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Estimation of Flow Capacity in Pipelines Based on the Intrinsic Variation of the Volumetric Properties of the Natural Gas Mixture

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Review Article

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Abstract

In this paper, the Weymouth equation was applied so as to consider the pipeline characteristics, thermodynamic and physical gas properties. From literature, volumetric parameters like the specific gravity and compressibility are mostly assumed to be constants. Since they are related to flow, pressure and temperature values; neglecting their variation during pipeline transportation may lead to significant misleading results in the computation of pipeline resistance. Considering that providing global optimal solutions to instances of considerable size can become time-consuming, thus a mathematical optimization method was applied to find the solution that will satisfy these systems. Critical property correlations (Thomas, Standing and Sulton) and Compressibility correlations (Hall-Yarborough, Danchuk-Purvis-Robinson are used mathematically to generate results that will optimize the gas pipeline transportation without assuming specific gravity and compressibility factor of the gas constant. The model proposed in this study showed that specific gravity and compressibility have an effect on gas pipeline flow rate. It was observed that at very low and very high specific gravity, that the gas flow rate is reduced by more than 10% while the gas density increases. It can also be stated from the results that, compressibility is directly proportional to flow rate and inversely proportional to density.

Keywords: Gas flow rate; Natural gas; Compressibility correlation; Critical property correlations; Danchuk-Purvis-Robinson

Introduction

For long gas pipeline flowing at high velocity, the pressure drop might be so significant that we may not ignore the change in density. Knowledge of the pressure-volume-temperature (PVT) behaviour of natural gases cannot be over-emphasized in solving most petroleum engineering problems.

The long road that normally covers natural gas from its source to its final destination programmed comprises a series of complex tasks [1]. Activities such as exploration, extraction, processing, storage, transportation and distribution of natural gas are among those tasks that certainly offer interesting challenges in the daily activities of the gas industry [2].

Due to the obvious complexity that would entail conducting all these physical processes together, the vast task undoubtedly has to be separated. For example, while some companies may be in charge of exploring the ground looking for gas bearing formations that may lead to substantial profits, other companies may be in charge of processing the gas to make it ready for its consumption. Typically, the former companies also drill the wellhead and extract the gas once a potential area has been mapped [3]. On the other hand, transnational companies are usually in charge of natural gas transportation through cities, states or even countries. They may feed their pipeline systems with natural gas coming from various sources, including preprocessing plants, storage facilities or wellheads, in order to deliver it at certain discharge points, such as local distribution centers and large customers. Moreover, local distribution centers deliver natural gas to a number of end consumers, including residential, commercial and industrial consumers [4].

This study will focus on the mathematical modeling of the pipeline resistance in transmission systems. The aim is to estimate in a more accurate way the flow capacity in pipelines based on the intrinsic variation of the volumetric properties of the natural gas mixture during the transmission process. In particular, this study will show the influence of the variability of the gas specific gravity (g) and compressibility (z-factor) on maximum flows.

Continuous and discrete models, as well as exact and heuristic methods, have been developed with the promise of substantially improving the performance of a company or institution (be it profit/lucrative or not). The natural gas industry is no exception [5]. The resolution methods for a gas pipeline system typically focus on finding an optimum operating plan, which includes ideal pressure settings and mass flow rate values through the pipeline network. This is a very challenging task since a large number of complicating (inequality and equality) constraints may be imposed in a typical natural gas transportation problem. Hence, two major approaches are commonly used to deal with these problems, namely Numerical simulation and Mathematical optimization [5].

A typical approach in steady-state models is to consider volumetric parameters such as specific gravity and compressibility as constants. However, since these thermodynamic parameters are associated with flow, pressure and temperature values, neglecting their changes can lead to more ambiguous results. This example can arise when calculating the resistance of a pipeline [6].

As noted in Shashi [7], pipeline system physical properties and the gas composition affect the resistance of the channels. To demonstrate the potential of the flow of pipes, several equations are proposed. The Weymouth equation was developed in 1912, the Panhandle A equation was developed in 1940, and the Panhandle B equation developed in 1956 among others. Because of their simplicity and accuracy when applied to the gas flow at different pressures, Weymouth's equation was chosen for this study.

Let $p_i$and p_j be then upstream and downstream pressure, respectively, in pipeline (i, j) ∈A. The equation can be put in the following form:

$$\boldsymbol{x^2{}_{ij} = W_{ij}\left(P^2{}_i - P^2{}_j\right), \forall (i.j) \in A} \; \mathbf{(1)}$$

Where W_{ij}, is the Weymouth factor which depends on pipeline and gas properties as show in equation 2;

$$\boldsymbol{W_{ij} = \frac{d^5{}_{ij}}{KZ_{ij}g_iTf_{ij}L_{ij}}} \; \mathbf{(2)}$$

Where z_{ij}= compressibility of the flow in pipeline (i, j), g_i= specific gravity of the flow arriving at node i, T = temperature of the gas, f_{ij}=friction factor in pipeline (i,j), L_{ij}= pipeline length (i, j), d_{ij}= inside pipeline diameter (i, j), and K =universal constant with value defined by the units used.

Equation (1) basically illustrate the relationship between the mass flow rate x_{ij}through a horizontal pipeline (i, j) A and the corresponding difference between the squares of the inlet and outlet pressures p_i and p_j, respectively.

By defining $w_{ij} = z_{ij} g_i W_{ij}$, equation (1) can be written as

$$Z_{ij} g_i x^2{}_{ij} = W_{ij}\left(P^2{}_i - P^2{}_j\right), \forall (i,j) \in A \ (3)$$

As observed, the pipeline parameter wij is independent of the flow properties z_{ij} and g_i.

Development of the Estimation Tool

The gas specific gravity can be defined in terms of molecular weights (M_w) as the ratio of the apparent molecular weight of the gas mixture to the molecular weight of air, given by:

$$g = \sum_{c \in NG} \Gamma_c M^c{}_w / \sigma \quad (4)$$

Where Γ_c is the relative content of compound c in the natural gas mixture, $M^c{}_w$ is the corresponding molecular weight of compound c, and σ is the molecular weight of air.

A complete list of molecular weights and other properties of various hydrocarbon gases is provided by Shashi (2005). Published values of the specific gravity of natural gas range from 0.554 to 0.870.

In this study, the specific gravity values used at the sources, i.e., g_i, $\forall_i \in V_s$, are calculated in advance as specified by equation (4) based on some natural gas mixtures found in the literature, and for nodes j ∈V /Vs, we assume that

$$g_i = \frac{\sum i \in V_j{}^- g_i x_{ij}}{\sum i \in V_j{}^- x_{ij}} \ (5)$$

That is, we let the specific gravity of a blend of different gases be the weighted average of specific gravities of entering flows. The specific gravity equation balance was obtained by multiplying equation (5) with total flow:

$$g_i \sum_{i \in V_j{}^-} x_{ij} - \sum_{i \in V_j{}^-} g_i x_{ij} = 0, \forall_j \in V \ (6)$$

Pressure in a Pipeline

The pressure is decreasing along the pipeline. According to Shashi [7],

$$\dot{P}_{ij} = \frac{2}{3}\left(P_i + P_j - \frac{P_i P_j}{P_i + P_j}\right) \ (7)$$

To account for this deviation factor (Z), numerous Empirical Correlations Methods (equations-of-state) have been proposed. They are Standing and Katz (SK), Hall & Yarborough Best Fit Equation, and Dranchuk-Purvis-Robinson Method. These correlations are considered while building the estimation tool (Figure 1) (Table 1).

Other proposed studies and correlation for optimization of gas transportation has been published in some literatures Bermúdez A, González-Díaz J, González-Diéguez FJ [8], Fodstad M, Midthun KT, Tomasgard A [9], Singh R [10], Ríos-Mercado RZ, Borraz-Sánchez C [11], Guo Y, Meng X, Wang D, Meng T, He R [12], Shunxi Li, Bowen Su, David L St-Pierre, Pang-Chieh Sui, Jinsheng Xiao [13], Qian Sun, Luis F Ayala [14], Ferraro MC, Hallack M [15].

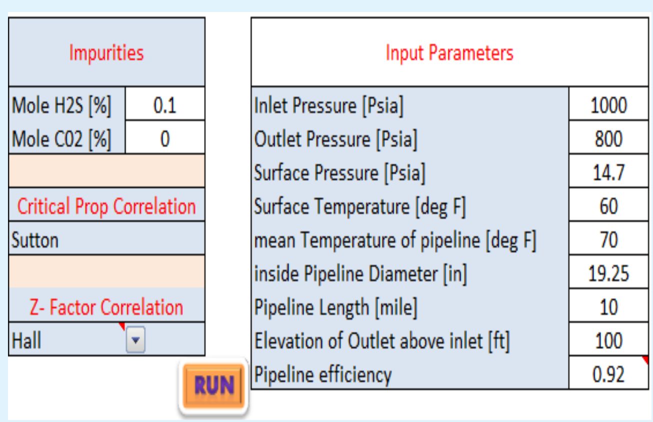

Figure 1: The Tool Interface.

Gas Properties Optimized for Pipelines						
Gravity	Critical Temp [deg F]	Critical Pres [Psia]	Z-Factor	Density [lb/cuft]	Viscosity [cP]	Gas Rate [MMScf/D]
0.54	319.52	647.81	0.9101	2.7306	0.0127	439.39
0.55	322.21	646.82	0.9069	2.791	0.0127	436.09
0.56	324.88	645.83	0.9037	2.8519	0.0126	432.9
0.57	327.54	644.83	0.9004	2.9134	0.0126	429.82
0.58	330.18	643.83	0.897	2.9755	0.0126	426.85
0.59	332.81	642.81	0.8936	3.0384	0.0126	423.97
0.6	335.43	641.79	0.8902	3.1018	0.0126	421.19
0.61	338.02	640.77	0.8867	3.166	0.0126	418.5
0.62	340.61	639.73	0.8831	3.2309	0.0126	415.9
0.63	343.18	638.69	0.8795	3.2965	0.0126	413.39
0.64	345.73	637.64	0.8758	3.3629	0.0126	410.96
0.65	348.28	636.59	0.8721	3.4301	0.0126	408.61
0.66	350.8	635.53	0.8683	3.4981	0.0126	406.34
0.67	353.31	634.46	0.8644	3.567	0.0125	404.15
0.68	355.81	633.39	0.8605	3.6367	0.0125	402.03
0.69	358.29	632.31	0.8565	3.7073	0.0125	399.98
0.7	360.76	631.23	0.8525	3.7789	0.0125	398
0.71	363.21	630.14	0.8484	3.8514	0.0125	396.09
0.72	365.64	629.05	0.8442	3.9249	0.0126	394.25
0.73	368.07	627.95	0.84	3.9994	0.0126	392.47
0.74	370.47	626.84	0.8357	4.0751	0.0126	390.76
0.75	372.87	625.73	0.8313	4.1518	0.0126	389.11
0.76	375.24	624.62	0.8269	4.2296	0.0126	387.52
0.77	377.61	623.5	0.8224	4.3087	0.0126	385.99
0.78	379.95	622.37	0.8179	4.389	0.0126	384.52
0.79	382.29	621.24	0.8132	4.4705	0.0126	383.11

Table 1: Data used for validation of the Tool's results.

Results and Discussion

Considering that providing global optimal solutions to instances of considerable size can become time consuming, thus a mathematical optimization method was applied to find the solution that will satisfy these systems. Assuming 0.1 – 0.3% impurity in the gas pipeline, Critical property correlations (Thomas, Standing and Sulton) and Compressibility correlations (Hall-Yarborough, Danchuk-Purvis-Robinson) are used mathematical to generate results that will optimize the gas pipeline transportation without assuming specific gravity and compressibility factor of the gas constant. These critical property correlations are combined to know the effect of specific gravity on the gas flow rate (Figure 2 to 4) and the effect of compressibility on gas flow rate and density (Figure 5 to 7). The figures are combination of best critical property correlations for gas pipeline optimization during transportation.

Effect of Specific Gravity on Gas Rate

Gas density depends heavily on pressure and temperature. Specific gravity is the ratio of the density of s gas to the density of air. Figure 2 to 4 shows the effect of specific gravity on gas flow. It was observed that at very low and very high specific gravity, that the gas flow rate is reduced by more than 10% while the gas density increases. Thus, this figures showed that the effect of specific gravity on gas flow is reduced by use of the square root. Though, Figure 3 showed an unstable prediction which can be interpreted as part of the limitation of Standing and Katz correlation when used for computation. Sutton and Thomas et al combination with Hall-Yarborough gave a better prediction of the effect of varying specific gravity in gas pipeline transportation.

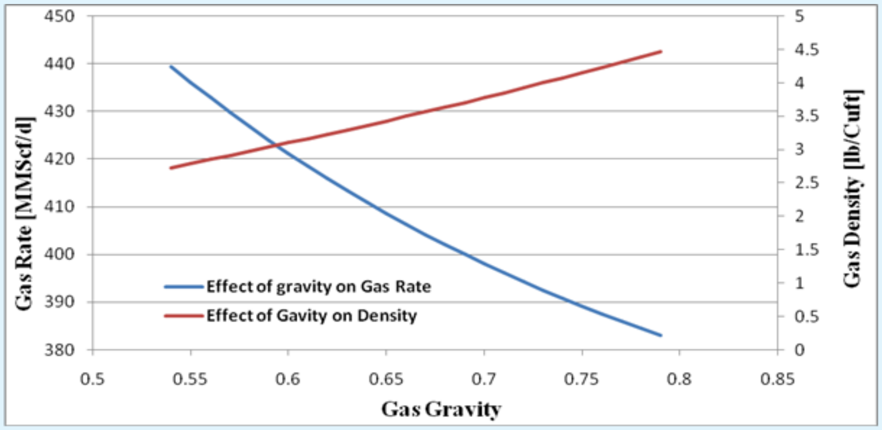

Figure 2: Optimization using Sutton and Hall-Yarborough combination.

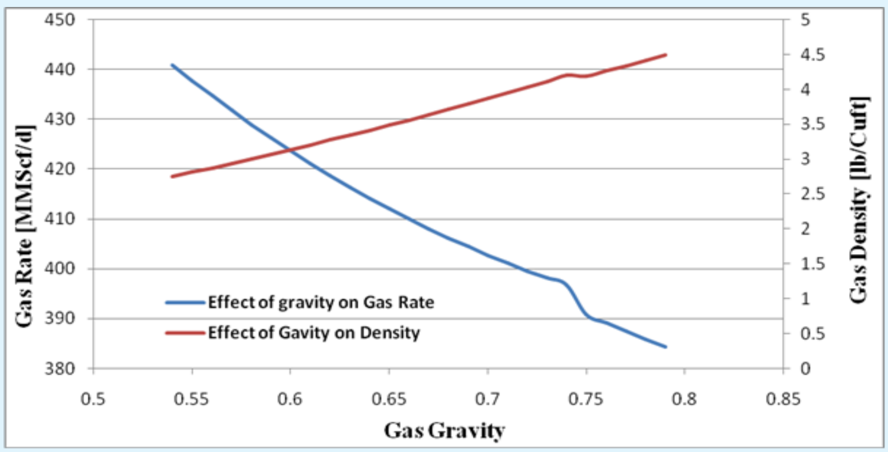

Figure 3: Optimization using Standing & Katz and Hall-Yarborough combination.

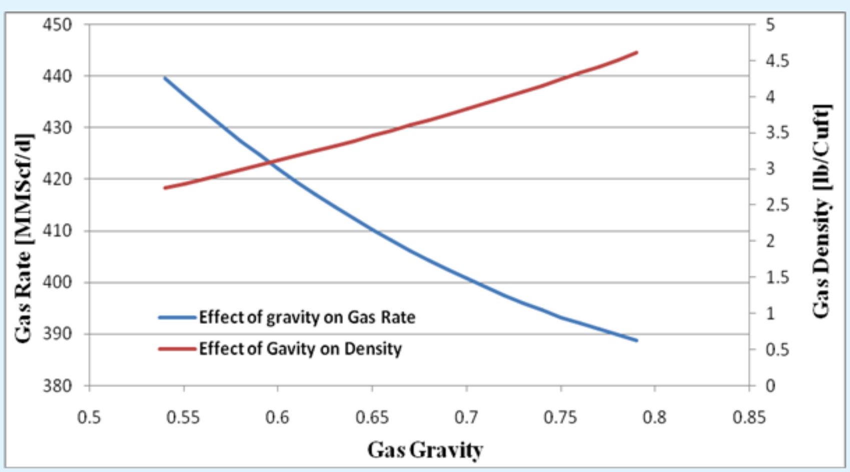

Figure 4: Optimization using Thomas et al and Hall-Yarborough combination.

Effect of Compressibility on Gas Rate and Density

There is a large amount of space between the particles in a gas, making gases more compressible. Though, Figures 5 and 7 show a smooth trend; it was observed that an increase in the value of compressibility also increases the flow rate while the density decreases Figure 6 showed an unstable prediction at a particular range of compressibility factor, which may suggest that the combination did not predict adequately at that particular conditions.. It can be deduced from the observation that, compressibility is directly proportional to flow rate and inversely proportional to density.

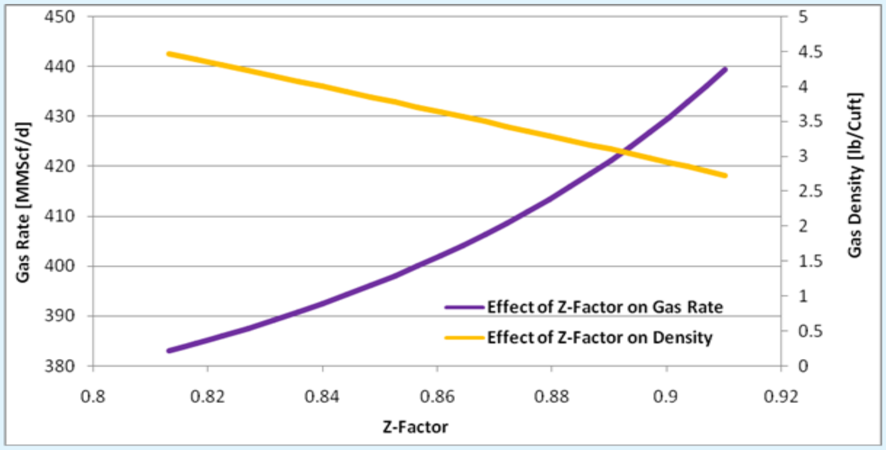

Figure 5: Optimization using Sutton and Hall-Yarborough combination.

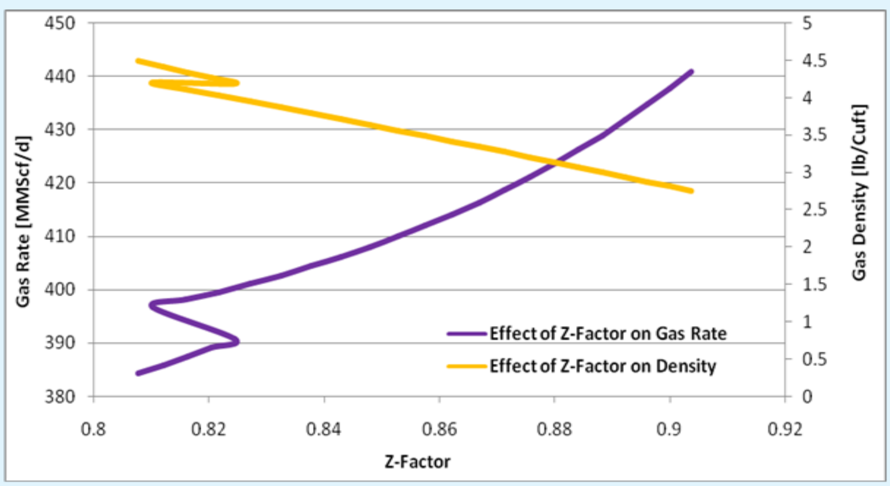

Figure 6: Optimization using Standing & Katz and Hall-Yarborough combination.

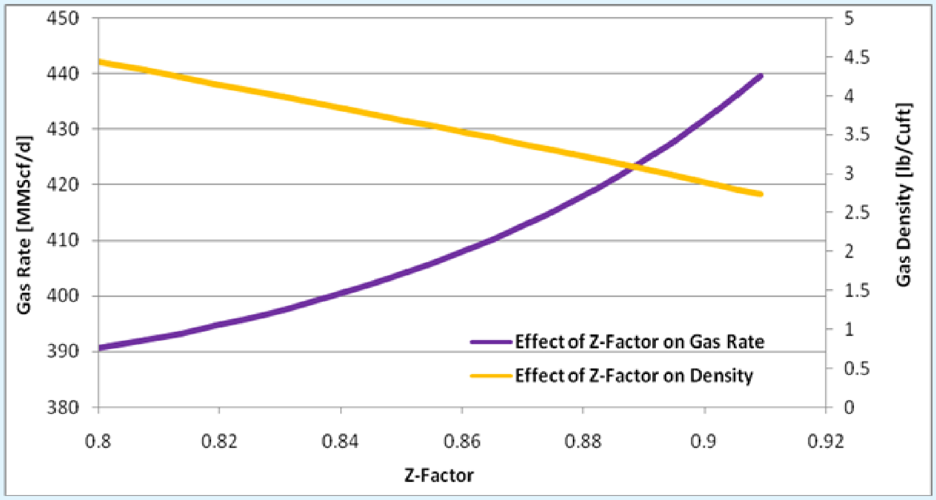

Figure 7: Optimization using Thomas et al and Hall-Yarborough combination.

Conclusion

It can be concluded that;

1. A Tool has been developed for estimation of flow capacity in gas pipeline, and that the Tool acknowledges the variations in gas compressibility and specific gravity.
2. The Tool proposed in this study showed that specific gravity and compressibility have anon-negligible effect on gas pipeline flow rate. Thus, should not mostly assume to be universal constants.

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