}{g_c} + Q - w - lw \quad (1)$$

Where,

U = internal energy
PV = energy of expansion or compression
$mu^2/2g_c$ = potential energy
Q = heat energy added to the fluid
w = shaft work done by the surrounding on the gas

Dividing Eq.1 through by *m* to obtain an energy per unit mass balance and writing the resulting equation in differential form yields

$$dU + vdp + u\frac{du}{g_c} + g\frac{dz}{g_c} - Q + lw = -w \quad (2)$$

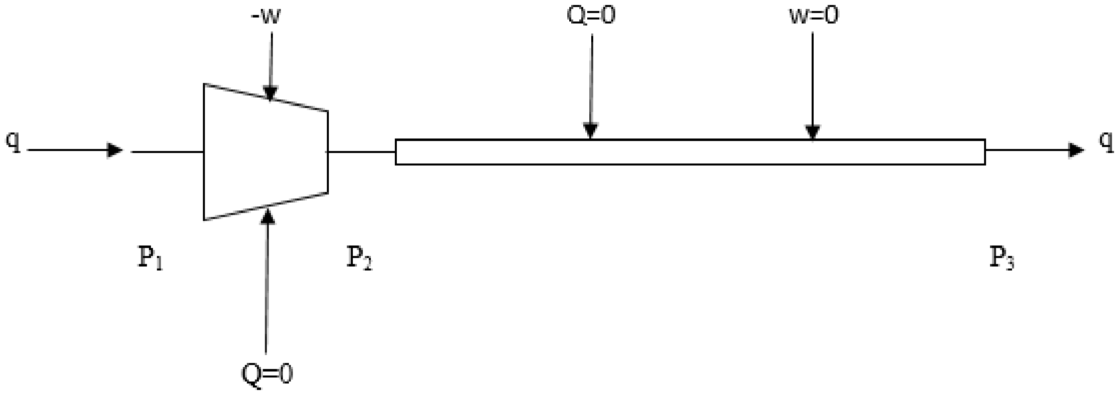

Fig. 6. A compressor-pipeline composite open system

Assuming the following:

- The kinetic energy change in both the compressor and pipeline is negligible and can be taken as zero.
- The flow is a steady-state plus steady flow.
- The flow is isothermal in the pipeline.
- The flow is horizontal.
- Heat is not transferred to or from the gas in the compressor and pipeline to the surroundings.
- There is no work done by the gas during the flow across the whole system.
- The only compression work done on the gas as it flows across the entire system is by the compressor.
- Work is lost only in the pipeline.

The general energy equation reduces to:

$$vdp + lw = -w \tag{3}$$

Or

$$(144)vdp + \frac{fu^2}{2g_cD}dl = -w \tag{4}$$

$$u = \frac{vol.\ flow\ rate}{cross\ sectional\ area\ of\ pipe}$$

$$u\left(\frac{ft}{sec}\right) = \frac{cuft}{sec}.\frac{1}{sq.ft}$$

$$= \frac{}{A}$$

$$= \frac{}{(\pi D^2/4)} \tag{5}$$

$$= \frac{4}{\pi D^2}$$

Also,

For real gases,

$$v\left(\frac{cuft}{lbm}\right) = \frac{zRT}{pM} \qquad = \frac{10.732zT}{29\gamma_g P} \tag{6}$$

Substituting accordingly,

$$(144)\left(\frac{10.732zT}{29\gamma_g P}\right)dp + \frac{f}{2g_c}\left\{\frac{4}{\pi D^2}\right\}^2 . \frac{dL}{D} = -w$$

$$\frac{53.29zTdP}{\gamma_g P} + 0.025196\frac{f}{D^5}{}^2\, dL = -w$$

Rearranging and integrating,

$$\frac{53.29zT}{\gamma_g}\int_{P_1}^{P_2}\frac{1}{P}dP + 0.025196\frac{f}{D^5}{}^2\int_0^L dL = -w$$

$$\frac{53.29zT}{\gamma_g}(lnP)_{p_1}^{p_2} + 0.025196\frac{f}{D^5}{}^2\, L = -w$$

$$\frac{53.29zT}{\gamma_g}[lnP_2 - lnP_1] + 0.025196\frac{f}{D^5}{}^2\, L = -w$$

$$\frac{53.29zT}{\gamma_g}\left[ln\frac{P_2}{P_1}\right] + 0.025196\frac{f}{D^5}{}^2\, L = -w \tag{7}$$

Where,

T = °R
P = psia
 = cu ft/sec
L = ft
γ_g= dimensionless
f= dimensionless
w = ft-lbf/lbm

Let $LHS\ \ of\ Eq.7 = A$, such that

$$-w = A$$

$$-W(lbf - ft) = mA \tag{8}$$

Where,

m = Mass

Recall,

$$m = nM_a$$

Where,

n = Number of moles
M_a = Relative molecular mass

Hence,

$$-W = nM_aA \tag{9}$$

But, for real gases,

$$pV = nzRT \tag{10}$$

And

$$n = \frac{pV}{zRT}$$

Also,

$$\dot{n} = \frac{p}{zRT} \tag{11}$$

Where,

$\dot{n}$ = molar flow rate

= volumetric flow rate

Also,

$$q = \frac{pT_b}{p_bTz} \qquad (12)$$

Substituting Eqs.11 and 12 into Eq. 9 accordingly,

$$-W = \frac{qp_bTz}{pT_b} \cdot \frac{pM_a}{zRT} A$$

$$-W = \frac{qp_bM_a}{RT_b} A$$

Where,

$$R = 10.732\, psia - cuft/lbmol°R$$

If $q = [MMcfd]$ and $-W = [hp]$,

Then,

$$-W \left[hp. \frac{550(ft-lbf)}{1hp}\right] = \frac{qP_bM_a}{10.732T_b} \cdot \frac{11.5741cfs}{1MMcfd} . A$$

$$-W = \frac{0.00196qP_bM_a}{T_b} A \qquad (13)$$

Therefore, on substituting for A in Eq.13,

$$-W = \frac{0.00196qP_bM_a}{T_b} \left\{ \frac{53.29zT}{\gamma_g} \left[ln \frac{P_2}{P_1} \right] + 0.025196 \frac{f}{D^5} {}^2 L \right\} \qquad (14)$$

Let

$$0.025196 \frac{f}{D^5} {}^2 L = B$$

If L is in miles, D in inches, and cuft/day,

Then,

$$B = 0.0252 \frac{f}{\left(\frac{D}{12}\right)^5} \left[\frac{}{86400}\right]^2 L.5280$$

Also, according to Weymouth, f varies with D in inches as follows

$$f = \frac{0.032}{D^{\frac{1}{3}}} \qquad (15)$$

On substituting and rearranging,

$$B = \frac{0.000142}{D^{\frac{16}{3}}} ()^2 L$$

Substituting for B in Eq.14,

$$-W = \frac{0.00196qP_bM_a}{T_b} \left[\frac{53.29zT}{\gamma_g} ln \frac{P_2}{P_1} + \frac{0.000142}{D^{\frac{16}{3}}} ()^2 L \right] \qquad (16)$$

But,

$$M_a = 29\gamma_g \qquad (17)$$

Substituting the Eq. 17 into Eq.16,

$$-W = \frac{0.00196qP_b}{T_b} \left[1545.41zTln \frac{P_2}{P_1} + \frac{0.00412\gamma_g}{D^{\frac{16}{3}}} ()^2 L \right] \qquad (18)$$

Where,

W = compressor power requirement, hp
q = gas throughput, MMcfd
P_b = base pressure at which q was measured, psia
T_b = base temperature at which q was measured, °R
γ_g = gas specific gravity, dimensionless
= gas volumetric flow rate, cuft/day
P_1 = suction pressure in psi
P_2 = discharge pressure in psia
D = pipe diameter, inches
L = pipe length, miles
T = temperature at suction condition, °R
z = gas deviation factor at suction condition, dimensionless

Where,

$$= \frac{qP_bTz}{PT_b} \qquad (19)$$

And

q = measured gas throughput, MMcfd
P_b = base pressure at which q was measured, psia
T_b = base temperature at which q was measured, °R
P = pressure at which is sought, psia
T = temperature at which is sought, °R
z = gas deviation factor at the condition which is sought.

2.2 Method of Error Analysis

The percentage absolute deviation equation used in this study is given as:

$$\% AD = \left| \frac{W_{promax} - W_{model}}{W_{promax}} \right| \times 100 \qquad (20)$$

3. RESULTS AND DISCUSSION

An analytical model was developed using the general energy equation to better capture interrelationships between compressor power and parameters, pipeline length, and gas throughput. The developed model was tested using ProMax software by simulating gas transmission lines (compression ratio = 2) and dividing the whole length of the pipeline into 50-mile sections, with a compressor unit situated at the end of every 50-mile section. Consequently, simulations for 50-mile, 100-mile, 150-mile, 200-mile, 250-mile, and 300-mile pipelines, for fixed throughput, were performed. Also, simulations were equally done for a fixed pipe length of 50 – mile, and variable gas throughput. The results of the simulations [19] were then used in comparisons with results obtained from the developed model. This was done to validate the developed model and establish its reliability and accuracy. Fig. 7 shows the comparison of ProMax and model compressor power results for different pipeline lengths at 200 MMscfd. Fig. 8 shows the Comparison of ProMax and model compression power results at different throughputs for a 50-mile pipeline.

It may be observed from Fig. 7, that the relationship between compressor power and pipe length for fixed throughput can be described as a positive correlation, which means compressor power requirements for the gas transmission lines increased for both the model and ProMax, as the pipe length increased. It shows clearly that the longer a pipeline, the higher the compressor horsepower needed to force natural gas through it. This is because the longer a pipeline's length, the higher the pressure drop a fluid flowing through it will experience. Likewise, Fig. 8 indicates a direct proportionality between compressor power and throughput for fixed pipe length. As a result, both ProMax and model compressor power were increasing as the gas throughput increased. And this agrees with the expected reality since the larger the volume of gas transported in a pipeline, the higher the energy required to compress it. The results from ProMax and model were also seen to have similar trends in both cases.

On comparing the results from the ProMax software and that of the developed model as presented in Figs. 7 and 8, it revealed that the error between ProMax and the model increased as the pipeline length and throughput increased, although the general trajectory of both curves remained the same. It shows that as pipeline length and throughput increases, the developed model gradually loses its accuracy. This necessitated the introduction of correction factors, to increase the reliability and accuracy of the developed model. The development of the correction factors is presented in the next section.

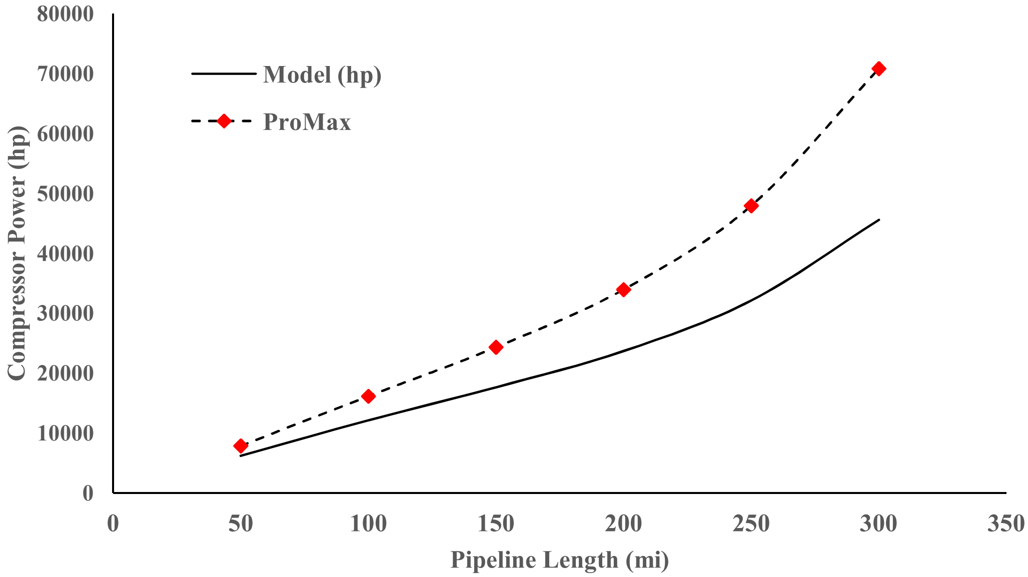

Fig. 7. Compressor power results for 200 MMSCFD throughput at different pipeline lengths

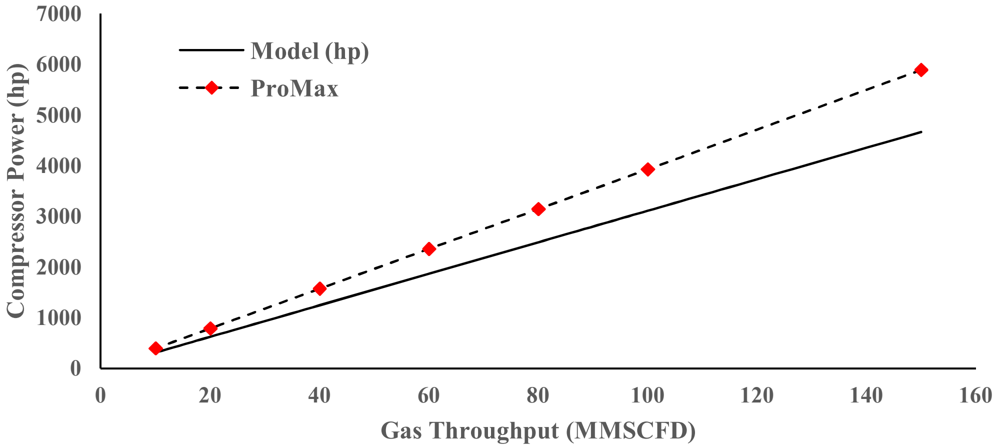

Fig. 8. Compressor power results for a 50-mile pipeline at different throughputs

3.1 Correction Factors

The compressor power results showed that as pipeline length and flow rate were increasing, so was the error between compressor power requirement predictions of the developed model and that of ProMax. Therefore, correction factors for pipeline length and flow rate were proposed to improve the accuracy of the model. This was done by adding a constant C to the model and developing error functions to account for the error based on the trend analysis. The coefficients of the error functions were obtained by regressing the ProMax software results. The final model becomes:

$$-W = \frac{0.00196qP_b}{T_b}\left[1545.41zTln\frac{P_2}{P_1} + \frac{0.00412\gamma_g}{D^{\frac{16}{3}}}()^2L\right] + \mathrm{C} \qquad (21)$$

For a constant throughput and varying length condition, the error function was found to be:

$$\mathrm{C} = aL^3 + bL^2 + c\mathrm{L} + d \qquad (22)$$

Where

a = 0.0016; *b* = - 0.4905; *c* = 97.159; *d* = - 2245

For a fixed length and varying throughput condition, the error function was found to be:

$$\mathrm{C} = a\mathrm{Q} + b\mathrm{L} + c \qquad (23)$$

Where

a = 11.02684; *b* = 76.58304; *c* = - 4226.24.

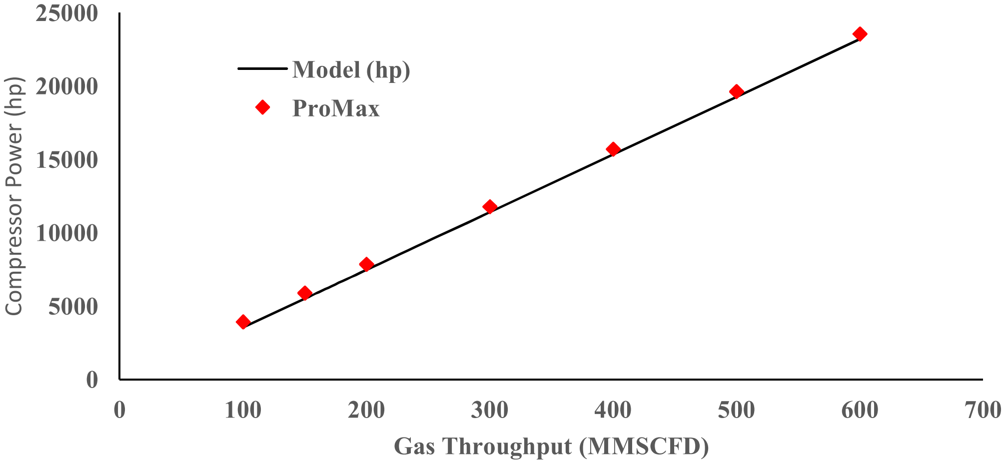

Fig. 9. Compressor power results for a 50-mile pipeline at different throughputs with a correction factor

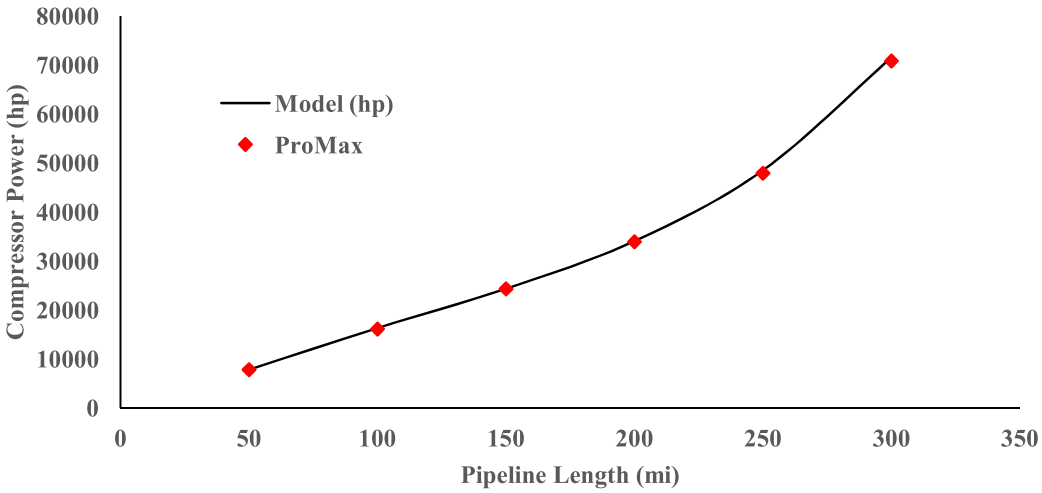

Fig. 10. Compressor power results for a 200 MMSCFD at different pipe lengths with a correction factor

Table 1. % AD of compressor power results with varying throughput for a 50-mile pipeline length with a correction factor

q (MMscfd)	Model (hp)	ProMax (hp)	% AD	
100	3532.68	3924.50	9.98	
150	5497.56	5886.75	6.61	
200	7462.44	7849.01	4.93	
300	11392.20	11773.50	3.24	
400	15321.97	15698.00	2.40	
500	19251.73	19622.50	1.89	
600	23181.49	23547.00	1.55	**% AAD = 4.37**

Table 2. % AD of compressor power results with varying pipe length for a 200 MMSCFD throughput with a correction factor

Length(mi)	Model (hp)	ProMax (hp)	% AD	
50	7806.92	7849.01	0.54	
100	16300.89	16139.85	0.99	
150	24340.27	24327.95	0.05	
200	34057.26	33945.98	0.33	
250	48511.24	47936.68	1.18	
300	71520.22	70830.48	0.96	**% AAD = 0.68**

Figs. 9 and 10 show the relationship between the compressor power results from the ProMax software and the model in this study, after the introduction of correction factors. The introduction of the correction factors further reduced the percentage absolute deviation between ProMax results and compressor power requirements predicted by the developed model. This is demonstrated by the fact that all the absolute deviations between ProMax results and predicted compressor power were below 10% for the fixed pipe length, variable throughput, and below 2% for the fixed throughput, variable length, case scenarios. Tables 1 and 2 show the % AAD.

4. CONCLUSION

A new model for predicting natural gas compressor power has been developed and presented. The validity, accuracy, and reliability of the new model were ascertained by comparing the results with those of the ProMax software, simulated for gas transmission lines. The conclusions from the study include.

- An analytical model for estimating compressor power required for transporting natural gas in pipelines is presented.
- The model applies to both short and long gas pipelines.
- The developed model can equally be used for gas pipelines of different throughputs and pipeline length.
- The introduction of correction factors successfully increased the accuracy of the developed model.

Pipeline profile effects on the results obtained in this study can be investigated. The model can further be investigated for other fluid applications.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Mordor Intelligence. Onshore Oil and Gas Pipeline Market - growth, trends, and forecast, 2020 - 2025. 2019. [Retrieved November 14;2019] Available:https://mordorintelligence.com/industry-reports/onshore-oil-and-gas-pipeline-market
2. Global Data Energy. North America has the highest oil and gas pipeline length globally; 2019. [Retrieved January 20; 2020] Available:https://www.offshore-technology.com/comment/north-america-has-the-highest-oil-and-gas-pipeline-length-globally/
3. Statista. Natural gas pipeline distance worldwide as of 2016, by region; 2016. [Retrieved October 16; 2019] Available:https://www.statista.com/statistics/267885/overall-length-of-planned-gas-pipelines-2010/
4. CIA World Fact book; 2015. [Retrieved January 16; 2020] Available:https://www.cia.gov/library/publications/the-world-factbook/index.html
5. Rios-Mercado R, Borraz-Sanchez C. Optimization problems in natural gas transportation systems: A state-of-the-art review. Applied Energy. 2015;147:536-555.
6. Folga SM. National gas pipeline technology overview. Argonne National Laboratory. Illinois, USA; 2007.
7. Sanaye S, Mahmoudimehr J. Optimal design of a natural gas transmission network layout. Chemical Engineering Research and Design. 2013;91(12):2465–2476.
8. Usterand H, Dilaveroˇglu S. Optimization for design and operation of natural gas transmission networks. Applied Energy. 2014;133:56–69.
9. Zeng J, Sun C. Zhu Z. Wu J, Chen, H. Uncertainty analysis for natural gas transport pipeline network layout: A new methodology based on Monte Carlo method. Journal of Advanced Transportation. 2018;1-10. Available:https://doi.org/10.1155/2018/9213648.
10. Pipeline Safety Trust. Pipeline Basics & Specifics About Natural Gas Pipelines; 2015. [Retrieved November 17; 2019] Available:http://pstrust.org/wp-content/uploads/2015/09/2015-PST-Briefing-Paper-02-NatGasBasics.pdf.
11. Ikoku CU. Natural gas production engineering, reprint edition. Florida. Krieger Publishing Company; 1992.
12. Luongo CA, Gilmour BJ, Schroeder DW. Optimization in natural gas transmission networks: A tool to improve operational efficiency. Technical report. Stoner Associates, Inc., Houston; 1989.
13. Perez RX. A brief introduction to compressors. Part 2 of 4; 2016. [Retrieved January 7; 2020] Available:https://empoweringpumps.com/brief-introduction-compressors-part-2-4/
14. Krishnaswami P. Chapman KS, Abbaspour M. Compressor station optimization for line-pack maintenance. Presented at the 36th PSIG Annual Meeting. Palm Springs; 2004.
15. Chebouba A, Yalaoui F, Smati A, Amodeo L, Younsi K, Tairi A. Optimization of natural gas pipeline transportation using ant colony optimization. Computers & Operations Research. 2009;36(6):1916–1923.
16. Jin L, Wojtanowocz AK. Optimization of large gas pipeline network – A case study in China. Journal of Canadian Petroleum Technology. 2010;49(4):36–43.

17. Wu S, Boyd EA, Scott LR. Minimizing fuel consumption at gas compressor stations. Advances in Industrial Engineering Applications and Practice. 2014;6(2):72–77.
18. Agwu OE, Markson IE, Umana MO. Minimizing energy consumption in compression stations along two gas pipelines in Nigeria. American Journal of Mechanical Engineering and Automation. 2016;3(4):29-34.
19. Ezendiokwere NE, Aimikhe VJ, Kinigoma B. Simulation analysis of natural gas transmission lines using promax. Leonardo Electronic Journal of Practices and Technologies. 2018;33:289-302.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/58790