PERFORMANCE ANALYSIS OF A NATURAL GAS GATHERING AND PRODUCTION SYSTEM AND DIAGNOSIS OF OPERATIONAL BOTTLENECKS

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by
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Maximum energy preservation of the transported fluid is a fundamental design criterion in pipeline networks, in order to curtail the maintenance and operating costs such as compression of gas in the production system. Improper planning of the network system layout during construction of the pipeline could lead to considerable loss of energy of the gas, and on the long run could prove detrimental to the cost incurred to operate the gas pipeline network. Hence it is important to adequately plan the architecture of the pipeline system for optimum operating strategy. The motivation behind this study is to comprehensively analyze a natural gas gathering and production system by developing a steady state gas pipeline network model which predicts the nodal pressures in the system for given flow rates and compressor operating conditions. In this study, a pipeline network model was developed and customized for the gas production and gathering system in Pennsylvania using fundamental principles of fluid mechanics. The network model was history matched to field data by means of flow efficiency adjustments. Upon achieving good history matches, the model was used as a diagnostic tool to analyze the network’s performance and to predict and evaluate the feasibility of any probable modifications that could be done to the pipeline system. Locations with high energy losses were identified, and necessary actions for remediation of these locations were recommended for optimal performance of the pipeline network. This work demonstrates the step-by-step protocol needed for the analysis of natural gas gathering systems and validates the methodology as a powerful tool to diagnose network performance and propose much needed guidance on required network change to field operators.
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NOMENCLATURE

Acc = Stoner’s acceleration value

$C = \text{Conductivity (MSCFD/psi}^2\text{)}$

$D = \text{Pipe internal diameter (inches)}$

$E_f = \text{Flow Efficiency (Dimensionless)}$

$f = \text{fanning’s friction factor (dimensionless)}$

$F = \text{Transmission factor (Dimensionless)}$

$g = \text{Specific gravity of the fluid (dimensionless)}$

$g_c = \text{Gravitational constant (lb}_f/s^2)$

$h = \text{Delta root}$

$H_1 = \text{Height of pipe at the upstream end (feet)}$

$H_2 = \text{Height of pipe at the downstream end (feet)}$

$IR = \text{Improvement Ratio}$

$k = \text{Iteration number}$

$L = \text{Pipe length (miles)}$

$L_e = \text{Pipe equivalent length (miles)}$
MW_g = Molecular weight of natural gas

NCompr : Number of Compressors

NLoops : Number of Loops

NNodes : Number of Nodes

NPipes : Number of Pipes

p = Pressure (psia)

P_1 = Pipe upstream pressure (psia)

P_2 = Pipe downstream pressure (psia)

R_b = Base pressure (psia)

P_d = Discharge Pressure (psia)

P_pc = Pseudo critical pressure (psia)

P_pr = Reduced pressure (dimensionless)

P_s = Suction Pressure (psia)

Q = Flow rate under standard conditions of temperature and pressure (SCFD)

R_e = Reynold’s number (Dimensionless)

s = Pipe elevation adjustment parameter

T_av = Average temperature (Rankine)
\( T_b = \) Base temperature (Rankine)

\( T_i = \) Gas temperature (Rankine)

\( T_{pc} = \) Pseudo critical temperature (Rankine)

\( T_{pr} = \) Reduced temperature (dimensionless)

\( v = \) Gas velocity (ft/s)

\( V_d = \) Discharge Volume \( (ft^3) \)

\( V_s = \) Suction Volume \( (ft^3) \)

\( x_{new} = \) New root

\( x_{old} = \) Old root

\( Z = \) Gas compressibility factor (dimensionless)

**GREEK**

\( \rho = \) Gas density \( (lb/ft^3) \)

\( \gamma_g = \) Gas specific gravity (dimensionless)

\( \mu = \) Gas viscosity (centipoise)

\( \rho_r = \) Reduced density (dimensionless)
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CHAPTER 1
INTRODUCTION

Natural gas production and gathering systems are widespread throughout the Northeastern and the Appalachian basin of the United States of America. The wells producing gas from these reservoirs are mostly stripper wells with low production flow rates; however they are valuable assets to the operators and are essential for the self sufficiency of heat energy for the regions under the influence of these pipeline networks.

Pipeline systems are the most economic option for transportation of natural gas from the source to the point of demand. The major part of the operational cost of these pipelines is the cost of compression. As gas travels through the pipes, the energy of the gas dissipates over the distance and gas compression becomes essential to energize the gas adequately such that it reaches the point of demand. This energy dissipation of gas in pipelines can be aggravated further due to improper design of the layout which may promote the formation of bottlenecks to the flow of the gas. In most of these wells there is inevitable production of water which enters the pipeline system; the presence of water along the pipes, affects the transmission capability of the pipes. By screening the entire network for such bottlenecks and pipes with poor transmission capability, necessary action can be advised to boost the performance of the pipeline network. This will directly reflect upon the economics of operational cost of the pipeline systems.

In this study, a tool has been developed to comprehensively analyze gas pipeline networks is a computer model which simulates gas flow at steady state and isothermal conditions. The model computes the pressures at every node in the pipeline system for the given flow rate of gas. This
model can be customized to any given field under consideration by the application of flow efficiency tuning for the pipes discussed in this study.

In order to customize the model to the given field, the field well head pressures are necessary and in most cases archived by the operators in their production record. Obtaining good history matches are the indicators for effective customization of the model to the field; once it is achieved, the model becomes a diagnostic tool to analyze the network performance and furthermore the model can be used as a decision making tool to forecast the network performance for any modifications in the pipeline network.

This technique was implemented to a gas gathering and production system located in Pennsylvania. The model results allowed the identification of potential bottleneck locations and pipes with poor transmission performance found in the actual field behavior.
CHAPTER 2
BACKGROUND

Gas pipeline network simulation tools are very important to evaluate network performance and a
decision making tool for development and expansion of a pipeline network, especially in large
pipeline networks the operators find it extremely difficult to track information. Several studies
have been performed to understand the flow dynamics and facility performances of natural gas
distribution systems through computer modeling. With natural gas network models as platforms,
add-on features such as compressors, economic evaluation algorithms, geographical information
systems etc., have been implemented to further enhance the capabilities of the gas network
model thereby improving the quality and quantity of information required for strategic
maintenance and development of the gas network system.

SIROGAS was a computer model developed to simulate steady state and transient behavior of
gas flowing in the pipeline network which may include a large variety of hydraulic devices such
as compressors. A two unit compressor station was incorporated into this model and the results
were validated by comparing with the measured data from an operating station.

Osiadacz (1988) developed a methodology to describe steady state simulation of any arbitrary
gas network. Equations are given for steady state analysis and for control elements such as
sources, compressors, regulators and valves equations linking inlet and outlet pressures was
described.

Gilmour (1987) developed a software package which optimizes natural gas pipeline operation for
minimum fuel consumption is in use on a commercial transmission pipeline. This optimization
program has resulted in pipeline fuel savings in daily pipeline operation. In addition, the effect of a new compressor unit on the pipeline system as a whole can be accurately and easily quantified through use of the Optimization Program before the unit is even installed.

Richwine and Sorem (1991) from the Stoner Association, Inc developed a model for managing a gas network for profit and performance. This paper proposed methods for automating key engineering applications with a purpose to improve the design, operation and maintenance of gas network. The major components in this system was the graphical user interface, regional database management systems, automated network design and other specialized applications were linked along with the steady state simulation model.

Hetch (1996) incorporated the Geographic Information System (GIS) for drafting purposes of the pipeline network layout using base maps of the area, this feature enhanced functions such as leakage, corrosion locations etc.

Zhou and Adewumi (1998) proposed an analytical flow equation for steady state flow through pipelines without neglecting any terms in momentum equation, the Linear theory method was used to solve the system of equations. The results were compared with real field data and also with Weymouth, Panhandle A and Panhandle B equations.

Costa (1998) developed a steady state model for pipeline network with compressible flow. The model was capable of predicting pressures, flow rates, temperature and gas composition at any point in the network.

Kessal (2000) developed a simplified numerical simulation for transients in gas networks. There were two cases addressed in his work. The first case was fast fluid flow in short pipes, the equations were written in conservative form and resolved by a predictor corrector scheme for
interior mesh points. The second case was slow fluid flow in relatively long pipes and was resolved using explicit finite difference scheme.

Nimmannoda, Uraikal, Chan and Tontiwachwuthikul (2002) developed a computer aided model for design of a simulation system for a natural gas pipeline network system with an objective to simulate and analyze the pipeline system behavior under different operating conditions. The model was capable of simulating the dynamic behavior of the pipeline network system for different configuration and varying diameter and length of pipes and sizes of compressors. The model was built using FLASH5 was accessible on the world wide web for developers to create pipeline network simulation and also use it as a forecasting tool for determining future demands of customers based on the historical data stored in the database.

Abbaspour (2004) developed a dynamic model for non isothermal gas pipeline system. The study revealed that treating the gas at non isothermal conditions was essential for pipeline flow calculations.

Seleznev (2007) described the numerical simulation of a gas network operation using a high accuracy computation fluid dynamics (CFD) simulator. The pipeline network was tailored as a full system of fluid dynamic equations for gas mixtures through long, branched and multi section pipelines for steady, unsteady and non isothermal flow. The compressors were described by the interior points of admissible sets as a system of nonlinear algebraic equalities and inequalities. The numerical model was validated by comparing it with computational results of gas flow parameters measured on site.

Several commercial softwares for steady state and transient flow in pipes have been developed. A few of the well-known softwares are PIPESIM 2007, Edition 2, developed by Schlumberger is
a steady-state, multiphase flow simulator for diagnostic analysis of oil and gas production systems and SynerGEE Gas 2007, version 4.3.0 was developed by Advantica Inc is a model capable of performing steady state and transient pressure flow simulation.
CHAPTER 3

STATEMENT OF THE PROBLEM

Natural gas gathering and production systems often cover extensive acreage, thus making the pipeline system very large. This makes it difficult for the operators to effectively evaluate the performance of the network due to the lack of vital information and the strong interdependence of all elements in the system. Pipeline network expansion or modification that may be done without the proper comprehensive study of the performance of the existing layout may prove to be detrimental to the operating costs of the pipeline network system.

A computer model was developed and the purpose of this study is to simulate the nodal pressures for the given flow rate in the system and evaluate the performance of the network based on energy losses across pipes. All the field information such as pipe length, pipe internal diameter, elevation details, supply and demand data of the network, compressor operating conditions are to be supplied to the model. The model was further refined to mimic the actual performance of the field under study by tuning the flow efficiencies of the pipes.

Once the model was validated to the given field, the pressure drop analysis can be made of the pipeline network system and the bottleneck locations and pipes suffering heavy energy losses can be flagged. Such flagged pipes and areas can be looked upon in the field for redesign or replacement to overcome these losses. The model can also be used a decision making tool to evaluate the pipeline performance when alterations are done to the system.

This model would be a handy tool for the operators to understand the flow dynamics of the pipeline network and provide valuable information which will be helpful for decision making.
CHAPTER 4

MODEL DESCRIPTION

The computer model developed in this work targets the study of production performance of large natural gas gathering and production systems. Steady state and isothermal conditions are employed for the flow through the pipes. All the physical parameters of the pipeline network under consideration such as pipe length, internal diameter, elevation changes, node supply and demand details, gas gravity, and compressor operating condition are provided to the model in a specific format.

The model tests the interconnectivity of the system with the given network input and evaluate the number of pipes, number of nodes, number of compressor and the number of pipe loops, any misinterpretation of the pipeline network architecture would mislead the analysis and loss of time going down technical cul-de-sacs. All the necessary properties of the gas such as viscosity, density, gas compressibility factor and pseudo critical condition are processed based on the available data.

In terms of pipe equation the model uses the fundamental flow equation with rigorous friction factor calculation, Weymouth, Panhandle A or Panhandle B to solve for pressures across each pipe. Each equation has its own friction model embedded into the equations. The compressors are modeled using theoretical compressor constant values to characterize their performance.

The energy losses in pipes are quantified between pipe elevation changes and pipe friction. Friction factor calculation is a very important parameter in measuring frictional losses; hence the flow efficiency of the pipe plays a vital role in compensating for the additional frictional losses
experienced by the pipe to undesirable physical condition which were not captured by the friction model used.

4.1 Governing Equations

This model of the natural gas gathering and production system is proposed to be a single phase gas devoid of any hydrocarbon condensation, and it is at steady state so there is no accumulation of mass or energy at any point in the system. In other words, the total gas supplied to the system is always equal to the total gas leaving the system through the demand ports at any point in time. The flow is at isothermal conditions; therefore the temperature of the gas is constant at all points of the pipeline network.

![Figure 4.1: Representation of a gas pipe segment assuming the gas to be flowing at steady state and isothermal conditions.](image_url)

Figure 4.1 represents a pipe segment transporting gas, as the gas travels from one point to another within a segment of the pipe, the energy of the gas dissipates. Bernoulli’s equation represents the fluid flow and the equation of energy balance per unit mass of gas can be given by:

\[
\frac{dp}{\rho} + \frac{vdv}{g_c} + \frac{gdz}{g_c} + d_{losses} = 0
\]  

(4.1)
where:

\[ p = \text{Pressure (psia)} \]

\[ \rho = \text{Gas density (lb/ft}^3) \]

\[ v = \text{Gas velocity (ft/s)} \]

\[ g = \text{Gravitational constant (ft/s}^2) \]

\[ g_c = \text{Unit conversion factor (lbf ft/lbf s}^2) \]

This equation can be split as follows to represent the different classifications of energies

\[ \frac{dp}{\rho} : \text{Pressure Energy} \]

\[ \frac{vdv}{g_c} : \text{Kinetic Energy} \]

\[ \frac{gdz}{g_c} : \text{Potential Energy} \]

\[ d_{\text{losses}} : \text{Energy losses due to friction and irreversibilities} \]

The pressure energy and kinetic energy are essentially a function of gas density and velocity respectively. The potential energy is a consequence of the arrangement of the pipeline network due to elevation changes in the terrain, where the pipeline network is constructed. When the gas has to transport itself against a pipe that run uphill some of its energy is utilized in overcoming gravitational effects and some energy is gained when the pipe runs downhill.
Figure 4.2 represents an elevated pipe segment; the pressure drop across this segment due to elevation is given in one dimensional flow in equation 4.2.

\[
\left( \frac{dp}{dx} \right)_{\text{elevation}} = -\rho \left( \frac{g}{g_c} \right) \sin \Theta
\]  

(4.2)

To understand the loss of energy due to friction for a given flow rate across a pipe of known diameter, the friction factor parameter is utilized. It is given by Fanning friction factor which associates Reynolds number for a given flow rate, inner pipe diameter and roughness of the pipe.
Frictional loss in one dimension flow can be expressed as:

\[
\frac{dp}{dx}\bigg|_{\text{friction}} = \frac{-2\rho \nu f}{g_e D}
\]  

(4.3)

where:

\( f = \text{Fanning's friction factor (dimensionless)} \)

With all these effects taken into consideration, and by application of gas laws the flow equations for a single phase, steady state, horizontal and isothermal flow were developed, the fundamental or the general flow equation is given in USCS units in equation 4.4 for the pipe with its physical parameters represented in Figure 4.3.

![Figure 4.3: Illustration of a pipe segment with all the essential physical parameters specified.](image)

\[
Q = 38.77F \left( \frac{T_b}{P_b} \right) \left( \frac{P_1^2 - P_2^2}{\gamma g L Z T_f} \right)^{0.5} D^{2.5}
\]  

(4.4)
where:

\[ Q = \text{Flow rate under standard conditions of temperature and pressure (SCFD)} \]

\[ F = \text{Transmission factor (Dimensionless)} \]

\[ T_b = \text{Base temperature, } 60^\circ F \text{ (Rankine, } 460 + ^\circ F) \]

\[ P_b = \text{Base pressure (14.7 psia)} \]

\[ P_1 = \text{Pipe upstream pressure (psia)} \]

\[ P_2 = \text{Pipe downstream pressure (psia)} \]

\[ \gamma_g = \text{Gas specific gravity (dimensionless)} \]

\[ L = \text{Pipe length (miles)} \]

\[ Z = \text{Gas compressibility factor (dimensionless)} \]

\[ D = \text{Pipe internal diameter (inches)} \]

\[ T_f = \text{Gas temperature (Rankine)} \]

When the elevation changes between the ends of the pipe segment as represented in Figure 4.4, the flow equation is modified mathematically and given in equation 4.5.
Figure 4.4: Illustration of an elevated pipe segment with all the essential physical parameters specified and change of elevation from height H1 to H2.

\[
Q = 38.77F \left( \frac{T_b}{P_b} \right) \left( \frac{P_1^2 - e^{sP_2^2}}{\gamma_g L_e ZT_f} \right)^{0.5} D^{2.5}
\]

(4.5)

where:

\( s \) = Pipe elevation adjustment parameter

\( L_e \) = Pipe equivalent length

The pipe elevation adjustment parameter ‘s’ in USCS units is given as:

\[
s = 0.0375 \gamma_g \left( \frac{H_2 - H_1}{T_f Z} \right)
\]

(4.6)
where:

\[ H_1 = \text{Height of pipe at the upstream end (feet)} \]
\[ H_2 = \text{Height of pipe at the downstream end (feet)} \]

And the pipe equivalent \( L_e \) in USCS units is given as:

\[
L_e = \frac{L}{s}(e^s - 1) \tag{4.7}
\]

\( L_e \) is the equivalent length of the pipe which compensates for the pressure loss or gain depending on the inclination or the declination of the pipe. \( L_e \) increases if the pipe is inclined upwards and decreases if the pipe is declined downward.

For a pipe having multiple pipe segments, the equivalent length can be calculated for each individual segment of the slope and summed up to give the total effective equivalent pipe length; it can be calculated with the help of equation 4.8 and equation 4.9.

\[
j = \frac{e^s - 1}{s} \tag{4.8}
\]

\[
L_e = j_1L_1 + j_2L_2e^{s_1} + j_3L_3e^{s_2} + \cdots \tag{4.9}
\]

To estimate the pressure loss in pipes due to friction we must understand the concept of friction factor. Friction factor is a dimensionless parameter which is a function of Reynolds number, for laminar flow and for turbulent flow; it is a function of Reynolds number, pipe’s inside diameter and
roughness. The Fanning friction factor \( f \) is employed in this model, the term transmission factor is also used, which is the opposite of friction factor and is given by:

\[
\text{Transmission factor, } F = \frac{1}{\sqrt{f}} \tag{4.10}
\]

The type of flow is determined by the value of Reynolds number, which in USCS units is given as:

\[
R_e = \frac{vD\rho}{\mu} \tag{4.11}
\]

where:

\( \mu \) = Gas viscosity (centipoise)

\( v \) = Gas velocity (ft/s)

\( \rho \) = Gas density (lb/ft\(^3\))

\( D \) = Pipe internal diameter (in)

If, \( R_e \) is less than 2100, the flow of fluid is said to be laminar and the friction factor is given by:

\[
\text{Friction Factor, } f = \frac{16}{R_e} \tag{4.12}
\]

If, \( R_e \) is greater than 2100, the fluid flow is said to be turbulent and the friction factor is given by the modified Colebrook equation which is given as:

\[
\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{0.0000316}{3.7} + \frac{2.825}{5331726\sqrt{f}}\right) \tag{4.13}
\]
Throughout the years, several flow equations have been developed based on different friction factor modifications, out of which the Weymouth, Panhandle A and Panhandle B equations have been incorporated into this model.

The Weymouth equation in USCS units is given by:

\[ Q = 433.5E_f \left( \frac{T_b}{P_b} \right) \left( \frac{P_1^2 - e^sP_2^2}{\gamma_g \Delta e Z T_f} \right)^{0.5} D^{2.667} \]  \hspace{1cm} (4.14)

The Panhandle A equation in USCS units is given by:

\[ Q = 435.87E_f \left( \frac{T_b}{P_b} \right)^{1.0788} \left( \frac{P_1^2 - e^sP_2^2}{\gamma_g \Delta e Z T_f} \right)^{0.5394} D^{2.6182} \]  \hspace{1cm} (4.15)

The Panhandle B equation is a revised Panhandle A equation which in USCS units is given by:

\[ Q = 737E_f \left( \frac{T_b}{P_b} \right)^{1.02} \left( \frac{P_1^2 - e^sP_2^2}{\gamma_g \Delta e Z T_f} \right)^{0.51} D^{2.53} \]  \hspace{1cm} (4.16)

where \( E_f \) is known as the flow efficiency of the pipe. Flow efficiency of a pipe is generally 0.9 (Mattar et al, 1984).
The Weymouth, Panhandle A and Panhandle B equations can be compared with the general flow equation and an equivalent transmission factor can be derived for each of the three equations with respect to the general flow equation.

The Weymouth transmission factor in USCS units is

$$F = 11.18(D)^{1/6} \quad (4.17)$$

The Panhandle A transmission factor in USCS units is

$$F = 7.211 \left( \frac{Q \gamma}{D} \right)^{0.07305} \quad (4.18)$$

The Panhandle B transmission factor in USCS units is

$$F = 16.7 \left( \frac{Q \gamma}{D} \right)^{0.01961} \quad (4.19)$$

In this model the general single phase, steady state and isothermal flow for compressible fluids is given as:

$$Q = C(P_1^2 - e^s P_2^2)^{0.50} \quad (4.20)$$
where \( C \) is the constant called conductivity and it can be expressed as:

\[
C = 38.77E_{f} \left( \frac{T_{sc}}{P_{sc}} \right) \sqrt[1]{\frac{1}{f} \left( \frac{d^{2.5}}{\gamma Z T L e} \right)^{0.5}} \tag{4.21}
\]

However, the conductivity term varies depending on the type of flow equation which contains different friction model calculations embedded in them. The main difference among the proposed flow equations is the functional relationship assumed for the calculation of friction factors as illustrated in Table 4.1.

Table 4.1: Steady state pipe flow equation and friction factors.

<table>
<thead>
<tr>
<th>Flow Equation</th>
<th>Friction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Flow Equation</td>
<td>Modified Colebrook – White friction factor ( \frac{1}{\sqrt{f}} = -2\log_{10} \left( \frac{0.0000316}{3.7} + \frac{2.825}{5331726\sqrt{f}} \right) )</td>
</tr>
<tr>
<td>Weymouth Equation</td>
<td>( f = \frac{0.008}{D^{1/3}} )</td>
</tr>
<tr>
<td>Panhandle A Equation</td>
<td>( f = \frac{0.019231}{\left( \frac{Q_{g}}{D} \right)^{0.1461}} )</td>
</tr>
<tr>
<td>Panhandle B Equation</td>
<td>( f = \frac{0.003586}{\left( \frac{Q_{g}}{D} \right)^{0.03922}} )</td>
</tr>
</tbody>
</table>
Gas Specific Gravity

Gas specific gravity ($\gamma_g$) is defined as the ratio of the apparent molecular weight of the natural gas to that of air. It is given by the expression:

$$\gamma_g = \frac{MW_g}{28.97} \tag{4.22}$$

Where $MW_g$ is the apparent molecular weight of the natural gas, and 28.97 is the molecular weight of air. The calculation of gas specific gravity is vital when the gas is a mixture of several components since we can calculate other needed properties such as pseudo critical conditions and compressibility factors of the gas.

The pseudo critical properties of the gas are calculated based on their gas gravity since the exact mixture of hydrocarbon compounds are not available at all times. The equations are expressed as:

$$T_{pc} = 170.491 + 307.344 \gamma_g \tag{4.23}$$

$$P_{pc} = 709.604 - 58.718 \gamma_g \tag{4.24}$$

where:

$T_{pc} = $ Pseudo critical temperature (Rankine)

$P_{pc} = $ Pseudo critical pressure (psia)
**Equation of the State**

Natural gas is a compressible entity, although isothermal conditions are observed, due to variations in pressures at different parts of the network, the volume of the gas may vary. This phenomenon is captured by the compressibility factor which is a dimensionless number. The compressibility factor is a function of gas gravity, temperature, pressure and the critical properties of the gas. In this model, the compressibility factor calculation is based on the Abou-Kassem and Dranchuk equation (Abou-Kassem & Dranchuk, 1975). The equation of the compressibility factor is given by:

$$Z = 1 + \left( A_1 + \frac{A_2}{T_{pr}} + \frac{A_3}{T_{pr}^3} \right) \rho_r + \left( A_4 + \frac{A_5}{T_{pr}} \right) \rho_r^2 + \frac{A_7 \rho_r^3}{T_{pr}^3} \quad (4.25)$$

where the reduced density $\rho_r$ is given by:

$$\rho_r = \frac{0.27 P_{pr}}{Z T_{pr}} \quad (dimensionless) \quad (4.26)$$

Reduced pressure, $P_{pr} = \frac{P}{P_{pc}} \quad (dimensionless) \quad (4.27)$

Reduced temperature, $T_{pr} = \frac{T}{T_{pc}} \quad (dimensionless) \quad (4.28)$
and the coefficients are as follows:

\[ A_1 = 0.3265 \quad (4.29) \]

\[ A_2 = -1.0700 \quad (4.30) \]

\[ A_3 = -0.5339 \quad (4.31) \]

\[ A_4 = 0.01569 \quad (4.32) \]

\[ A_5 = -0.05165 \quad (4.33) \]

\[ A_6 = -0.5475 \quad (4.34) \]

\[ A_7 = -0.7361 \quad (4.35) \]

\[ A_8 = 0.1844 \quad (4.36) \]

\[ A_9 = 0.1056 \quad (4.37) \]

\[ A_{10} = 0.6134 \quad (4.38) \]

\[ A_{11} = 0.7210 \quad (4.39) \]

When the equation of state is used to compute the compressibility factor, it also affects the equivalent length of the pipe since it is also a function of the compressibility factor. When compressibility factor \( Z \) decreases, the pipe equivalent length increases if the pipe runs uphill and decreases if it runs downhill, and vice versa when \( Z \) increases.
Gas Viscosity

The gas viscosity is calculated using the LGE method (Lee, Gonzales & Eakin, 1966). The equation is expressed as:

\[ \mu = K \times 10^{-4} \exp(X \times \rho^\gamma) \quad (4.40) \]

\[ K = \frac{(9.4 + 0.02MW_g)T^{1.5}}{209 + 19MW_g + T} \quad (4.41) \]

\[ X = 3.5 + \frac{989}{T} + 0.01MW_g \quad (4.42) \]

\[ y = 2.4 - 0.2X \quad (4.43) \]

Gas Compression

Compressor stations are installed in necessary parts of the pipe line network to transport the gas from one location to another. The locations of these compressors are determined by the maximum allowable pipe pressure, availability of power, environmental and geo technical factors.

Compressor performance varies based on the compressor type and the manufacturers; however they can be characterized by defining the compressor constant values \(K_1, K_2, K_3\) which are normally provided by the manufacturer. Apart from the compressor constant values, this model also requires the specification of operating conditions; the options are specification of suction pressure, discharge pressure or the horsepower of the compressor. The flow rates into the compressors are already known through the supply and demand details of the network, and since
it is steady state, the suction flow rate of the compressors is equal to the discharge flow rate.

Hence, the equation for the compressor can be approximated to

\[ Q = \frac{HP}{K_1(P_d/P_s)^{K_2} + K_3} \]  \hspace{1cm} (4.44)

where:

- \( Q \) = Gas flow rate (MMSCFD)
- \( HP \) = Compressor horse power
- \( K_1 \) = \( K_2 \) = \( (P_s/T_s) \times (n/n - 1) \times (T_{av}/Z) \times (1/\eta) \)
- \( K_3 \) = \( (n - 1/n) \)
- \( n \) = Polytropic exponent
- \( \eta \) = Efficiency of the compressor
- \( \left( \frac{P_d}{P_s} \right) \) is also known as compressor ratio (dimensionless)

Node Continuity Equations

The node continuity equations can be constructed in a Q – formulation or a P – formulation approach. In order to illustrate this, let us consider the gas pipeline network displayed in Figure 4.5. The pipeline system has four nodes and two loops. Node 1 is a supply node; node 2 and node 3 are the two demand nodes in the pipeline network.
Figure 4.5: Sample network for explanation of node continuity equations.

In a Q-formulation problem, the unknowns of the equations are the flow rates in the system. Therefore for a steady state system, the node continuity equations have to satisfy Kirchhoff’s first law which states that the flow of fluid coming into a node should be equal to the flow of fluid going out of that node.

\[
\sum q_{\text{in}} - \sum q_{\text{out}} = 0 \quad (4.45)
\]

Figure 4.6: Sample network for explanation of node continuity equations using Q-formulation method.
Assuming the gas in the pipeline network flows in the manner represented in Figure 4.6. The node continuity equations for every node in this system would be written as:

\[
\text{NODE 1 : } 465 - q_1 - q_3 = 0 \tag{4.46}
\]

\[
\text{NODE 2 : } q_1 + q_2 - q_4 - 150 = 0 \tag{4.47}
\]

\[
\text{NODE 3 : } q_4 + q_5 - 315 = 0 \tag{4.48}
\]

\[
\text{NODE 4 : } q_3 - q_2 - q_5 = 0 \tag{4.49}
\]

The unknowns in this pipeline network are the flow rates \(q_1, q_2, q_3, q_4\) and \(q_5\). In the equations above, only three of them are linearly independent and thus two more equations are needed to solve the system. In Q-approach, additional equations can be written by analyzing the loops of the network. This pipeline network system also contains two loops in the system. Kirchhoff’s second law states that the summation of pressure drop across the pipe segments constituting to a loop should be equal to zero.

\[
\sum_{i=1}^{n} (P_i^2 - P_2^2) = 0 \tag{4.50}
\]

Hence, the loop equations for this pipeline system are given by:

\[
\text{LOOP 1 : } R_1 q_1^n - R_2 q_2^n - R_3 q_3^n = 0 \tag{4.51}
\]

\[
\text{LOOP 2 : } R_4 q_4^n - R_5 q_5^n - R_2 q_2^n = 0 \tag{4.52}
\]

where \(R\) is the resistivity of the pipe which is the reciprocal of conductivity.

\[
R = \frac{1}{C} \tag{4.53}
\]
In the Q – formulation of this system, there are only five unknown flow rates and there are six equations (4 node continuity equations, 2 loop equations). Since one of the node continuity equation is redundant, number of loop equations equals number of unknowns and the system can be solved.

In a P-formulation approach, the unknowns are the nodal pressures. However, atleast one nodal pressure in the pipeline system should be known before a solution can be attempted. For the sample network represented in Figure 4.5, if the pressure at node 2 is known, the node continuity equations are now written as:

\[
\begin{align*}
\text{NODE 1 :} & \quad 465 - C_1(P_1^2 - P_2^2)^{1/n} - C_3(P_1^2 - P_4^2)^{1/n} = 0 \\
\text{NODE 3 :} & \quad C_4(P_2^2 - P_3^2)^{1/n} - C_5(P_4^2 - P_3^2)^{1/n} - 315 = 0 \\
\text{NODE 4 :} & \quad C_3(P_1^2 - P_4^2)^{1/n} - C_2(P_4^2 - P_2^2)^{1/n} - C_5(P_4^2 - P_3^2)^{1/n} = 0
\end{align*}
\]

(4.54) (4.55) (4.56)

In this case, there are three unknowns (P_1, P_3 & P_4) and three continuity equations. Therefore, the system of equations can be solved.

In this study, the P-formulation approach has been implemented. For the general case of N nodes in the pipeline system, the model solves for pressures of (N – 1) nodes using node continuity equations.
4.2 Pipeline Network and Interconnectivity

Pipeline interconnectivity is the key to the analysis; any ill posed description of the pipeline network will offset the results. Therefore, proper care has to be taken in representing the actual field network into the model. A pipeline network can be described in terms of nodes and node connecting elements. Nodes are the points of supply, demand or simply a junction between two or more node connecting elements. Node connecting elements are pipes, compressors, regulators and valves. In this model the node connecting elements are constituted only by pipes and compressors.

All the nodes are numbered sequentially and subsequent pipes are numbered. On completion of the numbering the physical data of the network has to be acquired, it is essentially of two sections. The pipe physical characteristics which include pipe internal diameter, roughness, flow efficiency, length of each pipe segment and the elevation details of each pipe. The node details such as the supply or the demand of gas details have to be entered, the sign convention is positive for supply and negative for demand, if the node happens to be just a junction of two node connecting elements then a zero entered. When a compressor is come across, it is also numbered sequentially along with the pipes and its upstream and downstream nodes which is the suction and discharge end of the compressor and zeros are entered in the place of pipe property specifications. Additional compressor specifications such as compressor constant values and operating scenarios which is a user based choice between suction pressure, discharge pressure or horsepower requirement.
The user has to input the number of nodes, pipes, compressors and loops initially. These values will further be validated by the model by testing the interconnectivity. The pipeline network system description has to satisfy the generic condition of network systems which is given by

\[ N\text{loops} = N\text{Pipes} + N\text{Compr} - (N\text{Nodes} - 1) \]  

(4.57)

where:

\( N\text{Nodes} \): Number of Nodes

\( N\text{Pipes} \): Number of Pipes

\( N\text{Compr} \): Number of Compressors

\( N\text{Loops} \): Number of Loops

**Pipeline Interconnectivity Test**

The pipeline interconnectivity in the model makes sure the network imposed to the model satisfies steady state conditions and if the network interconnection matched the users initial description of the number of nodes, node connecting elements and the number of loops. Essentially this test checks for the following features in the networks description

- Dead-end nodes
- Proper description of pipe inlet and outlet nodes for gas flow
- Node trails to confirm connectivity of the system
The number of pipes connected to every node is evaluated, a node with just one pipe connected to it will be identified as dead-end node, those nodes either have to be a supply or demand nodes. If it fails to have any supply or demand according to the node supply demand details, the model alerts a warning to the user. For example in Figure 4.7 node 3 has to be a supply or a demand node, else the necessity for the existence of such a pipe is questionable.

![Figure 4.7: Representation of a dead-end node](image)

The interconnectivity also tests if all the pipes have at least one incoming flow and one outgoing flow and when a pipe is defined with only incoming or outgoing nodes, it becomes an ill posed problem. This will be alerted to the user and appropriate corrections are to be implemented in the pipe description section of the input file.

The node trails are established starting at the node where the pressure has been specified, the model checks for the nodes connected to one another until all the nodes in the system are checked. If one or more nodes are unchecked, it is an indication that the connectivity of the system has been broken due to faulty pipe connectivity description.

Once the interconnectivity test becomes positive, the model will proceed with solving the system of equations.
4.3 Numerical Solution Approach

The approach employed in solving the system of equations is the Generalized Newton Raphson Iterative procedure. This technique finds the root of a non-linear function, when an initial guess is provided to it. Consider a function \( f(x) = 0 \), where \( x_1 \) is the actual root then \( f(x_1) = 0 \).

By assuming the initial guess to be \( x_0 \), \( x_1 = x_0 + h \)

Expanding \( f(x_0 + h) = 0 \), by Taylor’s theorem, we get

\[
f(x_0) + hf'(x_0) + \frac{h^2}{2!}f''(x_0) + \cdots = 0 \tag{4.58}
\]

Since \( h \) is small, higher powers of \( h \) can be neglected, therefore

\[
f(x_0) + hf'(x_0) = 0 \tag{4.59}
\]

\[
h = -\frac{f(x_0)}{f'(x_0)} \tag{4.60}
\]

Now we get

\[
x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{4.61}
\]

\( x_1 \) is a better approximation, by repeating the same steps a better approximation is obtained. This is done until improvement in the values of \( x \) is negligible, at which point we assume the solution has converged. In general, the Newton Raphson procedure for a single variable can be expressed as:
\( x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}, k = 0,1,2,3 \ldots \) \hspace{1cm} (4.62)

In the proposed model, the node continuity equations need to be solved simultaneously; therefore a matrix for \( N - 1 \) unknowns which would resemble equation 4.63 needs to be constructed. Each row in the matrices represents the non linear equations to be solved. On the left hand side there is the Jacobian matrix, and the deltas of the root matrix and on the right hand side is the residual matrix.

\[
\begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} & \cdots & \frac{\partial f_1}{\partial x_n} \\
\frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} & \cdots & \frac{\partial f_2}{\partial x_n} \\
\frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} & \cdots & \frac{\partial f_3}{\partial x_n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \frac{\partial f_n}{\partial x_3} & \cdots & \frac{\partial f_n}{\partial x_n}
\end{bmatrix}^k \begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\Delta x_3 \\
\vdots \\
\Delta x_n
\end{bmatrix}^k = - \begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
\vdots \\
f_n
\end{bmatrix} \hspace{1cm} (4.63)
\]
Jacobian Matrix

The Jacobian matrix can be constructed by two methodologies, the analytical and the numerical method. In the analytical method the first order derivative of the equations are obtained. For example if we consider a pipeline system as represented in Figure 4.8. Assuming the pressure at node 2 was known, the node continuity equations given by equations 4.64 & 4.65.

\[
\begin{align*}
\frac{d}{dp_1} f_1 & = 100 - C_1 (P_1^2 - P_2^2)^{1/n} = 0 \quad (4.64) \\
\frac{d}{dp_1} f_2 & = C_2 (P_2^2 - P_3^2)^{1/n} - 100 = 0 \quad (4.65)
\end{align*}
\]

Then the Jacobian matrix in the analytical form is represented by:

\[
J_F(p_1, p_3) = \begin{pmatrix}
\frac{df_1}{dp_1} & \frac{df_1}{dp_3} \\
\frac{df_2}{dp_1} & \frac{df_2}{dp_3}
\end{pmatrix}
\]

\[
J_F(p_1, p_3) = \begin{pmatrix}
-1/nC_1(P_1^2 - P_2^2)^{(1-n)/n} 2P_1 & 0 \\
0 & -1/nC_2(P_2^2 - P_3^2)^{(1-n)/n} 2P_3
\end{pmatrix}
\]

Alternatively, Jacobian entries can be computed numerically using backward difference methods. The Jacobian values are given by the difference of function at the k\(^{th}\) iteration and the k \(\rightarrow\) 1\(^{th}\) iteration divided by the difference in the value of the particular unknown. For example, consider the function in equation 4.64 and 4.65, the numerical Jacobian is given as:
Stoner’s Acceleration Scheme

Stoner acceleration method is a technique to improve the speed of convergence of the Newton–Raphson procedure. It checks for the improvement ratio of the solution after the third iteration, which is defined as:

\[
\text{Improvement Ratio (IR)} = \frac{h^{k+3}}{h^k}; k \text{ is the iteration number} \quad (4.69)
\]

Based on this improvement ratio the value ‘h’ is accelerated by imposing certain acceleration parameter ‘Acc’ under the following conditions

**Condition 1:**

When improvement ratio is less than -1.0, the acceleration parameter is given by

\[
\text{Acc} = 0.5 \times \text{abs(IR)}; \text{ for } IR < -1.0 \quad (4.70)
\]
Condition 2:

When improvement ratio is greater than -1.0 and less than 0, the acceleration parameter is given by

\[
\text{Acc} = 1.0 - 0.5 \times \text{abs(IR)}; \text{ for } -1.0 < IR < 0
\]  
(4.71)

Condition 3:

When improvement ratio is greater than 0 and less than 1, the acceleration parameter is given by

\[
\text{Acc} = 1.0 + 2 \times \text{abs(IR)}; \text{ for } 0 < IR < 1
\]  
(4.72)

Condition 4:

When the improvement ratio is greater than 1, the acceleration parameter is given by

\[
\text{Acc} = 3; \text{IR} > 1
\]  
(4.73)

Once the appropriate acceleration parameters are computed based on the acceleration ratio, the new root for the equation at iteration level \( k \) becomes

\[
\text{x}_{\text{new}} = \text{x}_{\text{old}} + \text{Acc} \times h
\]  
(4.74)

This method further improves the value of the unknown at the \( k^{\text{th}} \) iteration, thereby reducing the number of iteration the model takes to solve the system of equations.
Pressure Initialization

The Generalized Newton – Raphson iterative procedure for solving non linear systems of equations has a high dependency on the initial guess for its speed and accuracy. In a system containing a considerably large number of equations, computational speed will be compromised. Therefore by preserving a set of converged solution, we can make use of the converged solutions as initial guesses to the model, this is especially helpful for improving computational speed when different operating conditions are imposed to the model. During the calculation of flow efficiency, the model runs the same input file under different values of flow efficiencies for the pipes in every single iteration; therefore using good initial guesses dictates the speed of computation. When the model fails to converge for a particular node pressure specification, the converged solution for different inputs conditions can be provided as initial guesses for the system to converge.

4.4 In-house Model Demo

The network considered for illustration purposes contains three pipes, four nodes, one loop and one compressor. The network is shown in Figure 4.9 has a supply at node 1 and demand at node 4. Only one compressor is installed between node 2 and 3.
If the pressure at node 1 is known, then the node continuity equation for this system of pipeline can be given as:

**NODE 2:** \[ C_1(P_1^2 - P_2^2)^{1/n} - \frac{HP}{K_1(P_3/P_2)^{K_2} + K_3} = 0 \]  \hspace{1cm} (4.75)

**NODE 3:** \[ \frac{HP}{K_1(P_3/P_2)^{K_2} + K_3} - C_3(P_3^2 - P_4^2)^{1/n} = 0 \]  \hspace{1cm} (4.76)

**NODE 4:** \[ C_3(P_3^2 - P_4^2)^{1/n} - C_4(P_1^2 - P_4^2)^{1/n} - Q_{out} = 0 \]  \hspace{1cm} (4.77)

The essential input parameters to be entered in the model are as follows:

- Number of Pipes
- Number of Nodes
- Number of Compressors
- Pipe Properties
- Node with known pressure specification
- Supply and Demand details
- Fluid Information (Gas Gravity & Z factor)
- Type of Flow Equation
- Type of Jacobian Entry Calculation

All these inputs go into the model on a text file in the format given below in figure 4.10

```
TITLE: SINGLE-COMPRESSOR-EXAMPLE
IIPIPES
3
NNODES
4
NLOOPS ( NLOOPS = NPIPES + NCOMPR - NNODES + 1 )
1
NCOMPR
1
LOCATION(/fnr(1))/vdx(1)/isr(r)/id(r)/d(n)/e(n)/#elopes/L's-5f(1-1-1,#elopes)/ actual elevation-s-f(1-1-1,#elopes)/fromft(10000)
  1  2  100  8300  4  0.00300  1  50000  0  0
  2  2  300  8300  0  0.000  0  0  0  0
  3  1  100  8300  0  0.00000  1  199000  0  0
  4  0  100  8300  2  0.00000  1  199000  0  0
NODE-WITH-PRESSURE-SPECIFICATION: NodeNumber/Pressure(psa)
  1  324.04
COMPRRESSOR INFO: COMP No. / k1 / k2 / k3 / CHOICE / Specf-Value [CHOICE: 1-HR Spec'd; 2-Ad Spec'd; 3-Ps Spec'd]
  1  0.194000  0.17600  0.19400  3  CHOICE
NODE INFORMATION: NODE/SUPPLY AND DEMAND(MSCFD)/MEASURED
  1  5437.000
  2  0.000
  3  0.000
  4  -9921.000
Fluid Information: Gas Gravity / Zav (Use Zav=0.060 if Z factor is to be calculated)
  0.62  0.69
Base Conditions: Psc (psia) / Tsc (F)
  147.7  60.0
Type of flow equation to be used (1-generalized with rfg. friction factor; 2-weymouth; 3-panh-a; 4-panh-b)
  1
Type of Jacobian entry calculation (1=analytical; 2=analytical)
  1
PressInitial.txt file (0=Not needed; 1=Create it; 2=use it when available for P-Initial)}
2. Weymouth equation
3. Panhandle A equation
4. Panhandle B equation

- Compressor operating condition specification
  1. Horsepower specification
  2. Discharge pressure specification
  3. Suction pressure specification

- Equation of State
  1. The average compressibility factor can be fed to the input, or when 0 is entered in the place the model executes the Dranchuk equation of the state to compute for compressibility factor calculation.

- Selection of method for Jacobian construction
  1. Numerical method
  2. Analytical method

- Pressure Initialization for initial guesses
  0. Ignore this option
  1. Create a text file of converged solutions for pressure
  2. Use the text file as inputs for initial guesses for Newton Raphson execution.
After the model had obtained the appropriate information of the network it executes the following steps

1. The model runs the network interconnectivity test, and checks for consistency of the network described by the user and the network description provided to the model. All the node connecting elements are identified. The pressure and compressor specifications will be displayed. The supply demand information is checked across all the nodes to satisfy steady state condition. Once the interconnectivity test becomes a success, it will show all the node connecting elements and the pressure specified node and compressor operating condition. Figure 4.11 displays the snapshot of the interface that will be generated by the model.

<table>
<thead>
<tr>
<th>PIPE 1/1 Slope(s):</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATION 2</td>
<td>TAGGED AS A COMPRESSOR No. 1 **</td>
</tr>
<tr>
<td>PIPE 3/1 Slope(s):</td>
<td>0.0</td>
</tr>
<tr>
<td>PIPE 4/1 Slope(s):</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Simulation will assume as known (constant):

- $P_e$ at node 1 = 324.040000000000 psi
- $P_f$ for Compressor 1 = 289.930000000000 psi

(Node Number = 2)

NETWORK CONNECTIVITY DIAGNOSTICS:
Network is fully communicating!
OVERALL Interconnectivity test a SUCCESS
Node Trail followed to establish overall interconnectivity...
1 2 4 3
READY TO START COMPUTATIONS ... Please press [ENTER]

Figure 4.11: Snapshot of the output interface after interconnectivity test.

2. The number of Newton Raphson iterations, the maximum value of the delta root matrix and the residual matrix are displayed for verification of the proper functioning of the numerical solution method. The user shall expect to see the delta root and the residual numbers decreasing progressively. Once the system of equations is solved, the user can observe the two output parts.
i. Pressures at every node, the conductivity of each pipe, the flow rate across each pipe and the compressor performance details.

ii. Pressure drop across each pipe and the percentage contribution of loss due to friction and pipe elevation.

Figure 4.12 displays a snapshot of how the output interface will appear once the model is run.

3. The outputs are saved and can be retrieved to evaluate the performance of the pipelines by checking for pressure drop across it.

```
| PIPE 1/1 Slope(s): 0.0  |
| 2) LOCATION  |
| 3/1 Slope(s): 0.0  |
| 4/1 Slope(s): 0.0  |

Simulation will assume as known (constant):
  - Friction for Compressor: 324.0400000000000 psia
  - Node Number: 2

NETWORK CONNECTIVITY DIAGNOSTICS:
Network is fully communicating!
OVERALL Interconnection test a SUCCESS
Node Trail followed to establish overall interconnectivity...
1 2 4 3
READY TO START COMPUTATIONS ... Please press [ENTER]

NR It: 1 -- dPmax= 0.0036000 psia -- Resmax= 9834.62502 JacReu= 2
NR It: 2 -- dPmax= 1.0410601 psia -- Resmax= 9881.12495 JacReu= 2
NR It: 3 -- dPmax= 16.6843708 psia -- Resmax= 9484.22866 JacReu= 2
NR It: 4 -- dPmax= 63.2172711 psia -- Resmax= 5985.35596 JacReu= 2
NR It: 5 -- dPmax= 36.3000297 psia -- Resmax= 1977.67234 JacReu= 2
NR It: 6 -- dPmax= 33.3208071 psia -- Resmax= 154.88561 JacReu= 2
NR It: 7 -- dPmax= 0.8219463 psia -- Resmax= 0.99852 JacReu= 2
NR It: 8 -- dPmax= 0.0000015 psia -- Resmax= 0.0000000 JacReu= 2
NR It: 9 -- dPmax= 0.0000000 psia -- Resmax= 0.0000000 JacReu= 2
Successful N-R convergence achieved in 9 iterations

TITLE: SINGLE-COMPRESSOR EXERCISE
P.C.G PREDICTIONS BASED ON Viscous EQUATIONS:
Pc (1) = 324.04 psia - Q (1) = 36.566 - Qx (1) = 9034.623 MSCP
Pc (2) = 209.82 psia - Q (2) = 54.209 - Qx (2) = 9034.623 MSCP
Pc (3) = 419.63 psia - Q (3) = 2.896 - Qx (3) = 9034.623 MSCP
COMPR < 1 Horsepower = 362.8975529192036 HP

TITLE: SINGLE-COMPRESSOR EXERCISE
dP/dx PREDICTIONS BASED ON Viscous EQUATIONS:
dP/dx (1) = -17.7999 psd/mile - 100.00 x friction, 0.00 x elevation
```

Figure 4.12: Snapshot of the output interface after running the model.
CHAPTER 5
FIELD STUDY

The system under consideration is a natural gas gathering and production system owned and
operated by an independent energy company based in Texas. This gas pipeline network has been
in operation for well over two decades and the custody of the field has been acquired and
operated by several different companies, such multiple sales of this field to different operators
has lead to progressive loss in information about the field.

In spite of relatively low flow rates and low pressure of this network, this field has the potential
to produce natural gas in a profitable manner and, by further understanding the flow dynamics in
the network and performing a complete analysis of energy losses, necessary actions can be taken
to evade high energy losses. By doing so, the amplitude of compression will decrease, this
contributes to major savings in operational and maintenance cost of the network. This field also
contributes substantial energy to the regions in its influence; therefore maximum utilization from
this field is paramount for the self sufficiency of energy.

In this study the field pipeline network system under consideration was translated into the input
file by acquisition of every necessary data such as the pipe interconnectivity, pipe properties and
node properties. The flow dynamics of this pipeline network system was simulated using the
computer model developed and history matched with the pressure data available at the well heads.

Once a good match between the field pressure data and model pressure data was achieved, it
could be said that the computer model was in good agreement with the field. The model can now
be employed as a diagnostic tool to analyze the pressure drop and check the flow efficiency of the pipes for possible obstruction or damage.

### 5.1 Field Information

The natural gas gathering and production system under consideration is located in Centre and Clinton counties, Pennsylvania. It is located about 30 miles from University Park campus near the town of Snow Shoe, PA. The region within the black dotted circle in Figure 5.1 shows the terrain of the network and its proximity to The Pennsylvania State University which is indicated by the green arrow.

![Figure 5.1: Aerial view of the natural gas gathering and production system (Source: Google maps).](image)
The mapping of the pipeline network was made using the AutoCAD software (Autodesk 2005) to obtain topographical and the skeletal structure of the gas pipeline network which is displayed in Figure 5.2 and Figure 5.3. The different colors imply specific internal diameters of the pipe. Table 5.1 shows the color nomenclature and the respective internal diameter of the pipes. The pipeline network has five hundred and eighty producing wells and the produced gas is sold off through four supply points. There are five compressor stations, out of which two of the compressors are in-field compressors deployed to facilitate the transportation of the produced natural gas to the supply points. The field is considered very mature with average production rates between seven to ten thousand standard cubic feet. The overall pipe mileage of this network is approximately two hundred and eighty miles.

Extensive corrections were done to the maps in terms of pipe interconnectivity, pipe internal diameter and were brought in line with the actual field set up during the period of this case study. Every well was identified on the map and cross checked with the production data available. It was found that there were approximately 35 wells which were unmetered. With the consent of the operator, the production across these missing wells was set to 0.001MSCFD, since the production from these wells was considered negligible.
Table 5.1: Color nomenclature of pipe internal diameter.

<table>
<thead>
<tr>
<th>COLOR</th>
<th>PIPE INTERNAL DIAMETER (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORANGE</td>
<td>1.58</td>
</tr>
<tr>
<td>RED</td>
<td>2.00</td>
</tr>
<tr>
<td>GREEN</td>
<td>2.38</td>
</tr>
<tr>
<td>BLUE</td>
<td>4.00</td>
</tr>
<tr>
<td>PINK</td>
<td>6.00</td>
</tr>
</tbody>
</table>
Figure 5.2: Topographical map of the natural gas gathering and production system.
Figure 5.3: Skeletal map the natural gas gathering and production system.
Figure 5.4: Sectional split up of the natural gas gathering and production system.
Figure 5.5: Topographical and skeletal map the north section of the natural gas gathering and production system.
Figure 5.6: Topographical and skeletal map **central** section of the natural gas gathering and production system.
Figure 5.7: Topographical and skeletal map **south** section of the natural gas gathering and production system.
For the purpose of modeling, the network was split into three parts namely northern, central and the southern parts as displayed in Figure 5.4. It can be observed that all these parts have their respective sales points. The Figures 5.5, 5.6 and 5.7 display the topographical and the skeletal maps of the separate sections of the network. The northern part produces about 1,500 MSCFD of gas and sends out 500 MSCFD through the northern sales point. The central part and the southern parts produce about 2,500 and 1,500 MSCFD of gas and send out 4,500 MSCFD and 1,000 MSCFD of gas. It is to be noted that there is migration of gas from the southern part and northern part into the central part which contribute to additional gas being vented out from the central sales point.

Properties of the Gas

The gas produced from this field is very typical to any non-associated gas reservoir. It is further confirmed based on the chromatographic data shown in Table 5.2.

It can be noticed that methane makes the majority of the composition. The gallons of hydrocarbon liquid produced per million standard cubic feet of gas were calculated to be less than one. Hence, the hydrocarbon condensation is highly unlikely; thus supporting the assumption of a single-phase model. However, it is still possible to experience multiphase flow due to presence of water.

The specific gravity of the gas ranges between 0.5792 and 0.5879. An average specific gravity value of 0.5830 is used in modeling, which is very close to the specific gravity of pure methane (0.6).
The temperature of the gas is assumed to be 60°F and the maximum allowable operating pressure of the pipes is 700 psia. Hence the compressibility factor is expected to just vary between 0.9 and 1.0, therefore an average compressibility factor of 0.95 is assumed for simulation. The graph in Figure 5.8 displays the compressibility chart for this particular gas.

Table 5.2: Chromatographic analysis of the gas in the natural gas gathering and production system.

<table>
<thead>
<tr>
<th>Hydrocarbon</th>
<th>% mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 – Methane</td>
<td>94.0 – 95.0 %</td>
</tr>
<tr>
<td>C2 – Ethane</td>
<td>2.0 – 2.5 %</td>
</tr>
<tr>
<td>C3 - Propane</td>
<td>0.22 – 0.26 %</td>
</tr>
<tr>
<td>C4s , C5s</td>
<td>&lt; 4 %</td>
</tr>
<tr>
<td>C6**</td>
<td>&lt; 0.15 %</td>
</tr>
<tr>
<td>CO₂</td>
<td>&lt; 0.02 %</td>
</tr>
<tr>
<td>N₂</td>
<td>&lt; 3 %</td>
</tr>
</tbody>
</table>
5.2 Preliminary Modeling

The first step towards modeling the entire pipeline network was to find out the best suited flow equation and respective friction factor that would best suit this pipeline network. A small part of the network comprising approximately fifty pipe and forty one wells was modeled with the well head pressure specified at node 1. The three flow equations used were Weymouth, Panhandle A and Panhandle B. Figure 5.9 shows the map of the section of the network that was modeled followed by the cross-plots of the model simulated pressures to the pressure at the well head in Figure 5.10, Figure 5.11 and Figure 5.12.
Figure 5.9: Topographical & Skeletal map of the section used in preliminary modeling of the natural gas gathering and production system.
Figure 5.10: Cross-plot for Weymouth flow equation.

Figure 5.11: Cross-plot for Panhandle A flow equation.
It can be observed from the cross plot in Figure 5.12 that Panhandle B flow equation was in good agreement with this network. This encouraged the usage of Panhandle B flow equation for modeling the entire network as the matches obtained were good indicating the friction model in Panhandle B suits the pipeline network system.

The northern part of the network shown in Figure 5.9 was considered for modeling with a specific pressure specification corresponding to field data. The result of the modeling is displayed in the cross-plot in Figure 5.13. The points that are on the solid black line are good matches and the two red dotted lines indicate an allowable band width of 20% between the field and model prediction of pressures. It can be noticed that there is a large underprediction of pressures by the model for the given conditions of flow and pipe properties. This can be explained by frictional losses not captured by the Panhandle B flow equation and the multiphase
flow losses due to potential presence of water which could be stagnating in the pipelines. Hence, the flow efficiency of the pipes was considered to incorporate friction in the pipes and thus improve the model predictions.

Figure 5.13: Cross-plot for north section of the field before flow efficiency tuning

5.3 Flow Efficiency Calculation

The term Flow Efficiency ($E_f$) is defined as the ratio of flow rate actually passing through the pipeline to the theoretical capacity of flow rate passing through the pipe. The model initially assumes a flow efficiency of 0.95 for every pipe which is not the case for all the pipes. Hence, this flow efficiency has to be calculated in order to compensate for additional friction losses and multi phase loss due to presence of water in the pipe.
Flow Efficiency can be given by:

$$E_f = \frac{Q_{\text{field}}}{Q_{\text{theoretical}}}$$  \hfill (5.1)

Pipe selection for calculation of flow efficiency

In a large pipeline network system such as the one under consideration, it would be laborious and time consuming evaluate the flow efficiency across every single pipe. Therefore an efficient methodology was implemented to identify only those pipes which suffer high losses and are responsible for the migration of errors during the calculation of errors in the computer model.

The deviations between the model pressures and field pressures are measured as a function of the summation of the squared difference between the model pressure values and the field pressure values. It is represented by:

$$\xi = \sum_{i=1}^{\text{no.of nodes}} (P_{\text{field}} - P_{\text{model}})^2$$  \hfill (5.2)

With this function $\xi$, defined as the error parameter, the pipes most sensitive to error parameter for a change in flow efficiency are targeted. A dynamic search of such pipes is done by imposing a change in flow efficiency of a single pipe and evaluating the impact on the error function. The steps are explained as follows:
i. Run the model with global flow efficiency values of 0.95 for all the pipes.

ii. Evaluate the error function $\varepsilon$ which is now $\varepsilon_{0.95}$

iii. Initialize a loop which sets and resets the flow efficiency of every single pipe between 0.75 and 0.95, as well as calculate the error function value $\varepsilon$ at flow efficiency equal to 0.75 for every individual pipe ($\varepsilon_{0.75}$)

iv. Evaluate the difference $\Delta \varepsilon$ between $\varepsilon_{0.95}$ and $\varepsilon_{0.75}$ for all the pipes.

$$\Delta \varepsilon_i = \frac{\varepsilon_{0.95} - \varepsilon_{0.75}}{\varepsilon_{0.95} - \varepsilon_{0.75}} ; \ i = 1 \text{ to number of pipes} \tag{5.3}$$

v. Find the pipe with maximum value of $\Delta \varepsilon$, which will be $\Delta \varepsilon_{\text{max}}$

Normalize all values of $\Delta \varepsilon_i$ with $\Delta \varepsilon_{\text{max}}$, Therefore

$$\Delta \varepsilon_{i\text{norm}} = \frac{\Delta \varepsilon_i}{\Delta \varepsilon_{\text{max}}} \tag{5.4}$$

$$0 \leq \Delta \varepsilon_{i\text{norm}} \leq 1 \tag{5.5}$$

vi. The pipes with normalized values greater than 0.1 will be the target pipes whose flow efficiencies will be subject to tuning.

**Flow Efficiency Tuning**

The tuning of flow efficiency is an optimization procedure involving minimization algorithms with the following parameters

- Tuning Parameter: Flow Efficiency of target pipes $E_f$
- Objective function: Error Function $\varepsilon$
The algorithm employed to achieve minimum value for Error Function $\epsilon$ by tuning $E_f$ is the \textit{fminsearch} minimization algorithm which is provided by MATLAB optimization tool box. (MATLAB R2007b user’s manual)

This minimization technique provided by the \textit{MATLAB R2007b} optimization toolbox finds the minimum of the scalar objective function by starting with an initial starting point for the tuning parameter which in our case is the flow efficiency. In general, this procedure can be best described as unconstrained non linear optimization, given by

$$\min_{x} f(x) \quad (5.6)$$

where $x$ is a vector and $f(x)$ returns a scalar value.

The \textit{fminsearch} minimization technique in the optimization toolbox of \textit{MATLAB R2007b} uses a \textit{simplex} search method, which is a direct method that does not use numerical or analytical gradients. If $n$ is the length of $x$, then a simplex in ‘$n$’ dimensional space with $n + 1$ vector which are the vertices of the simplex is generated. For example if $n$ is one, then the simplex is a line segment which has two vertices, if $n$ is two then the simplex is a triangle with three vertices or if $n$ is three the simplex is a tetrahedron which has four vertices and so on. Each vertex, which is a vector, is given a new value and the objective function value is calculated, and a simplex with a new vertex is formed. This is repeated for all the vertices until a minimum tolerable diameter change of the simplex is achieved. The new vertices will be the final optimized values of the vector that were subject to the optimization procedure.

This algorithm can handle only real numbers and has the advantage of handling discontinuous functions; however it is less efficient while handling function that are greater than order of two.
UPDATE FLOW EFFICIENCIES

START

GAS NETWORK MODEL

CALCULATE OBJECTIVE FUNCTION (\(\varepsilon\))

FLOW EFFICIENCY MINIMIZATION TOOLBOX

IS \(\varepsilon\) MINIMUM?

NO → UPDATE FLOW EFFICIENCIES

YES → STORE THE FLOW EFFICIENCIES

STOP

Figure 5.14: Flow chart explaining the functionality of flow efficiency calculation.
Implementation of Flow Efficiency Tuning

To implement this optimization function, the gas network model is made to communicate with optimization toolbox. The establishment of this hand shaking algorithm between the gas network model and the optimization tool box is done as described in the flow chart in Figure 5.14 followed by the explanation of its algorithm.

Procedure:

- Provide input to the network for simulation along with the field values at nodes where the pressures are known and zero pressure is assigned to nodes with unknown pressure.
- Initial values of flow efficiency for the target pipes are provided to the toolbox.
- The model simulates the network and obtains an objective function value. This function value is obtained by the minimization algorithm; the toolbox tunes the flow efficiency values and sends them back to the network model.
- This back and forth communication between the network model and the minimization tool box until a minimum value of the objective function is achieved.
- The flow efficiency values for the minimum obtainable objective functions are stored and exported to the original input file.
This technique was initially tested on the Northern section of the network, the new flow efficiency values of the target pipes were calculated and later imported into the input file of the northern section. The results are displayed in the cross-plot on Figure 5.15.

![Figure 5.15: Cross-plot for north section field after flow efficiency tuning.](image_url)

This proved that by tuning the flow efficiencies, the model was able to be in good agreement with the field values. The pipes with poor flow efficiency were suspected to contain stagnant water which blocks the flow of gas and caused the deviation between the model and field pressures. This showed that the technique of flow efficiency tuning was an effective tool for capturing the field physical conditions not captured by the model due to lack of relevant data.
5.4 History Matching

The same procedure was done to the central and the southern sections. The obtained flow efficiencies were then fed into the input file of the entire system. This updated input file of the field was provided to the model. The initial history matching process helped in refining the errors in the pipeline system interconnectivity. By examining the outliers, it was possible to identify the misinterpretation of the pipe interconnectivity based on the original map. Upon visiting the field and cross checking the given map to the actual field interconnectivity, the discrepancies found were corrected and the input file given to the model was updated accordingly. The following results were obtained for four months of production data that was available. Figure 5.16, Figure 5.17, Figure 5.18 and Figure 5.19 each contain three parts each of the cross-plots of the corrected pipeline network system for four different months. The cross-plot for each month was presented in three separate graphs since the number of data points was very large.
Figure 5.16: Cross-plot of pressures for the pipeline system for month 1.
Figure 5.17: Cross-plot of pressures for the pipeline system for month 2.
Figure 5.18: Cross-plot of pressures for the pipeline system for month 3.
Figure 5.19: Cross-plot of pressures for the pipeline system for month 4.
The outliers found in the cross-plots in Figure 5.16, Figure 5.17, Figure 5.18 and Figure 5.19 after correcting the pipe interconnectivity was due to the wells which were producing at the same flow rate for different well head pressures. Figure 5.20, Figure 5.21, Figure 5.22 and Figure 5.23 display the production profiles of some of the outlying wells, the red line is the well head pressure and the blue lines are the production flow rates. The network complexity and the lack of exact field data compromises the accuracy of the model, however with over five hundred and fifty wells and only a handful of outlying wells the model results were declared to be satisfactory with ± 20 % tolerance between the field and model predictions for pressure. The model can now be used as a diagnostic tool for evaluating the network performance by checking for pressure losses in the system to locate potential bottleneck location and the check for pipes with poor transmission capability due to blockage.

Figure 5.20: Production profile of outlying well.
Figure 5.21: Production profile of outlying well.

Figure 5.22: Production profile of outlying well.
Figure 5.23: Production profile of outlying well
CHAPTER 6
ANALYSIS OF RESULTS

Once satisfactory history match of the well head pressures was achieved, this model can now be used as a tool to diagnose the network by checking for pipes with high energy losses. The key indicators of operational problems in a pipe operation optimization program are the pipe pressure drop and line flow efficiencies. Any modification made to the network should lead to the positioning of these two parameters within optimal ranges.

6.1 Flow Efficiency

A total of forty five pipes were subject to flow efficiency tuning, the graph in Figure 6.1 displays pipe flow efficiencies found to be less than 0.7. Figure 6.2, Figure 6.3 and Figure 6.4 indicate the spots where such low efficiency pipes are located in the field. For optimal operation, the line flow efficiency has to be 0.90 (Matar et al, 1984). The pipes with flow efficiencies less than 0.7 are unable to transport fluid to their actual capacity for the prevailing pressure drop, which indicates that they are suffering from blockage.

In Figure 6.2, the pipes with poor flow efficiency were found to contain water based on the feedback provided by the local operator. This section of the pipeline system is located on a hilly terrain and water tends to stagnate on the pipes running downhill. For example, pipe 56 and pipe 184 which are running into the suction of the compressors. The same situation was also noticed in pipe 446 in Figure 6.3 which is also a suction pipe into a compressor as well as pipes 670, 653 and 784 all of them being compressor suction pipes displayed in Figure 6.4. Pipe 653 with a
flow efficiency of 0.13 travels downhill and bends upward which is due to the hilly terrain, therefore the water produced from the wells before this pipe tends to run downhill and stay there as there is not enough energy to push the water upward. As a result the gas flow is blocked considerably. The rest of the pipes are to be checked for the physical condition, since there is a good possibility that those pipes are blocked due to scale formation over years of service.

The pipes with poor flow efficiency are to be examined in-situ and necessary maintenance procedures are to be taken to overcome this problem.

Figure 6.1: Column chart showing low flow efficiency pipes
Figure 6.2: Locations of the pipes with poor flow efficiencies (North section).
Figure 6.3: Locations of the pipes with poor flow efficiencies (Central section).
Figure 6.4: Locations of the pipes with poor flow efficiencies (South section).
6.2 Pressure Drop

Based on the good quality of predictions the pressure drop across the pipes for the production data across four months was calculated and are displayed in the histograms in Figure 6.5, Figure 6.6, Figure 6.7 & Figure 6.8. The red vertical line is the average pressure drop of the system and the pipes to the extreme right of the vertical red line are the pipes that are responsible for high pressure losses in the system and need to be looked upon for replacement. The Table 6.1 gives the four month average pressure drop across these pipes and their respective length. Figure 6.9, Figure 6.10 & Figure 6.11 displays the location of pipes in the field.

![Figure 6.5: Histogram of pressure drop for month 1.](image)

**Avg dp/dx = 1psi/mile**
Figure 6.6: Histogram of pressure drop for month 2

Figure 6.7: Histogram of pressure drop for month 3
In gas network systems, the allowable pressure drop across pipes for optimal operation of the network should not exceed 6.00 psi/mile (Mohitpour et al, 2003). The areas with pressure drop greater than 6.00 psi/mile are flagged as potential bottleneck locations. Table 6.1 displays the average pressure drop across pipes which suffer extensively.

In Figure 6.9, the pipelines indicated with the poorest transmission performance are found within the carrier pipes collecting production from all wells and at the loop convergence point upstream of the compressor. The suction pipe into the compressor suffers a massive pressure loss of about 18 psi/mile which would prove to be operationally expensive. Replacing this pipe with a pipe of a bigger internal diameter would diminish the pressure losses and the suction pressure would become higher and subsequently the compression ratios will lower. Hence, the cost associated to compression is reduced. It is noted that current carrier pipes in this section were poorly designed to handle the current production levels. The set of pipes configured after the discharge of compressor and the small looping pipe 167 that has been truncated before the water body due to
government regulations, and pipe 164 which carries the fluid off the loop suffers a massive pressure drop. In Figure 6.10, pipe 223 and pipe 224 suffer a high pressure drop of 8 psi/mile; these pipes transport almost 1100 MSCFD from the northern section to the central section. These pipes are unable to handle this large inflow of gas which leads to considerable loss of energy due to a bottleneck situation. In Figure 6.11 the pipes 578, 579, 580 and 581 are a typical example of poor design during the construction of this pipeline network, due to the lack of information regarding the dynamics of gas flow in this section of the network. These pipes transport the gas from the upper part of the southern section into the compressor located down south and, by the time they reach the compressor suction, the pressure drops from approximately 60 psia at the well heads to 15 to 20 psia. A remediation action is recommended in the pipes indicated, as they are proving to be detrimental to the natural energy of the gas. Such losses are due to the poor design of the pipeline network and directly affect the compression costs.
Table 6.1: Pressure drop of pipes with highest losses.

<table>
<thead>
<tr>
<th>PIPE</th>
<th>PRESSURE DROP (psi/mile)</th>
<th>AVERAGE PRESSURE DROP (psi/mile)</th>
<th>LENGTH (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Month 1</td>
<td>Month 2</td>
<td>Month 3</td>
</tr>
<tr>
<td>37</td>
<td>7.78</td>
<td>7.68</td>
<td>8.63</td>
</tr>
<tr>
<td>46</td>
<td>9.04</td>
<td>8.93</td>
<td>10.35</td>
</tr>
<tr>
<td>54</td>
<td>16.39</td>
<td>16.46</td>
<td>19.20</td>
</tr>
<tr>
<td>55</td>
<td>17.18</td>
<td>17.29</td>
<td>20.32</td>
</tr>
<tr>
<td>68</td>
<td>8.13</td>
<td>7.97</td>
<td>8.79</td>
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<tr>
<td>167</td>
<td>7.41</td>
<td>7.36</td>
<td>7.61</td>
</tr>
<tr>
<td>223</td>
<td>7.40</td>
<td>7.13</td>
<td>8.05</td>
</tr>
<tr>
<td>578</td>
<td>7.55</td>
<td>6.77</td>
<td>7.77</td>
</tr>
<tr>
<td>579</td>
<td>8.77</td>
<td>8.16</td>
<td>9.46</td>
</tr>
<tr>
<td>580</td>
<td>10.79</td>
<td>9.79</td>
<td>11.46</td>
</tr>
<tr>
<td>581</td>
<td>13.60</td>
<td>11.88</td>
<td>14.15</td>
</tr>
<tr>
<td>583</td>
<td>9.12</td>
<td>6.61</td>
<td>6.59</td>
</tr>
<tr>
<td>585</td>
<td>8.60</td>
<td>6.02</td>
<td>5.98</td>
</tr>
<tr>
<td>642</td>
<td>7.64</td>
<td>5.57</td>
<td>6.08</td>
</tr>
</tbody>
</table>
Figure 6.9: Location of pipes with high pressure losses (North section)

Pipe 37
\[ \frac{dp}{dx} = 8.17 \text{ psi/mile} \]
Length = 1764 ft

Pipe 46
\[ \frac{dp}{dx} = 9.64 \text{ psi/mile} \]
Length = 5773 ft

Pipe 54, 55
\[ \frac{dp}{dx} = 18 \text{ psi/mile} \]
Length = 370 ft

Pipe 68
\[ \frac{dp}{dx} = 8.48 \text{ psi/mile} \]
Length = 2893 ft

Pipe 164
\[ \frac{dp}{dx} = 14.26 \text{ psi/mile} \]
Length = 1347 ft

Pipe 167
\[ \frac{dp}{dx} = 7.5 \text{ psi/mile} \]
Length = 260 ft
Figure 6.10: Location of pipes with high pressure losses (Central section)

Pipe 223, 224

\[ \frac{dp}{dx} = 7.5 \text{ psi/mile} \]

Length = 3900 ft
Figure 6.11: Location of pipes with high pressure losses (South section)

Pipe 578, 579, 580 & 581
\[ \frac{dP}{dx} = 7.46, 8.93, 10.75 \text{ & } 13.2 \text{ psi/mile} \]
Length = 3868, 958, 1634 & 870 ft

Pipe 583 & 585
\[ \frac{dP}{dx} = 7.06 \text{ & } 6.49 \text{ psi/mile} \]
Length = 225 & 666 ft

Pipe 642
\[ \frac{dP}{dx} = 6.27 \text{ psi/mile} \]
Length = 3034 ft
6.3 Effect of new wells in the pipeline system

In the north section of the field, eight new wells were drilled and the production of these wells was introduced into the existing pipeline system in the north section using three inch internal diameter pipes. The eight new wells added an extra 800 MSCFD of gas, to the 113 wells producing approximately 1500 MSCFD of gas in the northern section of the field. The new wells produce at a higher pressure than its neighboring wells, this impacted in an average production loss of thirteen percent in the old wells and the average well head pressures of the wells in this region went up by seventy percent. The north section with the new volumes was modeled by carrying forward the tuned flow efficiencies of the pipes prior to the addition of new wells, the results of the matches are displayed in the cross plot in Figure 6.12, the red dotted lines indicate a 10% bandwidth of allowable tolerance between model pressures and field pressures.

Figure 6.12: Cross - plot of north section with the introduction of new volumes.
The outlying wells are those that are yet to be stabilized, that is the wells are producing the same volumes are different pressures, and some wells show abnormal characteristic such as having higher production rate with a relative increase in the well head pressure when compared with previous production data. However, since most of the points lie within the 10% bandwidth lines, that reinforces the credibility of the tuned flow efficiencies in spite of a considerable change in the flow rate in the system. This section was compared with the north section of the field to check if the pipeline system was efficient enough to accommodate the new production. Figure 6.13 and 6.14 are the histograms of pressure drops in this north section before and after the introduction of the new wells. It can be seen that the average pressure drop was increased from 1.5 psi/mile to 3.5 psi/mile. Table 6.2 and Figure 6.15 compares the pipes with significant pressure drop between the two cases.

![Histogram of pressure drop](image)

**Figure 6.13:** Histogram of pressure drop in the north section before the introduction of new volumes
Figure 6.14: Histogram of pressure drop in the north section after the introduction of new volumes

Table 6.2: Comparison of pressure drop across pipes before and after the introduction of new volumes

<table>
<thead>
<tr>
<th>PIPE NUMBER</th>
<th>OLD VOLUMES dp/dx (psi/mile)</th>
<th>NEW VOLUMES dp/dx (psi/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>14.73</td>
<td>51.74</td>
</tr>
<tr>
<td>54</td>
<td>14.12</td>
<td>48.72</td>
</tr>
<tr>
<td>10</td>
<td>1.61</td>
<td>28.20</td>
</tr>
<tr>
<td>11</td>
<td>0.65</td>
<td>25.87</td>
</tr>
<tr>
<td>37</td>
<td>8.30</td>
<td>24.19</td>
</tr>
<tr>
<td>68</td>
<td>7.82</td>
<td>23.03</td>
</tr>
<tr>
<td>35</td>
<td>7.22</td>
<td>21.78</td>
</tr>
<tr>
<td>46</td>
<td>7.61</td>
<td>21.69</td>
</tr>
<tr>
<td>32</td>
<td>5.59</td>
<td>19.52</td>
</tr>
<tr>
<td>164</td>
<td>13.58</td>
<td>18.09</td>
</tr>
<tr>
<td>30</td>
<td>4.25</td>
<td>17.20</td>
</tr>
<tr>
<td>28</td>
<td>4.23</td>
<td>15.74</td>
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<tr>
<td>26</td>
<td>3.48</td>
<td>14.55</td>
</tr>
<tr>
<td>44</td>
<td>4.82</td>
<td>12.08</td>
</tr>
<tr>
<td>45</td>
<td>4.82</td>
<td>12.08</td>
</tr>
<tr>
<td>22</td>
<td>1.86</td>
<td>11.93</td>
</tr>
</tbody>
</table>

Avg dp/dx = 3.5 psi/mile
By inspection of Figure 6.13 and Figure 6.14, it is clear that the system is currently working at higher nodal pressures with the addition of new volumes. The good matches in Figure 6.12 further validate the predictive capabilities of the model and the calculated flow efficiencies. The presence of few significant outliers (5 out of more of 100 wells) could be explained by the lack of stabilized conditions at the date of the measurement.

Figure 6.16 indicates the pipes with massive pressure losses. These pipes are upstream of the compressors, they are the collector pipes and the suction pipe into the in-field compressor in the northern section, which already had suffered large losses and are now aggravated by the addition of new volumes. The pipes around the area where the new wells have been installed, which previously were functioning within the optimal operating pressure drop range, have started to suffer huge pressure losses. And the discharge pipe from the compressor is also suffering as it is not designed to handle the current volume which has doubled with respect to the old volumes.
It is clear that the new volumes have exacerbated the energy losses in the system, which calls for changes in the existing network before even more volumes can be brought in. Using the existing network to transport additional volumes will lead to unjustifiable energy losses in the system which, on the long run, will impact the operational costs of the pipeline network system.

Figure 6.16: Map indicating the location of pipes suffering massive pressure losses after the addition of new volumes into the northern section.
The network model proved to be an efficient surface pipeline network model capable of diagnosing the field under consideration; the results of the analysis were in good agreement with the field behavior. The predictive capabilities of the model can be further enhanced by linking the surface pipeline network model to the reservoir by introducing the Inflow Performance Relationship of the wells. This will help evolve this model to evaluate the pipeline network from a static flow rate system to a dynamic flow rate system. A comprehensive analysis of the pipeline network and the reservoir can be made for any modifications or expansion that may be done to the pipeline network system.
CHAPTER 7
CONCLUDING REMARKS

A comprehensive single-phase gas network model, capable of performing efficiently and accurately has been demonstrated for a network system in Pennsylvania, was in good agreement with the field data. The methodology employed to capture the flow efficiency of pipes and spot areas of potential water stagnation was proved to be effective. Observation made during field trips confirmed that the model was in good agreement with the fields operating condition.

The model proved to be a good diagnostic tool for screening the whole network for bottlenecks and pipes with poor transmission capabilities. Immediate examination of the bottleneck locations and pipes with high energy losses was recommended for optimal operating conditions of the pipeline network system.

The predictive capability of the model was further tested, based on the good history matches for the system with new volumes; analysis was made to evaluate the performance of this pipeline network. The introduction of new volumes in the existing pipeline system exacerbated the energy losses in the pipeline network. It was recommended that the operator uses an alternate pipeline system to handle the new volumes being produced.

This model can be applied to different fields and customized according to relevant and available field data, by tuning the flow efficiencies of the pipes. By providing the actual compressor performance data to the model, a sub module can be created for evaluating the compression costs involved in the network. The capabilities of this model can be carried forward by linking reservoir and surface operation, thus making it a more comprehensive dynamic flow model.
REFERENCES


