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UNIVERSITI TEKNOLOGI PETRONAS

SIMULATION MODEL FOR PIPELINE NETWORK SYSTEM WITH NON-PIPE ELEMENTS FOR NATURAL GAS TRANSMISSION

by

ABRAHAM DEBEBE WOLDEYOHANNES

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfilment of the requirements for the degree stated.

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Date: 3rd May 2010

SIMULATION MODEL FOR PIPELINE NETWORK SYSTEM WITH NON-PIPE ELEMENTS FOR NATURAL GAS TRANSMISSION

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ABRAHAM DEBEBE WOLDEYOHANNES

A Thesis

Submitted to the Postgraduate Studies Programme

as a Requirement for the Degree of

DOCTOR OF PHILOSOPHY

MECHANICAL ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR,

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MAY 2010

DECLARATION OF THESIS

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DEDICATION

To my beloved wife, Meaza Feyssa, and my daughter, Halleluiah Abraham,

for being with me during this time

ACKNOWLEDGEMENTS

First and for most, thanks to my GOD for giving me the patience to start and finalize this thesis work. I would like to extend my sincere appreciation to my supervisor, Assoc. Prof. Ir. Dr. Mohd Amin Abd Majid, for his valuable support and guidance throughout the completion of this thesis. He spent many of his precious time to teach and guide me. His encouragement, creative suggestions, critical comments and everlasting enthusiastic support have greatly contributed to this thesis.

I would also like to thank my beloved wife, Meaza Feyssa Tolla, for her love and support during all the time. Not only has she encouraged me to pursue my academic interests, she also sacrificed a lot to be with me during this time. For this, I will be forever grateful and acknowledge with gratitude and love the importance of her in my life. Furthermore, great thanks to my daughter Halleluiah for bringing me many funs and pleasures in my life.

I would also like to thank the Universiti Teknologi PETRONAS (UTP) for providing me grant and facility for the research. Furthermore, great thanks for Addis Ababa University for granting my study leave to continue with my graduate studies. I would also like to express my gratitude to PETRONAS GAS BERHAD for the information and data about the gas pipeline networks. Great thanks to Dr. Dereje Engida for revising the thesis and forwarding his comments. It is my pleasure to acknowledge the support from Mr Noraz Al-Kahair Bin Noran for translating the abstract to Bahasa Melayu.

Last but not least, great thanks to my fellow friends for providing me a good atmosphere during my stay at UTP. There are also many people at UTP in one way or another who have helped me. Thank you very much.

ABSTRACT

The ever growing demand for natural gas enhances the development of complex transmission pipeline network system (TPNS) which requires simulation procedures for design and operation of the network. TPNS simulation is usually performed in order to determine the nodal pressures, temperatures and flow variables under various configurations. These variables are essential for analyzing the performance of the TPNS. The addition of non-pipe elements like compressor stations, valves, regulators and others make TPNS simulation analysis more difficult.

A new simulation model was developed based on performance characteristic of compressors and the principles of conservation of energy and mass of the system to analyze TPNS with non-pipe elements for various configurations. The TPNS simulation model analyzes single phase gas flow and two-phase gas-liquid flow. The simulation model also takes into account temperature variation and age of the pipes.

The model was designed for the evaluation of the unknown pressure, flow and temperature variables for the given pipeline network. The two solution schemes developed were iterative successive substitution scheme for simple network configurations and a generalized solution scheme which adopt Newton-Raphson algorithm for complex network configurations. The generalized Newton-Raphson based TPNS simulation model was tested based on the three most commonly found network configurations, namely: gunbarrel, branched and looped pipeline. In all the tests conducted, the solutions to the unknown variables were obtained with a wide range of initial estimations. A maximum of ten iterations were required to get solutions to nodal pressure, flow and temperature variables with relative percentage errors of less than 10^{-11}.

The results of TPNS simulation model were compared with Newton loop-node method based on looped pipeline network configurations and an exhaustive optimization technique based on gunbarrel pipeline network configuration. For both cases, the results indicate that the model is able to provide solutions similar to the compared models. In addition, the TPNS simulation model provides detail information for the compressor stations. This information is essential for evaluation of the performance of the system.

The application of the TPNS simulation model for real pipeline network system was also conducted based on existing pipeline network system. Three modules of TPNS simulation model which included input parameter analysis, function evaluation and network evaluation module were evaluated using the data taken from the real system. Analyses of the performance of compressor for existing pipeline network system which included discharge pressure, compression ratio and power consumption were also conducted using the developed TPNS simulation model. The performance characteristics maps generated by the developed TPNS simulation model show the variation of discharge pressure, compression ratio, and power consumption with flow rate similar to the one available in the literatures.

Based on the results from the simulation tests and validation of the model, it is noted that the developed TPNS simulation model could be used for performance analysis to assist in the design and operations of transmission pipeline network systems.

ABSTRAK

Permintaan yang semakin tinggi untuk gas asli memerlukan pembangunan kompleks sistem penghantaran saluran paip berangkaian (transmission pipeline network system; TPNS) ditingkatkan di mana ia memerlukan prosedur-prosedur simulasi untuk rekaan dan operasi rangkaian. Simulasi TPNS biasanya digunakan bagi tujuan untuk menentukan pelbagai tekanan, suhu dan pembolehubah aliran berbuku di bawah pelbagai konfigurasi. Pembolehubah ini adalah penting untuk mengkaji prestasi TPNS. Penambahan elemen selain paip seperti stesen pemampat, injap, pengatur dan lain-lain menyebabkan analisis simulasi TPNS lebih sukar.

Model simulasi baru dimajukan berasaskan kepada prestasi mesin pemampat dan prinsip penjimatan tenaga dan juga jisim pada sistem bagi menganalisis TPNS dengan unsur selain paip untuk pelbagai konfigurasi. Model simulasi TPNS menganalisis aliran gas satu-fasa dan aliran cecair gas dua-fasa. Model simulasi ini turut mengambil kira pelbagai suhu dan usia paip itu.

Model ini direka untuk menilai pembolehubah tekanan, aliran dan suhu yang tidak diketahui untuk rangkaian saluran paip. Dua skim penyelesaian yang dirangka adalah skim lelaran penggantian berturut-turut untuk konfigurasi rangkaian mudah dan skim penyelesaian am yang menggunakan algoritma Newton-Raphson untuk konfigurasi rangkaian yang sukar. Model simulasi am Newton-Raphson berasaskan TPNS diuji berdasarkan tiga rangkaian paling umum yang didapati di konfigurasi rangkaian iaitu: laras, bercabang dan lingkaran paip. Dalam semua ujian yang dijalankan, penyelesaian pada pembolehubah yang tidak dikenali itu diperolehi dengan satu anggaran julat awal yang luas. Iterasi yang diperlukan adalah sepuluh lelaran untuk mendapatkan penyelesaian untuk pembolehubah tekanan, aliran dan suhu berbuku dengan peratusan kesilapan relatif kurang daripada 10^{-11}.

Keputusan model simulasi TPNS dibandingkan dengan kaedah gelung nod Newton berdasarkan konfigurasi menggelung rangkaian saluran paip dan teknik pengoptimuman yang lengkap berdasarkan konfigurasi laras rangkaian saluran paip. Untuk kedua-dua kes, keputusan menunjukkan bahawa model ini boleh menyediakan

penyelesaian yang mirip dengan model yang sebanding dengannya. Seperkara lagi, model simulasi TPNS menyediakan maklumat terperinci untuk stesen pemampat. Maklumat ini adalah penting untuk penilaian prestasi sistem.

Penggunaan model simulasi TPNS juga diterapkan untuk sistem rangkaian saluran paip sebenar berdasarkan saluran paip sistem rangkaian yang sedia ada. Tiga modul bagi model simulasi TPNS ini termasuklah analisis parameter input, penilaian fungsi dan penilaian rangkaian modul yang dinilai menggunakan data yang diambil dari sistem sebenar. Analisis prestasi pemampat untuk sistem rangkaian saluran paip sedia ada termasuklah tekanan luahan, nisbah mampatan dan penggunaan kuasa juga dikendalikan dengan menggunakan model simulasi TPNS yang dibangun kan. Ciri prestasi 'peta' dihasilkan oleh model simulasi TPNS yang dibangun kan menunjukkan pelbagai tekanan luahan, nisbah mampatan, dan penggunaan kuasa dengan kadar aliran yang menyerupai dengan hasil kajian orang lain.

Berdasarkan keputusan dari simulasi dan pengesahan model ini, ia menunjukkan model simulasi TPNS yang dibangun kan boleh digunakan untuk menganalisis prestasi bagi memudahkan reka bentuk dan pengendalian sistem penghantaran saluran paip berangkaian.

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NOMENCLATURES

$A_1 - A_4$	Constants for normalized compressor head equations
A_P	Cross-sectional area of pipe
AGA	American gas association
$B_1 - B_4$	Constants for normalized compressor efficiency equations
BHP	Break horse power
BSCFD	Billion standard cubic feet per day
C_1, C_2	Constants used to name pipes
C_P	Specific heat at constant pressure
CR	Compression ratio
CS	Compressor station
C_v	Specific heat at constant volume
D	Diameter
D_i	Customer located at *i*
D_{ij}	Diameter of pipe joining node *i* and *j*
D_l	Volumetric flow rate of load pipe *l*
DP	Dynamic programming
E	Pipeline efficiency
f	Darcy's friction factor
f'	Fanning friction factor
F	Transmission factor
g	Acceleration due to gravity
G	Gas gravity
GA	Genetic algorithm
GRG	Generalized reduced gradient
h	Elevation height

H	Adiabatic head
H_L	Liquid holdup
IFD	Information flow diagram
k	Specific heat ratio
K_{ij}	Pipe flow resistance between pipe node *i* and *j*
L	Length
L_{ij}	Length of pipe joining node *i* and *j*
LNG	Liquefied natural gas
M	Mass flow rate
M_f	Total mass flux
M_G	Mass flow rate for the gas
M_L	Mass flow rate for the liquid
MINLP	Mixed integer non linear programming
MMSCMD	Million metric standard cubic meters per day
MMSCFD	Million standard cubic feet per day
n	Rotational speed of the compressor, exponent
n_c	Number of compressors
NDP	Non sequential dynamic programming
n_j	Number of junctions within the pipeline network system
n_l	Number of loops within the pipeline network system
NLP	Non linear programming
N_P	Number of unknown pressure variables
N_Q	Number of unknown flow variables
n_s	Number of compressor stations within the pipeline network system
N_T	Number of unknown temperature variables
N_{Total}	Total number of unknown variables
P	Pressure
P_{av}	Average pressure

P_s, P_d	Suction, discharge pressure of the compressor
P_D	Demand pressure
P_n	Standard pressure condition
q_j	Volumetric flow rate of outgoing pipe j from the node
Q	Volumetric flow rate
Q_{Ci}	Gas flow rate to customer *i*
Q_i	Volumetric flow rate through pipe *i*
Q_m	Volumetric flow rate of the mixture
Q_n	Volumetric flow at standard conditions
r	Roughness of the pipe as function of age
R	Gas constant
R_{air}	Gas constant for air
Re	Reynolds number
Re_m	Mixture Reynolds's number
SA	Simulated annealing
SS	Successive substitution
S_P	Perimeter of the pipe
SCADA	Supervisory control and data acquisition
t	Number of incoming pipe to a node
T	Temperature of gas
T_s	Average soil temperature
T_S	Temperature of the gas at the suction side of the compressor
T_{ij}	Temperature constant between upper node *i* and down node *j*
T_n	Standard temperature conditions
TPNS	Transmission pipeline network system
u	Number of outgoing pipes from a node
U	Overall heat transfer coefficient

v_G	Velocity of the gas
v_L	Velocity of the liquid
v_m	Velocity of the mixture
w	Number of load pipes from a node
x	Mass fraction (quality)
X	Vector representing unknown variables
y	Age of the pipe
Z	Gas compressibility
Z_1, Z_2	Suction, discharge side compressibility of gas

Greek letters

α	Void fraction
η	Efficiency
λ_L	No-slip liquid holdup
μ_G	Viscosity of the gas
μ_L	Viscosity of the liquid
μ_m	Viscosity of the mixtures
υ_G, υ_L	specific gravity of the gas, liquid
θ	Inclination angle
ρ	Density
ρ_G	Density of the gas
ρ_L	Density of the liquid
ρ_{NS}	The no-slip density of the mixture
ρ_m	Density of the mixtures
τ_w	Shear stress at the wall of the pipe

PREFACE

This thesis is submitted as a requirement for the degree of Doctor of Philosophy in Mechanical Engineering for the author. It consists of the research work conducted in the area of simulation of natural gas transmission from July 2006 to March 2010.

The problem was started from the observation of the congestions that usually happened at natural gas distribution centers. The revision of the various literatures on natural gas transportation showed that the distribution centers are the last system and involved less volume of gas. It was observed that the problems occurred on the transmission part of the pipeline network system. The main issues in transmission pipeline network system (TPNS) were the determination of the nodal pressures, flows and temperature variables which were used to evaluate the performance of the system.

A simulation model was developed based on performance characteristic of compressors and the principles of conservation of energy and mass of the system to analyze TPNS with non-pipe elements for various configurations. The TPNS simulation model analyzes single phase gas flow and two-phase gas-liquid flow. The simulation model also takes into account temperature variation and age of the pipes.

The model was designed for the evaluation of the unknown pressure, flow and temperature variables for the given pipeline network. The two solution schemes developed were iterative successive substitution scheme for simple network configurations and a generalized solution scheme which adopt Newton-Raphson algorithm for complex network configurations. The results of TPNS simulation model were compared with Newton loop-node method based on looped pipeline network configurations and an exhaustive optimization technique based on gunbarrel pipeline network configuration. For both cases, the results indicated that the model is able to provide solutions similar to the compared models.

Based on the results from the simulation tests and validation of the model, it is noted that the developed TPNS simulation model could be used for performance analysis to assist in the design and operations of transmission pipeline network systems.

CHAPTER 1

INTRODUCTION

1.1 Background

Natural gas is becoming one of the most widely used sources of energy in the world due to its environmental friendly characteristics. Usually, the location of natural gas resources and the place where the gas is needed for various applications are far apart. As a result, the gas has to be moved from deposit and production sites to consumers either by trucks in the form of liquefied natural gas (LNG) or through pipeline network systems. As reported in [1], short distances gas transportation by pipelines is more economical than LNG transportation. The LNG transportation incurs liquefaction costs irrespective of the distance over which it is moved. As a result, the development of transmission pipeline network system (TPNS) for natural gas is a key issue in order to satisfy the ever growing demand from the various customers.

When the gas moves by using the TPNS, the gas flows through pipes and various devices such as regulators, valves, and compressors. The pressure of the gas is reduced mainly due to friction with the wall of the pipe and heat transfer between the gas and the surroundings. Compressor stations are usually installed to boost the pressure of the gas and keep the gas moving to the required destinations. It is estimated that 3 to 5% of the gas transported is consumed by the compressors in order to compensate for the lost pressure of the gas [2]-[4]. This is actually a huge amount of gas especially for the network transmitting large volume of gas. At the current price, this represents a significant amount of cost for the nation operating large pipeline network system. For instance, considering the U.S. TPNS, Wu [2] indicated that a 1% improvement on the performance of the transmission pipeline network system could result a saving of 48.6 million dollars. Carter [3] also presented that the cost of natural gas burned to power the transportation of the remaining gas for the year 1998 is equivalent to roughly 2 billion dollars for U.S. transmission system.

Investigation on various TPNS indicated that the overall operating cost of the system is highly dependent upon the operating cost of the compressor stations which represents between 25% and 50% of the total company's operating budget as discussed in [5] and [6]. Hence, compressor station is considered as one of the basic elements in TPNS.

The main issues associated with both design and operating TPNS are minimizing the energy consumption and maximizing the flow rate through pipes. Over the years, numerical simulations of TPNS have been carried out in order to determine the optimal operational parameters for given networks with various degrees of success [2], [3], [7]-[9]. From the optimization perspective, the problem of developing an optimal TPNS is nonlinear programming problem where the objective function is typically nonlinear and non-convex, and some of the constraints are also nonlinear. Different techniques are proposed in order to get the optimal parameters of TPNS by either modifying the objective function or relaxing some of the constraints [10]-[15]. However, due to the complexity of the objective function and the constraints, the determination of optimal parameters for TPNS is yet challenging from the optimization perspective.

On the other hand, simulation has contributed significant achievements in analyzing the TPNS problems [7], [9], [14], [16]- [20]. TPNS simulation is used to determine the design and operating variables of the pipeline network for various configurations. The applications of simulation for TPNS can be summarized as follows:

1. Generate and evaluate various configurations of TPNS in order to guide in the selection of optimal system.

2. Assist in making decisions regarding the design and operations of pipeline network systems. During the design process, simulation could assist in selecting the structure of the network and the geometric parameters of the pipes which satisfy the requirements. Furthermore, it also facilitates the selection of sites where compressors, valves, regulators and other elements should be installed.

3. Predict the behavior of TPNS under different operating conditions.

4. Plays a vital role in analyzing the existing TPNS to study how the system responds for future variations in demand and supply. The effect of additional customer sites, the addition of new pipes or compressor stations on the existing system can also be studied with the aid of simulation.

TPNS in most countries consist of a large set of highly integrated pipe networks operating over a wide range of pressures. An increase in demand for natural gas enhanced the development of complex TPNS. The basic problems associated with reasonable operations of TPNS are proper supply of gas to the consumers and low system operating costs. Proper (optimum with regard to a certain criterion) development of transmission pipeline network system, as well as its economically rational exploitation, are only possible if simulation procedures are applied [7].

There are three types of gas transmission networks which include gunbarrel, branched and looped pipeline configurations [6]. The complexity of the simulation analysis depends on the extent of the pipeline network configurations (gunbarrel, branched, looped, etc.), the nature of the gas (single phase dry gas, two-phase gas-liquid mixture) and other factors such as temperature of the gas, the number of sources of the gas (single source, multi-source) and internal pipe corrosion.

TPNS consists of pipes and non-pipe elements such as compressors, regulators, valves, scrubbers, etc. The simulation of TPNS system without the non-pipe elements is relatively easier to handle and developed by Osiadacz [7]. The addition of non-pipe elements makes the simulation of TPNS more complex due to the modeling of the non-pipe elements. More equations have to be added into the governing simulation equations when the non-pipe elements are considered during analysis. Compressor station is one of the main non-pipe components of gas transmission system and considered as a key element.

One of the basic differences among TPNS simulation analysis models with non-pipe elements is in the way compressor station is modeled during simulation. There have been attempts reported by various researchers on modeling compressor stations within the TPNS during simulation [7], [16], [18], [21]. One of the options is to consider the compressor station as a black box by setting either the suction or discharge pressures [21]. Only little information can be obtained to be incorporated into the simulation model to represent the compressor station. The effect of compressor station during simulation of TPNS has been incorporated by pre-setting the discharge pressures [7], [16], [18]. However, the speed of the compressor, suction pressure, suction temperature, and flow through the compressor were neglected during the analysis. Even though there have been attempts reported regarding the simulation of TPNS with non-pipe elements, there are issues that are not addressed.

1.2 Problem Statement

Generally, from the previous approaches on TPNS simulation, it is observed that compressor station is considered as a black box by setting few parameters or its effect is oversimplified during simulation. This is due to the fact that the addition of non-pipe elements makes the TPNS simulation more difficult to analyze. As a result, few attempts [2], [7], [9], [16], [18] and [21]. have been done to have a complete TPNS simulation with all its components. Since compressor station is one of the basic elements in TPNS, the detail incorporation of all its parameters, namely: speed, suction pressure, discharge pressure, flow rates, number of compressors and suction temperatures is essential for a complete simulation of gas pipeline networks.

As the age of the pipe increases, the roughness of the pipe increases due to the accumulation of various elements around the internal surface of the pipe [22]. This might results in decrease in performance of the TPNS system, i.e. lower flow rate capacity and higher pressure drop [23]. Limited information are available in the literatures regarding the roughness with the age of the pipe and the performance of the system. It is beneficial to have a TPNS simulation model to evaluate the performance of the system with the age of the pipes.

In the petroleum industry the transportation of gas and low loads of liquids (usually less than 0.005 holdups) occurs frequently in transmission pipelines for both onshore and offshore operations. The liquids are usually heavy hydrocarbon fractions and water which may be introduced from several sources. Liquids from the compression facilities, and treatment plants as well as products of condensation may also accompany the gas during transportation [24]. The use of single phase flow equation for the analysis of TPNS with two-phase mixtures might lead to underestimation of the pressure drop and flow capacity of the system. As a result, a TPNS simulation model with appropriate flow equations which take into consideration for the existence of liquid in the system is very useful.

1.3 Research Objective

The main objective of this research is to develop a TPNS simulation model for the analysis of the performance of pipeline network system incorporating compressor characteristics, effect of two-phase flow and the age of the pipes.

In order to achieve the objective, the thesis addresses the following issues within the developed methodology:

1. Identifying factors that should have been considered for the design and operation of natural gas transmission pipeline network with non-pipe elements.

2. Formulating detailed mathematical model for the simulation which takes into account the pipeline configurations (gunbarrel, branched and looped), compressor characteristics, nature of the gas (single phase, two-phase gas-liquid), temperature of the gas and the age of the pipes.

3. Developing iterative successive substitution solution scheme for determining the unknown pressure and flow variables and using excel based spreadsheet to assist in evaluating different scenarios of operation of TPNS.

4. Developing Newton-Raphson solution scheme for determining the unknown variables and using visual C++ code to help in evaluating the different scenarios for the design and operation of pipeline network system.

5. Validating the Newton-Raphson simulation model with the aid of appropriate validation techniques which includes simulations,

comparison with previous models, and case study based on the existing pipeline network system.

1.4 Research Scopes

The scopes of the research are summarized as follows.

1. Pipeline network system for moving gas is divided into three classes: gathering, transmission and distribution system. Gathering pipeline network system is responsible for collecting individual gases from gas wells and storage system and move to the gas processing plant. Transmission pipeline network system is used to move the gas from gas processing plant and deliver to the distribution centers and large industrial customers. The distribution network system is responsible for routing of gases to individual customers. This research focuses on the transmission system since all the gases from the gas processing plant passes through this network system. Single source flow with one pipe directing the gas to the compressor station is assumed as the gas processing plant is the only source of gases to the transmission system.

2. Development of TPNS simulation model to make performance analysis for the gas pipeline networks involving flow capacity, compressor ratio and power consumption for the system.

3. In a TPNS problem, the system can be modeled as steady state or transient model depending on how the gas flow changes with respect to time. In a steady state TPNS, the values characterizing the flow of gas in the system are independent of time. On the other hand, transient

analysis requires the use of partial differential equations to describe the relationships between parameters which make the problem more difficult to analyze. In case of transient simulation, variables of the system, such as pressures and flows, are function of time. This research focuses on steady state system which is a common practice in gas pipe line network system.

4. TPNS mainly consists of pipes and many other non-pipe devices such as compressor stations (CS), valves and regulators. Although there are many non-pipe elements in TPNS, CS is the key characteristics in the network. This research focuses on addressing TPNS simulation with CS as non-pipe element. Centrifugal compressor is assumed throughout this study due to its frequent application in gas industry. All the compressors within the compressor stations are arranged in parallel.

1.5 Structure of Thesis

The remainder of the thesis is organized as follows.

Chapter 2 presents the literature review on the existing single phase optimization and the simulation approaches for TPNS problem. It also includes the review of the various two-phase flow models, modeling temperature variations and internal corrosion. The basic solution methods applied in TPNS simulation are also discussed.

The third Chapter describes the methodology used to achieve the objective described in Chapter 1. It includes the detail description of the basic mathematical formulation for the governing simulation equations based on pipeline configurations, nature of the gas, temperature of the gas and internal corrosion of the pipes. The detailed description of the iterative solution schemes to get the unknown variables are also presented in this Chapter. Furthermore, the applications of the TPNS simulation model based on successive substitution and Newton-Raphson for modeling various network configurations are also presented.

The results of the research are discussed in detail in Chapter 4. The results of TPNS simulation model based on successive substitution and Newton-Raphson scheme using various TPNS configurations are presented. Moreover, the simulation model is also tested based on the existing pipeline network system. Results of the simulation model compared with the previous models are also discussed.

Chapter 5 presents summary of the research and the main contributions derived from this research. Issues requiring further study are also addressed in this Chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For the last several decades, numerical simulations of TPNS have been carried out at various stages of TPNS development like feasibly study, economic evaluation, sizing, operations and monitoring of the network with various degree of success. The simulation and optimization of TPNS have been done on the basis of different assumptions. The process of TPNS simulation and optimization become complex depending on the situations considered. The complexity arises from whether the simulation or optimization model consists of single phase or multiphase flow conditions, transient or steady state conditions, isothermal or non-isothermal conditions and single pipe or pipeline networks conditions. Auer [25] discussed the importance of building useful simulation model. The determining factor on how useful the simulation model is its ability to predict the parameters of TPNS under a wide range of conditions.

This chapter discusses the review of the most relevant literatures on the area of single phase flow optimization by introducing the brief history of pipeline development. The review of single phase flow simulation of pipeline networks with non-pipe elements and with only pipe elements are also discussed. Simulation models which consider two-phase flow analysis, temperature variations and internal corrosion are also reviewed. The last part of this Chapter discusses the review of the solution schemes applied for pipeline network simulations.

2.2 Optimization of Gas Pipeline Networks

With increased applications of natural gas in power, industrial, commercial and residential customers, the demand for natural gas is increasing for the past decades [26]. The pipeline network gets more complex as the demand for natural gas increases. This enhanced the importance of optimum design of pipeline network for natural gas distribution system.

The first pipelines were built in the late 1800s to transport coal gas through cast iron and lead pipes for street lighting. Long distance, high pressure pipeline began operating in the United States in 1891 [27]. The development of seamless steel pipes allowed transmission of gas at high pressure and greater quantities [28].

The world pipeline network expanded rapidly when it became apparent that pipelines were an efficient, economic way to move oil, gas, and products to consumers. The main contributing factors for the expansion of pipelines network system were large discoveries of oil and gas in remote areas where there is only little local demand. Pipelines were needed to move these supplies to market [29].

One of the main concerns with both design and operating TPNS is minimizing the energy consumption by the system while satisfying the specified delivery requirements throughout the system. The mathematical formulation for energy minimization of gas transmission network is given by Mercado [6]:

Minimize $$\sum_{(i,j)\in n_s} g_{ij}(Q_{ij},P_i,P_j) \tag{2.1}$$

Subject to

$$\sum_{i=1}^{t} Q_i - \sum_{j=1}^{u} q_j - \sum_{l=1}^{w} D_l = 0 \tag{2.2}$$

$$P_i^2 - P_j^2 = K_{ij}Q_{ij}^2 \tag{2.3}$$

$$P_i \in \left[P_i^L, P_i^U\right] \tag{2.4}$$

$$(Q_{ij}, P_i, P_j) \in D_{ij} \tag{2.5}$$

where D_{ij} represent the feasible operating domain of the compressor stations and $g_{ij}(Q_{ij}, P_i, P_j)$ is the fuel consumption function at the compressor station.

In equation (2.1), the term Q_{ij} represents the flow through the compressor station while P_i and P_j are the suction and discharge pressures. Equation (2.2) is the mass balance equation at each junction where Q_i is the flow through all incoming pipes, q_j is the flow through all outgoing pipes, and D_l is the load flow at each junction node. Equation (2.3) is the pressure drop equation relating the pressures at the upstream and downstream. The term K_{ij} is the pipe resistance which is a function of pipe physical properties. Equation (2.4) represents the upper and lower pressure limits at each node while equation (2.5) is the constraints introduced for compressors to work within the feasible domain.

From the optimization perspective, the problem of developing an optimal TPNS is a nonlinear programming problem where the objective function, equation (2.1), is typically nonlinear and non-convex, and some of the constraints, equation (2.3) and equation (2.5), are also nonlinear. The problem is very difficult due to the non-convex nature of both the objective function and the feasible region. However, various researchers attempted different techniques in order to get the optimal parameters of TPNS by either modifying the objective function or relaxing some of the constraints. The following sections discuss the most commonly used techniques in TPNS optimization.

2.2.1 Dynamic Programming

One of the techniques for TPNS optimization which has been widely applied in previous studies since the late 1960s is dynamic programming (DP). DP approach [30] and [31] for pipeline network optimization was first applied by Wong and

Larson [8]. They applied the method for fuel cost minimization of straight line system and used recursive formulation. The gunbarrel system (Figure 2.1), which is basically straight line type pipeline network system, possesses an appropriate serial structure to be solved by DP.

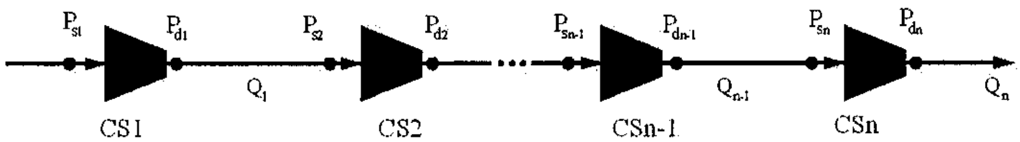


Figure 2.1 Gunbarel structure transmission pipeline network adapted from [8]

Wong and Larson [32] then extended the principle of the application of DP from gunbarrel type gas transmission system to a more general single source tree structured pipeline network system. They decomposed the tree structured network into sequential one dimensional DP problem in order to optimize the network.

For the looped structure, DP has been applied to simplified cases. Carter [3] proposed a DP approach on more general structure with flow rates being fixed. He developed a non sequential dynamic programming (NDP) technique which allows pure DP to general branched and looped systems. In NDP, rather than attempting to formulate DP as a recursive algorithm, two or three connected compressor or regulator elements are replaced by a virtual composite element that behaves just like its components operating in an optimal manner. Three types of composition operations were developed in order to reduce complex system to simple one.

DP has been also combined with other techniques in order to optimize TPNS. Ríos-Mercado et al. [6] and [33] proposed a heuristic solution procedure for fuel cost minimization on TPNS with cyclic (looped) network configurations. The heuristic procedure was based on a two stage iterative. At first stage, gas flow variables are fixed and optimal pressure variables are found via DP. At a second stage, pressure variables are fixed and an attempt is made to find a set of flow variables that improve the objective by exploiting the basic network structure.

Borraz-S'anchez and R'ıos-Mercado [4] developed a hybrid meta-heuristic solution procedure for fuel cost minimization of TPNS with cyclic topology on the basis of DP. The heuristic methodology was based on two stage iterative procedure. In the first stage, gas flow variables are fixed in each network arc and optimal pressure variables in each network node were found via NDP approach developed by Carter [3]. In the second stage, pressure variables are fixed and a short-term memory tabu search procedure was used for guiding the search in the flow variable space. Empirical evaluations have been made on TPNS with different configurations and the results were compared with NDP and Generalized Reduced Gradient (GRG) solution technique. The algorithm is capable of obtaining solution for the instances considered. However, it is computationally expensive when compared to NDP and GRG.

Kim [5] proposed a heuristic solution procedure for minimizing fuel cost consumption of TPNS based on DP. The algorithm used DP as part of an iterative procedure that modifies flow and pressure separately in an attempt to find a better solution. The solution procedure is an iterative process. First, flow variables were fixed by flow modification, and then DP was used to find an associated set of pressure variables. Due to the non convexity of the objective function and the constraints set, there is no theoretical guarantee of convergence to a local or global minimum.

The major reason DP is attractive for optimization of TPNS problem is because it is a general model to apply for this types of problems. Nonlinearities in the system constraints and performance criterion can easily be handled, and constraints on both decision and state variables introduce no difficulties. However, the application of DP is limited to linear (gun barrel) or tree topologies. Furthermore, the computation process increases exponentially with the dimension of the problem as presented in Carter [3].

2.2.2 Mathematical Programming

Although non-linearity of the TPNS problem makes it very difficult to apply the mathematical programming technique as a solution procedure, several researchers have attempted to develop optimal TPNS using mathematical programming approach. The limitation in mathematical programming is that, the nonlinear relationships that exist either in the objective function or constraints have to be approximated by linear relationships. This could result in a deviation from the original problem.

Mőller [11] formulated the optimization of TPNS problem as mixed integer linear programming. The non-linearity in both the objective function and the constraints functions are approximated by piecewise linear functions. A separation and branch-and-bound algorithm were developed in order to get rid off binary variables and to fasten the calculations. The algorithm was tested on large networks to obtain the optimal values for the TPNS. However, the non-linearity and complex relationship between flows and pressures of pipes and compressors make the modeling difficult for the optimization of TPNS.

Wolf and Smeers [12] proposed piecewise linear programming method to solve the gas transmission problem. The authors formulated the problem in gas transmission as cost minimization problem subject to the nonlinear flow pressure relationships, material balance and pressures bounds. The solution method was based on piecewise linear approximation of nonlinear relationships that exist during the problem formulation. The approximated problem is solved by an extension of the simplex method.

Ruz et al. [13] developed modular, constrained based model for TPNS in order to answer questions concerning the supply, demand and transportation in the context of optimization. The goal of the model was precise estimation of its transport capacity to be used in a wider logistic model. The planning and scheduling for gas supply used a mixed integer optimization model and consists of a set of interconnected modules. Each module implements the behavior of a physical device of the gas transmission network. The model approximates the nonlinear relationships for pipes and compressor stations by linear functions.

Hoeven [14] formulated the gas transmission problem as constrained network simulation model by linearizing the nonlinear relationships. The method was based on modeling each of the elements of TPNS (compressors, pipes, valves, reducer, etc) as constraints and relationships. The linearized equations were finally solved using an iterative scheme.

Pratt and Wilson [10] proposed a mathematical programming approach for optimization of the operation of TPNS. Their approach solves the nonlinear optimization problem iteratively by linearizing the gas flow equations, constraints and objective functions to give a linear constrained problem. The linear constrained problem then optimized by mixed integer linear programming and solved using branch and bound algorithm technique. The re-linearization about the optimum will repeat until a convergence is obtained for the system. They included compressor fuel cost and cost of flows from sources as the objective functions.

Percell and Ryan [34] proposed an algorithm using generalized reduced gradient scheme for minimizing the fuel consumption problem for TPNS. Being a method based on gradient search, there is no guarantee for a global optimal solution, especially when there are discrete decision variables.

Abbaspour [9] developed a solution procedure for tackling pipeline operation problem using simulation based optimization. The first step is to device an analysis scheme that provides the simulation support required by the optimization. By gaining some information from the simulation, the problem of gas transmission operation was modeled as non linear programming (NLP) and solved with the sequential unconstraint minimization technique. Since the method is based on gradient search, there is no guarantee for global optimal solution. Furthermore, the optimization is done at the station level rather than at network level.

Baumann et al. [15] presented a gas network optimization program (GassOpt) as a decision support to the design of pipeline network system. The program has been developed for transport analysis and planning purpose in order to calculate optimal routing of natural gas in pipeline network system. The simulation program is developed based on linear programming and optimizing engine.

Osiadacz and Gorecki [35] and Wu et al. [36] proposed solution algorithms that tries to minimize the cost of development of pipes. The algorithms are based on approximation of the non-linear relationships with linear constraints. A statistical modeling technique for the design and operation of TPNS based on Monte Carlo simulation has been proposed by Chmilar [37]. The approach is based on performing successive approximations or estimations of the system load (flow) and capability to generate an overview of how the system can be expected to perform.

2.2.3 Expert System

Different scholars [38]–[41] have used expert systems approach in order to optimize the operations of TPNS. One of the main challenges that exist in applying the expert system for optimizing TPNS operation is knowledge extraction. The knowledge that may be extracted through interviews of experts from the natural gas industry might not be sufficient enough to actually represent the real situations.

Sun et al. [38] proposed expert system to enhance the decision making abilities of the dispatcher in order to optimize the natural gas operation. Sun et al. [39]

developed an integrated approach, both expert systems and operations research techniques to model the operations of the gas pipelines. In the integrated model, the expert system performs the decision to inform the dispatcher on the current system linepack level with the associated control action to be issued and how much horsepower should be added/reduced to satisfy future demand. On the other hand, the decisions to turn on/off which compressor are handled by the mathematical model adopted in the operations research. The model was tested on branched TPNS with two compressor stations serving two customers. The optimization program exhaustively tests all possible combinations of the compressors which increase the complexity of the decision when the number of compressors increases.

Uraikul et al. [40] and [41] proposed an expert system as a decision support tool to optimize natural gas pipeline operations. The expert system was developed as a feasibility study on applicability of expert system technology to pipeline optimizations. The three major tasks that the proposed expert system performs in order to provide decision support to the operators are:

- Determining whether the linepack is high, low or enough,
- Suggesting the amount of break horsepower needed to increase or decrease the linepack, and
- Recommending a compressor unit to turn on or off.

The proposed technique highly depends on the knowledge acquisition which has been derived from historical data analysis, heuristic knowledge from expert operators from the natural gas industry and a computer simulation model. Furthermore, the expert system in its current version does not adequately deal with uncertain information.

Chebouba et al. [42] proposed ant colony optimization algorithm to solve how to operate TPNS efficiently. The algorithm was tested on straight line pipeline (gun barrel) network system with five compressor stations. An optimal operating policy for TPNS was developed for two different flow rates. The results were compared with that of DP approach and it was reported that the results obtained were similar in most of the cases with less computational time.

Mora and Ulieru [43] used genetic algorithm to reduce the energy used to operate compressor stations in TPNS problem. The solution methodology was based on two stages. The first stage of the methodology was the use of genetic algorithm for speeding up the searching process to provide a solution in a timely manner. Each candidate solutions generated by the search algorithm has been evaluated by hydraulic model that simulates the steady state gas flow in the TPNS to obtain the reaction of the system at specific control nodes and determine the feasibility of the given solution at the second stage. Genetic algorithm has been attempted for gas transmission network [44] and [45].

2.2.4 Analytical Hierarchical and Network Reduction

Hierarchical structure and network reduction techniques have been suggested by various researchers as solution procedures when it is difficult to solve the gas transmission problem in an integrated way. Analytical hierarchical approach involves the decomposition of the gas transmission network problem into pipeline network level and compressor station level. Some degree of success has been achieved as far as the optimization of the compressor station subproblem is concerned. However, as stated by Mercado [6], these approaches have limitations in globally optimizing the minimum cost.

Osiadacz [46] developed an algorithm for optimal control of gas network based upon hierarchical control technique. The network was divided into physically small subsystems by imposing a constraint of incorporating at least one operating compressor in each subsystem. Local problems were solved using gradient technique. The subsystems were coordinated using "goal coordination" method to find the overall optimum.

Wu et al. [47] developed an algorithm for optimal operation of pipeline network system based on relaxation of the objective function (fuel cost minimization) and the constraint (the feasible domain of the compressor station). The authors generated four different problems for the given network and showed the differences that exist by solving the original problem and,

- The modified problem by relaxing the feasible domain of compress stations,
- The modified problem by relaxing the fuel cost function, and
- The modified problem by relaxing both the feasible domain of the compressor stations and the fuel cost function at the same time.

The authors considered three network problem instances. The first two problems were a kind of network where one can get the optimal solution through exhaustive search method. It has been reported that, lower bound solution gave an approximated solution with good relative optimality gap for the two problem instances considered in the paper. However, no comparison was made about the approximation of the lower bound for the third problem as it is difficult to get the optimal solution.

Rios-Mercado et al. [48] proposed a network reduction technique for TPNS optimization problem based on a combination of graph theory and non-linear functional analysis. It has been reported that, the reduction technique reduced the problem size significantly without disrupting its mathematical structure. However, no comparison has been made to justify the applicability of the procedure and its effectiveness compared to the existing approaches. Mohring et al. [49] presented a methodology of automated model reduction for TPNS. The method is based on computer algebra to compose automatically the model equation for different components of TPNS (pipe, compressor, regulator, etc...). It has been reported that the model complexity could be reduced significantly when the method is applied for the network. However, checking of whether the parameter is within the predefined errors is also a time consuming process.

2.3 Simulation of Gas Pipeline Networks

There are various definitions for the term simulation. One of the definitions which is adopted in this thesis is the definition by Chung [50]. Simulation modeling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system. A system is defined as a collection of interacting components that receives input and provides output for some purpose.

The simulation modeling and analysis of different types of systems are conducted for the purposes of gaining insight into the operation of the systems. The simulation analysis can be used for developing operating or resource policies to improve system performance and testing new concepts. It is also used for gaining information without disturbing the actual system and generating sample operations of the system with different patterns and configurations [50].

Simulation of gas pipeline networks could be used to determine pressure, flow and temperature variables of the network under different conditions. As a result, based on the variables obtained, simulation could assist in the decisions regarding the design and operation of the real system. Osiadacz [7] stated that at the stage of designing TPNS, simulation could help to select the structure of the network and the geometric parameters of the pipes which satisfy supply and demand requirements. At the stage of operating TPNS, simulation could help to make various scenario analyses in order to guide for optimal operations.

The complexity of simulation of gas pipeline network depends on the extent of the system. Some authors performed pipeline network simulation analysis by neglecting the non-pipe elements of the network or oversimplify their effect. The following sections discuss the most related literatures on pipeline network simulation with or without the non-pipe elements.

2.3.1 Simulation of Gas Networks without Non-pipe Elements

Pipeline network simulation without non-pipe elements like compressor stations, valves, regulators is less challenging as it involves only pipes. The number of equations and the type of equations are less compared to the simulation of pipeline network elements with all its components. For instance, assuming constant temperature of the gas, only pipe flow equations and mass balance equations are involved during the simulation of the pipeline network system without non-pipe elements. The simulation of pipeline network system without non-pipe elements are developed by Osiadacz [7] based on graph theory.

One of the governing equations during the simulation of TPNS without non-pipe elements is pipe flow equation. The flow of gas through pipes can be affected by various factors such as the gas properties (specific gravity, viscosity, compressibility and density), friction factor and the geometry of the pipes.

The relationships between the upstream pressure, downstream pressure and flow of the gas in pipes for steady state conditions can be described by various equations [7] and [23]. Friction factor is one of the main reasons for the variation of flow equations.

In this thesis, general flow equation is adopted due to its frequent application in gas industry [2], [5], [7] and [8] to describe the relationships between pressure difference and gas flow in pipes. The general flow equation for the steady flow of gas in a pipe is derived from Bernoulli's equation. For an inclined pipe shown in Figure 2.2, with length L and diameter D, the pressure drop between upstream node 1 and downstream node 2 of the pipe can be expressed using general flow equations as [7]:

$$P_1^2 - P_2^2 = \frac{64}{\pi^2}\frac{fGZT}{R_{air}D^5}Q_n^2\left(\frac{P_n}{T_n}\right)^2 L + \frac{2P_{av}^2 G}{ZR_{air}T}gh \tag{2.6}$$

Hence, from equation (2.6), the flow Q_n is given by

$$Q_n = \sqrt{\left(\frac{\pi^2 R_{air}}{64}\right)} \times \frac{T_n}{P_n}\sqrt{\frac{\left\{\left[\left(P_1^2 - P_2^2\right) - \frac{2P_{av}^2 Ggh}{ZR_{air}T}\right]D^5\right\}}{fGZTL}} \tag{2.7}$$

If the pipe is horizontal, the elevation term $2P_{av}^2 Ggh/(ZR_{air}T)$ is zero and equation (2.7) reduces to

$$Q_n = C \times \frac{T_n}{P_n}\sqrt{\frac{[(P_1^2 - P_2^2)\, D^5]}{fGZTL}} \tag{2.8}$$

where $C = \sqrt{\left(\frac{\pi^2 R_{air}}{64}\right)}$

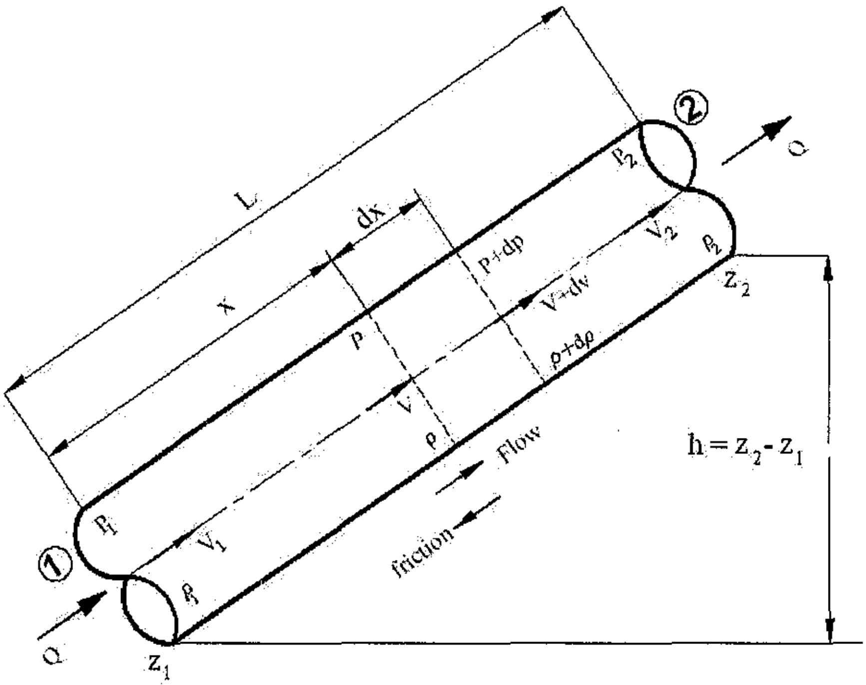


Figure 2.2 Flow of the gas though pipe adapted from [7]

Several flow equations are in use in the gas industry, all of which are modification of the general flow equations. The differences between them depend mainly on what expression is assumed for the friction factor f. Table 2.1 shows the summary of the various flow equations relating the upstream node i and downstream node j pressures for horizontal pipes. Note that for determination of the pipe flow resistance K_{ij}, $G = 0.589$, $T = 288^0 K$, $P_n = 101 kPa$, $T_n = 288^0 K$, $R_{air} = 287.5 J/kg K$, $Z = 0.95$ are assumed throughout all equations.

Table 2.1 Gas flow equations and range of applications adapted from [7] and [23]

Name of Equation	Range of pressure	Equation
General	> 700 kPa	$P_i^2 - P_j^2 = K_{ij}Q_{ij}^2$ $K_{ij} = 3.69\times10^4 \frac{fL}{D^5}$
Panhandle 'A'	>700 kPa	$P_i^2 - P_j^2 = K_{ij}Q_{ij}^{1.854}$ $K_{ij} = 1.67\times10^5 \frac{L}{E^2 D^{4.854}}$
Weymouth	>700 kPa	$P_i^2 - P_j^2 = K_{ij}Q_{ij}^2$ $K_{ij} = 8.15\times10^8 \frac{L}{E^2 D^{7.113}}$
Polyflo	75 to 700 kPa	$P_i^2 - P_j^2 = K_{ij}Q_{ij}^{1.848}$ $K_{ij} = 2.79\times10^5 \frac{L}{E^2 D^{4.848}}$
Lacey	0 to 75 kPa	$P_i - P_j = K_{ij}Q_{ij}^2$ $K_{ij} = 1.80\times10^6 \frac{fL}{D^5}$

In addition to the pipe flow equations, mass balances provide the remaining basic equations of the governing equations for the simulation of TPNS without non-pipe elements. The mass balance equations can be obtained based on the principle of conservation of mass at each junction of TPNS as presented in equation (2.2).

In practical situations, the non-pipe elements like compressor stations are usually encountered in gas transmission network systems. As a result, it is important to address the effect of these elements into the simulation model. This study focuses on the simulation of TPNS with non-pipe elements.

2.3.2 Simulation of Gas Networks with Non-pipe Elements

The addition of non-pipe elements makes the simulation of pipeline network system more complex and difficult to handle. More equations have to be added into the governing simulation equations when the non-pipe elements are considered during simulation analysis. Compressor station is one of the main non-pipe components of any gas transmission system and considered as a key elements [5] and [6]. It adds energy to the gas in order to overcome the frictional losses and to maintain the required delivery pressures and flows. Bloch [51] and Hanlon [52] discussed the applications and basic principles of compressors.

One of the basic differences among TPNS simulation models is the way how compressor station is modeled during simulation. Several attempts have been made by various researchers on modeling compressor station within the pipeline network system during simulation. One of the option which is suggested by Letniowski [21] is to consider the compressor station as a black box by setting either the suction or discharge pressures. In this case, only little information can be obtained to be incorporated into the simulation model. Compressor station provides mass balance equation and information regarding the suction pressure which are the two equations added to the remaining pipe flow equations to have a complete model for the network.

Osiadacz [7] incorporated the effect of compressor station for simulation of pipeline network system by presetting the discharge pressures at each compressor stations. The procedure started by making a cut-off at compressor stations. The nodes representing compressor stations in the node data table become input nodes and the compressor station output is denoted by an additional node. After the cut-off is made, all nodes with preset discharge pressures become reference nodes. Reference nodes are nodes where the pressure is known in advance of the simulation.

Nimmanonda et al. [16] developed a computer aided model for design of a simulation system for TPNS which enhance iteration between the user and the system. The simulation design program obtains the input data (pipeline pattern, natural gas constituents, number of compressors at each station, compressors' horsepower, pipe size, range of operating pressure, and customers' consumption) to generate the variables of gas properties, pressures, and flow rate of the entire pipeline system. Continuity, mass balance, and energy balance equations were considered to simulate the pipeline system. The simulation system can generate sample operations of the TPNS with different configurations. However, the authors did not mention how the compressor stations are handled during the simulation. Only TPNS without loop was considered during the simulation model. Furthermore, the simulation model is developed for specific geographic location which limits its applicability to the various weather conditions.

Nimmanonda [18] developed computer aided simulation model for natural gas pipeline network system operations where the compressor stations are modeled based on the relationships between flow rate, break horse power (BHP), and compression ratio. The relationship between compression ratio, BHP, and flow was developed for three flow categories. The model needs presetting either the suction or discharge pressure and also the speed of the compressors was not taken into considerations.

The modeling of compressor station integrated in TPNS is very difficult as the compressor stations may contain various compressors with different arrangements. However, there have been various attempts conducted to optimize and simulate the operation of only the compressor stations [19], [53]-[58]. The most commonly used compressors in gas industries are centrifugal and reciprocating. Centrifugal compressor is assumed throughout this study due to its frequent application in gas industry.

Usually, the data related to compressor are available in the form of compressor performance characteristics as shown in Figure 2.3. In order to integrate the characteristics of the compressor into the simulation model, it is necessary to approximate the characteristics map with mathematical models. The basic quantities related to a centrifugal compressor unit are inlet volume flow rate Q, speed n, adiabatic head H, and adiabatic efficiency η. The mathematical approximation of the performance map of the compressor can be done based on the normalized characteristics.

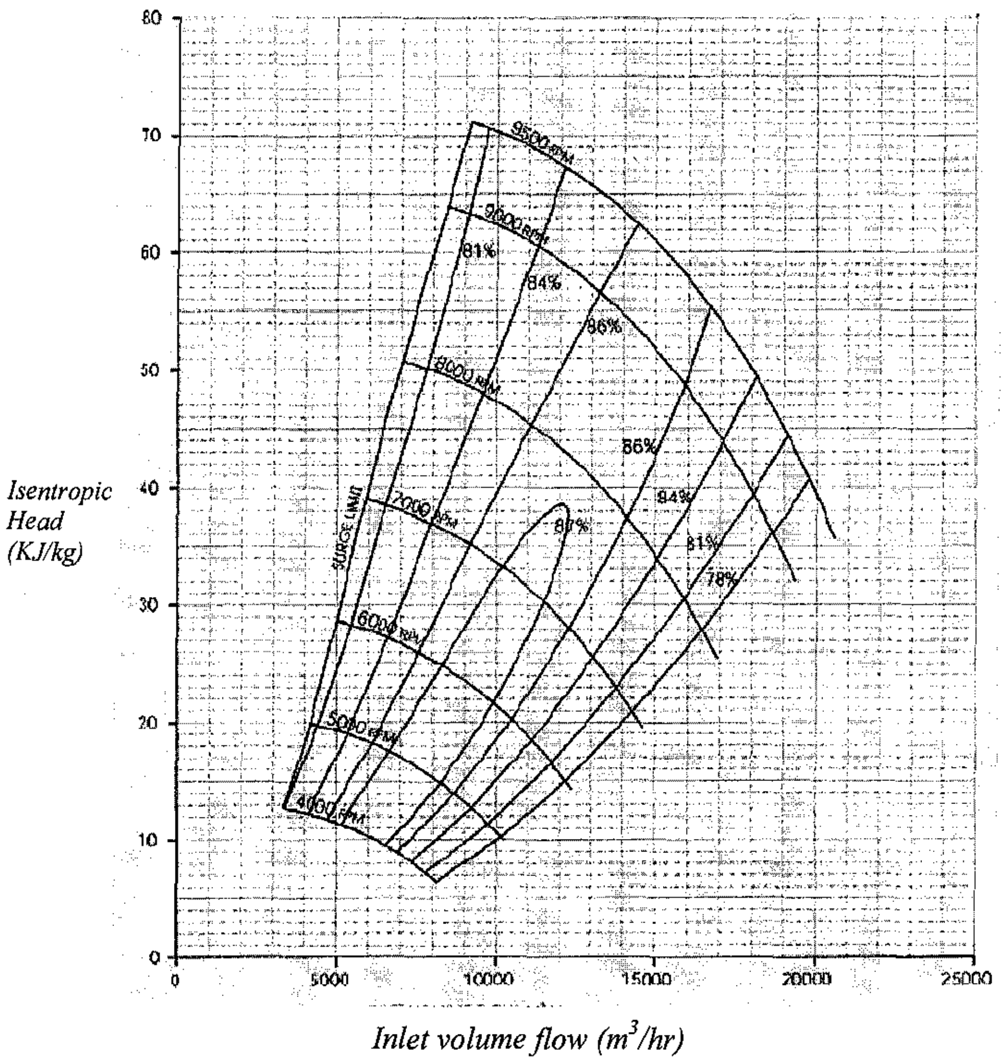


Figure 2.3 Typical performance map of centrifugal compressor [59]

The three normalized parameters which are necessary to describe the performance map of the compressor includes, H/n^2, Q/n and η [60]. Based on the normalized parameters, the characteristics of the compressor can be approximated either by two degree [9] or three degree polynomials [2]. Three degree polynomial which gives more accurate approximation is used in this study. Applying the principles of polynomial curve-fitting procedures for each compressor, the relationship among the basic normalized parameters can be best described by the following two equations:

$$H/n^2 = A_1 + A_2(Q/n) + A_3(Q/n)^2 + A_4(Q/n)^3 \tag{2.9}$$

$$\eta = B_1 + B_2(Q/n) + B_3(Q/n)^2 + B_4(Q/n)^3 \tag{2.10}$$

where A_1, A_2, A_3, A_4 and B_1, B_2, B_3, B_4 are constants which depends on the unit to define a particular compressor.

Equation (2.9) was used as basis for modeling the governing simulation equation to represent the compressor stations. The detail modeling of compressor stations within the TPNS will be discussed in Chapter 3.

2.4 Simulation Models with Two-phase, Temperature and Corrosion

As discussed in the previous section, one of the variations among the simulation models is whether the model addresses the non-pipe elements or not. Apart from the elements of the pipeline network system, TPNS simulation models have variations among themselves based on nature of the gas. Some models assume only single phase dry gas during the modeling of the flow equations. On the other hand, some models perform the simulation based on two-phase gas-liquid mixture assumption. The other variation among simulation models for gas transmission systems comes from assumption of temperature of the gas and internal pipe corrosion during modeling. This section presents the review of related literatures on the effect of two-phase gas-liquid mixtures analysis, temperature, and internal corrosion during the simulation of TPNS.

2.4.1 Two-phase Flow Models

Usually, in a petroleum industry both gas and low load liquids might occur in natural gas gathering and transmission pipelines network system [61] and [62]. The sources of the accompanying liquids could be compression facilities, treatment plants, and/or condensation of the gas during transportation process. Several researches have been conducted on modeling the effect of the liquids on the transmission efficiency of the TPNS. The followings are the review of most related literatures on the area of the transmission of gas and low load liquids.

The accompanying liquids during the transmission of gas will affect the transportation efficiency of the system. Asante [24] suggested that, most gathering pipelines (which typically have liquids loads up 560m^3/Million m^3 of gas) transport fluids as multiphase components. On the other hand, for transmission pipelines, where the liquid entrainment is usually less than 56m^3/Million m^3 of gas, most pipeline companies typically employ "dry gas" models to predict the transport capabilities of the system. In reality, the accompanying liquid may travel as a film or may be distributed as dispersed droplets in the predominant gas phase. Both the film and the droplets impede the flow of gas through the pipe. It has been reported in [62] that, liquid loads of 5.6m^3/Million m^3 of gas reduced the transmission factor of the pipeline network system by 1%.

Ellul et al. [63] presented the summary of the basic available equations in multiphase flow conditions. The authors described the current available techniques for the analysis of multiphase flows. The two methods for the analysis of multiphase flow conditions are empirical approach and mechanistic approach. The former is developed based on setting a correlation among parameters of the flow on the basis of the experimental data for the range of conditions. The later is developed based on the physical phenomenon of the fluids. One of the limitations that are observed in the empirical approach is that, the method primarily aims to produce correlation valid mainly over range of the measured data. On the other hand, the mechanistic modeling approach could be used to generate relationships which are useful for wide range of data.

Golczynski [64] emphasized on the importance of addressing the effect of multiphase during the design of pipeline network for optimal operation of TPNS. Asante [61] proposed the application of various two-phase flow analysis models based on the liquid holdups. For liquid holdups less than 0.005 (typical in gas transmission system), homogeneous approach has been recommended. When the liquid holdups is greater than 0.005 (which is common in gas gathering pipeline systems), stratified two-phase flow approach has been recommended.

Boriantoro and Adewumi [65] and Leksono [66] developed an integrated single/two- phase steady state hydrodynamic model for predicting the phase change and flow regime of fluid flow in pipes. The model predictive capability has been tested using limited field data and published data in flow regimes. Stanley and Vaderford [67] presented an online simulation to track the operation of two-phase wet gas pipelines. The simulation continually receives supervisory control and data acquisition (SCADA) updates assuring accurate conformance to the actual pipeline.

Taitel and Dukler [68] developed a mechanistic model for analytical prediction of transition between flow regimes. The approach also provided considerable insight into the mechanisms of the transitions. The model was tested against data mainly collected in small diameter pipe under low pressure conditions. An attempt of flow regime prediction for inclined, large diameter pipes has been done by Wilkens [69] which could be used as basis for developing the pressure drop equations.

More recently, Shoham [70] developed a mathematical mechanistic model for predicting of various two-phase flow behaviors. The model is based on the physical phenomenon of the important flow parameters. However, the derivation of the basic equations which represents the entire physical phenomenon requires rigorous computations.

Generally, as it is reported in various literatures [24], [66], and [70], single phase modeling approaches might not be adequate enough to predict the transport capabilities of the pipelines when gas and liquids move as mixture. A two-phase analysis or single phase analysis with modified friction factors may be required to adequately predict the transport capabilities of such system.

There are various two-phase flow models reported in literatures [62], [65], and [70]. The types of two-phase flow models that could be implemented for the system depends on the nature and the amount of liquid that exist within the system. The parameters of two-phase flow like the pressure drop, liquid holdup, and others are strongly dependent on the existing flow pattern. As a result, the determination of flow pattern is a key issue in two-phase flow analysis. The following sections discuss the basics of flow patterns and the detail of homogeneous flow patters which is the common flow pattern that exists in transmission pipeline network system.

2.4.1.1 Flow Pattern

The review of literatures on flow patterns reveals that there have been variations among two-phase flow researchers on the definition and classification of flow patterns. One of the main variation resulted from the complexity of flow phenomena that occurred during the two-phase flow.

Flow pattern is the geometrical configuration of the gas and liquid phases in the pipe and it occurs in a gas-liquid two-phase flow. When a gas and a liquid flow simultaneously in a pipe, the two phases can distribute themselves in a variety of flow configurations. The flow configurations differ from each other in the special distribution of the interface, resulting in different flow characteristic, such as velocity and holdup distributions. Flow pattern in a given two-phase flow system depends on operational parameters, geometrical variables, and physical properties of the two-phases [70].

Flow pattern developed by Taitel and Dukler [68] is the most commonly used flow pattern in the analysis of two-phase flow. Figure 2.4 shows the flow patterns existing in horizontal and near-horizontal ($\pm$ 10^0 inclined) pipes developed by Shoham [70].

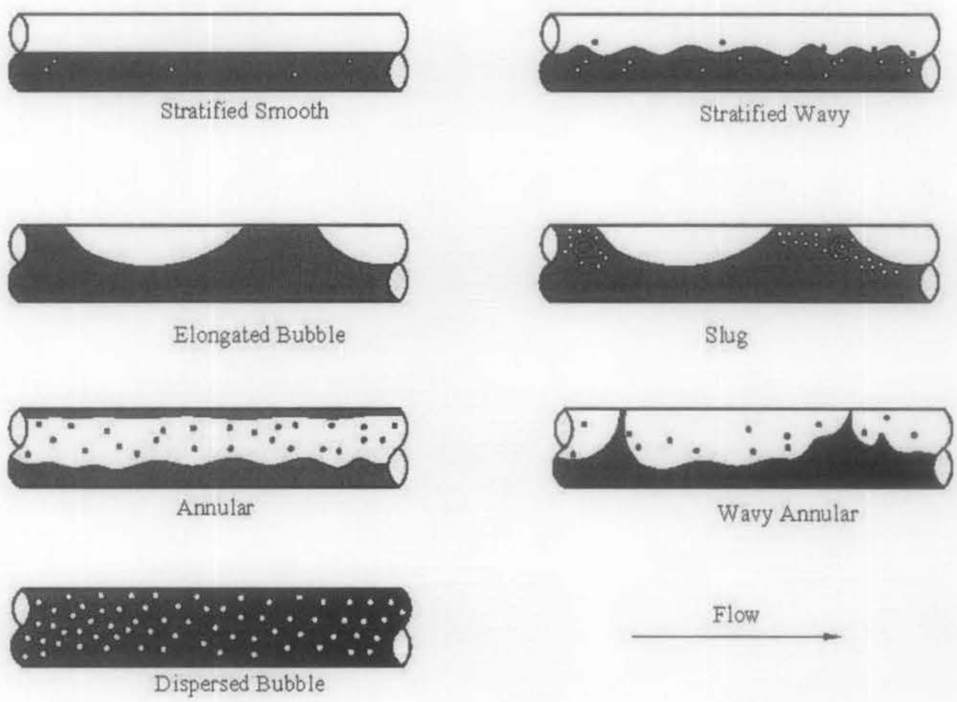


Figure 2.4 Flow pattern in horizontal and near-horizontal pipes [70]

The existing flow patterns in horizontal and near-horizontal flow configurations can be classified as [9] and [70]:

- ***Stratified smooth flow:*** this flow pattern occurs at relatively low gas and liquid flow rates. The two phases separated by gravity, where the liquid-phase flows at the bottom of the pipe and the gas-phase on the top. The interface between them is smooth.

- ***Stratified wavy flow:*** increasing the gas velocity in a stratified flow, waves are formed on the interface and travel in the direction of flow.

- ***Elongated bubble flow:*** the mechanism of the flow in the elongated bubble flow is that of a fast moving liquid slug overriding the slow-moving liquid film ahead of it. It occurs when the liquid slug is free of entrained bubbles and at lower gas flow rates. This flow is sometimes referred to as plug flow.

- ***Slug flow:*** occurs at higher gas flow rates, where the flow at the front of the slug is in the form of an eddy which entrained bubbles.

- ***Annular flow:*** this flow occurs at a very high gas flow rate. The gas-phase flows in a core of high velocity, which may contain entrained liquid droplets and the liquid flows as a thin film around the pipe wall.

- ***Wavy annular flow:*** this flow occurs at the lowest gas flow rates. Most of the liquid flows at the bottom of the pipe while aerated unstable waves are swept around the pipe periphery and wet the upper pipe wall occasionally. This flow occurs on the transition boundary between stratified way, slug and annular flow.

- ***Dispersed bubble flow:*** this flow is one of the homogeneous flows where either of the two-phases flowing simultaneously in the pipeline is completely dispersed in the other. Dispersed bubble flow occurs at very high liquid rates. On the other hand, at a very high gas rates coupled with low liquid loading the flow is termed as mist flow. In both dispersed bubble flow and mist flow, the two phases move at the same velocity, and the flow is considered homogeneous with no-slip.

2.4.1.2 Homogeneous Flow Model

The homogeneous (dispersed bubble and mist) flow models treat the gas-liquid mixtures as a pseudo single phase with average fluid properties [70] and [71]. It was reported in [61], low load liquids (usually less than 0.005) holdup exist in natural gas transmission pipeline network systems. Hence, the best flow pattern to describe the two-phase gas-liquid mixtures in gas TPNS is mist flow. Because of this, homogeneous (pseudo single phase) approach is applied in this thesis to describe the behavior and transport properties of the system of gas and low loads of liquids in the pipeline.

The model for homogenous two-phase flow analysis is developed based on the assumption of compressible flow, variable cross-sectional area of pipe, variable quality of the gas along the length of the pipe [70]. The conservation equations of mass, momentum, and energy for the model are developed using a control volume with a cross-sectional are A_P and differential length dL in the axial direction as shown in Figure 2.5.

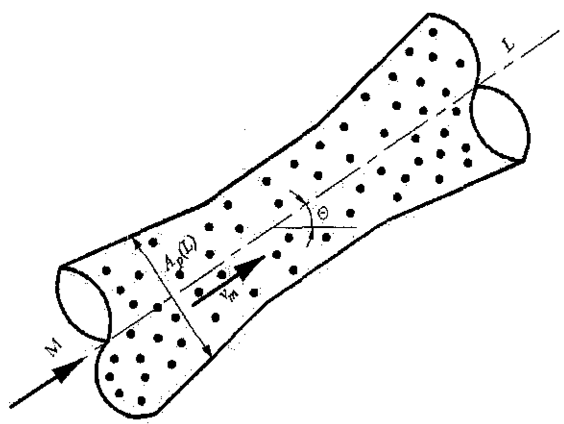


Figure 2.5 Schematic of homogeneous no-slip flow model adapted from [70]

The continuity equation for the mixture is given by

$$M = \rho_m v_m A_P = Constant \tag{2.11}$$

where M is the total mass flow rate, and ρ_m and v_m are the mixture average density and velocity, respectively.

A momentum balance on the control volume can be defined as

$$M\frac{dv_m}{dL} = -A_P\frac{dp}{dL} - S_P\tau_w - A_P\rho_m g\sin\theta \quad (2.12)$$

where L is the axial direction, P is the pressure, τ_w is the shear stress at the wall, S_P is the pipe perimeter, and θ is the inclination from the horizontal.

Dividing equation (2.12) by the cross-sectional area A_P and solving for the pressure gradient yields

$$-\frac{dp}{dL} = \frac{S_P}{A_P}\tau_w + \rho_m g\sin\theta + \frac{M}{A_P}\frac{dv_m}{dL} \quad (2.13)$$

As shown in equation (2.13), the total pressure gradient equation is composed of three components: frictional, gravitational, and acceleration components. This equation will be further developed in Chapter 3 to enable the calculation of each of the pressure gradient components and the total pressure gradient which provide one of the governing simulation equations.

2.4.2 Simulation Model with Temperature Variations

One of the variations among the different models developed for the analysis of TPNS is whether the model takes into account the effect of temperature or not. The model for the analysis of TPNS can be done on the basis of constant gas flow temperature i.e. isothermal condition. In reality, as indicated in Menon [23], the temperature of the gas in TPNS varies along the length of the pipeline due to heat transfer between the gas and the surrounding soil.

Osiadacz and chaczykowski [72] made a comparison of flow of gas in gunbarrel pipelines under isothermal and non-isothermal conditions. A significant pressure profile difference along the pipeline was reported between the isothermal and non-isothermal analysis. This difference increases with increase in quantity of gas transmitted. Thermal model for single pipe is also presented in [73].

For the variation of gas temperature in TPNS, Menon recommended the calculation of pressure drop to be done by considering short lengths of pipe that make up the total pipeline. Figure 2.6 shows a buried pipeline transmitting gas from node A to node B. Considering a short segment with length of ΔL from the pipeline, the variation of temperature along the pipeline can be analyzed by applying the principles of heat transfer.

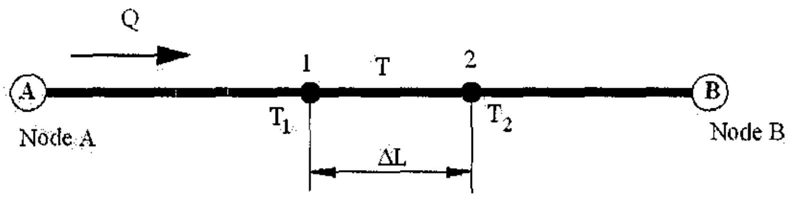


Figure 2.6 Analysis of temperature variations adapted from [23]

When the gas flows from upstream end with temperature of T_1 to downstream end of the pipe segment with temperature of T_2, the temperature of the gas will drop. On the other hand, there will be heat transfer between the gas and surrounding due to temperature difference. The temperature equation relating the two nodes 1 and 2 of the segment can be expressed as [23]

$$T_2 = T_s + (T_1 - T_s)e^{-\theta} \tag{2.14}$$

$$\theta = \frac{\pi U D \Delta L}{M C_P} \tag{2.15}$$

where T_s is the average soil temperature surrounding pipe segment, M is mass flow rate of the gas, C_P is average specific heat of gas, U is the overall heat transfer coefficient, and D is the diameter of the pipe.

It can be seen from equation (2.14) that as the pipe length increases, the term $e^{-\theta}$ approaches zero and the temperature T_2 becomes equal to soil temperature, T_s.

Therefore, in a long gas pipeline, the gas temperature ultimately equals the surrounding soil temperature.

The temperature of the gas is also affected by the compression process. In adiabatic compression of natural gas, the final temperature of the gas can be determined knowing the initial temperature and initial and final pressures. From the adiabatic compression equation and perfect gas law, the discharge temperature is given by [23, 60]:

$$\left(\frac{T_2}{T_1}\right)=\left(\frac{Z_1}{Z_2}\right)\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad (2.16)$$

where Z_1 and Z_2 are gas compressibility factor at suction and discharge side respectively and k is the specific heat ratio.

From equations (2.14) and (2.16), it can be seen that the variations of temperature in gas TPNS are controlled by these equations. Hence, these equations will be further developed in Chapter 3 to be incorporated into the governing simulation equations.

2.4.3 Internal Corrosion

Corrosion in oil and gas industries is one of the serious challenges which affect the performance of the pipeline network system. As presented in [74], corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment. The phenomenon of corrosion involves reactions which lead to the creation of ionic species, by either loss or gain of electrons. Corrosion of material depends on several factors. Some of them includes: nature of the material or alloy, surface condition/roughness, composition, moisture absorptivity, environment, temperature, humidity and corrosive elements.

It has been reported in [22] that an increase in ages of the pipes resulted in higher pipe roughness due to the accumulation of various elements around the internal surface of the pipe. Figure 2.7 shows the effect of service life of the pipe on roughness. An increase in roughness has major effect on the performance of the transmission system i.e. lower flow rate capacity and high pressure drop as indicated in [23].

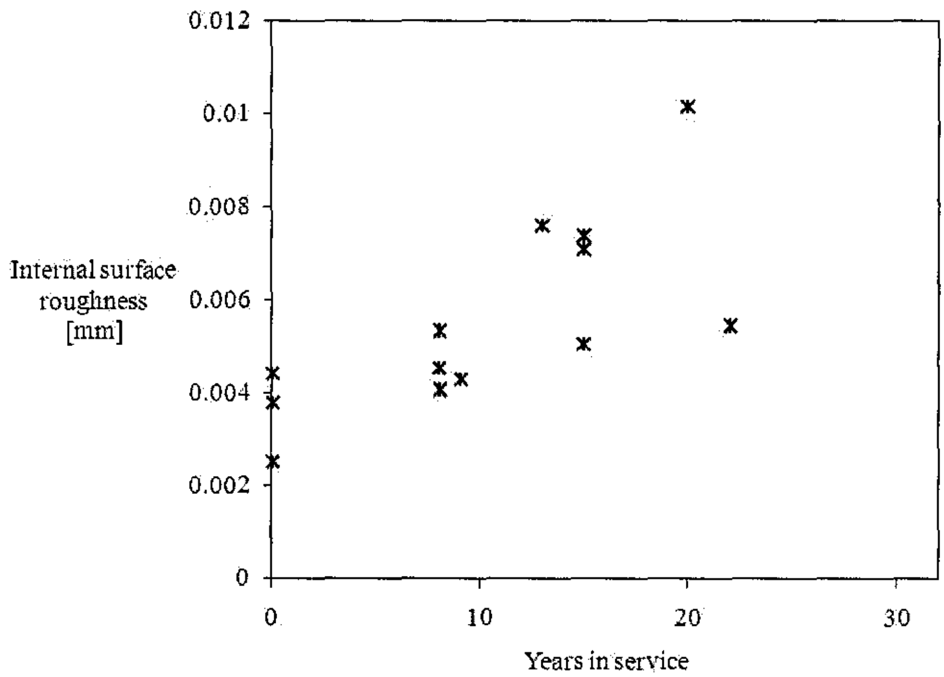


Figure 2.7 Effect of years in service on pipe roughness [22]

So far, limited information is available from literature about how the roughness of the pipes varies with the age of the pipe. However, there are several studies conducted on corrosion of pipelines for both single phase flow and two-phase gas-liquid mixtures flow [75]-[78]. One of the issues addressed in this thesis is that, the effect of ages of the pipes on the performance of TPNS has been incorporated within the simulation model.

2.5 Solution Principles Applied in Gas Pipeline Network Simulations

The selection of an appropriate solution scheme is essential in order to get the required parameters which are necessary to analyze the performance of the TPNS. The most commonly used solution schemes for analyzing the governing equations of the simulation are successive substitution (SS) and Newton-Raphson (NR) solution schemes[79].

Successive substitution scheme [79] and [80] has been applied for simulation of water pumping system [81] and for obtaining solutions for boundary value problems [82]. The major advantage of using successive substitution scheme is that the method is easy to use when the numbers of equations within the system are few.

Newton-Raphson scheme [79]-[81] has been also applied in gas pipeline network simulation and other networks for various analysis [83]-[86]. One of the major advantages of Newton-Raphson algorithm is that the method is more reliable and rapidly convergent. Furthermore, it is not necessary to list the equations in any special order. Abbaspour et al [83] used the Newton-Raphson algorithm to solve the nonlinear finite difference thermo-fluid equations for two-phase flow in a pipe. Brkic [84] used Newton-Raphson method to solve the nonlinear flow equations in natural gas distribution networks. Beck and Boucher [85] also applied the Newton-Raphson algorithm to analyze steady state fluid circuits. Kessal [86] used the Newton-Raphson algorithm for analyzing fluid flow in gas pipelines.

The maximum relative percentage error at each iteration for both successive substitution and Newton-Raphson is calculated based on the relationships given as [79]:

$$Maximum\ \%age\ Error = [\max(X_{new} - X_{old}) / \max(X_{new})] \times 100 \tag{2.17}$$

where X is the vector that represents the unknown variables.

In order to take the advantages of both solution schemes, two solutions are developed in this thesis. The first one is based on successive substitutions and applied for simple TPNS configurations. The second one is a generalized solution scheme based on Newton-Raphson which is applied for complex TPNS configurations. Detailed analysis of the solution schemes for the application of TPNS simulation is discussed in Chapter 3.

2.6 Summary

This Chapter presented the review of optimization of gas pipeline network systems, simulation of gas pipeline networks, the simulation models with two-phase flow, temperature variations and corrosion, and solution principles applied in gas pipeline network simulation.

The various TPNS simulation models revised in this thesis are summarized in Table 2.2. From the review of the TPNS simulation models, it is observed that while there is significant progress on the area of TPNS simulation methodologies, there are still issues that need to be addressed. The effects of the compressor characteristics, two-phase flow and internal corrosion during TPNS simulation modeling are addressed in this research.

Table 2.2 Summary of TPNS Simulation Models

Method	Author	Main features	Limitations
Newton-loop	Osiadacz [7]	• Preset the discharge pressures at each compressor stations. • Single phase flow and constant temperature	• Speed, discharge pressures, suction temperature neglected • Constant corrosion
Black box	Letniowski [21]	• Consider the compressor station as a black box • Single phase flow, constant temperature	• Speed, discharge pressures, suction temperature neglected • Constant corrosion
Graph theory	Wu et al. [47]	• Describing the feasible region of compressors mathematically and optimizing the operation of TPNS. • Single phase flow , constant temperature	• Based on approximation of fuel cost functions. • Constant corrosion
Correlation	Nimmanonda et al [16] and [18]	• Continuity, mass balance, and energy balance equations used. • The relationship between compression ratio, BHP, and flow was developed for three flow categories. • Single phase flow, constant temperature	• Compressor stations handling and only TPNS without loop • Requires presetting either the suction or discharge pressure • Speed of the compressors was not taken into considerations.
Mathematical approximation	Abbaspour [9]	• Use of polynomial approximation for modeling the compressor to develop simulation based optimization. • Two phase flow and variable temperature	• Perform optimization or simulation on station level. • Constant corrosion

Most of the studies on optimization of pipeline network system used either relaxation of the constraints or approximation of the constraints with equivalent constraints to facilitate for computation. These could result in deviation from the original problem. Furthermore, the optimization of pipeline gives only the optimal operation of the system. On the other hand, simulation of the pipeline network system is used to investigate the off design operation of the system.

The review of simulation models developed for natural gas TPNS indicated that the models were either limited for pipe only or treat the non-pipe elements based on simplified approach by neglecting the importance of the parameters such as speed, suction pressure, discharge pressure, and suction temperatures. In some cases, the applications of the models may be limited to either simple pipeline configurations or fixed environmental conditions. Pressure drop and flow rate of the gas may be affected as the age of the pipe increase. However, limited studies on the relationships between the age of the pipe and its effect on pressure drop and flow are reported on literatures. The study conducted on non-isothermal model of TPNS lies mostly on single pipe or limited to simplified network configurations like gunbarrel.

In the following Chapter, the details of the development of the methodology to address the objective of this research are presented. The basic principles adopted in this Chapter are utilized to develop the methodology.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this Chapter, a suitable methodology was developed to achieve a TPNS simulation model for performance analysis of gas pipeline networks. The determination of operational and design variables for the TPNS were conducted based on the analysis of factors involved during the transmission process. Appropriate mathematical formulations and suitable solution procedures were established to get reliable simulation results that predict the actual situations. The basic equations for the TPNS simulation were derived from the principles of flow of fluid through pipe, compressor characteristics and the principles of mass balance at the junction of the network.

First, the mathematical formulation of the TPNS simulation model is discussed. The basic single phase flow equations, compressor characteristics equations, mass balance and looping conditions which form the governing simulation equations are presented. Then, the solution schemes to get the flow and pressure variables based on iterative successive substitution and Newton-Raphson schemes are presented. The enhanced Newton-Raphson based TPNS simulation model which contains additional features such as two-phase flow analysis, temperature variations and internal corrosion is also discussed. The last two sections present the performance evaluation of TPNS and summary of the Chapter. Figure 3.1 shows the structure of the simulation model for natural gas TPNS.

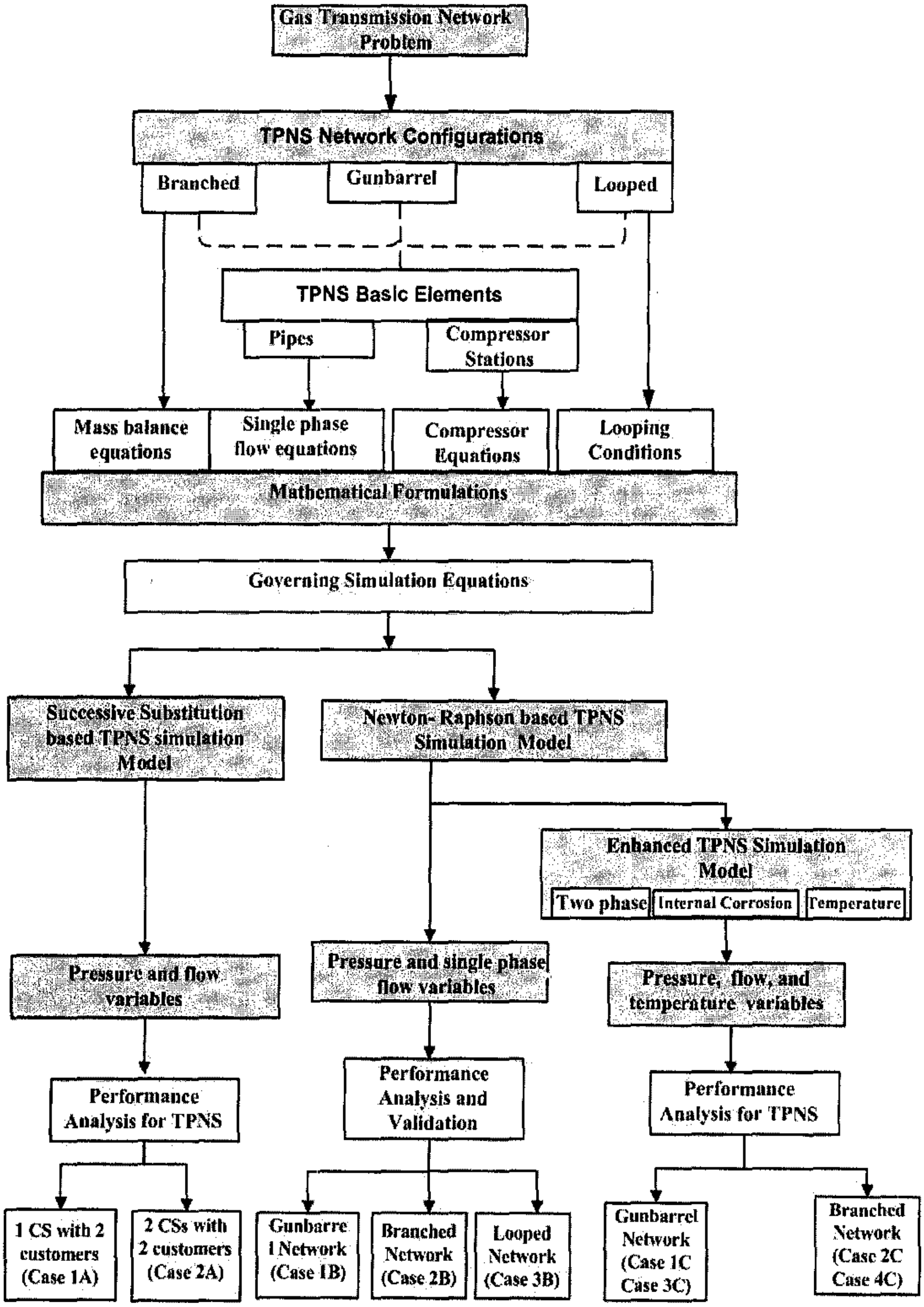


Figure 3.1 Structure of the simulation model for transmission pipeline networks

3.2 Mathematical Formulation of the Simulation Model

The mathematical formulation and the types of equations incorporated into the governing simulation equations depend on the configurations of the network and elements of the TPNS as shown in Figure 3.1. The mathematical model for the TPNS simulation is developed based on equations which govern the flow of the gas through pipes, the performance characteristics of the compressors, and the principles of conservation of mass.

3.2.1 Single Phase Flow Equations Modeling

One of the governing equations for the simulation is derived based on the principle of flow analysis of gas in pipes. The flow of gas through pipes can be affected by various factors such as the gas properties, friction factor, and the geometry of the pipes. As discussed in section 2.3.1, several flow equations are in use in the gas industry for single phase gas flow. In general, for a horizontal pipe connecting node *i* and *j* (Figure 3.2), the general flow equation for relating upstream pressure P_i, downstream pressure P_j and the flow through pipe Q_{ij} can be expressed as:

$$P_i^2 - P_j^2 = K_{ij} Q_{ij}^2 \tag{3.1}$$

where K_{ij} is to be determined by the gas properties and the characteristics of pipe connecting node i and j.

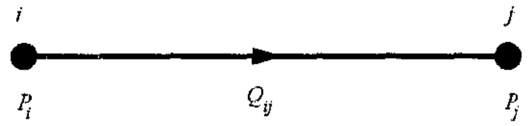


Figure 3.2 Pipe joining two consecutive nodes

Equation (3.1) can be represented as functional form [81]. If all nodal pressures and flow rate are unknown, the functional representation of equation (3.1) takes the form:

$$f(P_i, P_j, Q_{ij}) = 0 \quad (3.2)$$

If the upstream pressure and the flow rate are the only unknowns, the functional representation for equation (3.1) takes the form

$$f(P_i, Q_{ij}) = 0 \quad (3.3)$$

Note that functional form of representation for an equation consists of only parameters which are unknown in that equation. Figure 3.3 shows part of the TPNS consisting of three compressor stations (CS1, CS2 and CS3) and six pipes i.e. pipe 0-1, 2-3, 3-4, 5-6, 3-7 and 8-9.

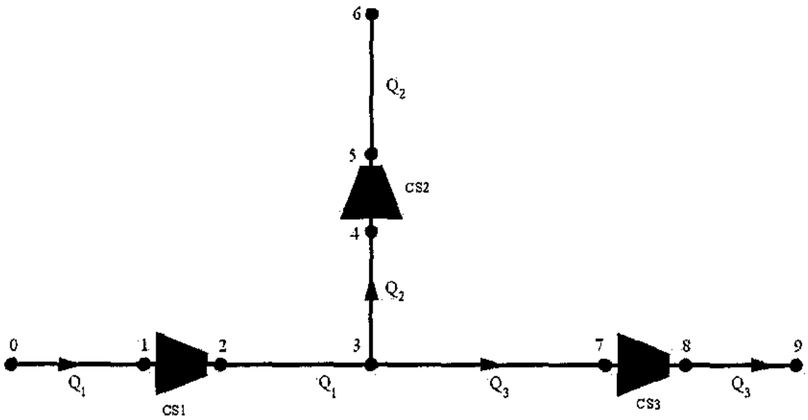


Figure 3.3 Part of transmission pipeline network system

Assuming that the source pressure at node 0 and the demand pressures at node 6 and 9 are known, the general flow equations for the pipes for single phase flow and the corresponding functional representation can be summarized as shown in Table 3.1.

Table 3.1 Single phase flow equations and functional representations

Pipe node		General flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q_1^2$	$f_1(P_1, Q_1) = 0$
2	3	$P_2^2 - P_3^2 = K_{23}Q_1^2$	$f_2(P_2, P_3, Q_1) = 0$
3	4	$P_3^2 - P_4^2 = K_{34}Q_2^2$	$f_3(P_3, P_4, Q_2) = 0$
3	7	$P_3^2 - P_7^2 = K_{37}Q_3^2$	$f_4(P_3, P_7, Q_3) = 0$
5	6	$P_5^2 - P_6^2 = K_{56}Q_2^2$	$f_5(P_5, Q_2) = 0$
8	9	$P_8^2 - P_9^2 = K_{89}Q_3^2$	$f_6(P_8, Q_3) = 0$

For ease of representation, from now onwards, the term flow equation will be frequently used to mean the general flow equation. Furthermore, the functional form of representation will be used interchangeably with the flow equation.

3.2.2 The Looping Conditions

When the TPNS contains loops, additional equations must be incorporated to the flow equations for the pipes. These additional equations are obtained from looping condition. The looping condition states that for each closed loop within the network system the pressure drop is zero [7, 23].

Looped piping system, as shown in Figure 3.4, consists of two or more pipes connected in such a way that the gas flow splits among the branch pipes and eventually combine downstream into a single pipe. It can be constructed of the same diameter pipe as the main pipeline or based on different size. The reason for installing loops is to reduce pressure drop in a certain section of the pipeline due to pressure limitation or for increasing the flow rate in bottleneck sections. For instance for the TPNS shown in Figure 3.4, by installing a pipe loop from node 3 to node 6, the overall pressure drop can be reduced due to the split of flow rate through the two pipes. Based on the looping condition, the pressure drop in pipe branch 3-C_1-4 must equal the pressure drop in pipe branch 3-C_2-4. This is due to the fact that both pipe branches have a common starting point (node 3) and common ending point (node 4).

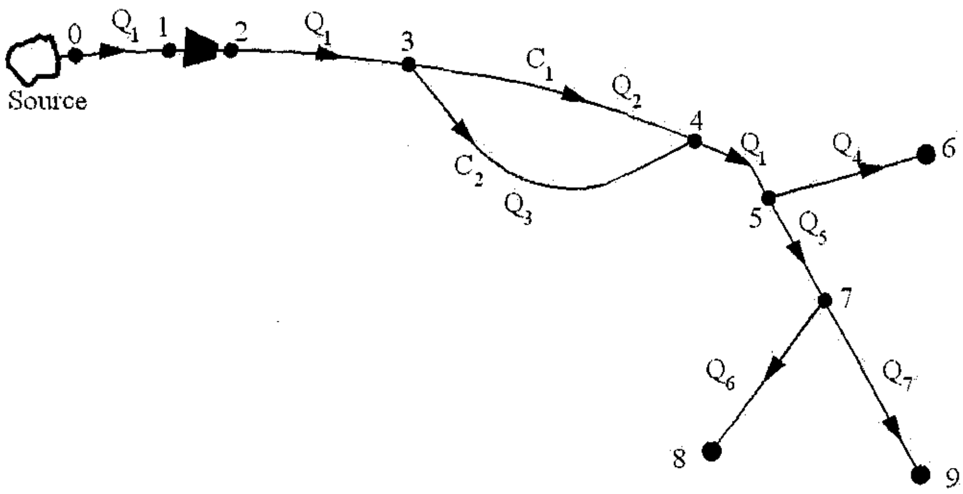


Figure 3.4 Looped pipeline network system

The pressure drop due to friction for single phase flow in branch 3-C_1-4 can be formulated based on the general flow equation as

$$P_3^2 - P_6^2 = \frac{K_1 L_1 Q_2^2}{D_1^5} \tag{3.4}$$

where, K_1 is a parameter that depends on gas properties and friction factor, Q_2 is the flow rate, L_1 and D_1 are the length and diameter of the pipe branch 3-C_1-4, respectively.

Similarly, the pressure drop due to friction for single phase flow in branch 3-C_2-4 can be given as

$$P_3^2 - P_6^2 = \frac{K_2 L_2 Q_3^2}{D_2^5} \tag{3.5}$$

where, K_2 is a parameter that depends on gas properties and friction factor, Q_3 is the flow rate, L_2 and D_2 are the length and diameter of the pipe branch 3-C_2-4, respectively.

In equations (3.4) and (3.5), the constants K_1 and K_2 are equal, since the same gas is flowing through both branch pipes. Combining both equation results in

$$\frac{L_1 Q_2^2}{D_1^5} = \frac{L_2 Q_3^2}{D_2^5} \tag{3.6}$$

Further simplification of equation (3.6) gives

$$\frac{Q_2}{Q_3} = \left(\frac{L_2}{L_1}\right)^{0.5} \left(\frac{D_1}{D_2}\right)^{2.5} \tag{3.7}$$

Equation (3.7) is referred to as the looping condition and it is one of the governing simulation equations when the pipeline network system contains loops. For the unknown flow rate Q_2 and Q_3, the functional representation for equation (3.7) takes the form

$$f\,(Q_2, Q_3) = 0 \tag{3.8}$$

3.2.3 Compressor Characteristics Equations

When the TPNS contains non-pipe elements, one of the governing simulation equations should have to be derived from compressor. Compressors are usually characterized by the performance map. In order to integrate the performance characteristics of compressor to the governing simulation equations, each of the constant speed curves from the map should have to be represented by mathematical model. Even though this type of representation results an accurate approximation for the curves, it is time consuming. Hence, the compressor map is usually represented based on single curve by using normalized parameters.

Figure 3.5 shows the plot of normalized head against the normalized flow rate for typical centrifugal compressor data taken from [55] for speeds of 8856, 8000, 7000, 6000, 5000, 4000, and 3630rpm. The corresponding plot for efficiency against the normalized flow rate is shown in Figure 3.6. It can be seen from both the figures that all the constant speed curves had the tendency to coincide as single line.

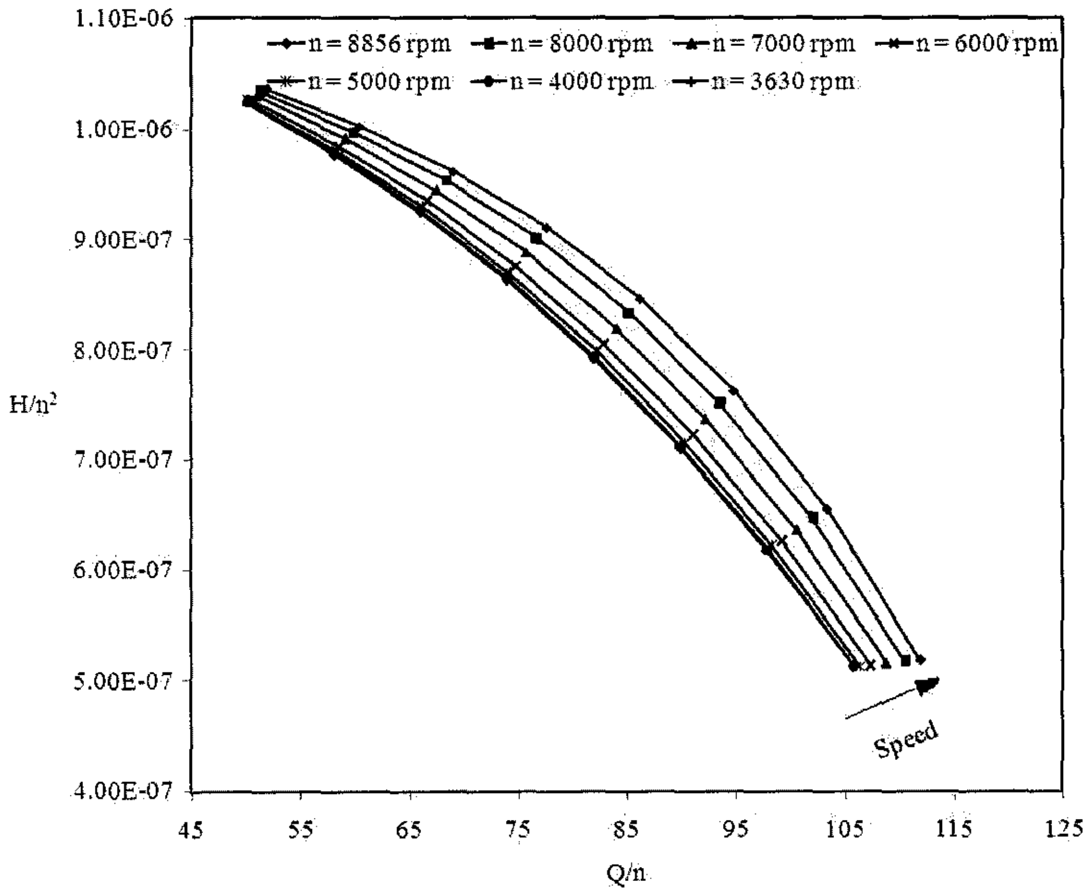


Figure 3.5 Normalized head and normalized flow rate for different speeds of a typical centrifugal compressor

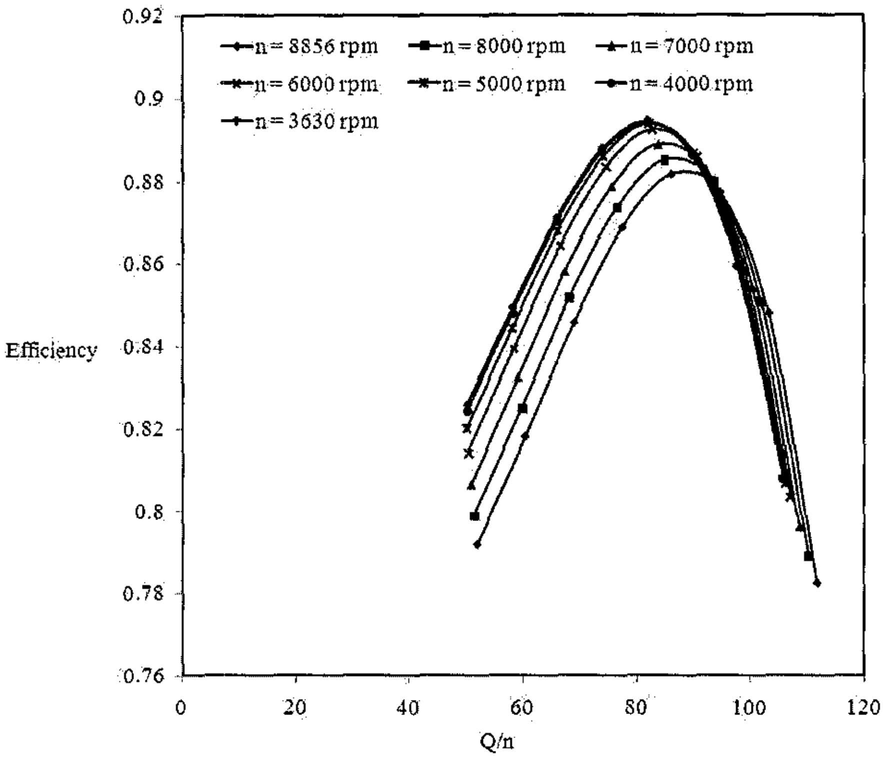


Figure 3.6 Efficiency and normalized flow rate for different speeds of a typical centrifugal compressor

In considering the effect of compressors for the TPNS simulation model, the relationships as in equation (2.9) and equation (2.10) might not be used directly. The information from the compressor map should have to relate the discharge pressure, the suction pressure and flow rate. The relationships between suction pressure P_s, and discharge pressure P_d with the head H is given as [60] :

$$H = \frac{ZRT_S}{m}\left\{\left[\frac{P_d}{P_s}\right]^m - 1\right\} \tag{3.9}$$

where $m=(k-1)/k$ with k to be specific heat ratio, R is gas constant, T_S is the suction temperature and Z is the compressibility of the gas.

Substituting the value of H from equation (3.9) into equation (2.9) and rearranging yields the required compressor performance equation which can be incorporated as governing equation for the simulation model.

$$\left(\frac{P_d}{P_s}\right)^m = \frac{mn^2}{ZRT_S}\left\{ A_1 + A_2(Q/n) + A_3(Q/n)^2 + A_4(Q/n)^3 \right\} + 1 \tag{3.10}$$

Equation (3.10) represents a general compressor equation for single compressor. It can be seen that most of the parameters that describe the compressor are incorporated in the general compressor equation. This is one of the significant contributions in the area of simulation of TPNS with compressor stations as non-pipe elements.

If the suction side pressure, discharge side pressures and flow rates are unknown, equation (3.10) can also be represented with short functional form as

$$f(P_d, P_s, Q) = 0 \tag{3.11}$$

The coefficients A_1, A_2, A_3, A_4 used in equation (2.9) and the corresponding coefficients B_1, B_2, B_3, B_4 for equation (2.10) are unique and depend on the units used in the compressor map. For gas pipeline compressors taken from [55] and [59], the different coefficients for equation (2.9) and (2.10) are summarized as shown in Table 3.2.

Table 3.2 Values of coefficients for compressor equations

Types of compressor	Coefficients for equation (2.9)		Coefficients for equation (2.10)	
Centrifugal compressor from [55]	A_1	$1.20 x 10^{-06}$	B_1	$9.7 x 10^{-01}$
	A_2	$-2.48 x 10^{-09}$	B_2	$-1.14 x 10^{-02}$
	A_3	$-4.60 x 10^{-12}$	B_3	$2.56 x 10^{-04}$
	A_4	$-3.17 x 10^{-13}$	B_4	$-1.51 x 10^{-06}$
Centrifugal compressor from [59]	A_1	$1.08 x 10^{-06}$	B_1	$7.99 x 10^{-01}$
	A_2	$-1.96 x 10^{-08}$	B_2	$-1.03 x 10^{-02}$
	A_3	$4.71 x 10^{-10}$	B_3	$6.19 x 10^{-04}$
	A_4	$-5.83 x 10^{-12}$	B_4	$-7.86 x 10^{-06}$

Equation (3.10) represents a general compressor equation for single compressor. However, there are cases where several compressors may work within compressor stations either on the basis of serial or parallel arrangements. When the compressors operate in series within the station as shown in Figure 3.7, compressor equations for each compressor should have to be developed to represent the effect of all compressors.

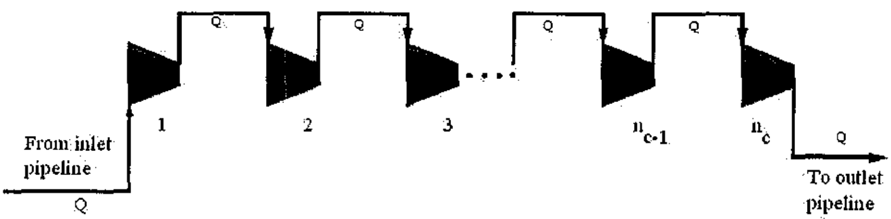


Figure 3.7 Compressors operating in series within a station

For instance, if there are n_c number of compressors operating in series within the station, there will be n_c number of independent compressor equations for the station.

Equation (3.12) shows the compressor equation for the first compressor within the station.

$$\left[\frac{P_{d1}}{P_{s1}}\right]^m = \frac{m\,n^2}{ZRT_S}\left\{A_1 + A_2(Q/n) + A_3(Q/n)^2 + A_4(Q/n)^3\right\} + 1 \tag{3.12}$$

where P_{s1} and P_{d1} are the suction and discharge pressures for the first compressor.

The remaining compressor equations within the station were developed by following the same procedure as in equation (3.12).

For compressors operating in parallel within the stations as shown in Figure 3.8, only a single equation may represent the compressor station assuming that identical compressors are working within the station. For instance, for the compressor station with n_c number of compressors working in parallel, the general compressor equation can be modified to represent the compressor station as

$$\left[\frac{P_d}{P_s}\right]^m = \frac{m\,n^2}{ZRT_S}\left\{A_1 + A_2\left[(Q/n_c)/n\right] + A_3\left[(Q/n_c)/n\right]^2 A_4\left[(Q/n_c)/n\right]^3\right\} + 1 \tag{3.13}$$

where P_s and P_d are the suction and discharge pressures for the compressor station.

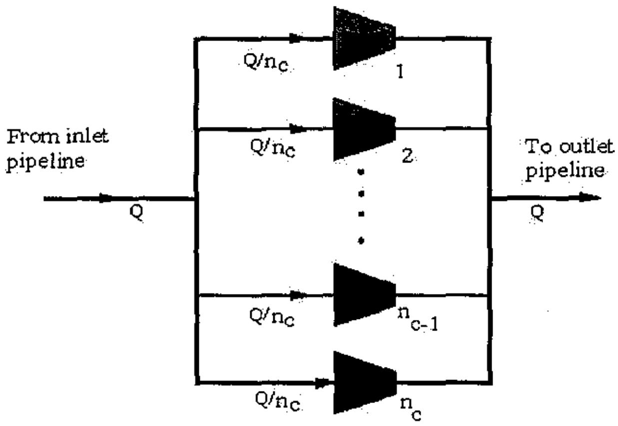


Figure 3.8 Compressors working in parallel within a station

The general compressor equation was validated based on the performance map of the compressor. Figure 3.9 shows a comparison of the plot of the performance characteristics of the compressor generated by Equation 3.10 and actual data collected from the performance map of the compressor shown in Figure 2.3. It is observed that the maximum percentage error introduced when the performance of the map is approximated by the general compressor equation was 3%.

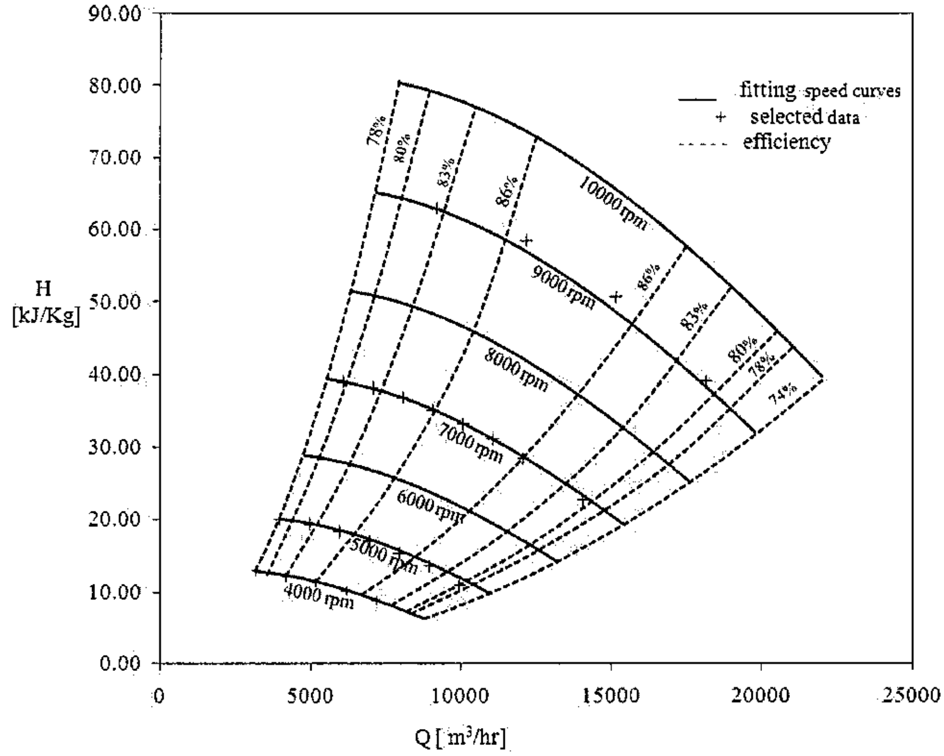


Figure 3.9 Comparison of selected data and approximated data based on the compressor data from [59]

Figure 3.10 shows the plot of the approximated pressure ratio (Pd/Ps) based on Equation 3.10 against actual pressure ratio from the characteristic curve for the typical compressor taken from [55] at speed of 8000 rpm. As the speed of the compressor increased, the deviation between the actual and calculated pressure ratio increased which made the approximation a bit far from the real values. For gas pipeline centrifugal compressor where the maximum pressure ratio is limited to around 1.5, the mathematical model developed in Equation 3.10 could be taken as reasonable approximation for the performance characteristics.

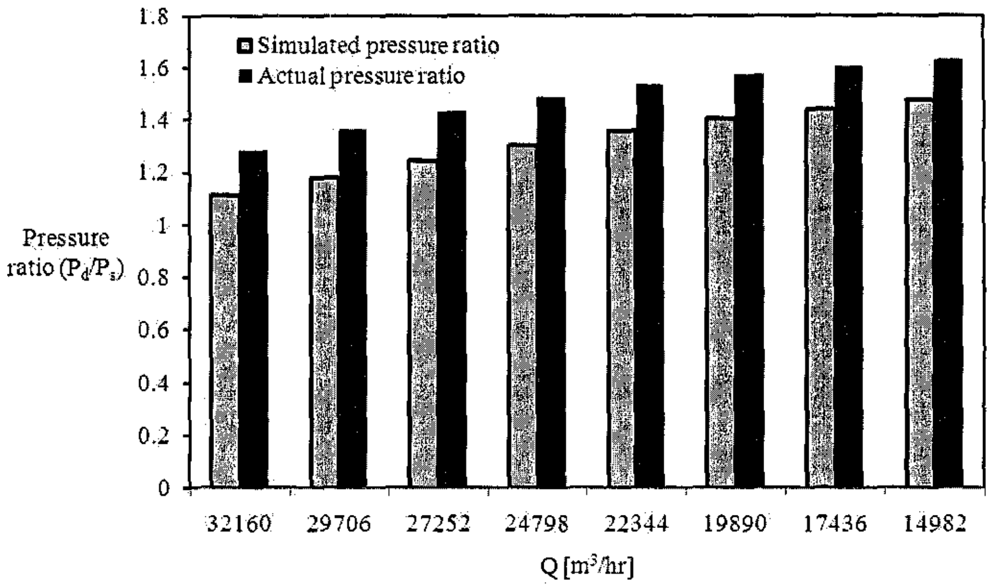


Figure 3.10 Comparison of calculated and actual pressure ratios

3.2.4 Mass Balance Equations

In addition to the pipe flow equations, looping conditions, and compressor equations, mass balances provide the remaining basic equations for the simulation of TPNS configurations with branches. The mass balance equations were obtained based the principle of conservation of mass at each junction of TPNS.

At any junction node c within the TPNS, shown in Figure 3.11, the generalized mass balance equation for t incoming pipes, u outgoing pipes, and w load pipes can be summarized as:

$$\sum_{i=1}^{i=t} Q_i - \sum_{j=1}^{j=u} q_j - \sum_{l=1}^{l=w} D_l = 0 \tag{3.14}$$

where $Q_1, Q_2, \ldots, Q_t$ are flow through incoming pipes to junction c, $q_1, q_2, \ldots, q_u$ are flow through outgoing pipes from junction c and $D_1, D_2, \ldots, D_l$ are the load from junction node c.

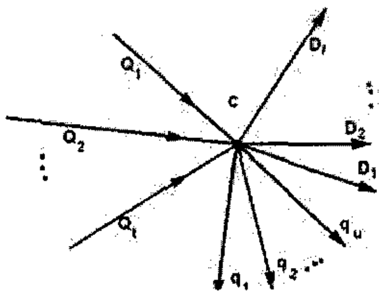


Figure 3.11 Mass balance formulation

The functional representation of equation (3.14) takes the form shown in equation (3.15) if all the flow rates through the incoming and outgoing pipes are unknown.

$$f(Q_1, Q_2, \ldots, Q_t,\ q_1, q_2, \ldots, q_u) = 0 \tag{3.15}$$

3.3 Successive Substitution based TPNS Simulation Model

In section 3.2, the details of the mathematical formulation for a given TPNS have been presented. The number of variables (flow and pressure) to be determined depends on the configurations (number of pipes, number of compressor stations, number of branches, and number of loops). The principles of flow through pipes, performance characteristics of the compressor, conservation of mass, and looping conditions were able to provide sufficient number of equations to determine the unknown variables.

Once the basic governing simulation equations for TPNS are developed, the result for unknown pressure and flow variables could be determined. The most commonly used solution schemes for analyzing the governing equations of the simulation are iterative successive substitution and Newton-Raphson solution schemes. The major advantage of using successive substitution scheme is that the method is easy to use when the numbers of equations within the system are few. One of the advantages of Newton-Raphson algorithm is that the method is more reliable and rapidly convergent. Furthermore, it is not necessary to list the equations in any special order.

In order to take the advantages of both solution schemes, two solutions are developed in this thesis. The first one is based on successive substitutions and applied for simple TPNS configurations. The second one is a generalized solution scheme based on Newton-Raphson which is applied for complex TPNS configurations.

A relationships between the number of pipes n_p, number of compressor stations n_s with compressors working in parallel, number of loops n_l, and the number of branches (junctions) n_j with the total number of unknown pressure and flow variables are developed. Table 3.3 shows the summary of the relationships between the number of equations available and the total number of unknown variables.

Table 3.3 Number of equations and unknowns for TPNS configurations

Items		No. of equations				No. of unknowns	
		Flow	Comp.	Mass balance	Looping conditions	P	Q
Basic configurations and elements of TPNS	Pipes	n_p	-	-	-	$(n_p+n_s) - (n_j+1)$	$2n_l + 2n_j + 1$
	Comp.	-	n_s	-	-		
	Branches	-	-	n_j	-		
	Loops	-	-	-	$2n_l$		
Total number of equations and unknowns		$n_p + n_s + n_j + 2n_l$				$n_p + n_s + n_j + 2n_l$	

The data shown in Table 3.4 were used throughout the analysis for the numerical evaluations. All the properties of the gas were collected from the nearest operational gas transmission company. For the compressor station, all units within the stations are assumed to be identical and are connected in parallel. The data related to pipe diameters, lengths and customer requirements are based on existing TPNS and literatures. The dimensions used for the parameters are $P[kPa], T[K], L[km], Q[m^3/hr]$ and $D[mm]$. The pipe flow resistance $K_{ij} = 7.60E+09 \times fL/D^5$.

Table 3.4 Gas properties

Gas properties		Numerical values used for analysis
Gas composition	Methane	92%
	Ethane	5%
	Nitrogen	1%
	Others	2%
Gas gravity (G)		0.5
Gas flowing temperature (T)		308 K
Base pressure (P_n)		101kPa
Base temperature (T_n)		288K
Gas constant for air (R_{air})		287.5J/kgK
Gas compressibility (Z)		0.91
Isentropic exponents (k)		1.287

In this section, successive substitution based TPNS simulation model is discussed. The application of the model is demonstrated based on two pipeline network configurations.

When the successive substitution scheme is to be applied for the determination of unknown variables for the given TPNS, information flow diagram (IFD) is an important tool [81]. IFD involves the representation of the basic equations of the TPNS as an input-output information blocks and arranging them in such a way that only one output can be calculated from each block. A compressor might appear in TPNS diagram like the one shown in Figure 3.3. But, the information flow block of the compressor might take one of the forms shown in Figure 3.12. Note that the blocks in this figure represent a compressor equation presented in function form as $f(Q,P_1,P_2)=0$. In order to develop the IFD for the TPNS, all the components of the network should have to be represented as information block and arranged in such a way that only one output can be determined from single block.

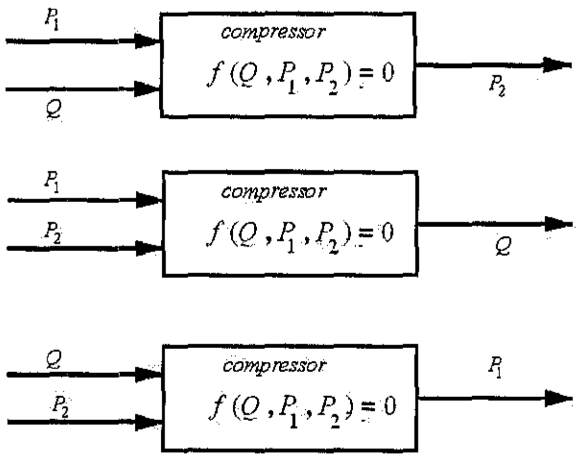


Figure 3.12 Possible information flow blocks for compressor

The method of successive substitution is closely associated with the IFD of the system. The solution procedure starts by assuming a value of one or more variables, beginning the calculation, and proceeding through the system until the originally assumed variables have been recalculated. The recalculated value is then substituted successively and the calculation loop is repeated until satisfactory convergence is achieved. Figure 3.13 shows the developed flowchart of the simulation model based on the iterative successive substitution scheme.

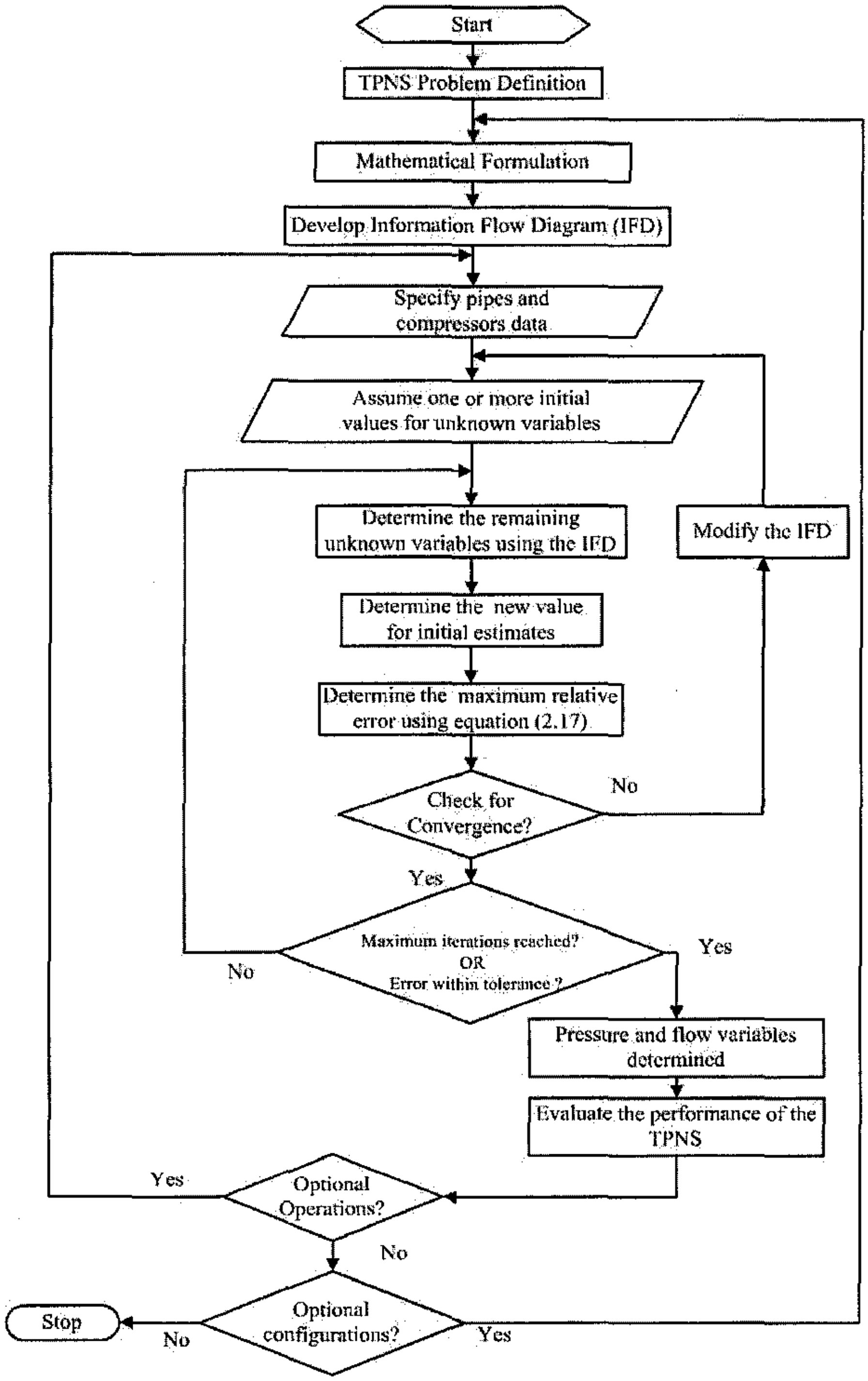


Figure 3.13 The developed flow chart for successive substitution based TPNS simulation model

3.3.1 Case 1A: Single Compressor Station and Two Customers Module

In single compressor station two customers network, it is required to transmit gas from source to two different customers with the required pressure and flow rate. Figure 3.14 shows schematic diagram of the TPNS when the gas is delivered from source to two different customer sites of station D1 and D2 using single compressor station (CS).

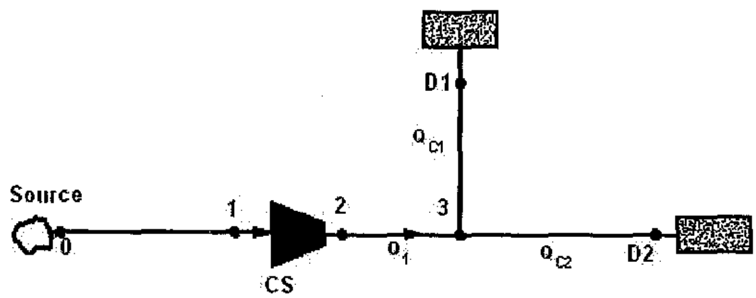


Figure 3.14 Gas transmission system for two customers

The TPNS consists of 4 pipes, 1 compressor station, 1 junction, and with no loop. Therefore, $n_p = 4$, $n_s = 1$, $n_l = 0$, and $n_j = 1$. As a result, based on Table 3.3, there are 3 nodal pressures and 3 flow variables to be determined. A total of 6 independent equations were obtained in order to solve the network problem. The basic governing equations for TPNS were developed from pipe flow equations, compressor stations equations and mass balance equations based on the discussion in section 3.2. There are 4 pipe flow equations, 1 compressor station equation and 1 mass balance equation which form the required number of equations to solve for the unknown variables.

The summary of flow equations and their corresponding functional representation for the given TPNS are shown in Table 3.5.

Table 3.5 Summary of flow equations and their corresponding functional representations for the given TPNS

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q_1^2$	$f_1(P_1, Q_1) = 0$
2	3	$P_2^2 - P_3^2 = K_{23}Q_1^2$	$f_2(P_2, P_3, Q_1) = 0$
3	D1	$P_3^2 - P_{D1}^2 = K_{3D1}Q_{C1}^2$	$f_3(P_3, Q_{C1}) = 0$
3	D2	$P_3^2 - P_{D2}^2 = K_{3D2}Q_{C2}^2$	$f_4(P_3, Q_{C2}) = 0$

The compressor equation for the TPNS is given as:

$$\left(\frac{P_2}{P_1}\right)^m = \frac{mn^2}{ZRT_S}[A_1 + A_2(Q_1/n) + A_3(Q_1/n)^2 + A_4(Q_1/n)^3] + 1 \tag{3.16}$$

The corresponding functional representation for equation (3.16) takes the form

$$f_5(P_1, P_2, Q_1) = 0 \tag{3.17}$$

The mass balance equation is given by:

$$Q_1 = Q_{C1} + Q_{C2} \tag{3.18}$$

The corresponding functional representation for equation (3.18) takes the form

$$f_6(Q_1, Q_{C1}, Q_{C2}) = 0 \tag{3.19}$$

Based on the functional representations for the mathematical formulation of the governing simulation equations for the given TPNS, the IFD can be drawn as shown in Figure 3.15. Using this IFD, the successive substitution solution scheme could be started by assuming one or more variables. For the given TPNS, the solutions can be obtained by assuming initial value for Q_1 and P_3. Once these variables are assumed, the value of Q_{C2} can be calculated, then Q_{C1}, P_2, etc. by following the IFD. The iteration will continue till the desired error limits or the number of iterations is achieved.

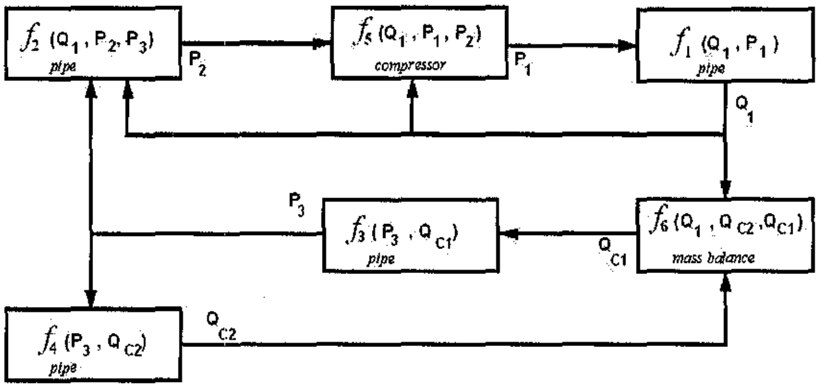


Figure 3.15 IFD of pipeline network system with two customers

The application of the SS based TPNS simulation model for the given network was conducted based on nodal pressure requirements and pipe data shown in Table 3.6 and Table 3.7 , respectively.

Table 3.6 Pressure data for single CS and two customers

Node	Pressure[kPa]
D1	1800
D2	1800
Source	4000

Table 3.7 Pipe data for single CS and two customers

Pipe node		Diameter [mm]	Length [km]
Start node	End node		
0	1	400	80
2	3	400	60
3	D_1	400	80
3	D_2	300	60

3.3.2 Case 2A: Two Compressor Stations and Two Customers Module

The problem in two compressor stations and two customer network is to transmit gas from source to two customers using two compressor stations. Figure 3.16 shows TPNS when gas is delivered from source to two different customers' sites designated as D_1 and D_2 using two compressor stations.

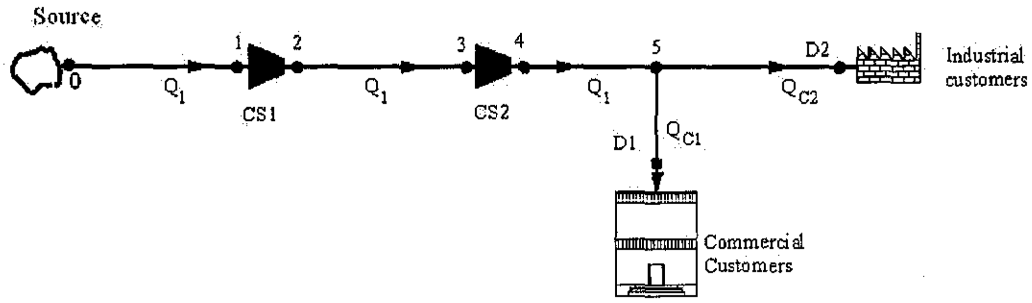


Figure 3.16 Pipeline network with two CSs and two customers

This TPNS consists of 5 pipes, 2 compressor stations, 1 junction, and with no loop. Therefore, n_p = 5, n_s = 2, n_l = 0, and n_j = 1. As a result, based on Table 3.3, there are 5 nodal pressures and 3 flow parameters to be determined. Therefore a total of 8 independent equations should have to be obtained in order to solve the network problem. The basic governing equations for TPNS were developed from pipe flow equations, compressor stations equations and mass balance equations based on the discussion in section 3.2. There are 5 pipe flow equations, 2 compressor station equations and 1 mass balance equation which formed the required number of equations to solve for the unknown parameters.

The summary of flow equations and their corresponding functional representation for the given TPNS are shown in Table 3.8.

Table 3.8. Summary of flow equations and their corresponding functional representations for the given TPNS

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q_1^2$	$f_1(P_1, Q_1) = 0$
2	3	$P_2^2 - P_3^2 = K_{23}Q_1^2$	$f_2(P_2, P_3, Q_1) = 0$
4	5	$P_4^2 - P_5^2 = K_{45}Q_1^2$	$f_3(P_4, P_5, Q_1) = 0$
5	D1	$P_5^2 - P_{D1}^2 = K_{5D1}Q_{C1}^2$	$f_4(P_5, Q_{C1}) = 0$
5	D2	$P_5^2 - P_{D2}^2 = K_{5D2}Q_{C2}^2$	$f_5(P_5, Q_{C2}) = 0$

The compressor equations for the given TPNS were summarized in equation and function forms as shown in Table 3.9.

Table 3.9 Summary of compressor equations and functional representations

Compressor stations	Compressor equation	Functional representations
CS1	$\left(\frac{P_2}{P_1}\right)^m = \frac{mn_1^2}{ZRT_S}[A_1 + A_2(Q_1/n_1) + A_3(Q_1/n_1)^2 + A_4(Q_1/n_1)^3] + 1$	$f_6(P_1, P_2, Q_1) = 0$
CS2	$\left(\frac{P_4}{P_3}\right)^m = \frac{mn_2^2}{ZRT_S}[A_1 + A_2(Q_1/n_2) + A_3(Q_1/n_2)^2 + A_4(Q_1/n_2)^3] + 1$	$f_7(P_3, P_4, Q_1) = 0$

Mass balance equation at junction node 5 is given by:

$$Q_1 = Q_{C1} + Q_{C2} \tag{3.20}$$

The corresponding functional representation for equation (3.20) takes the form

$$f_8(Q_1, Q_{C1}, Q_{C2}) = 0 \tag{3.21}$$

Based on the functional representations for the mathematical formulation of the governing simulation equations for the given TPNS, the IFD is as shown in Figure 3.17. Similar procedure was followed as in the case of single compressor station with two customers. Using this IFD, the successive substitution solution scheme can be started by assuming two variables. For the given TPNS, the solution is obtained by assuming initial value for Q_1 and P_5. Based on the assumed variables, the value of Q_{C2} will be calculated, then Q_{C1}, P_4, etc. by following the IFD. The iterations will be continued till the desired error limits or the number of iteration is achieved.

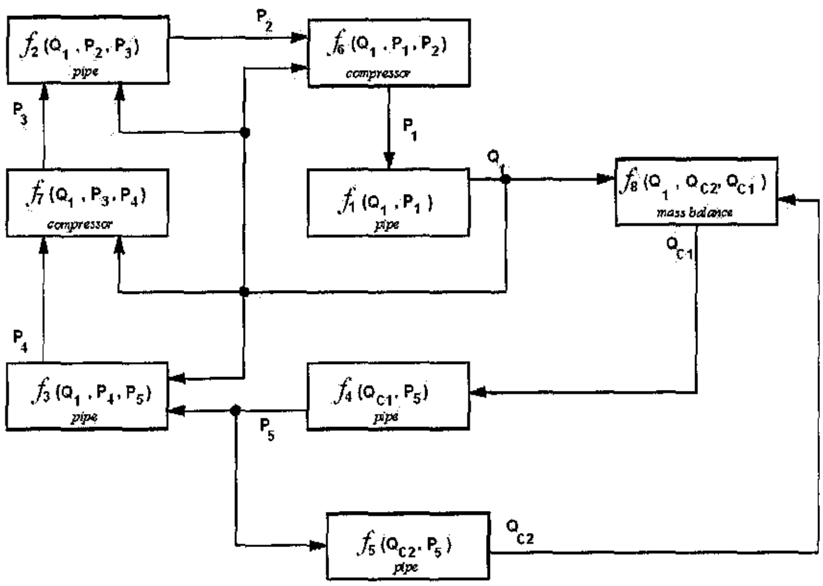


Figure 3.17 IFD for pipeline network with two CSs

The application of the SS based TPNS simulation model for the given network was conducted based on nodal pressure requirements and pipe data shown in Table 3.6 and Table 3.10 , respectively.

Table 3.10 Pipe data for two CSs and two customers

Pipe node		Diameter [mm]	Length [km]
Start node	End node		
0	1	200	100
2	3	200	50
4	5	200	100
5	D_1	200	150
5	D_2	200	100

3.4 Newton-Raphson based TPNS Simulation Model

As presented in section 3.3, the solution to the unknown pressure and flow variables are also obtained based on Newton-Raphson solution schemes. Newton-Raphson technique is complex but powerful for analysis of pipeline network problems with large number of pipes and compressor stations. The multivariable Newton-Raphson method which is very important for the analysis of the TPNS can also be derived following the same procedure as that of the single variable.

A set of nonlinear equations which are obtained from single phase flow modeling, compressor modeling, looping condition, and mass balance formulations discussed in section 3.2 can be represented in matrix form.

Let N_P = total number of unknown pressure variables.

N_Q = total number of unknown flow variables.

The total number of unknown variables N_{Total} is given as:

$$N_{Total} = N_P + N_Q \tag{3.22}$$

The set of single phase pipe flow, looping, compressor, and mass balance equations can be represented as

$$\left\{\begin{array}{l} F_1\left(P_1, P_2, \cdots, P_{N_P}, Q_1, Q_2, \cdots, Q_{N_Q}\right)=0 \\ F_2\left(P_1, P_2, \cdots, P_{N_P}, Q_1, Q_2, \cdots, Q_{N_Q}\right)=0 \\ \quad \bullet \qquad \bullet \qquad \bullet \\ \quad \bullet \qquad \bullet \qquad \bullet \\ \quad \bullet \qquad \bullet \qquad \bullet \\ F_{N_{Total}}\left(P_1, P_2, \cdots, P_{N_P}, Q_1, Q_2, \cdots, Q_{N_Q}\right)=0 \end{array}\right\} \tag{3.23}$$

Equation (3.23) can be written in matrix form as [79]

$$\tilde{F}\left(\tilde{X}\right)=\tilde{0} \tag{3.24}$$

where the vector $\tilde{X}$ represents the total number of unknown pressure, flow and temperature variables and $\tilde{F}$ is the corresponding equations generated from pipe, compressor, mass balance and looping conditions.

The multivariable Newton-Raphson iterative procedure for equation (3.24) takes the form

$$\tilde{X}_{new} = \tilde{X}_{old} - \left[\tilde{A}\Big|_{\tilde{X}_{old}}\right]^{-1} \tilde{F}\left(\tilde{X}_{old}\right) \tag{3.25}$$

where $\tilde{A}$ is called Jacobian matrix whose elements are partial derivatives of the functions with respect to the variables.

The matrix $\tilde{A}$ in equation (3.25) is defined as

$$\tilde{A} = \begin{bmatrix} \frac{\partial F_1}{\partial P_1} & \cdots & \frac{\partial F_1}{\partial P_{N_P}} & \frac{\partial F_1}{\partial Q_1} & \cdots & \frac{\partial F_1}{\partial Q_{N_Q}} \\ \frac{\partial F_2}{\partial P_1} & \cdots & \frac{\partial F_2}{\partial P_{N_P}} & \frac{\partial F_2}{\partial Q_1} & \cdots & \frac{\partial F_2}{\partial Q_{N_Q}} \\ \bullet & & & & & \\ \bullet & & & & & \\ \bullet & & & & & \\ \frac{\partial F_{NTotal}}{\partial P_1} & \cdots & \frac{\partial F_{NTotal}}{\partial P_{N_P}} & \frac{\partial F_{NTotal}}{\partial Q_1} & \cdots & \frac{\partial F_{NTotal}}{\partial Q_{N_Q}} \end{bmatrix} \tag{3.26}$$

From equation (3.25), the inverse of the Jacobian matrix needs to be computed at each iterations. However, there is another approach that does not require the rigorous computation of associated with the inversion of the Jacobian matrix. Equation (3.25) can be rewritten as[79]

$$\tilde{A}\Big|_{\tilde{X}old} \left[\tilde{X}_{new} - \tilde{X}_{old}\right] = -\tilde{F}\left(\tilde{X}_{old}\right) \tag{3.27}$$

The value of the unknown variables were calculated from equation (3.27) iteratively until the maximum relative percentage error defined in equation (2.17) is less than the specified tolerance or the number of iterations reached the desired value. Figure 3.18 shows the flowchart of the TPNS simulation model based on the iterative Newton-Raphson solution scheme.

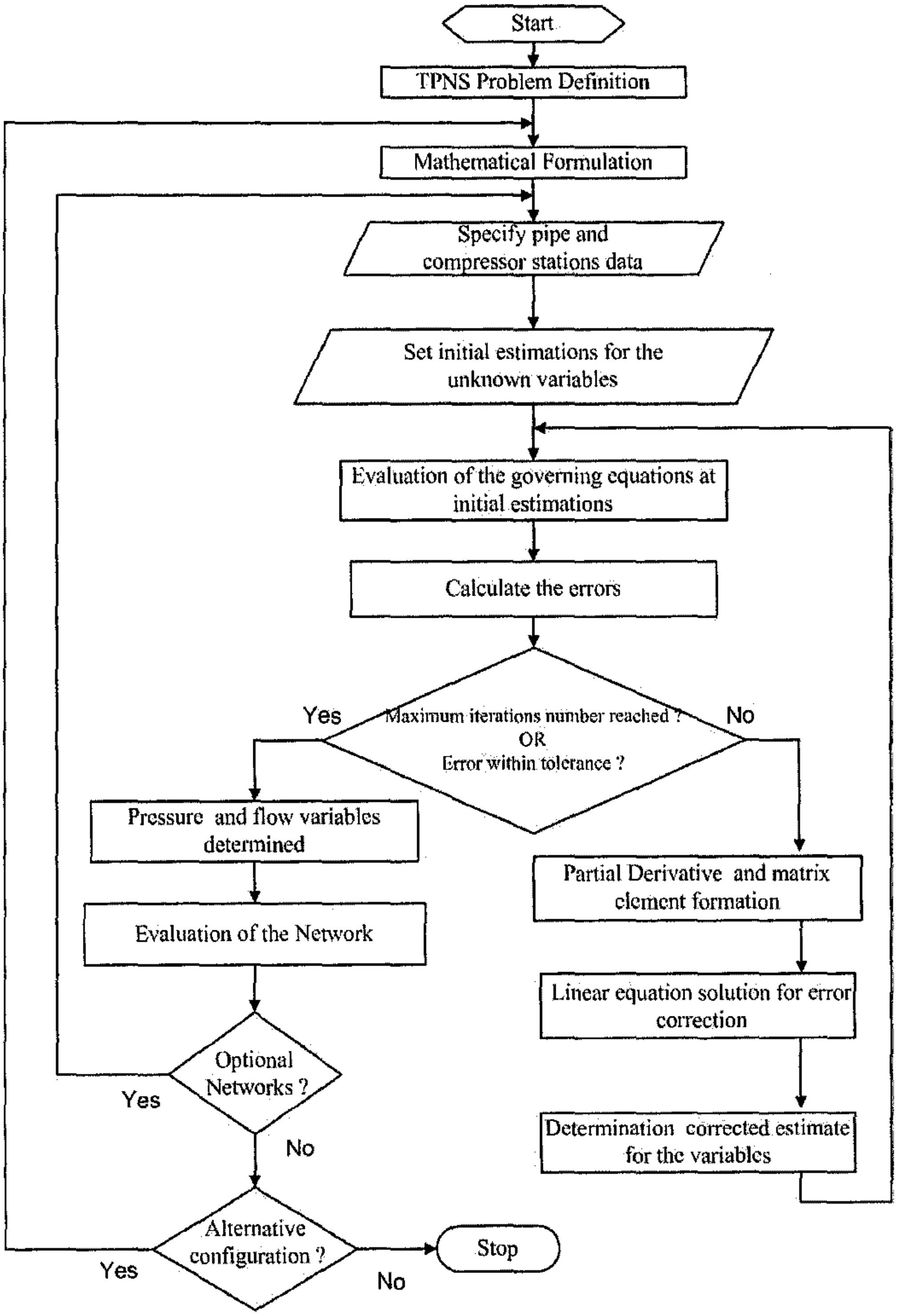


Figure 3.18 Flow chart of the TPNS simulation model based on Newton-Raphson scheme

A visual C++ code is developed for the TPNS simulation based on Newton-Raphson solution technique. In order to handle the visual C++ program efficiently, the overall code is grouped into several subtasks. These include, subtask for mathematical formulation, subtasks for matrix elements generation, subtask for input data, subtask for Gaussian eliminations, subtask for error sorting, subtask for evaluating the networks, etc. The snapshot of the typical TPNS source code for analyzing part of Malaysian gas transmission system is shown in Appendix A. Sample simulation results from the Newton-Raphson based TPNS simulation model for gunbarrel pipeline network is as shown in Appendix B.

The applications of Newton-Raphson based TPNS simulation model is demonstrated using three different network configurations. These include gunbarrel, branched and looped TPNS configurations. These network configurations are the most widely used in natural gas industry. The application of the Newton-Raphson based TPNS simulation model also demonstrated using part of the Malaysian gas transmission network system. The applications of the Newton-Raphson based TPNS simulations are presented in the following sections.

3.4.1 Case 1B: Gunbarrel Pipeline Network Module

In gunbarrel (linear) pipeline network system where the gas is transported from source to demand station linearly, there are no junctions and loops involved. As a result, the basic simulation equations include only flow and compressor equations. Figure 3.19 shows a typical gunbarrel transmission network system with two compressor stations. This network was used in order to demonstrate the application of the TPNS simulation model for the gunbarrel pipeline network system.

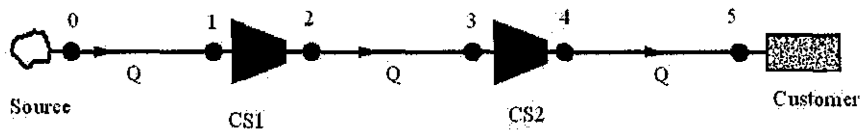


Figure 3.19 Gunbarrel pipeline network system with two CSs

For the TPNS shown in Figure 3.19, the number of pipes $n_p = 3$ and the number of compressor stations $n_s = 2$. As a result, based on Table 3.3, there will be 4 pressure variables and 1 flow variable to be determined. There are 3 flow equations and 2 compressor equations available to solve the problem.

From the discussion in section 3.2.1, the pipe flow equations for single phase gas flow based on general flow equation is summarized as shown in Table 3.11.

Table 3.11 Summary of flow equations for the given gunbarrel TPNS

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q^2$	$f_1(P_1, Q) = 0$
2	3	$P_2^2 - P_3^2 = K_{23}Q^2$	$f_2(P_2, P_3, Q) = 0$
4	5	$P_4^2 - P_5^2 = K_{45}Q^2$	$f_3(P_4, P_5, Q) = 0$

Similarly, based on the discussion on compressor stations modeling in section 3.2.3, the remaining compressor equations for the network can be formulated and represented in functional forms as shown in Table 3.12.

Table 3.12 Summary of compressor equations and functional representations

Compressor stations	Compressor equation	Functional representations
CS1	$\left(\frac{P_2}{P_1}\right)^m = \frac{mn_1^2}{ZRT_S}[A_1 + A_2(Q/n_1) + A_3(Q/n_1)^2 + A_4(Q/n_1)^3] + 1$	$f_4(P_1, P_2, Q) = 0$
CS2	$\left(\frac{P_4}{P_3}\right)^m = \frac{mn_2^2}{ZRT_S}[A_1 + A_2(Q/n_2) + A_3(Q/n_2)^2 + A_4(Q/n_2)^3] + 1$	$f_5(P_3, P_4, Q) = 0$

Based on the flow equations shown in Table 3.11 and the compressor equations shown in Table 3.12, the solution to the unknown pressure and flow variables are obtained using the developed Newton-Raphson based TPNS simulation model.

The application of the Newton-Raphson based TPNS simulation model for the gunbarrel network was conducted based on nodal pressure requirements and pipe data shown in Table 3.13 and Table 3.14 , respectively. The pipe data was based on [47]. The results of the pressure and flow variables and their convergence graphs will be discussed in Chapter 4.

Table 3.13 Pressure requirements for two CSs and single customer

Node	Pressure [kPa]
0	3000
5	4000

Table 3.14 Pipe data for two CSs and single customer

Pipe node		Diameter [mm]	Length [km]
Start node	End node		
0	1	900	80
2	3	900	80
4	5	900	80

3.4.2 Case 2B: Branched Pipeline Network Module

The second type of transmission network analyzed using the developed Newton-Raphson based TPNS simulation model is branched system. In this system, gas is transported from the source to different demand stations by branching from the main source. Figure 3.20 shows typical branched transmission network system with one compressor station and branching to five customers. In order to demonstrate the application of the simulation model for the branched pipeline network system, this network is considered for the analysis.

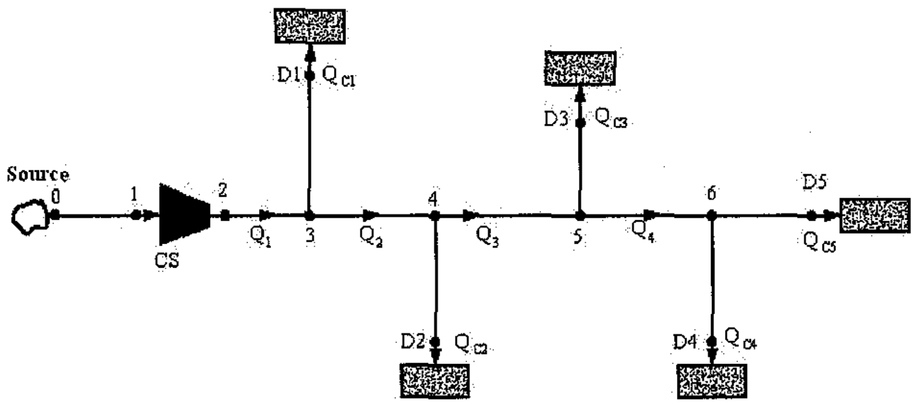


Figure 3.20 Branched pipeline network system

For this TPNS, the number of pipes $n_p = 10$, the number of compressor stations $n_s = 1$, and the number of junctions $n_j = 4$. As a result, based on Table 3.3, there will be 6 pressure variables and 9 flow variable to be determined. There are ten flow equations, one compressor equation and four mass balance equations available to solve the problem. From the discussion in section 3.2.1, the pipe flow equations for single phase gas flow based on general flow equation are summarized as shown in Table 3.15.

Table 3.15 Summary of flow equations and their functional representation

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q_1^2$	$f_1(P_1, Q_1) = 0$
2	3	$P_2^2 - P_3^2 = K_{23}Q_1^2$	$f_2(P_2, P_3, Q_1) = 0$
3	D1	$P_3^2 - P_{D1}^2 = K_{3D1}Q_{C1}^2$	$f_3(P_3, Q_{C1}) = 0$
3	4	$P_3^2 - P_4^2 = K_{34}Q_2^2$	$f_4(P_3, P_4, Q_2) = 0$
4	D2	$P_4^2 - P_{D2}^2 = K_{4D2}Q_{C2}^2$	$f_5(P_4, Q_{C2}) = 0$
4	5	$P_4^2 - P_5^2 = K_{45}Q_3^2$	$f_6(P_4, P_5, Q_3) = 0$
5	D3	$P_5^2 - P_{D3}^2 = K_{5D3}Q_{C3}^2$	$f_7(P_5, Q_{C3}) = 0$
5	6	$P_5^2 - P_6^2 = K_{56}Q_4^2$	$f_8(P_5, P_6, Q_4) = 0$
6	D4	$P_6^2 - P_{D4}^2 = K_{6D4}Q_{C4}^2$	$f_9(P_6, Q_{C4}) = 0$
6	D5	$P_6^2 - P_{D5}^2 = K_{6D5}Q_{C5}^2$	$f_{10}(P_6, Q_{C5}) = 0$

The compressor equation for the TPNS is given as:

$$\left(\frac{P_2}{P_1}\right)^m = \frac{mn^2}{ZRT_S}[A_1 + A_2(Q_1/n) + A_3(Q_1/n)^2 + A_4(Q_1/n)^3] + 1 \tag{3.28}$$

The corresponding functional representation for equation (3.28) takes the form

$$f_{11}(P_1, P_2, Q_1) = 0 \tag{3.29}$$

The remaining mass balance equations for the network were formulated and summarized as shown in Table 3.16.

Table 3.16 Summary of mass balance equations and functional representations

Node	Mass balance equation	Functional representation
3	$Q_1 = Q_2 + Q_{C1}$	$f_{12}(Q_1, Q_2, Q_{C1}) = 0$
4	$Q_2 = Q_3 + Q_{C2}$	$f_{13}(Q_2, Q_3, Q_{C2}) = 0$
5	$Q_3 = Q_4 + Q_{C3}$	$f_{14}(Q_3, Q_4, Q_{C3}) = 0$
6	$Q_4 = Q_{C4} + Q_{C5}$	$f_{15}(Q_4, Q_{C4}, Q_{C5}) = 0$

Thus, the solutions to the unknown pressure and flow variables are obtained using the developed Newton-Raphson based TPNS simulation model based on the flow equations shown in Table 3.15, compressor equation (3.29) and the mass balance equations shown in Table 3.16. The application of the Newton-Raphson based TPNS simulation model for the branched network was conducted based on the pipe data shown Table 3.17.

Table 3.17 Pipe data for single CS and five customers

Pipe nodes			
Start node	End node	Diameter [mm]	Length [km]
0	1	900	100
2	3	900	80
3	D1	600	70
3	4	900	80
4	D2	600	90
4	5	900	70
5	D3	600	80
5	6	900	90
6	D4	600	70
6	D5	600	80

3.4.3 Case 3B: Looped Pipeline Network Module

The third type of transmission network system where the developed Newton-Raphson based TPNS simulation model applied is looped system. In the case of looped TPNS, gas pipelines diverge and re-converge when gas is transported from the source to demand stations.

Figure 3.21 shows typical looped transmission network system with one compressor station for transmitting gas to eight different customers. For this TPNS, there are 16 pipes, 1 compressor station, 1 loop and 7 junctions. As a result, based on Table 3.3, there will be 9 pressure variables and 17 flow variable to be determined.

There are 16 pipe flow equations, 1 compressor equation, 2 looping equations and 7 mass balance equations which form the 26 independent equations to analyze the TPNS.

From the discussion in section 3.2.1, the pipe flow equations for single phase gas flow are formulated and summarized as shown in Table 3.18.

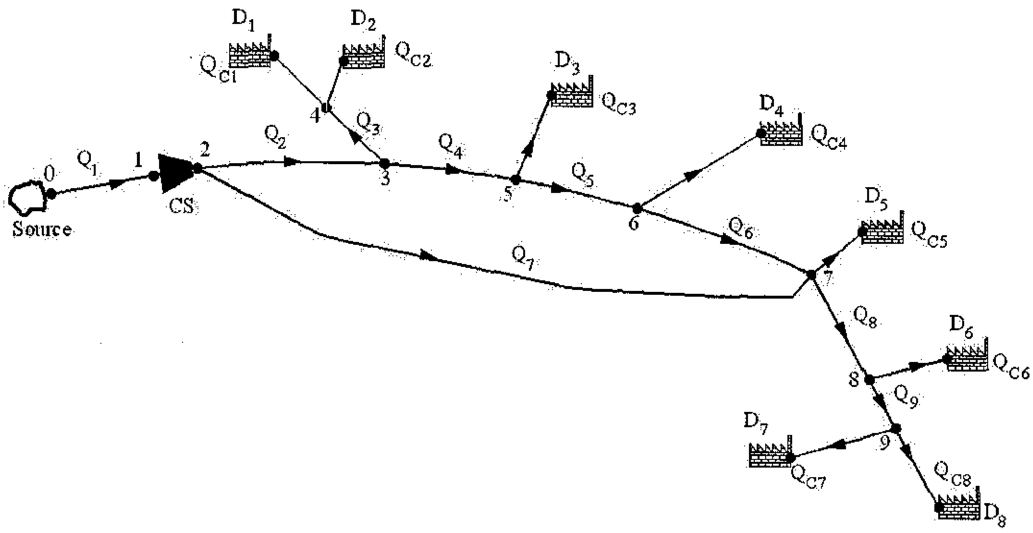


Figure 3.21 Looped pipeline network system

Table 3.18 Summary of flow equations and functional representations

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01}Q_1^2$	$f_1(P_1,Q_1)=0$
2	3	$P_2^2 - P_3^2 = K_{23}Q_2^2$	$f_2(P_2,P_3,Q_2)=0$
3	4	$P_3^2 - P_4^2 = K_{34}Q_3^2$	$f_3(P_3,P_4,Q_3)=0$
4	D1	$P_4^2 - P_{D1}^2 = K_{4D1}Q_{C1}^2$	$f_4(P_4,Q_{C1})=0$
4	D2	$P_4^2 - P_{D2}^2 = K_{4D2}Q_{C2}^2$	$f_5(P_4,Q_{C2})=0$
3	5	$P_3^2 - P_5^2 = K_{45}Q_4^2$	$f_6(P_3,P_5,Q_4)=0$
5	D3	$P_5^2 - P_{D3}^2 = K_{5D3}Q_{C3}^2$	$f_7(P_5,Q_{C3})=0$
5	6	$P_5^2 - P_6^2 = K_{56}Q_5^2$	$f_8(P_5,P_6,Q_5)=0$
6	D4	$P_6^2 - P_{D4}^2 = K_{6D4}Q_{C4}^2$	$f_9(P_6,Q_{C4})=0$
6	7	$P_6^2 - P_7^2 = K_{76}Q_6^2$	$f_{10}(P_6,P_7,Q_6)=0$
7	D5	$P_7^2 - P_{D5}^2 = K_{7D5}Q_{C5}^2$	$f_{11}(P_7,Q_{C5})=0$
7	8	$P_7^2 - P_8^2 = K_{78}Q_8^2$	$f_{12}(P_7,P_8,Q_8)=0$
8	D6	$P_8^2 - P_{D6}^2 = K_{8D6}Q_{C6}^2$	$f_{13}(P_8,Q_{C6})=0$
8	9	$P_8^2 - P_9^2 = K_{89}Q_9^2$	$f_{14}(P_8,P_9,Q_9)=0$
9	D7	$P_9^2 - P_{D7}^2 = K_{9D7}Q_{C7}^2$	$f_{15}(P_9,Q_{C7})=0$
9	D8	$P_9^2 - P_{D8}^2 = K_{9D8}Q_{C8}^2$	$f_{16}(P_9,Q_{C8})=0$

Based on the discussion on sections 3.2.2, the looping condition of the network can be formulated for the given network as

$$\frac{l_l Q_7^2}{D_l^{\,5}} = \frac{l_{23}Q_2^2}{D_{23}^{\,5}} + \frac{l_{35}Q_4^2}{D_{35}^{\,5}} + \frac{l_{56}Q_5^2}{D_{56}^{\,5}} + \frac{l_{67}Q_6^2}{D_{67}^{\,5}} \tag{3.30}$$

The functional representation for equation (3.30) takes the form

$$f_{17}(Q_2,Q_4,Q_5,Q_6,Q_7)=0 \tag{3.31}$$

The compressor equation for the TPNS is given as:

$$\left(\frac{P_2}{P_1}\right)^m = \frac{mn^2}{ZRT_S}[A_1 + A_2(Q_1/n) + A_3(Q_1/n)^2 + A_4(Q_1/n)^3] + 1 \quad (3.32)$$

The corresponding functional representation for equation (3.32) takes the form

$$f_{18}(P_1, P_2, Q_1) = 0 \quad (3.33)$$

The remaining mass balance equations for the network were formulated and summarized as shown in Table 3.19.

Table 3.19 Summary of mass balance equations and functional representations

Node	Mass balance equation	Functional representation
2	$Q_1 = Q_2 + Q_7$	$f_{19}(Q_1, Q_2, Q_7) = 0$
3	$Q_2 = Q_3 + Q_4$	$f_{20}(Q_2, Q_3, Q_4) = 0$
4	$Q_3 = Q_{C1} + Q_{C2}$	$f_{21}(Q_3, Q_{C1}, Q_{C2}) = 0$
5	$Q_4 = Q_5 + Q_{C3}$	$f_{22}(Q_4, Q_5, Q_{C3}) = 0$
6	$Q_5 = Q_6 + Q_{C4}$	$f_{23}(Q_5, Q_6, Q_{C4}) = 0$
7	$Q_6 + Q_7 = Q_8 + Q_{C5}$	$f_{24}(Q_6, Q_7, Q_8, Q_{C5}) = 0$
8	$Q_8 = Q_9 + Q_{C6}$	$f_{25}(Q_8, Q_9, Q_{C6}) = 0$
9	$Q_9 = Q_{C7} + Q_{C8}$	$f_{26}(Q_9, Q_{C7}, Q_{C8}) = 0$

Based on the flow equations in Table 3.18, looping condition (3.31), the compressor equation (3.33) and mass balance equations in Table 3.19, the solutions to the unknown pressure and flow variables were obtained using the developed Newton-Raphson based TPNS simulation model. The application of the Newton-Raphson based TPNS simulation model for the looped network was conducted based on the pipe data shown Table 3.20.

Table 3.20 Pipe data for single CS and eight customers

Pipe nodes		Diameter [mm]	Length [km]
Start node	End node		
0	1	900	80
2	3	900	60
3	4	600	40
4	D1	600	20
4	D2	600	17
3	5	900	55
5	D3	600	18
5	6	900	70
6	D4	600	50
6	7	900	75
7	D5	600	40
7	8	900	184
8	D6	600	18
8	9	900	6
9	D7	200	33
9	D8	900	87

3.4.4 Case Study: Malaysia Gas Transmission System

In this section, the Newton-Raphson based TPNS simulation model was tested with the actual data from the existing pipeline network system. The network was identified since it consists of all the pipeline configurations, namely: gunbarrel, branched, and looped pipeline network systems.

The objective of the case study was to have a comparison between the results of TPNS simulation model and the actual data collected in the field. However, some data, like the performance of the compressor and flow consumption by the customers are considered confidential by the pipeline company. Hence, it would be difficult to make actual comparison between the results of the simulation with that of the field data. Several options were also tried in order to get the performance of the compressor.

As an alternative to making an actual comparison between the results of the TPNS simulation and the field data, the case study was applied to illustrate the application of the TPNS simulation model to real pipeline network system. The detail applications of the major subtasks of the TPNS simulation model were evaluated based on the network system. Sensitivity analysis was also conducted on the basis of the pipeline configuration system.

The TPNS considered for the case study consists of one compressor station with two compressors working in parallel and having power capacity of 18 to 24 MW each. The pipeline network system serves nine major power plant customers and one Gas District Cooling (GDC) system. The two compressors are working in order to satisfy the daily requirement of natural gas ranging from 0.8 to 1.7 billion standard cubic feet per day (BSCFD) which is equivalent to the consumption of gas raging from 22.65 to 48.14 million metric standard cubic meters per day (MMSCMD). Each compressor has a capacity of 1 to 1.2 BSCFD which gives a cumulative capacity of the compressors delivering 2 to 2.4 BSCFD to various customers which is equivalent to 56.63 to 67.96 MMSCMD.

Due to the limitation of data regarding the performance map of the actual compressors working in the field, gas pipeline compressors from [55] were used for the analysis of the network. The compressor has a maximum capacity of 680m^3/min which is equivalent to 40800m^3/hr (0.98 MMSCMD). The maximum speed is limited to 10500rpm and the maximum head of the compressor is 108kJ/kg.

The gas flow rates in the pipe sections are Q_1, Q_2, ... etc. and the flow rates passing out the gas pipeline to various customers are Q_{C1}, Q_{C2},.. etc. Each customer is identified by their customer station as D_1, D_2 , etc. Figure 3.22 shows the network configuration of part of the Malaysia gas pipeline network system considered for case study.

There are 19 pipe elements connecting the various nodes with length of pipes ranges from 6 km to 200 km. The diameter of the pipes ranges from 200 mm to 900 mm. Since the installation of the pipes was done on three different phases, the age of the pipes is assumed to be ten years for determination of coefficient of friction of the pipes. This TPNS consists of 1 loop and 8 junctions. As a result, based on Table 3.3, there are 10 nodal pressures and 20 flow variables to be determined. Therefore, a total of 30 independent equations were obtained in order to solve the network problem. There are 19 pipe flow equations, 1 compressor equation, 2 looping equations and 8 mass balance equations which formed the 30 independent equations to analyze the TPNS. All the equations were formulated based on the discussion in section 3.2, page 47. The results for unknown variables were determined on the basis of multivariable Newton-Raphson algorithm.

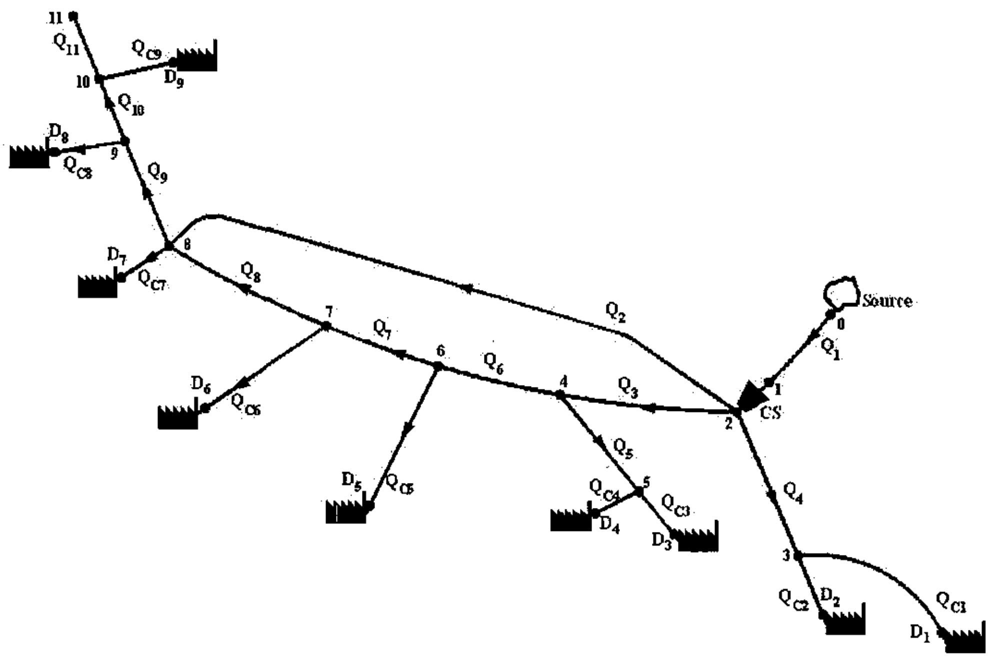


Figure 3.22 Part of the existing pipeline network system

3.5 Enhanced Newton-Raphson based TPNS Simulation Model

The enhanced Newton-Raphson based TPNS simulation consists of additional features such as two-phase flow analysis, internal corrosion and temperature variations. Corrosion and two-phase flow analysis modified the flow equations. When temperature variation was considered during analysis, it added (n_p+ n_s) temperature equations with equal number of unknowns. This section discusses two-phase flow modeling, effect of internal corrosion and temperature variation in TPNS simulation model.

3.5.1 Two-phase Gas-liquid Flow Modeling

As shown in equation (2.13), the total pressure gradient equation is composed of three components: frictional, gravitational, and acceleration components. This equation further developed here to enable the calculation of each of the pressure-gradient components and the total pressure gradient. The basic facts and relationships between the parameters are developed based on Figure 2.5.

The frictional pressure-gradient component is given by:

$$-\left.\frac{dP}{dL}\right)_F = \frac{2}{D} f' \rho_{NS} v_m^2 = \frac{2}{D} f' \frac{M_f^2}{\rho_{NS}} \qquad (3.34)$$

where M_f is the mixture total mass flux, and $M_f = \rho_{NS} v_m$ for no-slip condition and f' is the fanning friction factor.

For rough pipes, $f' = f'(Re_m, \varepsilon/D)$, and it can be determined from a Moody chart [23] or from the following equation developed in [70].

$$f' = 0.001375\left[1 + \left(2\times10^4 \frac{\varepsilon}{D} + \frac{10^6}{\text{Re}}\right)^{1/3}\right] \qquad (3.35)$$

For smooth pipes, the friction factor is a function of the Reynolds number only, $f = f(Re)$, and a Blasius–type equation can be used as given [70]

$$f = C(Re)^{-n} \qquad (3.36)$$

where C is constant.

In equation (3.36), for laminar flow, the exponent n is 1 and that the values of the constant are $C = 16$ and $C = 64$ for fanning and Darcy's friction, respectively. For turbulent flow, different values are available for different ranges of the Reynolds number. For all practical purpose, the correlation covering the widest range of the Reynolds number is $n = 0.2$ with $C = 0.046$ and $C = 0.184$ for fanning and Darcy's friction respectively.

The gravitational pressure gradient component of the pressure drop for two-phase flow can be determined as

$$-\left.\frac{dP}{dL}\right)_G = \rho_m g \sin\theta = \rho_{NS} g \sin\theta \tag{3.37}$$

The acceleration pressure gradient component is given as in [70]:

$$-\left.\frac{dP}{dL}\right)_A = M_f^2\left\{\upsilon_{GL}\frac{dx}{dL}+\frac{dP}{dL}\left[x\frac{d\upsilon_G}{dP}+(1-x)\frac{d\upsilon_L}{dP}\right]\right\}-\frac{M_f^2}{\rho_{NS}}\frac{1}{A_P}\frac{dA_P}{dL} \tag{3.38}$$

Therefore, the total pressure gradient can be obtained by combining the frictional, gravitational, and acceleration pressure gradient component given in equation (3.34), (3.37) and (3.38) respectively, which can be written as:

$$\begin{aligned}-\frac{dP}{dL} &= \frac{2}{D}f'\rho_{NS}v_m^2 + \rho_{NS}\, g\sin\theta \\ &\quad + M_f^2\left\{\upsilon_{GL}\frac{dx}{dL}+\frac{dP}{dL}\left[x\frac{d\upsilon_G}{dP}+(1-x)\frac{d\upsilon_L}{dP}\right]\right\}-\frac{M_f^2}{\rho_{NS}}\frac{1}{A_P}\frac{dA_P}{dL}\end{aligned} \tag{3.39}$$

Solving for the total pressure gradient from equation (3.39) yields

$$-\frac{dP}{dL}=\frac{\frac{2}{D}f'\rho_{NS}v_m^2 + \rho_{NS}\, g\sin\theta + M_f^2\upsilon_{GL}\frac{dx}{dL}-\frac{M_f^2}{\rho_{NS}}\frac{1}{A_P}\frac{dA_P}{dL}}{1+M_f^2\left[x\frac{d\upsilon_G}{dP}+(1-x)\frac{d\upsilon_L}{dP}\right]} \tag{3.40}$$

Numerical evaluation

In order to see the effect of each component of the total pressure gradient, numerical example in [70] is considered here.

The followings are detail of the oil and gas mixture considered for the analysis.

$D = 0.051\,m$, $\theta = 10^0$, $M_L = 1.5\ kg/s$, $M_G = 0.015\,kg/s$. The temperature of the mixture is assumed to be 25^0C and the physical properties of the fluids are: $\rho_G = 1.5kg/m^3$, $\rho_L = 850kg/m^3$, $\mu_L = 2.0\times10^{-3}\,kg/ms$, $\mu_G = 2.0\times10^{-5}\,kg/ms$.

Based on the above data and principles of homogeneous two-phase flow analysis, the frictional pressure gradient can be evaluated based on equation (3.34) as:

$$-\left.\frac{dP}{dL}\right)_F = 741.3 pa/m$$

The gravitational pressure gradient can be obtained from equation (3.37) as:

$$-\left.\frac{dP}{dL}\right)_G = 219.4 Pa/m$$

Similarly, the acceleration pressure gradient component can also be obtained based on equation (3.38). Note that for constant x, the value of υ_L is also constant. Furthermore, from the given information the cross-sectional area of the pipe A_P is constant. As a result, the acceleration pressure gradient equation (3.38) reduces to

$$-\left.\frac{dP}{dL}\right)_A = M_f^2 x \frac{d\upsilon_G}{dP}\frac{dP}{dL} \tag{3.41}$$

Based on equation (3.41) and assuming ideal gas law, the acceleration pressure gradient is determined to be

$$-\left.\frac{dP}{dL}\right)_A = 19.80 Pa/m$$

As a result the total pressure gradient is

$$-\left.\frac{dP}{dL}\right) = 1980.5 Pa/m$$

Note that for the above homogeneous two-phase gas-liquid mixtures, the acceleration pressure gradient component contributes only 2.02% to the total pressure gradient. Hence, the acceleration pressure gradient is usually omitted from calculation. Neglecting the effect of acceleration component of the pressure gradient, equation (3.40) can be simplified for horizontal pipe flow as

$$-\frac{dP}{dL}=\frac{2}{D}f'\rho_m v_m^2 \tag{3.42}$$

As given in equation (3.36), the frictional coefficient for smooth turbulent flow can be described as function of Reynolds number as

$$f'=0.046Re_m^{-0.2} \tag{3.43}$$

The mixture Reynolds number for the two-phase flow is given

$$Re_m=\frac{4\,Q_m\,\rho_m}{\pi\,\mu_m D} \tag{3.44}$$

The mixture velocity can also be expressed for two-phase flow as

$$v_m=\frac{4\,Q_m}{\pi\,D^2} \tag{3.45}$$

Substituting equations (3.43), (3.44), and (3.45) into equation (3.42) results

$$-\frac{dP}{dL}=\frac{2}{D}\rho_m\left(0.046\times\left(\frac{4Q_m\,\rho_m}{\pi\,\mu_m\,D}\right)^{-0.2}\right)\left(\frac{4\,Q_m}{\pi\,D^2}\right)^2 \tag{3.46}$$

By integrating equation (3.46) from $L=0$, $P=P_1$, to $L=L$, $P=P_2$ we get

$$P_1-P_2=\frac{2}{D}\rho_m\left(0.046\times\left(\frac{4Q_m\,\rho_m}{\pi\,\mu_m\,D}\right)^{-0.2}\right)\left(\frac{4\,Q_m}{\pi\,D^2}\right)^2 L \tag{3.47}$$

For two-phase flow mixture, the pressure drop equation for any pipeline element connecting node i and j shown in Figure 3.2, relating upstream pressure P_i, downstream pressure P_j, and the mixture flow through pipe Q_m can be expressed as:

$$P_i - P_j = K_{ij} Q_m^{1.80} \quad (3.48)$$

where K_{ij} is to be determined by the mixture properties and the characteristics of pipe connecting node i and j.

K_{ij} takes different forms depending on the dimensions of the parameters used in the flow equations. When $P[kPa]$, $L[km]$, $Q_m[m^3/hr]$, $D[mm]$, $\rho_m[kg/m^3]$, $\mu_m[Kg/ms]$, the expression for K_{ij} takes the form

$$K_{ij} = 3.0791 \times 10^8 \rho_m \left(\frac{\rho_m}{\mu_m} \right)^{-0.2} \frac{L}{D^{4.8}} \quad (3.49)$$

If the pipeline networks system shown in Figure 3.3 is used to transmit two-phase gas-liquid mixtures, the flow equations governing the simulation can be generated for the pipes based on equation (3.48). Assuming that the source pressure at node 0 and the demand pressures at node 6 and 9 are known, the two-phase flow equations for the pipes and the corresponding functional representation can be summarized as shown in Table 3.21. Note that for ease of simplification, the mixture flow rate Q_m and single phase gas flow rate Q are represented by same variable Q.

Table 3.21 Two-phase flow equations and functional representations

Pipe node		Two-phase flow equation	Functional representation
Start node	End node		
0	1	$P_0 - P_1 = K_{01} Q_1^{1.80}$	$f_1(P_1, Q_1) = 0$
2	3	$P_2 - P_3 = K_{23} Q_1^{1.80}$	$f_2(P_2, P_3, Q_1) = 0$
3	4	$P_3 - P_4 = K_{34} Q_2^{1.80}$	$f_3(P_3, P_4, Q_2) = 0$
3	7	$P_3 - P_7 = K_{37} Q_3^{1.80}$	$f_4(P_3, P_7, Q_3) = 0$
5	6	$P_5 - P_6 = K_{56} Q_2^{1.80}$	$f_5(P_5, Q_2) = 0$
8	9	$P_8 - P_9 = K_{89} Q_3^{1.80}$	$f_6(P_8, Q_3) = 0$

The application of the enhanced Newton-Raphson TPNS simulation model for two-phase flow analysis is demonstrated based on gunbarrel and branched network configurations.

i) Case 1C: Gunbarrel Pipeline Network Module

When two-phase gas-liquid flows through the gunbarrel TPNS, the flow equations were affected. It is assumed that only the gas flows to the compressor station for compression due to severe effect of the liquid to the compressor stations. In practice, scrubbers are usually installed in front of the compressor station to remove any unwanted elements.

For the gunbarrel pipeline network system shown in Figure 3.19, the pipes flow equations for two-phase gas-liquid flow are given based on equation (3.48) and summarized as shown in Table 3.22.

Table 3.22 Summary of flow equations for the given gunbarrel TPNS

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0 - P_1 = K_{01}Q^{1.80}$	$f_1(P_1, Q) = 0$
2	3	$P_2 - P_3 = K_{23}Q^{1.80}$	$f_2(P_2, P_3, Q) = 0$
4	5	$P_4 - P_5 = K_{45}Q^{1.80}$	$f_3(P_4, P_5, Q) = 0$

Similarly, based on the discussion on compressor stations modeling in section 3.2.3, the remaining compressor equations for the network can be formulated and represented in functional forms as shown in Table 3.12.

Based on the flow equations shown in Table 3.22 and the compressor equations shown in Table 3.12, the solution to the unknown pressure and flow variables were obtained using the enhanced Newton-Raphson based TPNS simulation model.

ii) Case 2C: Branched Pipeline Network Module

The branched pipeline network discussed in 3.4.2 is considered here. Based on equation (3.48), the pipe flow equations for two-phase gas-liquid flow were formulated and summarized as shown in Table 3.23.

Table 3.23 Summary of flow equations and their functional representation

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0 - P_1 = K_{01}Q_1^{1.80}$	$f_1(P_1, Q_1) = 0$
2	3	$P_2 - P_3 = K_{23}Q_1^{1.80}$	$f_2(P_2, P_3, Q_1) = 0$
3	D1	$P_3 - P_D = K_{3D1}Q_{C1}^{1.80}$	$f_3(P_3, Q_{C1}) = 0$
3	4	$P_3 - P_4 = K_{34}Q_2^{1.80}$	$f_4(P_3, P_4, Q_2) = 0$
4	D2	$P_4 - P_D = K_{4D2}Q_{C2}^{1.80}$	$f_5(P_4, Q_{C2}) = 0$
4	5	$P_4 - P_5 = K_{45}Q_3^{1.80}$	$f_6(P_4, P_5, Q_3) = 0$
5	D3	$P_5 - P_D = K_{5D3}Q_{C3}^{1.80}$	$f_7(P_5, Q_{C3}) = 0$
5	6	$P_5 - P_6 = K_{56}Q_4^{1.80}$	$f_8(P_5, P_6, Q_4) = 0$
6	D4	$P_6 - P_D = K_{6D4}Q_{C4}^{1.80}$	$f_9(P_6, Q_{C4}) = 0$
6	D5	$P_6 - P_D = K_{6D5}Q_{C5}^{1.80}$	$f_{10}(P_6, Q_{C5}) = 0$

The remaining equations from the compressor maps and mass balance were formulated following the same procedure as in section 3.4.2. The compressor equation for the TPNS is given as in equation (3.28) and represented in functional form as in equation (3.29). The remaining mass balance equations for the network were formulated and summarized as shown in Table 3.16.

The solutions to the unknown pressure and flow variables were obtained using the developed enhanced Newton-Raphson based TPNS simulation model based on the flow equations shown in Table 3.23, compressor equation (3.29) and the mass balance equations shown in Table 3.16.

3.5.2 The Effect of Internal Corrosion

The effect of corrosion is to modify the flow equation during the development of the governing simulation equations. Since corrosion in oil and gas industries is one of the serious challenges which affect the performance of the pipeline network system, the effect of corrosion on the performance of the gas transmission system have to be analyzed and incorporated during the development of TPNS simulation model.

So far, limited information is available from the literatures about how the roughness of the pipes varies with the age of the pipe. In this section, a solution scheme is developed to incorporate the age of the pipe to flow equation. Figure 3.23 shows the general procedure proposed to incorporate the effect of corrosion with age of the pipe and flow modification.

Data of roughness of the coated pipe with service life of the pipe from [22] was used for developing the correlation between the age of the pipe and roughness. Several options were tried in order to get the best fit for the data of pipe roughness against the service life of the pipe. It is observed that, even if the effect of pipe roughness increase with increase in age of the pipe, the best fit for the data was obtained when the approximation was done with 6 degree polynomial function with correlation coefficient of $R^2 = 0.88$. However, this approximation gave negative roughness values when the age of the pipe increased beyond the data points. A better approximation for the given data was obtained when the data is approximated with exponential function with correlation coefficient of $R^2 = 0.592$.

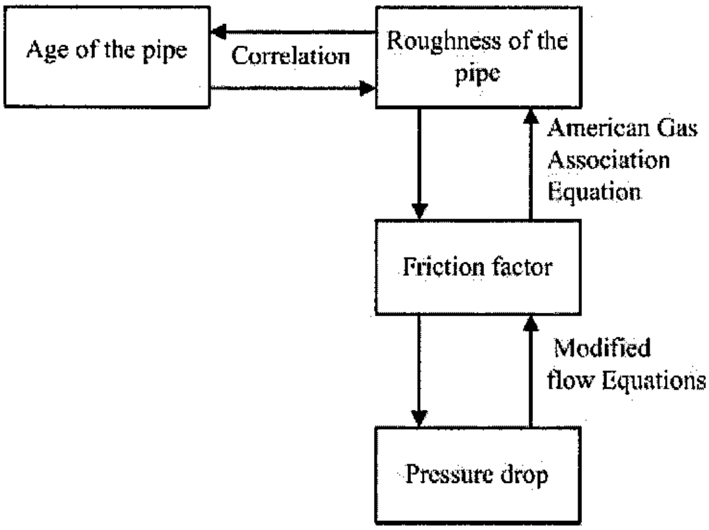


Figure 3.23 Proposed scheme for incorporating the age of the pipes in flow equations

Based on the data points, exponential function for approximating the relationship between the roughness of the pipe with that of the age of the pipe is obtained to be:

$$r = 0.00353e^{0.03802y} \tag{3.50}$$

where r is the roughness of the pipe in mm and y is the age of the pipe in year.

Most gas pipelines operate in the turbulent zone. For the fully turbulent zone, American Gas Association (AGA) recommends using the following formula for calculating the transmission factor F which is based on the relative roughness r/D and independent of the Reynolds number [23] .

$$F = 4Log_{10}\left(\frac{3.7D}{r}\right) \tag{3.51}$$

where F is the transmission factor, r is the roughness of the pipe and D is the diameter of the pipe.

The relationships between the transmission factor F and friction factor f can be express as [23]:

$$F = \frac{2}{\sqrt{f}} \tag{3.52}$$

Substituting equation (3.52) in equation (3.51) and rearranging gives:

$$f = \frac{1}{\left[2Log_{10}\left(\frac{3.7D}{r}\right)\right]^2} \tag{3.53}$$

From equations (3.50) and (3.53), it can be seen that the friction factor is a function of the age of the pipe. Figure 3.24 shows the effect of the years in service of the pipe on friction factor for various diameters of the pipe.

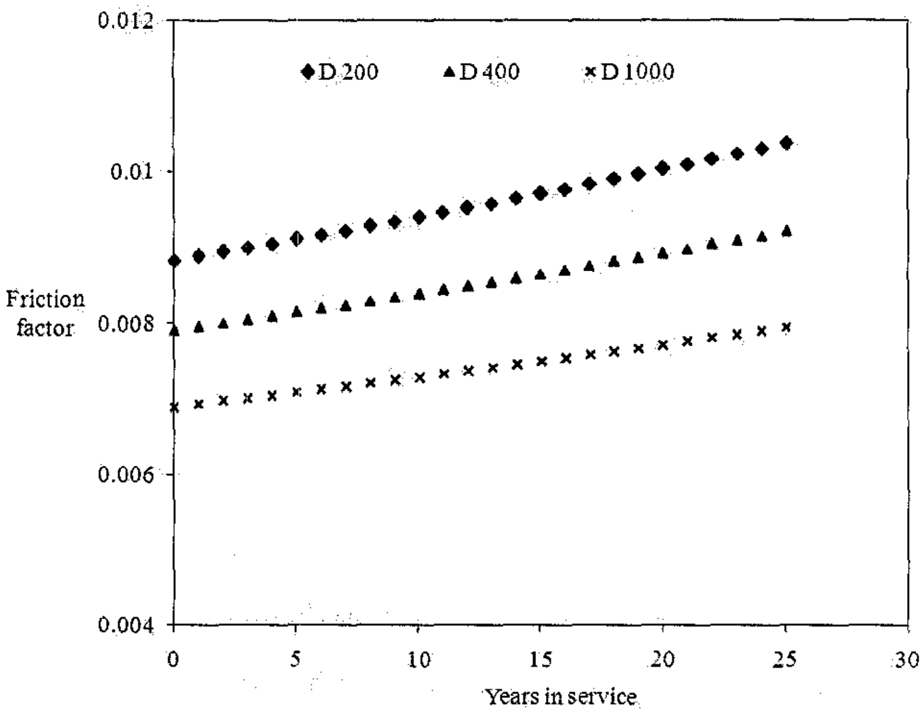


Figure 3.24 The effect of length of service of the pipe on friction factor

The general flow equation for a single phase gas flow in equation (3.1) can be modified based on the friction factor in equation (3.53) in order to incorporate the effect of the age of the pipe on the pressure drop of the TPNS. For any pipe (Figure 3.2) connecting the upstream node i, downstream node j, and the flow through pipe

Q, the single phase flow equation with corrosion relating the two nodes can be represented as

$$P_i^2 - P_j^2 = K_{ij}^{'} f Q^2 \tag{3.54}$$

where

$$K_{ij}^{'} = 4.3599 \times 10^8 \frac{GZT}{D^5} \left(\frac{P_n}{T_n} \right)^2 L \tag{3.55}$$

If all the pressure and flow variables are unknown, equation (3.54) can also be represented in functional form as

$$f(P_i, P_j, Q) = 0 \tag{3.56}$$

The application of the enhanced Newton-Raphson based TPNS simulation model for incorporating the effect of internal corrosion is demonstrated based on gunbarrel and branched network configurations.

i) Case 3C: Gunbarrel Pipeline Network Module

When corrosion is considered during the analysis of gas transmission system, the overall effect is to modify the pressure drop equations. The gunbarrel transmission network configuration shown in Figure 3.19 is considered here. For this pipeline network, based on equation (3.54), the pipe flow equations for single phase gas flow with corrosion were formulated and summarized as shown in Table 3.24.

Table 3.24 Summary of flow equations for the given gunbarrel TPNS

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01} f_1 Q^2$	$f_1(P_1, Q) = 0$
2	3	$P_2^2 - P_3^2 = K_{23} f_2 Q^2$	$f_2(P_2, P_3, Q) = 0$
4	5	$P_4^2 - P_5^2 = K_{45} f_3 Q^2$	$f_3(P_4, P_5, Q) = 0$

Similarly, based on the discussion on compressor stations modeling in section 3.2.3, the remaining compressor equations for the network were formulated and represented in functional forms as shown in Table 3.12.

Based on the flow equations shown in Table 3.24 and the compressor equations shown in Table 3.12, the solution to the unknown pressure and flow variables were obtained using the enhanced Newton-Raphson based TPNS simulation model.

ii) Case 4C: Branched Pipeline Network Module

For the branched pipeline network shown in Figure 3.20, based on equation (3.54), the pipe flow equations for single phase gas flow with corrosion were formulated and summarized as shown in Table 3.25.

Table 3.25 Summary of flow equations and their functional representation considering corrosion

Pipe node		Flow equation	Functional representation
Start node	End node		
0	1	$P_0^2 - P_1^2 = K_{01} f_1 Q_1^2$	$f_1(P_1, Q_1) = 0$
2	3	$P_2^2 - P_3^2 = K_{23} f_2 Q_1^2$	$f_2(P_2, P_3, Q_1) = 0$
3	D1	$P_3^2 - P_D^2 = K_{3D1} f_3 Q_{C1}^2$	$f_3(P_3, Q_{C1}) = 0$
3	4	$P_3^2 - P_4^2 = K_{34} f_4 Q_2^2$	$f_4(P_3, P_4, Q_2) = 0$
4	D2	$P_4^2 - P_D^2 = K_{4D2} f_5 Q_{C2}^2$	$f_5(P_4, Q_{C2}) = 0$
4	5	$P_4^2 - P_5^2 = K_{45} f_6 Q_3^2$	$f_6(P_4, P_5, Q_3) = 0$
5	D3	$P_5^2 - P_D^2 = K_{5D3} f_7 Q_{C3}^2$	$f_7(P_5, Q_{C3}) = 0$
5	6	$P_5^2 - P_6^2 = K_{56} f_8 Q_4^2$	$f_8(P_5, P_6, Q_4) = 0$
6	D4	$P_6^2 - P_D^2 = K_{6D4} f_9 Q_{C4}^2$	$f_9(P_6, Q_{C4}) = 0$
6	D5	$P_6^2 - P_D^2 = K_{6D5} f_{10} Q_{C5}^2$	$f_{10}(P_6, Q_{C5}) = 0$

The remaining equations from the compressor maps and mass balance were formulated following the same procedure as in section 3.4.2. The compressor equation for the TPNS is given as in equation (3.28) and represented in functional form as in equation (3.29). The remaining mass balance equations for the network were formulated and summarized as shown in Table 3.16.

The solutions to the unknown pressure and flow variables were obtained using the developed enhanced Newton-Raphson based TPNS simulation model based on the flow equations shown in Table 3.25, compressor equation (3.29) and the mass balance equations shown in Table 3.16.

3.5.3 Modeling Temperature Variations

When the temperature of the gas varies due to heat transfer and compression, it is essential to consider temperature variations during modeling. As presented in section 2.4.2, the variations of temperature within the TPNS are described based on equations (2.14) and (2.15). These two equations should have to be integrated into the governing simulation equations to represent the effect of temperature variations for the enhanced Newton-Raphson based TPNS simulation.

Equation (2.14) is modified before it is integrated into the governing simulation equations as the governing simulation equation takes only equations which are functions of pressure, flow, and temperature variables. The mass flow rate M used in equation (2.15) is given as function of volumetric flow Q and density of the gas as

$$M = \rho Q \tag{3.57}$$

Substituting equation (3.57) in equation (2.15) yields

$$\theta = \frac{\pi U D \Delta L}{\rho C_P Q} \tag{3.58}$$

Therefore, equation (2.14) is modified for any pipe element (Figure 3.2) connecting the upstream node i, downstream node j, and the flow through pipe Q, as

$$T_j = T_s + (T_i - T_s)e^{Tij/Q} \tag{3.59}$$

where $Tij = \frac{\pi UD\Delta L}{\rho C_P}$

If all the variables in equation (3.59) are unknown, it can also be represented in terms of function form as

$$f(T_1, T_2, Q) = 0 \tag{3.60}$$

The second equation to represent the variation of temperature in gas transmission network system is equation (2.16). Since equation (2.16) is function of the required variables, it was used without any modifications on it. If all the variables are unknown in equation (2.16), the functional form of the equation takes the form

$$f(T_1, T_2, P_1, P_2) = 0 \tag{3.61}$$

Equation (3.60) and (3.61) are the basic equations which govern the enhanced Newton-Raphson based TPNS simulation under variable temperature conditions.

The application of the enhanced Newton-Raphson TPNS simulation model for temperature variations is demonstrated based on the gunbarrel pipeline network configurations shown in Figure 3.19. If the temperature of the gas is assumed to be constant, there were 4 pressure variables and 1 flow variable to be determined for the TPNS. When temperature variation is considered during the analysis, n_p+n_s temperature equations with equal number of unknown temperature variables were added to the governing simulation equations. As a result, there were five more temperature equations and five unknown temperature variables introduced to the system. The numbers of total unknown pressure, flow, and temperature variables became ten.

Single phase flow model was used for the flow analysis. The summary of the pipe flow equations for single phase gas flow model using general equation was given as in Table 3.11. The remaining compressor equations for the network were formulated and represented in functional forms as shown in Table 3.12.

The temperature equations were developed and represented in functional form for the given pipeline network as shown in Table 3.26.

Table 3.26 Summary of temperature equations for gunbarrel TPNS

Temperature equation	Functional representation
$T_1 = T_s + (T_0 - T_s)e^{T_{01}/Q}$	$f_6(T_1, Q) = 0$
$\left(\frac{T_2}{T_1}\right) = \left(\frac{Z_1}{Z_2}\right)\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$	$f_7(T_1, T_2, P_1, P_2) = 0$
$T_3 = T_s + (T_2 - T_s)e^{T_{23}/Q}$	$f_8(T_2, T_3, Q) = 0$
$\left(\frac{T_4}{T_3}\right) = \left(\frac{Z_1}{Z_2}\right)\left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}$	$f_9(T_3, T_4, P_3, P_4) = 0$
$T_5 = T_s + (T_4 - T_s)e^{T_{45}/Q}$	$f_{10}(T_4, T_5, Q) = 0$

Therefore, based on the flow equations in Table 3.11 , the compressor equations in Table 3.12, and temperature equations in Table 3.26, the solutions to the unknown pressure, flow, and temperature variables were obtained using the enhanced NR based TPNS simulation model.

3.6 Performance Evaluation of the TPNS Simulation Model

As it is observed from the solution schemes discussed in the previous sections, the successive substitution and Newton-Raphson methods provided solutions to the unknown pressure, flow and temperature variables which are essential for evaluating the performance of TPNS. The performance of the TPNS includes evaluation of the flow capacities through each pipe elements, compression ratios at each compressor stations, and the overall power consumption of the TPNS.

The flow capacities through each pipe are determined directly from the value of the unknown variables obtained using either of the solution schemes discussed above. The compression ratios (CR) at each compressor stations are evaluated based on the pressure variables obtained by using the solution schemes. Based on the nodal pressures, the compression ratio is defined as the ratio of discharge pressure to suction pressure.

Based on the pressure and flow variables obtained, the simulation model is used to evaluate the energy consumption of the TPNS. The amount of energy input to the gas by the compressors is dependent upon the pressure of the gas and flow rate. The power required by the compressor that takes into account the compressibility of gas is given as [23]

$$HP = 4.0639\left(\frac{k}{k-1}\right)QT_S\left(\frac{Z_1+Z_2}{2}\right)\left(\frac{1}{\eta_a}\right)\left[\left(\frac{P_d}{P_s}\right)^{\frac{k}{k-1}}-1\right] \tag{3.62}$$

where HP is the compression power in kW.

3.7 Summary

The basic equations for the TPNS simulation are derived from the principles of flow of fluid through pipe, compressor characteristics and the principles of mass balance at the junction of the network. The existences of loops within the TPNS create additional equations to the simulation model. These equations are developed from the principle of looping conditions which states the pressure drop along any closed loop is zero.

The solution for the unknown variables could be determined on the basis of an iterative successive substitution or Newton-Raphson schemes. The method of successive substitution is closely associated with the IFD where the governing simulation equations are arranged in such a way that only one output is obtained from the blocks. On the other hand, the Newton-Raphson solution scheme is complex but powerful for the analysis of TPNS where the number of equations is large.

The modeling of the application of iterative successive substitution scheme based TPNS simulation model is demonstrated using two network configurations. The development of the basic governing equations and the corresponding IFD generation were discussed for the networks considered. The application of the Newton-Raphson based TPNS simulation is also demonstrated using the three most commonly networks configurations, namely: gunbarrel, branched and looped.

The next chapter discusses the results obtained by testing the developed TPNS simulation model for different TPNS configurations. Table 3.27 shows the summary of the different cases considered for the analysis.

Table 3.27 Various cases considered for the analysis using developed TPNS simulation model

Model	Case	Module	Section
Successive substitution based TPNS simulation model	Case 1A	1CS 2 Customers	4.2.1
	Case 2A	2CSs 2 Customers	4.2.2
Newton-Raphson based TPNS simulation model	Case 1B	Gunbarrel	4.3.1
	Case 2B	Branched	4.3.2
	Case 3B	Looped	4.3.3
	Malaysia TPNS	General	3.4.4
Enhanced Newton-Raphson based TPNS simulation model	Case 1C	Gunbarrel	4.4.1
	Case 2C	Branched	4.4.1
	Case 3C	Gunbarrel	4.4.2
	Case 4C	Branched	4.4.2

The enhanced Newton-Raphson based TPNS simulation consists of additional features such as two-phase flow analysis, internal corrosion and temperature variations. Corrosion and two-phase flow analysis modified the flow equations. When temperature variation is considered during analysis, it added temperature equations with equal number of unknowns.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the results of detail application of the TPNS simulation model for various pipeline configurations are presented. The first part discusses the results of the application of the TPNS simulation model based on successive substitution solution scheme. The second part discusses the results of the application of the TPNS simulation model based on the iterative Newton-Raphson solution scheme. The application of the TPNS simulation model for real pipeline network system is also discussed in this section. The third part discusses the results of enhanced Newton-Raphson based TPNS simulation model. The fourth part of this Chapter discusses the verification and validation of the simulation model.

4.2 Successive Substitution based TPNS Simulation Model

The results of the applications of successive substitution solution scheme for TPNS simulation are demonstrated based on two different pipeline configurations discussed in section 3.3.1 and 3.3.2. The successive substitution based simulation model was implemented using excel based spreadsheet. The results of the analysis were reported by Woldeyohannes and A. Majid [87].

4.2.1 Case 1A: Single Compressor Station and Two Customers Module

The single compressor station with two customers' network shown in Figure 3.14 on page 66 is considered here for the analysis. Using the procedures described in section 3.3.1, the results of the pressure and flow variables for this TPNS for the first 50 iterations are presented in Appendix C.

The convergences of the pressure and flow variables were studied. As stated in [81], the calculation sequence dictated by the structure of the IFD determines whether the sequence will converge or diverge. P_3 and Q_1 were the variables identified from the IFD shown in Figure 3.15 on page 68 to start the analysis. When the initial estimations for P_3 and Q_1 varied, there were two phenomena observed from the simulation. The first case was the divergence case. In this case, the relative errors calculated from each successive iterations followed irregular trends. The second case was the slow convergence rate. In this case, when the initial estimations were far from the final solutions of the variables, it took longer iterations to arrive the final solution.

The convergence of the pressure variables for the TPNS is as shown in Figure 4.1. The pressure variables converged to their final solution with different rate of convergence. The relative errors of the pressure variables started to become stable at the 17^{th} iteration for P_2 and 16^{th} iterations for P_1 and P_3.

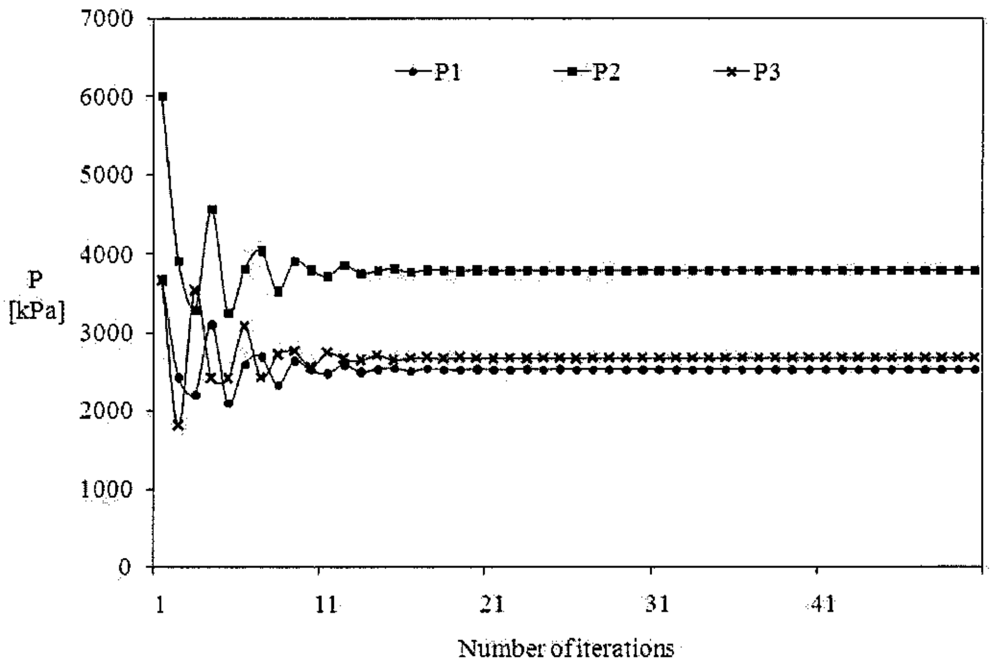


Figure 4.1 Convergence of pressure variables (case 1A)

The convergences of the flow variables are shown in Figure 4.2. Around 20 iterations were required to get stable convergence graph for the flow variables. However, Q_{C1} and Q_{C2} became stable starting from the 16^{th} iterations as the initial assumed values are near to these variables compared to Q_1. The negative flow observed for Q_{C1} for the two iterations was due to the high initial estimation for P_3.

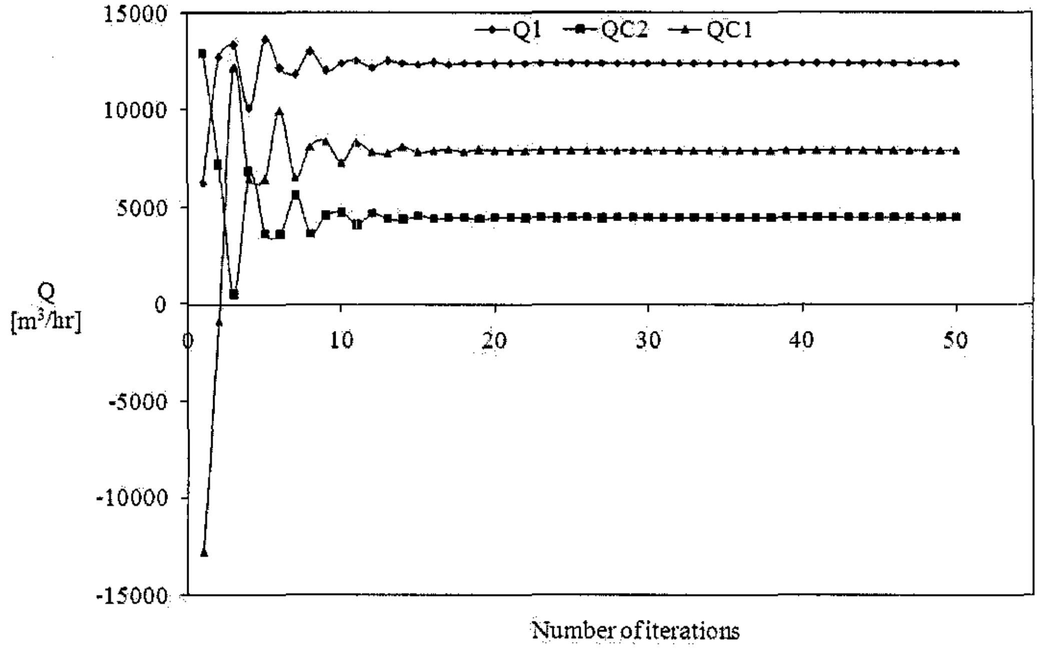


Figure 4.2 The convergence of flow variables (Case 1A)

From the convergence graphs (Figure 4.1 and Figure 4.2), it is observed that, the maximum relative percentage error after the 20th iterations is 1.21%. At the end of the 50th iterations the maximum relative percentage error is 1.33E-04.

4.2.2 Case 2A: Two Compressor Stations and Two Customers Module

The two compressor stations two customers network shown in Figure 3.16 on page 69 is considered here for the analysis. Using the procedures described in section 3.3.2, the results of the pressure and flow variables for this TPNS for the first 200 iterations.

The convergences of the pressure and flow variables were also studied. Figure 4.3 shows the convergence of the pressure variables for the first 200 iterations. The corresponding convergences of the flow variables are shown in Figure 4.4. After the 20th iterations, the maximum relative percentage error observed was 32.7%. At the end of the 50th iterations the maximum relative percentage error is 8.15E-02. These show that as the number of unknown variables increased, the successive substitution scheme took longer time to arrive at the specified tolerance as presented in [81].

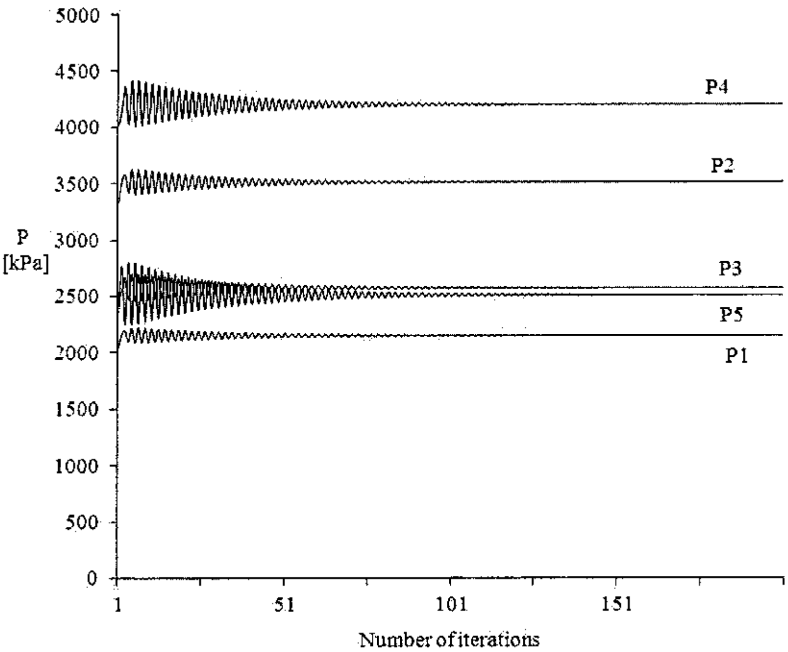


Figure 4.3 The convergence of pressure variables (case 2A)

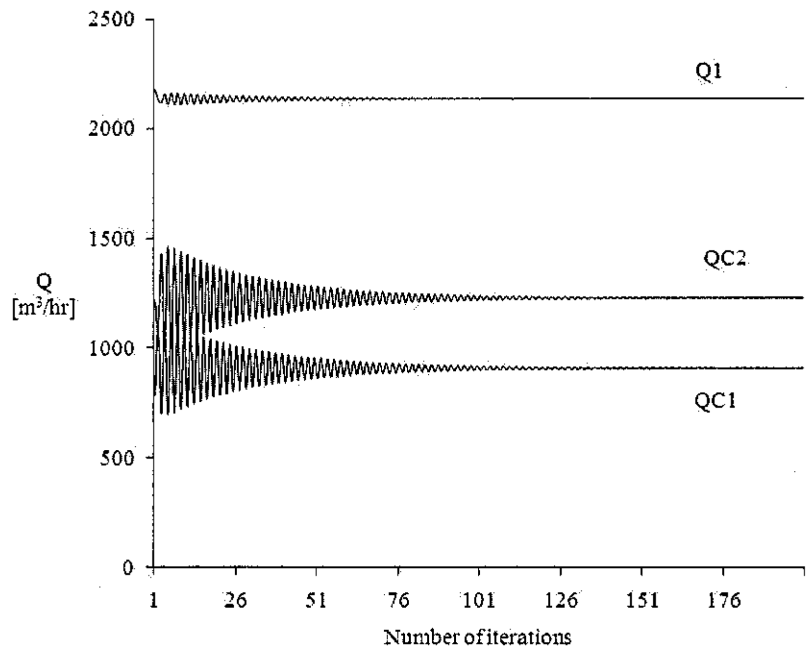


Figure 4.4 The convergence of flow variables (case 2A)

4.2.3 Limitations of Successive Substitution TPNS Simulation Model

Results from the numerical evaluation of the networks shown in Figure 3.14 on page 66 and Figure 3.16 on page 69 revealed that the successive substitution based TPNS simulation model could be applied to determine the flow and pressure variables. However, it was observed that it took 50 iterations for case 1A and 200 iterations for case 2A to converge to relative percentage of errors of $1.33x10^{-4}$ and $8.15x10^{-4}$, respectively. As the number of pressure and flow variables increased, it required more iteration to converge to the final solutions. Comparison of successive substitution based TPNS simulation with that of Newton-Raphson based TPNS simulation is reported by Majid and Woldeyohannes [88] based on two different network configurations.

Although successive substitution scheme is straight forward technique and is usually easy to program, sometimes the method may result in very slow convergence rate depending on the IFD and the initial estimation for the unknown variables.

Hence, the method is limited only for TPNS with few numbers of pipes, compressor stations and junctions. In addition, it is difficult to get the IFD of the given pipeline network as the number of branches increases. Several correct IFD can be developed for the given pipeline network system. However, it is very difficult to identify the IFD which is convergent as discussed in [81]. For instance, for the TPNS shown in Figure 4.5, one of the correct IFD is shown in Figure 4.6. It required testing many alternatives to arrive at the correct IFD.

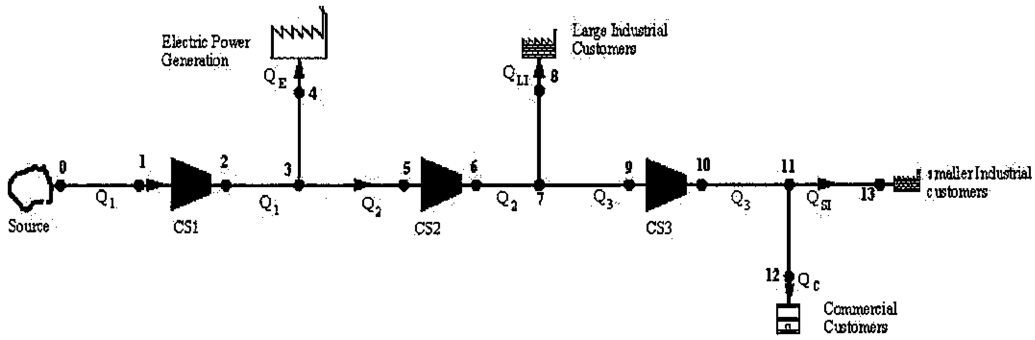


Figure 4.5 Pipeline network with three CSs serving four customers

The TPNS consists of 10 pipes, 3 compressor stations, 3 junction, and with no loop. Therefore, n_p = 10, n_s = 3, n_l = 0, and n_j = 3. As a result, there are 9 nodal pressures and 7 flow parameters to be determined. Therefore, a total of 16 independent equations have to be obtained in order to solve the network problem. The IFD is developed based on the governing simulation equations and shown in Figure 4.6.

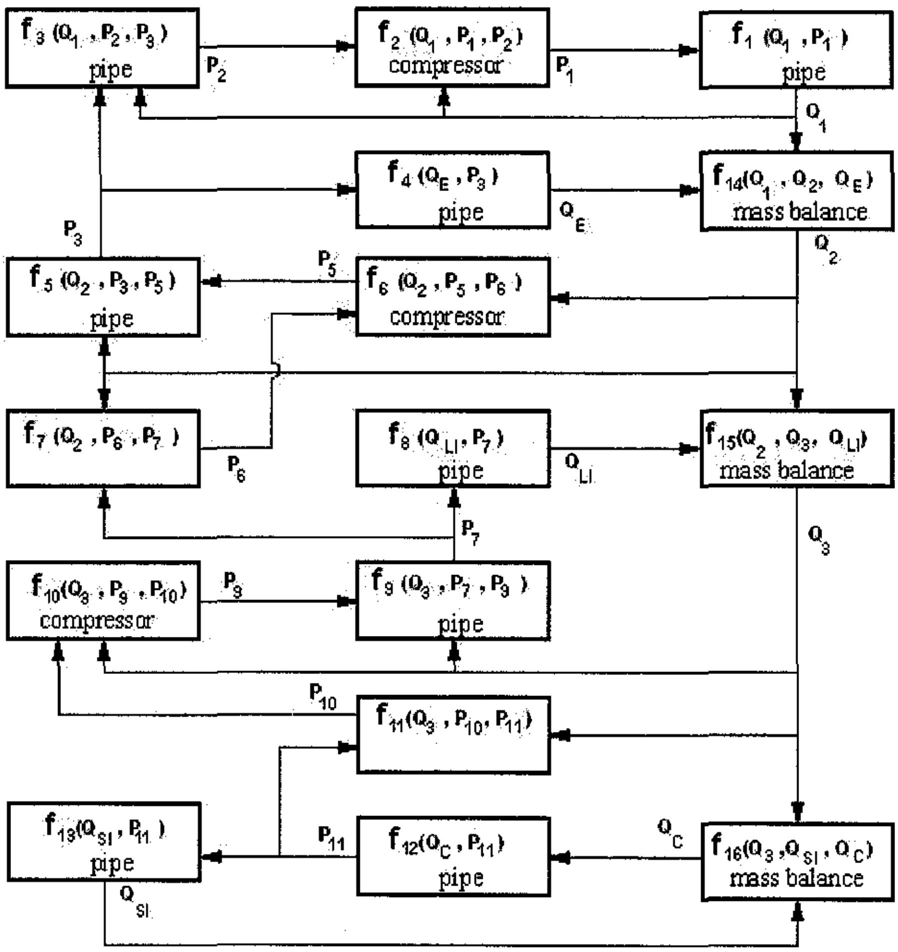


Figure 4.6 IFD for pipeline network with three CSs and four customers

4.3 Newton-Raphson based TPNS Simulation Model

The multivariable Newton-Raphson method which is discussed in section 3.4 on page 72 is used for the analysis of TPNS with large number of pipes, compressor stations, branches and loops. This section discusses results of detailed application of the Newton-Raphson based TPNS simulation model using gunbarrel, branched and looped configurations.

4.3.1 Case 1B: Gunbarrel Pipeline Network Module

The results and discussions presented in this section are based on the gunbarrel TPNS network configurations shown in Figure 3.19 on page 77 and the methodology presented in section 3.4.1 on page 76.

The network was analyzed with the aid of the developed Newton-Raphson based TPNS simulation model. Gas pipeline compressors from [55] were used for the analysis. The speed of the compressor was 8000 rpm. Note that the analysis could also be done based on various speeds as long as the compressor speed is within the operational limit. In order to make the multivariable Newton-Raphson convenient for application, only single estimation that was used for all unknown variables was required to start the iterations. The results for the unknown pressure variables and flow variable were obtained with less than ten iterations. Table 4.1 shows the results of the unknown nodal pressures and flow variable for the first ten iterations. Note that pressure is measured in kPa and flow rate is measured in m^3/hr.

Table 4.1 Results of nodal pressures and flow variables (case 1B)

Iteration	P_1	P_2	P_3	P_4	Q	Max. error
0	3000.00	3000.00	3000.00	3000.00	3000.00	
1	2982.71	3591.98	3574.69	4183.96	2.40E+06	0.99875
2	1308.05	3665.21	2253.81	5210.26	1.49E+06	0.60892
3	2109.82	3691.36	2997.95	4638.76	987089	0.510994
4	2438.82	3545.31	3064.63	4384.63	715543	0.379496
5	2471.25	3505.5	3064.8	4346.88	638202	0.121187
6	2472.77	3505.01	3065.89	4345.74	632588	0.008874
7	2472.77	3505.01	3065.9	4345.73	632559	4.56E-05
8	2472.77	3505.01	3065.9	4345.73	632559	1.2E-09
9	2472.77	3505.01	3065.9	4345.73	632559	9.94E-16
10	2472.77	3505.01	3065.9	4345.73	632559	1.13E-16

The convergences of the pressure and flow variables were studied. Based on the results obtained in Table 4.1, the convergence of nodal pressures and flow variables for the network system are shown in Figure 4.7 and Figure 4.8, respectively. Convergence was achieved in most of the initial estimations attempted for the Newton-Raphson based TPNS simulation model. An initial estimation near to the demand pressure requirements for both pressure and flow variables gave convergences for the attempted simulation runs.

The convergence graphs shown in Figure 4.7 and Figure 4.8 indicated that the relative percentage errors became stable starting from the 4^{th} iteration. The high value for Q that is observed at the second iteration in Figure 4.8 is due to the value of initial estimation which is far off compared to the final solution.

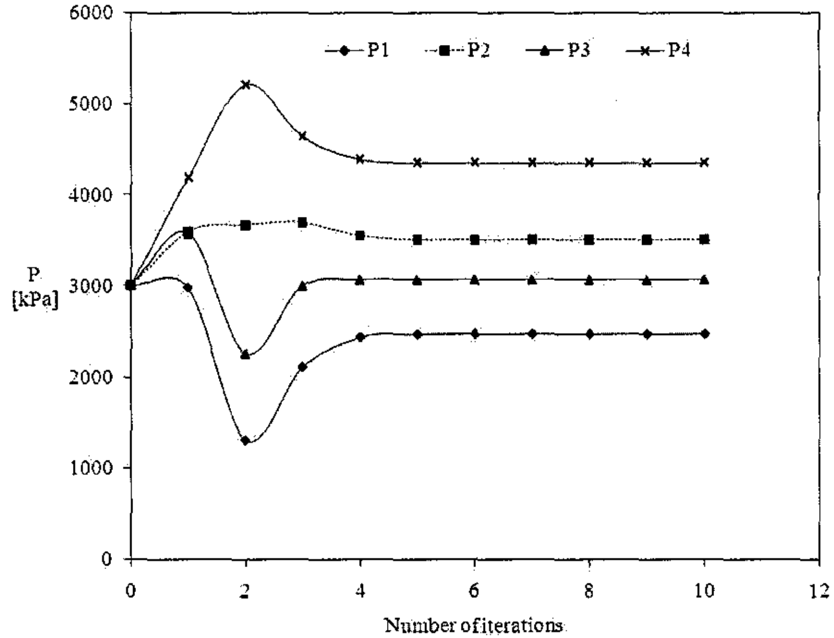


Figure 4.7 Convergence of pressure variables (case 1B)

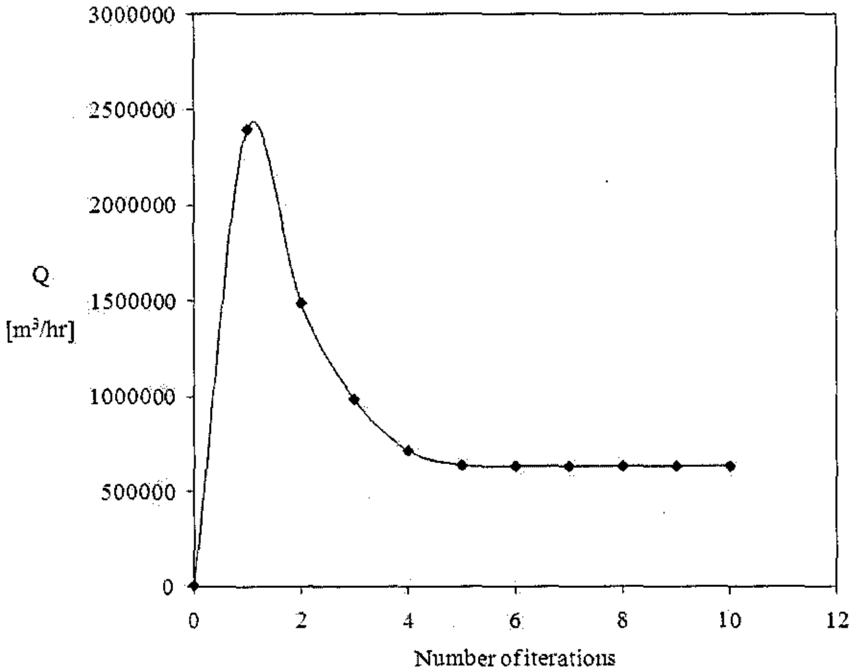


Figure 4.8 Convergence of flow variable (case 1B)

The results of Newton-Raphson based TPNS simulation model for the gunbarrel network configurations are compared with the method proposed by Wu et al [47]. The pressure range for each node is between 689.5 kPa and 6895 kPa. There are 5 compressors within each compressor stations. The flow through pipes is assumed to be 600 million standard cubic feet per day (MMSCFD) or equivalent to 707,921 million metric standard cubic meters per day (MMSCMD). The problem for the network is the determination of nodal pressures which minimizes the fuel cost of the compressors.

Wu et al [47] determined solutions for the optimal nodal pressures for minimizing the fuel consumption of the system using exhaustive search method. The results of the nodal pressures are shown in Table 4.2.

Table 4.2 Results of nodal pressures [47]

Node	Pressure [kPa]
0	4112.88
1	3433.59
2	3640.43
3	2850.70
4	3088.85
5	2101.13

The pipeline network was also analyzed using the TPNS simulation model. In TPNS simulation model, it is assumed that maintaining pressure requirement is critical and therefore, the source pressure P_0 and the demand pressure P_5 are assumed to be known. Therefore, the problem in TPNS simulation is finding the remaining nodal pressures, flow rate, number of compressors within the stations, power consumption and the speed of the compressors which satisfies the requirement.

A compressor map from the existing pipeline network system [89] was used for the analysis. The characteristic map of the compressor was available in terms of the discharge pressure versus flow capacity. As a result, the discharge pressure versus flow capacity curves were approximated based on three degree polynomials.

For each compressor stations, identical compressors working with the same speed are assumed. The simulation experiments were conducted by varying the number of compressors and speed of the compressors in order to study the flow capacity and the nodal pressures. From the simulation experiments, it was observed that the minimum number of compressors required to meet the flow requirement was 8. Several speeds of compressor were tested for meeting the customer specifications. The compressor speeds starting from 5550 rpm satisfied the requirement with various power consumptions, nodal pressures and compression ratios.

It was observed that as the speed of the compressors increased, the results of nodal pressures from the TPNS simulation were getting closer to the results of nodal pressures obtained by Wu et al [47]. However, an increase in deviation of flow parameter was observed when speed of compressors increased. After conducting simulation experiments, compressor speed of 5775 rpm gave better results of nodal pressures with maximum percentage error of 2.37% which was obtained at node 5 of the network. The corresponding flow deviation was 10.71%. Figure 4.9 shows comparison of the result of nodal pressures obtained from the TPNS simulation model at speed of 5775 rpm and the results obtained in [47].

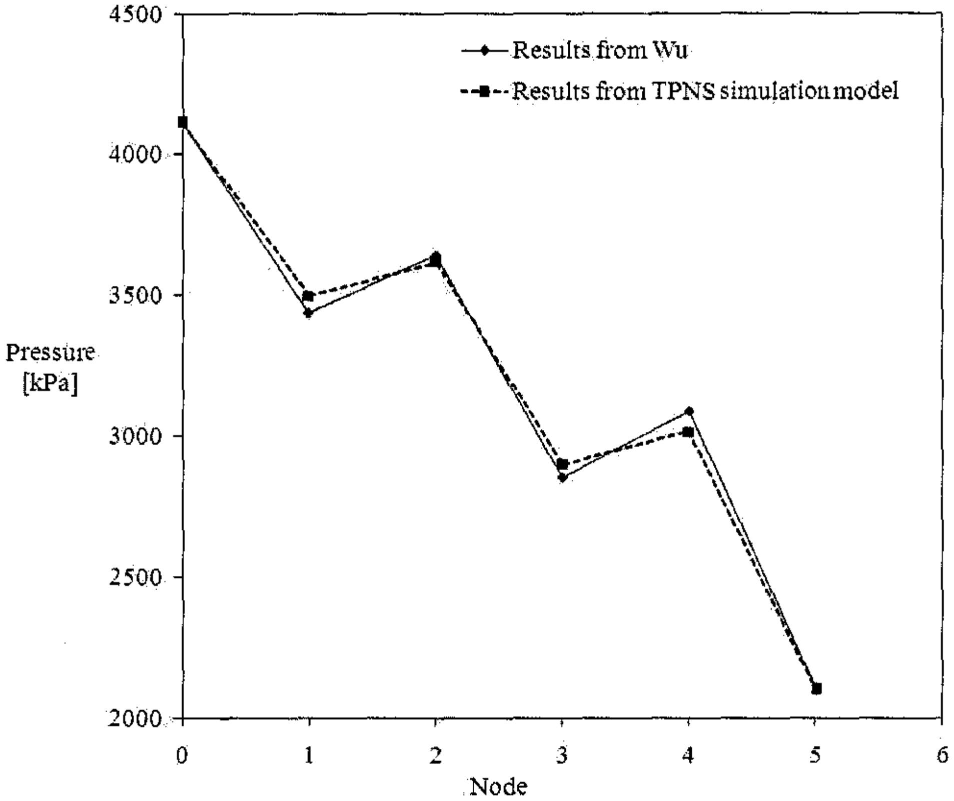


Figure 4.9 Comparison of nodal pressures

Wu et al [47] obtained the solution for nodal pressures so that the fuel consumption for the system is minimized. The results obtained from TPNS simulation model using the Newton-Raphson shows that the simulation model could be used to compare various operations of the compressor. This could help to compare the alternatives and select the one with minimum power consumption.

4.3.2 Case 2B: Branched Pipeline Network Module

The results and discussions presented in this section are based on the branched TPNS network configurations shown in Figure 3.20 on page 79 and the methodology presented in section 3.4.2 on page 79. The analysis was done based on source pressure of 3500kPa and demand pressure requirement 4500kPa. The results and analyses on the network were reported by Woldeyohannes and Majid [90].

The network was analyzed using TPNS simulation model based on Newton-Raphson solution method. Two compressors were working for the system. The characteristics map of the compressors were taken from Kurz and Ohanian [59]. For the specified condition, it was assumed that the speed of the compressor is 8800 rpm. Note that the analysis could also be done at any arbitrary speed within the working limits of compressors. The results for the unknown pressure variables and flow variables were obtained with less than ten iterations with relative percentage error of 1.76979E-15. Figure 4.10 shows the convergence of some of the nodal pressures to the final pressure solutions for the first ten iterations. The convergences of the remaining nodal pressure variables followed the same trends. The convergence of the corresponding flow parameters are shown in Figure 4.11 and Figure 4.12.

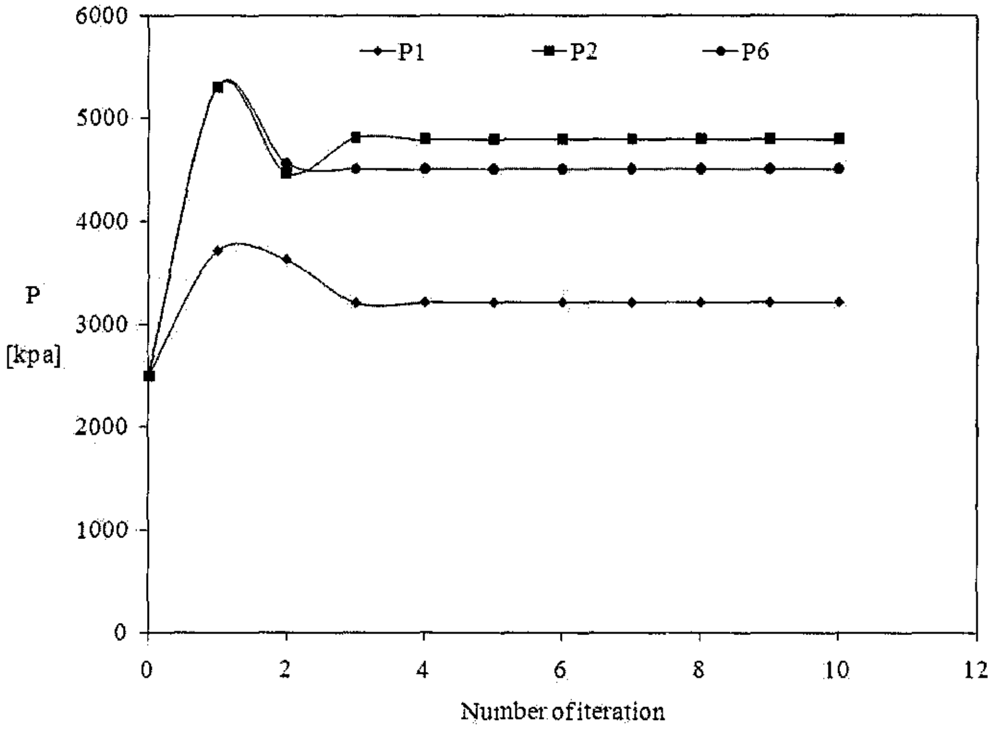


Figure 4.10 Convergence of pressure (case 2B)

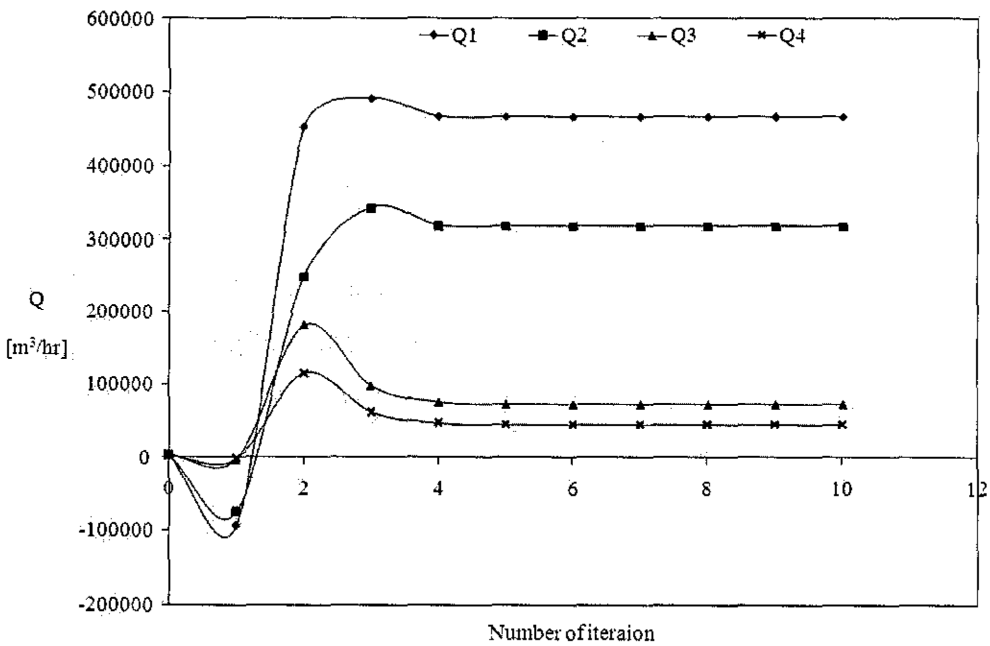


Figure 4.11 Convergence of main flow variables (case 2B)

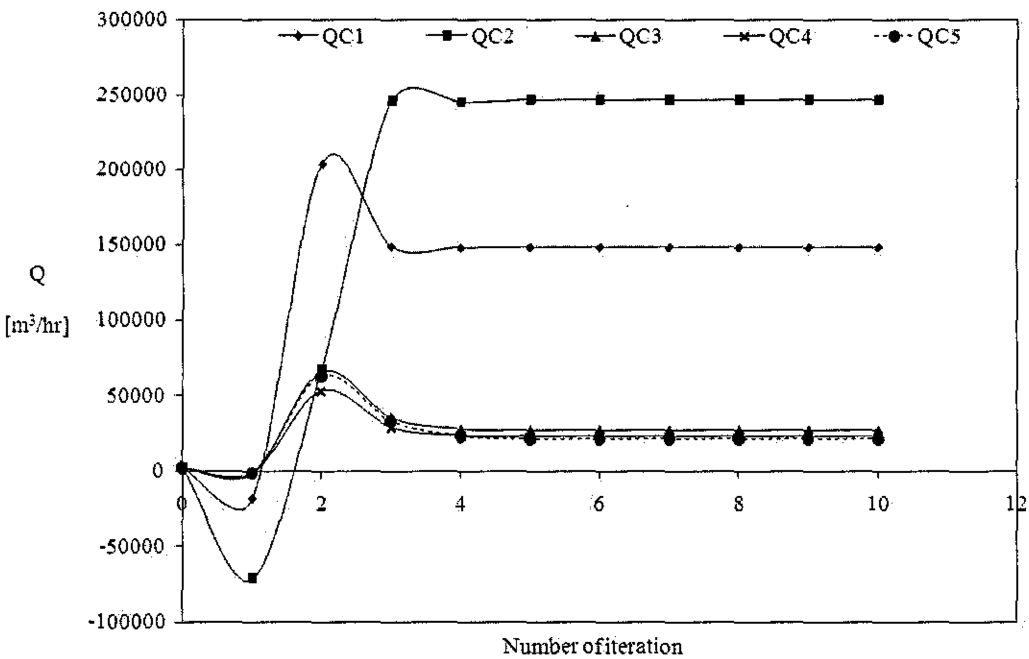


Figure 4.12 Convergence of lateral flow variables (case 2B)

4.3.3 Case 3B: Looped Pipeline Network Module

The results and discussions presented in this section are based on the looped TPNS network configurations shown in Figure 3.21 on page 82 and the methodology presented in section 3.4.3 on page 81. The network was analyzed based on single phase gas flow analysis. The pressure at node 0 was 3500kPa and the demand pressure from the customer was assumed to be 4000kPa. The results of the analysis using TPNS simulation for looped network configuration were reported by Woldeyohannes and Majid [91].

The rate of convergence to the final solution depends on the initial estimation and usually high at the beginning of the iterations. Based on the pipe data shown in Table 3.20 and gas compressor data from [55], the results of the unknown pressure and flow variables were obtained for the first ten iterations. The analysis was performed based on compressor speed of 8500 rpm. For the initial estimations of 4000kPa for unknown pressure variables and 4000m^3/hr for unknown flow variables, the results from the TPNS simulation model using Newton-Raphson method at the end of the 10^{th} iterations are shown in Table 4.3 and Table 4.4. The corresponding compression ratio and power consumption for the system were obtained to be 1.49837 and 14.1147 MW, respectively. At the end of the 10^{th} iteration, the maximum percentage relative error was 7.197×10^{-11}.

Table 4.3 Results of nodal pressures after ten iterations

Node	Pressure [kPa]
0	3500.00
1	2880.47
2	4316.02
3	4136.33
4	4014.28
5	4064.4
6	4047.89
7	4046.37
8	4006.1
9	4005.68

Table 4.4 Results of main and branch flow variables after 10 iterations

Main flow	[m^3/hr]	Branch flow	[m^3/hr]
Q_1	740381	Q_{C1}	88740.9
Q_2	529934	Q_{C2}	96253
Q_3	184994	Q_{C3}	199260
Q_4	344940	Q_{C4}	102997
Q_5	145679	Q_{C5}	113299
Q_6	42682.8	Q_{C6}	61105.3
Q_7	210447	Q_{C7}	2564.04
Q_8	139831	Q_{C8}	76161.8
Q_9	78725.9	-	-

The convergences of the pressure variables at node 1 and 2 and the main flow variable Q_1 were studied under various initial estimations. Figure 4.13 and Figure 3.14 show the convergence of nodal pressures to the final pressure solutions for the first ten iterations at node 1 and 2 for initial estimations of 3000, 4000 and 10000kPa. The convergences of the remaining nodal pressures followed the same trend as that of the pressure at node 2.

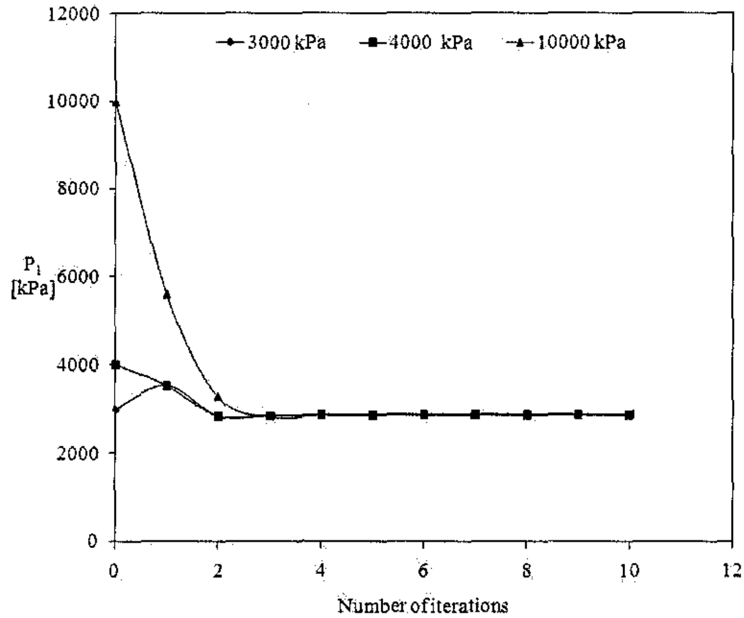


Figure 4.13 Convergence of P_1 for the first ten iterations for the initial estimations (case 3B)

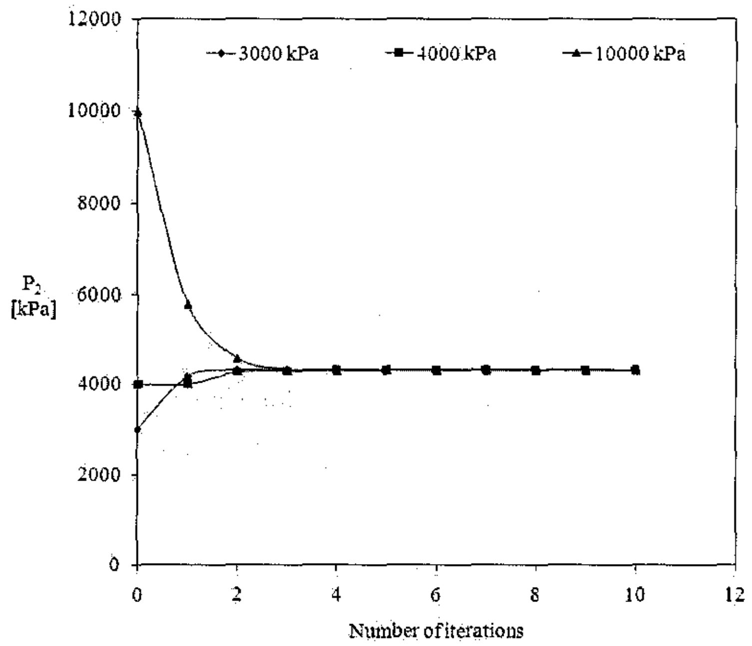


Figure 4.14 Convergence of P_2 for the first ten iterations for the initial estimation (case 3B)

The convergence of the main flow variable Q_1 for the initial estimations of 3000, 4000 and 10000 m^3/hr is shown in Figure 4.15. The simulation model produced solutions for the unknown variables with wide range of initial estimation.

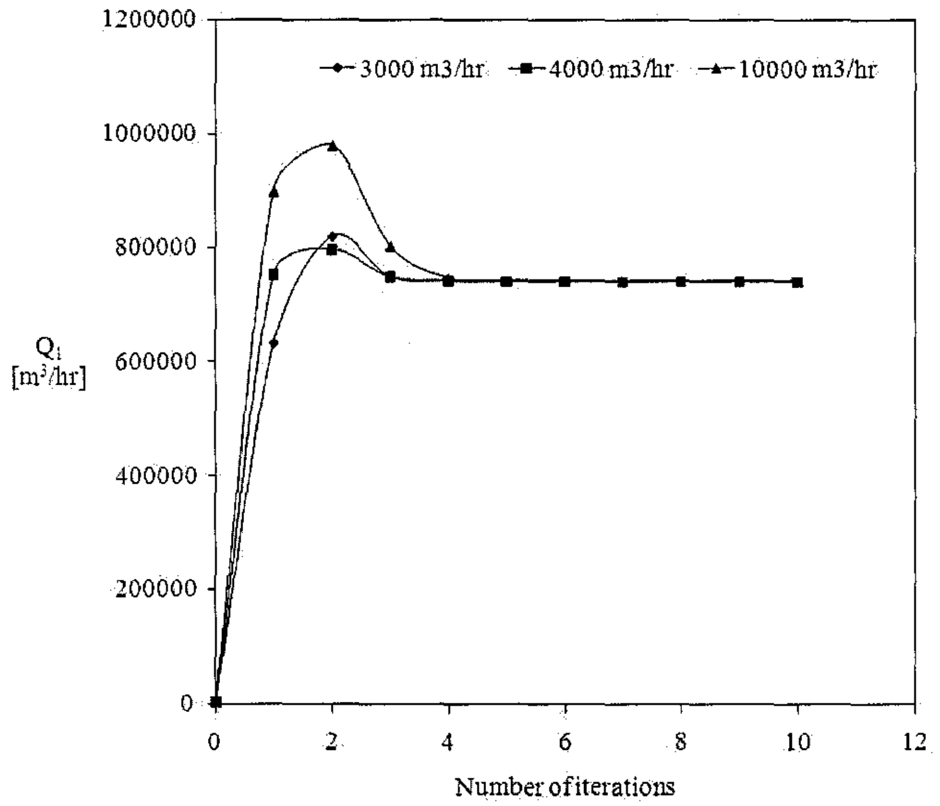


Figure 4.15 Convergence of Q_1 for the first ten iterations for the initial estimations (case 3B)

The results of the TPNS simulation model for single phase gas flow analysis were compared with the method proposed by Osiadacz [7] based on the looped network configuration shown in Figure 4.16. The pipeline details and the demand requirements for the TPNS are shown in Table 4.5 and Table 4.6, respectively. For this problem, Osiadacz applied Newton loop-node method in order to get the flow and pressure variables by assuming fixed pressure ratios for each compressor. However, the final nodal pressures obtained after achieving the predefined error limits failed to satisfy the previously assumed pressure ratios. For instance, the pressure ratio at CS1 was assumed to be 1.8 and that of CS2 was assumed to be 1.4. However, the pressure ratios after the solutions were obtained were actually 1.34 and 1.1832 for CS1 and CS2, respectively.

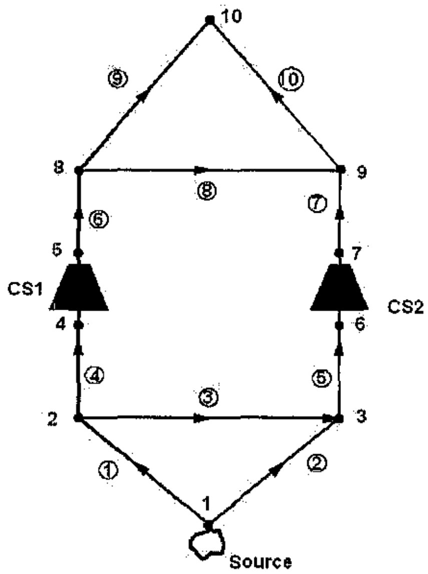


Figure 4.16 Pipeline networks with 10 pipes and two compressor stations [7]

Table 4.5 Pipe data [7]

Pipe nodes		Diameter [mm]	Length [km]
Start node	End node		
1	2	700.00	70.00
1	3	700.00	60.00
2	3	700.00	90.00
2	4	600.00	50.00
3	6	600.00	45.00
5	8	600.00	70.00
7	9	600.00	80.00
8	9	500.00	70.00
8	10	500.00	45.00
9	10	500.00	75.00

Table 4.6 Pressure and flow requirements [7]

Node	Flow [m^3/hr]	Pressure [kPa]
1	-	5000
2	20000	-
3	20000	-
4	0	-
5	0	-
6	0	-
7	0	-
8	15000	-
9	30000	-
10	45000	-

The simulation experiments were conducted by varying the number of compressors and speed of compressors. The analysis was conducted using the performance characteristics of the compressors taken from [59]. Similar compressors are assumed to work on both compressor stations. From the simulation experiments, it was observed that one compressor for each compressor station is sufficient to meet the customer requirements.

Simulation experiments based on the given compressors characteristics showed that, the two compressor stations have to work nearly with the same compression ratios. An increase in compression ratio for the first station could result more flow through pipe 1 and reversal flow through pipe 3. This might cause flow reversal in the second compressor station. For instance, the compressor ratio mentioned for CS2 by Osiadacz [7] was achieved when the compressor runs with speed of 4800rpm. Based on this reference speed for CS1, the speed of the compressor increased to improve the compression ratio of CS2. The compressor speed at CS1 was increased till flow reversal starts to CS (i.e. 5450 rpm). It was observed that, the deviations of the nodal pressures and flow variables increased as the speed increase towards the speed of 5450 rpm.

After conducting simulation analyses based on the requirements, compressors speeds of 5025 rpm for CS1 and 4750 rpm for CS2 gave results of nodal pressures and flow variables close to Osiadacz [7]. Mean absolute percent error of 5.10% was observed between the two methods. The variations of the flow and nodal pressure variables could be as a result of the type of flow equations that were used in the analysis and the oversimplification of compressor stations in the case of the method in [7]. Panhandle 'A' flow equation was used in [7] where as general flow equation has been applied in the developed TPNS simulation. As developed in section 3.2.3, the TPNS simulation model consists of detailed characteristics of the compressor rather than only limited to compression ratio.

The results of comparison of the TPNS simulation model and that of Osiadacz [7] for flow rate through pipes is shown in Figure 4.17. From the figure, it is observed that the maximum deviation between the results of TPNS simulation model and the results from Osiadacz [7] occurred at pipe 1, 4 and 6. This is as a result of the higher compression ratio assumed at CS1 which was far from the calculated value. The negative flow observed in pipe 3 of the network showed that the actual flow direction for the gas is opposite to the assumed direction. Hence, the actual flow in pipe 3 is from node 3 to node 2.

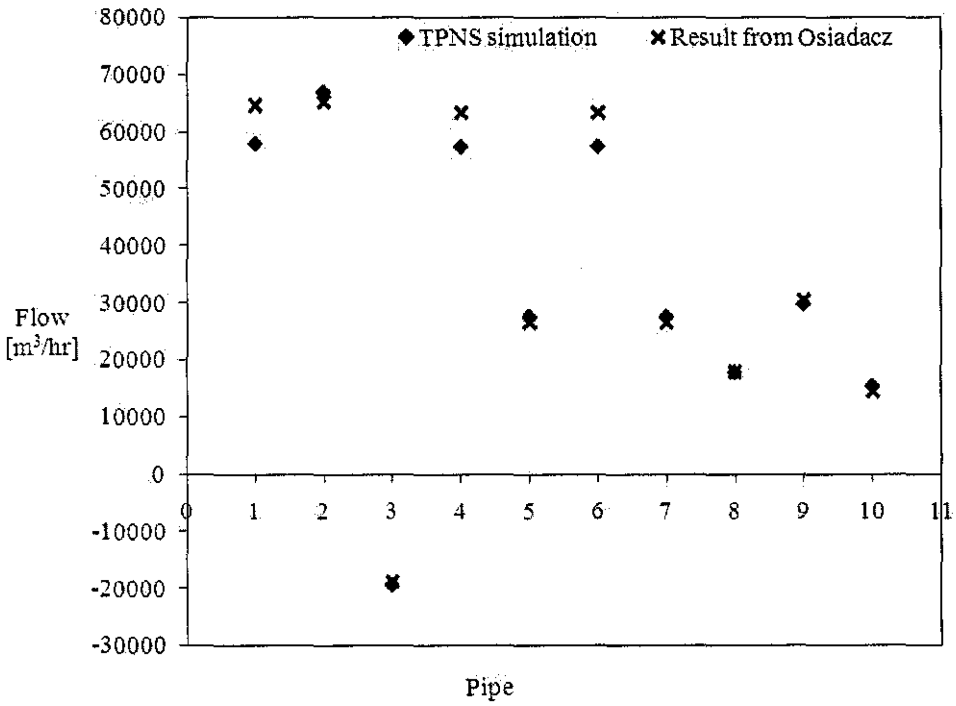


Figure 4.17 Comparison of flow rates between TPNS simulation and results of Osiadacz [7]

The comparison of the corresponding nodal pressures between the two methods is shown in Figure 4.18. From the figure, it is observed that higher deviation at nodal pressures between the Osiadacz [7] and the results from the developed TPNS simulation model happened at node 4. This is as a result of the value of the CR assumed at CS1. Generally, the results of nodal pressure from the TPNS simulation model is higher than the nodal pressures obtained from Osiadacz [7]. This could be as a result of the flow equations used in both methods. The general flow equation which was used in TPNS simulation model result less pressure drop compared to the Panhandle 'A' flow equation which was used by Osiadacz [7].

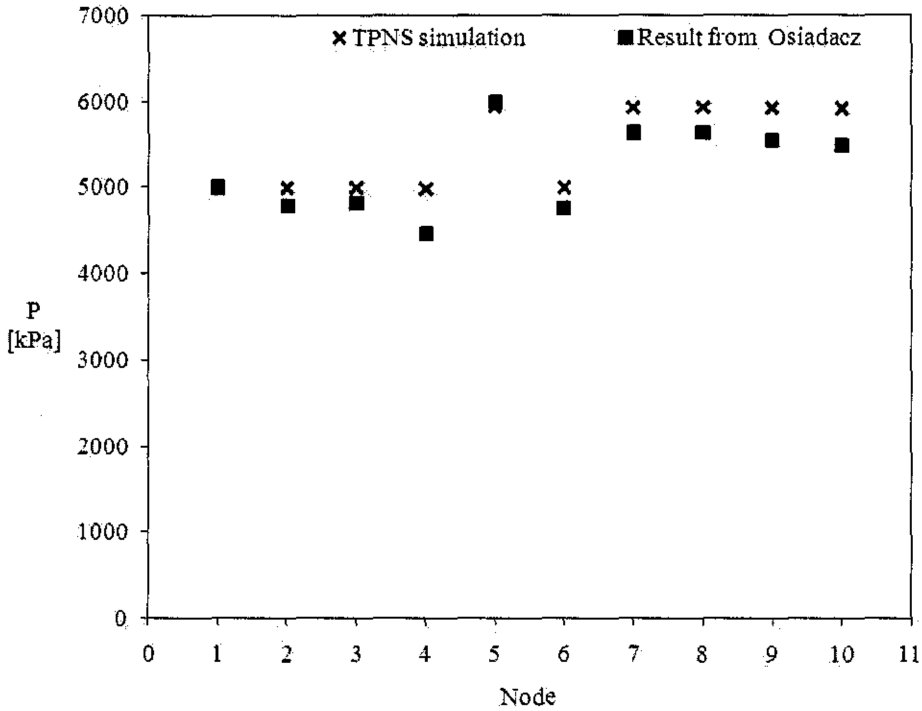


Figure 4.18 Comparison of nodal pressures between TPNS simulation and results of Osiadacz [7]

4.3.4 The Malaysia Gas Transmission Network Case Study

In this section, the TPNS simulation model using the Newton-Raphson method was tested with the actual data from the existing pipeline network system. The network was identified since it consists of all the pipeline configurations, namely: gunbarrel, branched, and looped pipeline network systems.

Based on the data from the existing pipeline network system presented in section 3.4.4 on page 85, the TPNS simulation was evaluated. The various subtasks of the simulation model were evaluated on the basis of the data taken from the field. The main modules of the TPNS simulation model include input parameter analysis, function evaluation module, and network evaluation module. Single phase flow analysis at constant gas flow temperature is assumed for the evaluation of the TPNS simulation model with the existing pipeline network system.

i) Input Parameter Analysis

This phase of the TPNS simulation consists of taking the input from the user and making analysis in order to make the data suitable for the next phase of the simulation. The input to the simulation includes pipe data, compressors data and customer requirements.

a) Pipe Input Data

The TPNS under consideration for the case study consists of 19 pipes with various diameter and length. The first step of the simulation is to take the relevant input regarding the number of pipes involved, diameter of the pipes, length of the pipes and age of the pipes. Using the input information, the TPNS simulation analyzes the pipe data to determine the friction factor of each pipes as well as the pipe flow resistance K_{ij} which was defined in equation (3.1) on page 47. Based on the data of the pipeline network system under consideration, the flow resistance and friction factor for each pipe were determined and shown in Table 4.7.

Table 4.7 Results of input analysis for pipes

Pipe nodes		Friction factor	Flow resistance
Start node	End node	f	K_{ij}
0	1	0.007407	7.62395E-06
2	3	0.007407	5.71796E-06
3	D1	0.007878	4.61777E-05
3	D2	0.007878	4.61777E-05
2	4	0.007407	5.71796E-06
4	5	0.007878	3.07851E-05
5	D3	0.007878	1.53926E-05
5	D4	0.007878	1.30837E-05
4	6	0.007407	5.24147E-06
6	D5	0.007878	1.38533E-05
6	7	0.007407	6.67096E-06
7	D6	0.007878	3.84814E-05
7	8	0.007407	7.14746E-06
8	D7	0.007878	3.07851E-05
8	9	0.007407	1.75351E-05
9	D8	0.007878	1.38533E-05
9	10	0.007407	5.71796E-07
10	D9	0.009403	0.00736663
10	11	0.007407	8.29105E-06

b) Compressor Input Data

After the preprocessing of the pipeline information has been completed, the next step of the TPNS simulation is to take the data related to compressor station as an input. The data related to compressors consists of the performance map of the compressors, number of compressors working within the station and the compressor speed. Based on the performance map of the compressor used, the Newton-Raphson based TPNS simulation model carried out the analysis to determine the coefficient of the mathematical equation which represents the characteristics of the compressor. The coefficients were determined as discussed in section 3.2.3 on page 52.

c) Customer Requirement

One of the basic inputs for the TPNS simulation model is to take data related to the pressure requirement of the customers. The customer specification in terms of pressure requirement is usually given to satisfy the remote customer pressure requirement. This is because, if the pressure at the end point is satisfied, the entire system will have sufficient pressure requirement. For the case study under consideration, the maximum pressure at the end point of the TPNS could reach 6800kPa and the minimum pressure is limited 4000kPa. The pressures at the end of the pipe joining the customer with the system will be regulated to the customer requirement. The source pressure varies from 3000kPa to 3500kPa.

d) Initial Estimations and Maximum Error Limit

The TPNS simulation requires an initial estimation of the unknown variables. The relative error introduced depends on the initial estimation of the unknown variables. The simulation model was tested by giving wide range of initial estimations for the unknown variables and convergences were achieved in most of the trails. Proper estimation for the nodal pressures could be obtained from the exit pressure requirements at the various demand stations. Furthermore, proper estimation for the flow variables could be obtained from the performance characteristics of the compressor provided for the simulation.

ii) Output of TPNS Simulation

The final results from the TPNS simulation for the required nodal pressure and flow through pipes depend on the number of iterations or the predefined percentage error limit. After the predefined number of iteration or the maximum relative percentage error for the unknown variables was satisfied, the TPNS simulation gave the value of each of the unknown variables, compression ratio, and power consumption for the system. The results were displayed on the basis of iterations.

The rate of convergence to the final solution depends on the initial estimation and usually high at the beginning of the iterations. Based on the pipe data shown in Table 4.7, source pressure of 3500kPa and an end pressure requirement of 4000kPa, compressor speed of 7600 rpm, the results of the unknown nodal pressure and flow variables were obtained for the first ten iterations. At the end of the 10th iteration, the maximum relative percentage error was obtained to be 8.66347E-17. The results from the TPNS simulation for the unknown nodal pressures and flow variables are shown in Table 4.8. The corresponding compression ratio and power consumption for the system were obtained to be 1.4951 and 10.9378 MW, respectively.

Table 4.8 Results of nodal pressures and flow variables after 10 iterations

Node	Pressure[kPa]	Main flow	m3/hr	Branch flow	m3/hr
0	3500.00	Q_1	770480.0	Q_{C1}	135404.0
1	2779.23	Q_2	142038.0	Q_{C2}	135404.0
2	4155.23	Q_3	357634.0	Q_{C3}	59865.3
3	4104.47	Q_4	270808.0	Q_{C4}	64933.0
4	4066.28	Q_5	124798.0	Q_{C5}	134465.0
5	4006.89	Q_6	232836.0	Q_{C6}	69509.2
6	4031.19	Q_7	98371.1	Q_{C7}	76459.2
7	4023.17	Q_8	28861.9	Q_{C8}	41252.3
8	4022.43	Q_9	94440.5	Q_{C9}	1726.45
9	4002.95	Q_{10}	53188.2	-	-
10	4002.74	Q_{11}	51461.8	-	-

The convergences of the pressure variables at node 1 and 2 and the main flow variable Q_1 were studied under various initial estimations.

Figure 4.19 and Figure 4.20 show the convergence of nodal pressures to the final solutions for the first ten iterations at node 1 and 2 of the pipeline network system shown in Figure 3.22 based on the initial estimations of 2000, 4000 and 10000kPa. The convergence of the remaining nodal pressures can also be plotted following the same procedures as that of the nodal pressures at node 1 and 2.

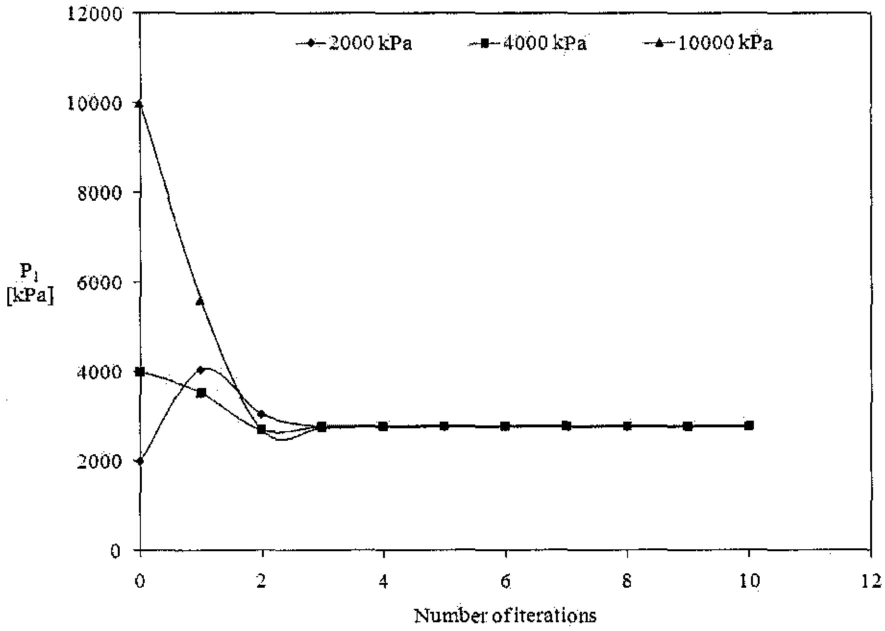


Figure 4.19 Convergence of P_1 for the first ten iterations for the initial estimations

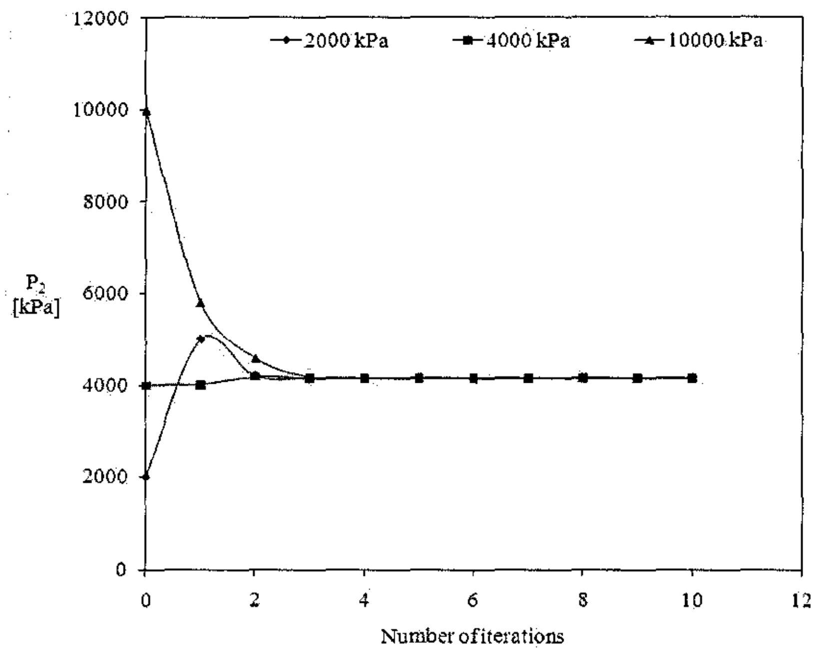


Figure 4.20 Convergence of P_2 for the first ten iterations for the initial estimations

From the study of the convergence of the nodal pressures at node 1 and 2, it was observed that the TPNS simulation model could provide solutions to pressure variables with a wide range of initial estimations. From the simulation experiments, the initial estimation near to the end pressure requirement was obtained to be a good initial estimation and resulted solutions in all the tests conducted. The convergence of the main flow parameter Q_1 for the initial estimations of 2000, 4000 and 10000m^3/hr is shown in Figure 4.21.

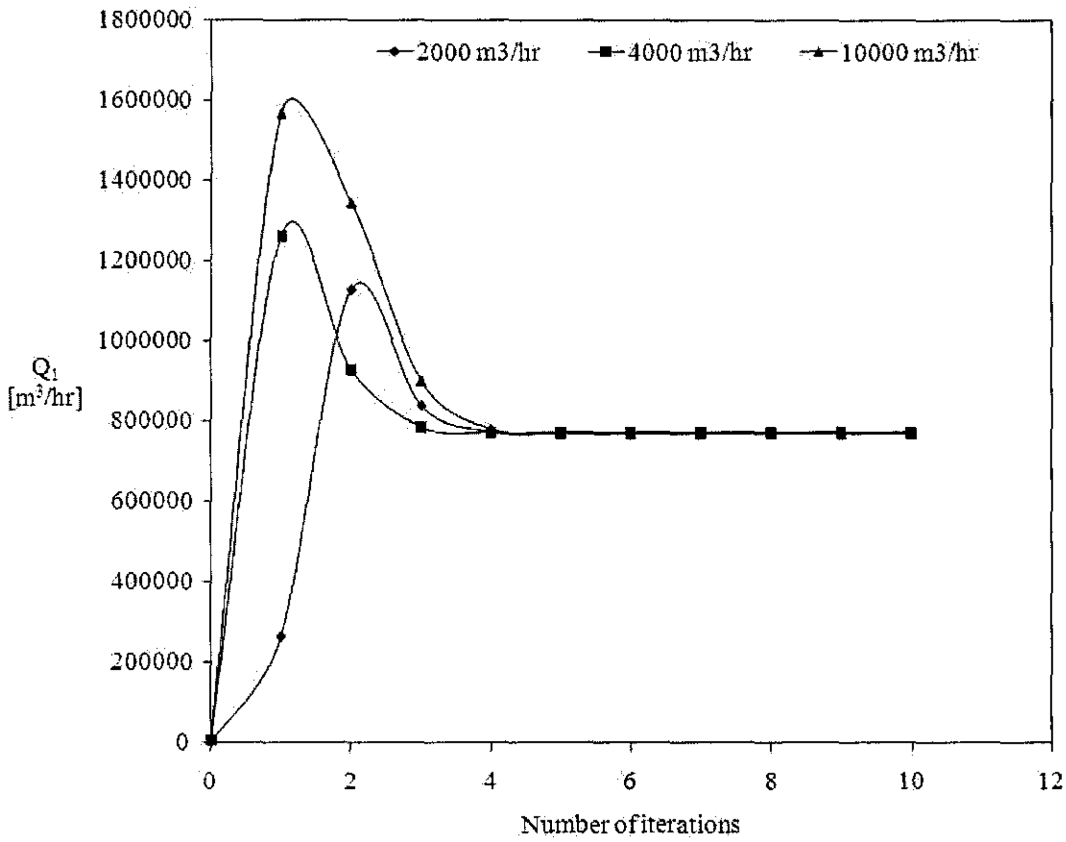


Figure 4.21 Convergence of Q_1 for the first ten iterations for the initial estimations

The convergence of the flow variables through the main pipes and the lateral pipes were also plotted. Figure 4.22 shows the convergence of the remaining main flow variables for the first ten iterations. As indicated in the figure, almost all the main flow variables solutions were obtained starting from the third iteration.

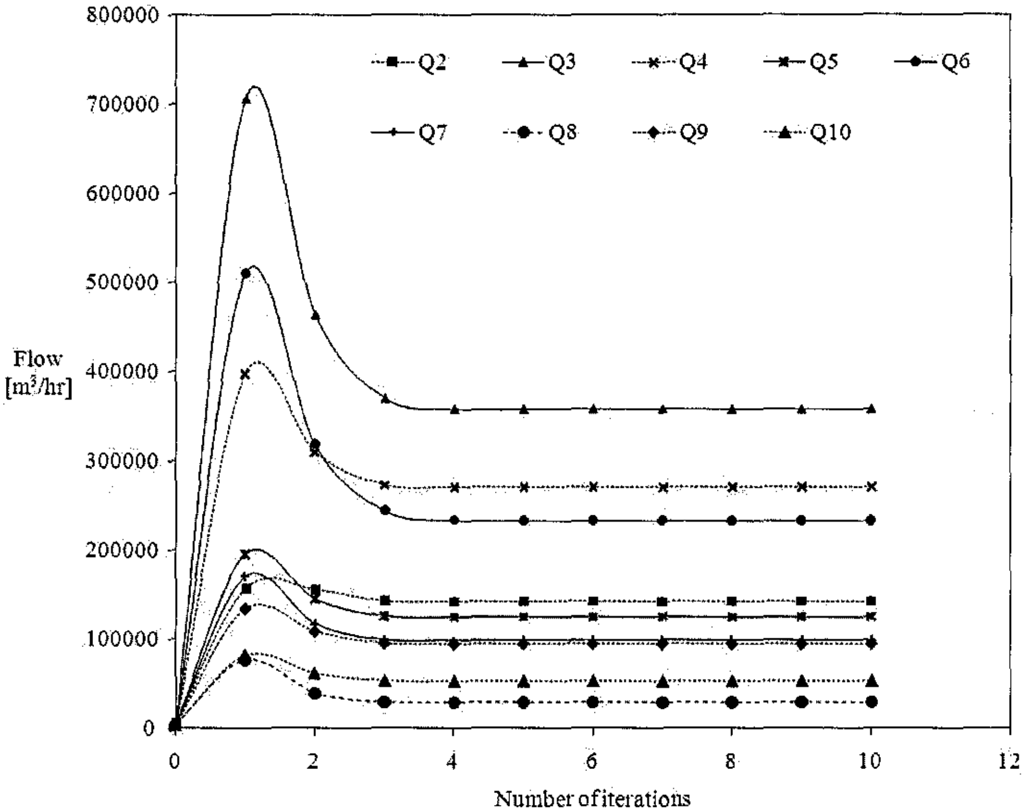


Figure 4.22 Convergence of the main flow variables

iii) Application of TPNS Simulation for Compressor Performance Analysis

Further simulation study was conducted in order to apply the TPNS simulation model for performance analysis of the compressor used for the pipeline network system shown in Figure 3.22. For the performance analysis of the compressor, suction pressure (P_1), discharge pressure (P_2) and the flow rate through the compressor (Q_1) were considered. The performance of the compressor was studied for source pressure of 3500kPa to meet pressure requirements of various demand pressures ranging from 4000 to 5000kPa. The analysis was performed with compressor speeds of 5000, 5500, 6000 and 6500rpm. Note that the analysis can also be made at any speed of the compressor as long as the speed is within the working limit of the compressor. The results of the application of the Newton-Raphson based TPNS simulation for performance analysis was reported in [92].

The variation of the discharge pressure (P_2) of the compressor with flow rate (Q_1) is shown in Figure 4.23. As it is observed from the figure, for a constant speed operation of the compressor, an increased in discharge pressure gave rise to a decrease in flow capacity of the system and vice versa. This showed that the characteristic map generated using the TPNS simulation model is similar to the characteristics maps of the compressors described in [60, 93]. As a result, the simulation model could be used to analyze the performance of the compressors.

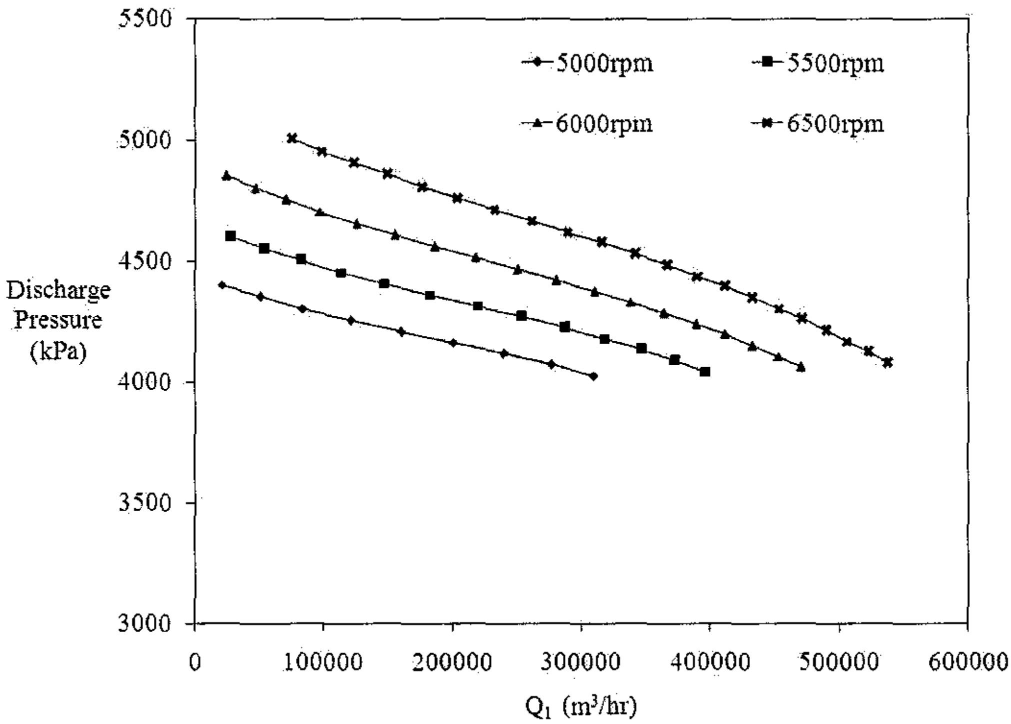


Figure 4.23 Discharge pressure variations with flow for various speeds

The variation of CR with flow and speed is shown in Figure 4.24. As it is seen from the figure, higher CR for the system was achieved at lower flow capacities. This is because, based on equation (3.76), power consumption of the system is a function of CR, flow rate and other properties of the gas. From this equation, it is observed that lower flow rate results higher CR values. For a constant flow operation, an increase in speed of the compressor increased the CR of the system.

The results in the figure also showed the characteristic map of the compressor based on CR which is similar in trend with that of the characteristic map plotted in [60].

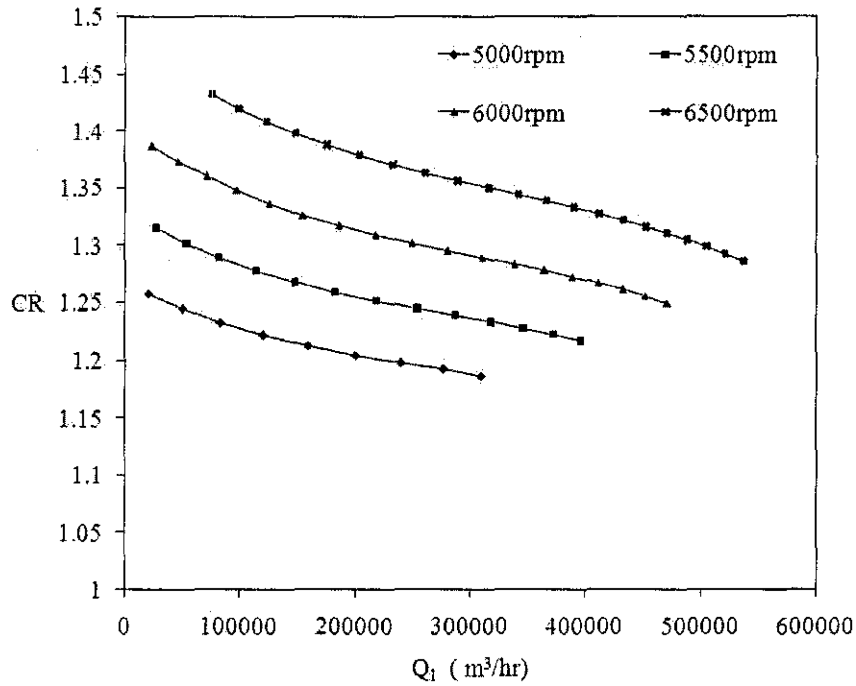


Figure 4.24 Compression ratio variations with flow for various speeds

Power consumption variation with flow rate through the compressor based on various speed is shown in Figure 4.25. It is observed that an increase in flow rate increased the power consumption. For a constant flow operation, an increase in speed of the compressor increased the power consumption of the system. As it is given in [23], power consumption by the system is function of the flow rate, CR and properties of the gas. When the speed of the compressor increased at constant flow operation, it is shown in Figure 4.24 that the CR of the compressor is also increased. Hence, the power consumption of the system increased due to an increment in CR of the system.

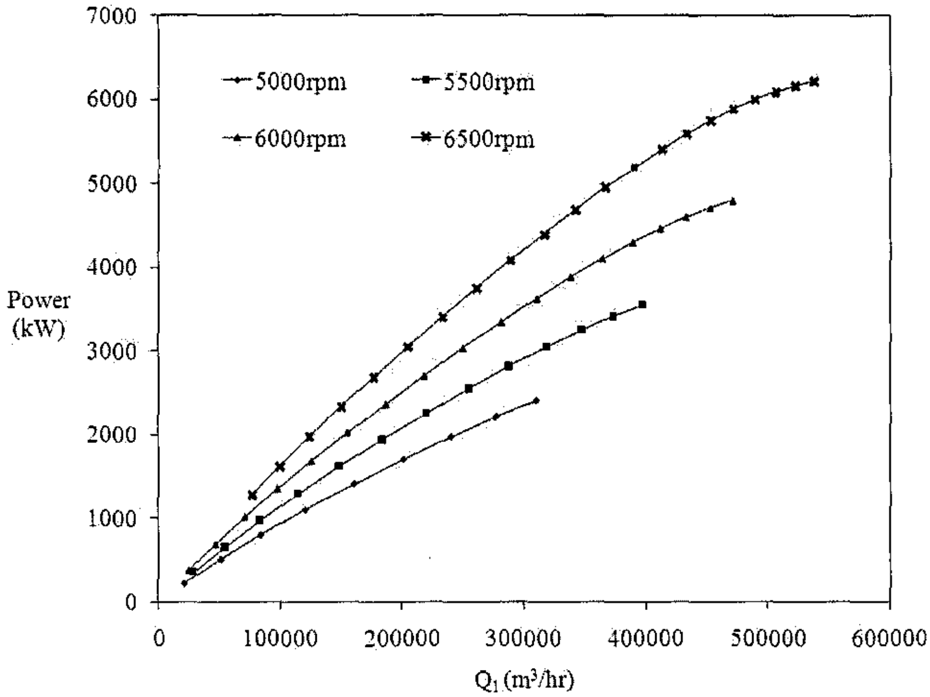


Figure 4.25 Variation of power consumption with flow for various speed

4.3.5 The Case of Divergent in TPNS Simulation Model

The Newton-Raphson based TPNS simulation model plays significant role in achieving the required pressure, flow, and temperature variables usually within four to six iterations depending on the error tolerance limit. However, the Newton-Raphson solution scheme has limitations depending on the initial estimations as reported in [81]. Initial estimations which are too far from the final solution usually result in divergence. In order to guide for successful convergence, several attempts were conducted on TPNS simulation model and an initial estimations which gives solution for the variables were identified. Initial estimations near to the demand pressure requirements resulted in convergence for the attempts made on TPNS simulation model. Sample of the divergent case for branched TPNS is shown in Appendix D.

4.4 Enhanced Newton-Raphson based TPNS Simulation Model

The results and discussions in this section are based on the enhanced Newton-Raphson based TPNS simulation model presented in section 3.5 on page 88. The model was applied for analyzing gunbarrel and branched pipeline network configurations considering two-phase gas-liquid flow analysis, single phase with corrosion effect and single phase with temperature variations.

4.4.1 Two-phase Gas-liquid Flow Analysis

The analyses conducted in this section for the gunbarrel and branched network configurations were based on the methodology discussed in section 3.5.1 on page 88. For the analysis of the networks, it was assumed that the liquid holdup is $H_L = \lambda_L = 0.005$ which is very common in transmission network system [61]. As a result, the density of the mixture and the viscosity of the mixture were determined to be $\rho_m = 5.7425\, kg/m^3$ and $\mu_m = 2.99E-05\, kg/ms$, respectively.

i) Case 1C: Gunbarrel Pipeline Network Module

The results and discussions presented in this section are based on the gunbarrel TPNS network configurations shown in Figure 3.19 on page 77. The analysis is based on the pipe data shown in Table 3.14 and the nodal pressure requirements data shown in Table 3.13. The network was analyzed based on the enhanced Newton-Raphson based TPNS simulation model considering effect of two-phase flow analysis. The same compressors as in section 4.3.1 with speed of 8000 rpm were used for the analysis. The results for the unknown pressure variables and flow variable were obtained with less than ten iterations. The convergences of nodal pressures and flow variable for the network system were studied. Based on the results obtained from the iterations, the convergence of the pressure variables and flow variable are as shown in Figure 4.26 and Figure 4.27, respectively.

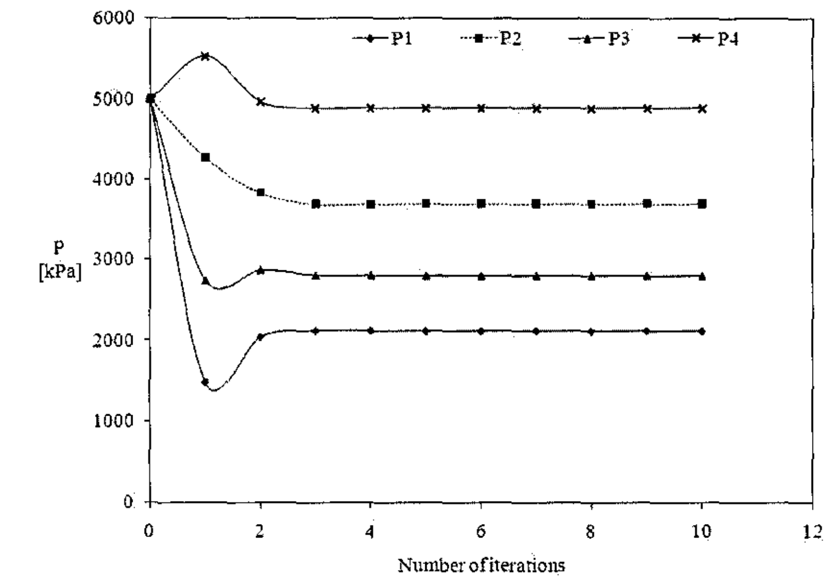


Figure 4.26 Convergence of pressure variables (Case 1C)

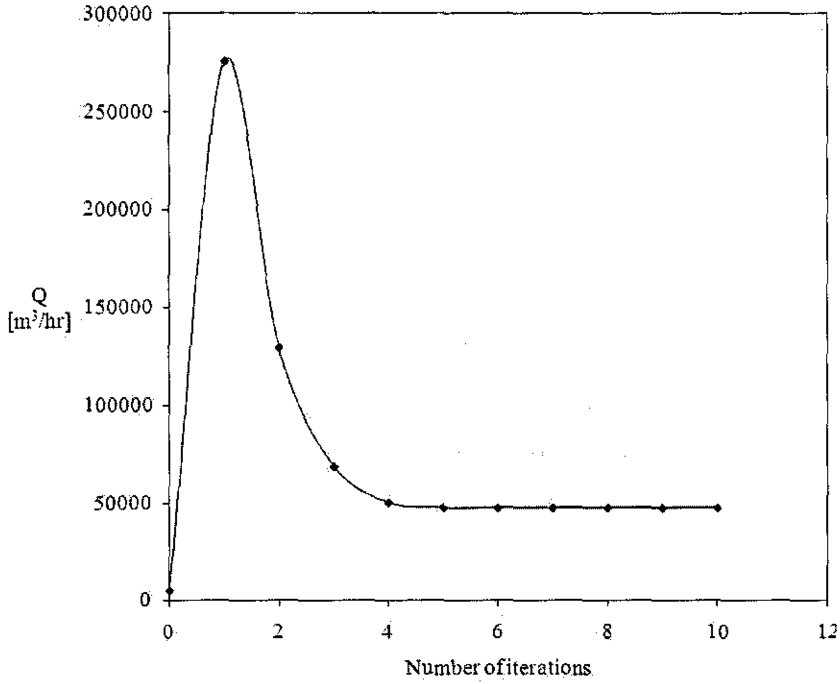


Figure 4.27 Convergence of flow variable (Case 1C)

ii) **Case 2C: Branched Pipeline Network Module**

The results and discussions presented in this section are based on the branched TPNS network configurations shown in Figure 3.20 on page 79. The network was analyzed using the enhanced Newton-Raphson based TPNS simulation model considering the effect of two-phase flow. The analyses regarding the network were based on the pipe data shown in Table 3.17. The same compressor specifications with speed 7800rpm was used as in 4.3.2. The pressure at node 0 was 3500kPa and the demand pressure from the customer was assumed to be 4000kPa.

The results for the unknown pressure variables and flow variables were obtained with less than ten iterations with relative percentage error of 8.16639E-17. Figure 4.28 shows the convergence of nodal pressures to the final pressure solution for the first ten iterations with an initial estimation of 2000kPa for all pressure variables and 2000m^3/hr for all flow variables. The simulation model was also tested by giving wide range of initial estimations and convergence was achieved in most of the trials. An initial estimations near to the demand pressure resulted in convergences in all the tests conducted on the pipeline network system. Most of the pressure parameters converged to their final solution after the third iterations.

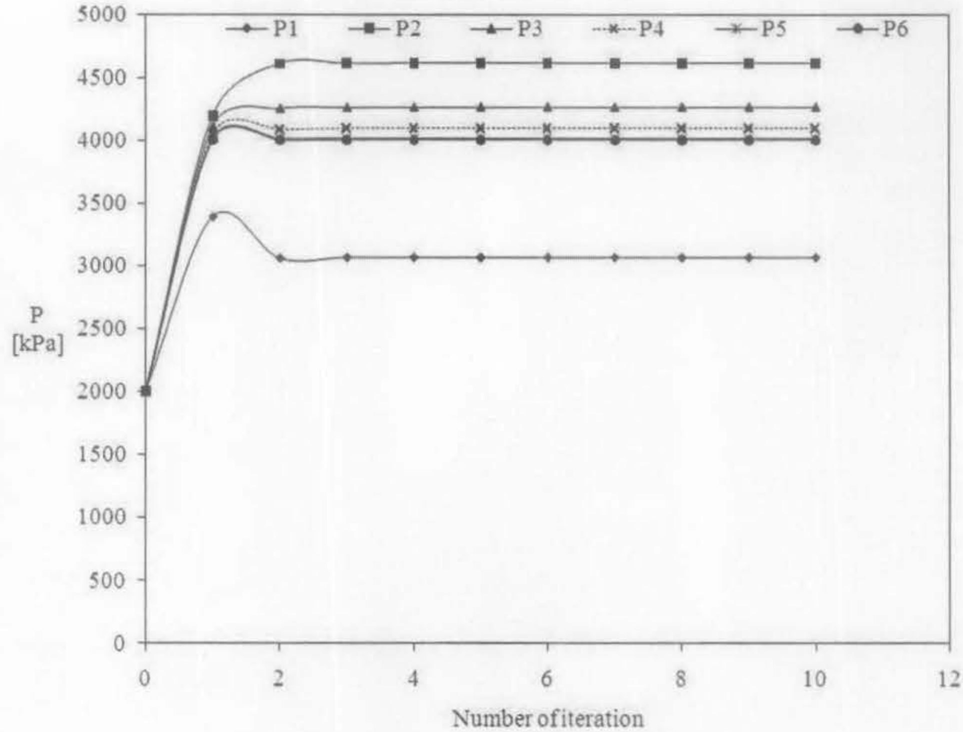


Figure 4.28 Convergence of pressure variables (Case 2C)

The flow through main pipe joining node 5 and node 6 is less compared to the other main pipe flows. As a result, the pressure drop from node 5 to node 6 is small compared to the other main pipes. Hence, the convergence of the nodal pressure at node 5 and node 6 coincides nearly to the same line. The result from the simulation model showed that the pressure at end of the tenth iteration at node 5 and 6 were 4013.48 kPa and 4008.43kPa, respectively. The convergence of the corresponding flow variables are shown in Figure 4.29 and Figure 4.30.

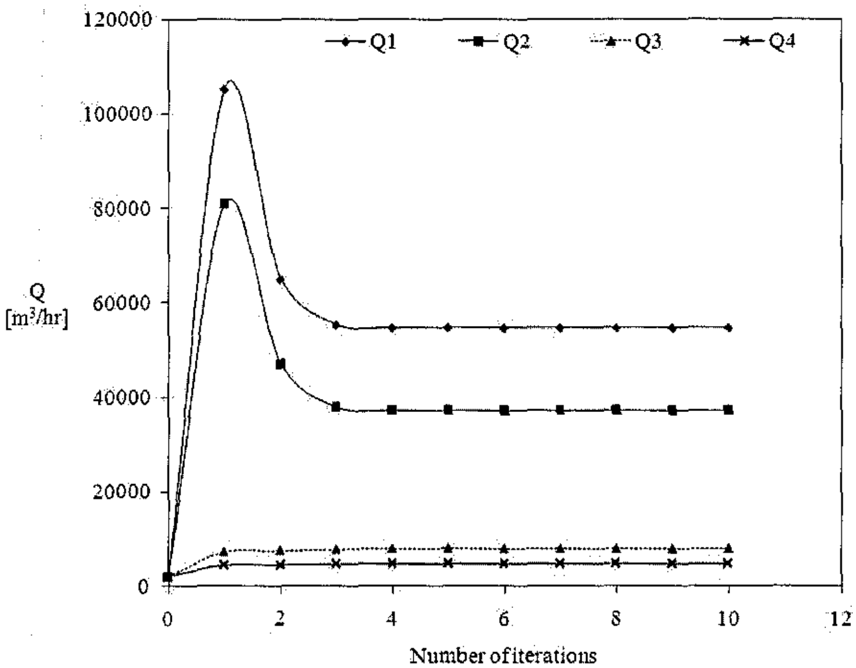


Figure 4.29 Convergence of main flow variables (Case 2C)

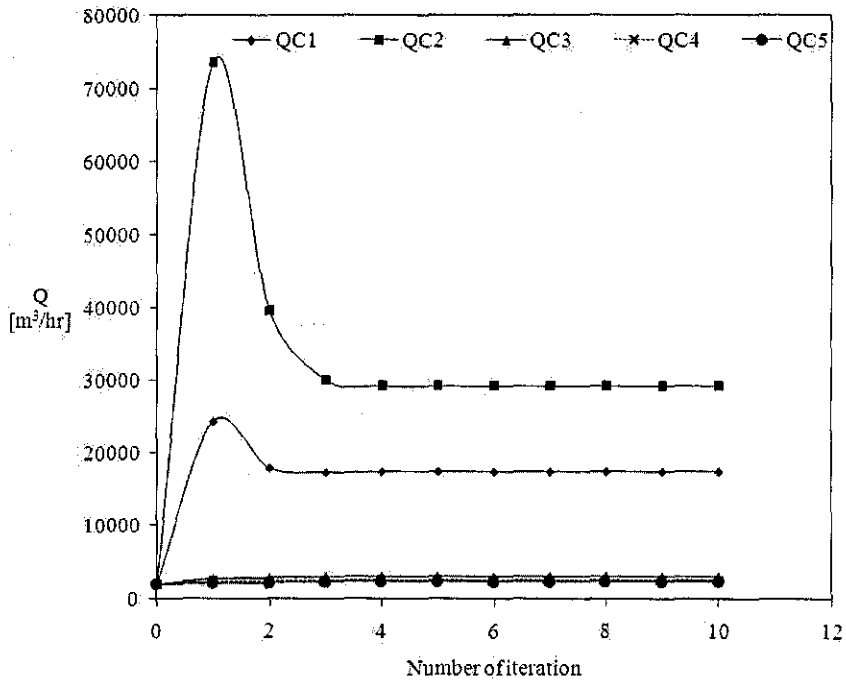


Figure 4.30 Convergence of lateral flow variables (Case 2C)

The effect of the variation of the liquid holdup on nodal pressures and flow through pipes were also studied. Figure 4.31 shows the effect of liquid holdup on nodal pressures. Since the customer requirements have to be satisfied in terms of pressure, the nodal pressures remain nearly the same for various liquid holdups. However, slight increment in pressure drop was observed when the liquid holdup increased.

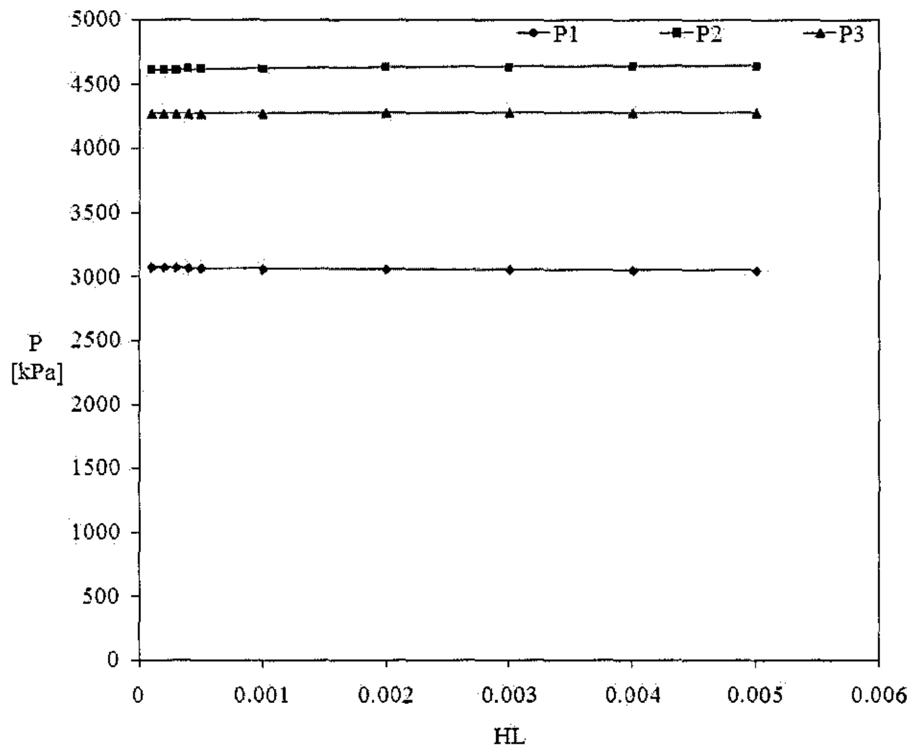


Figure 4.31 Effect of liquid holdup on nodal pressures

Liquid holdup had a significant effect on flow through pipes. An increase in holdup decreased the flow through pipes as shown in Figure 4.32. This is because, when the liquid holdup increased, flow resistance increased to result in a decrease in flow of the mixture through pipes.

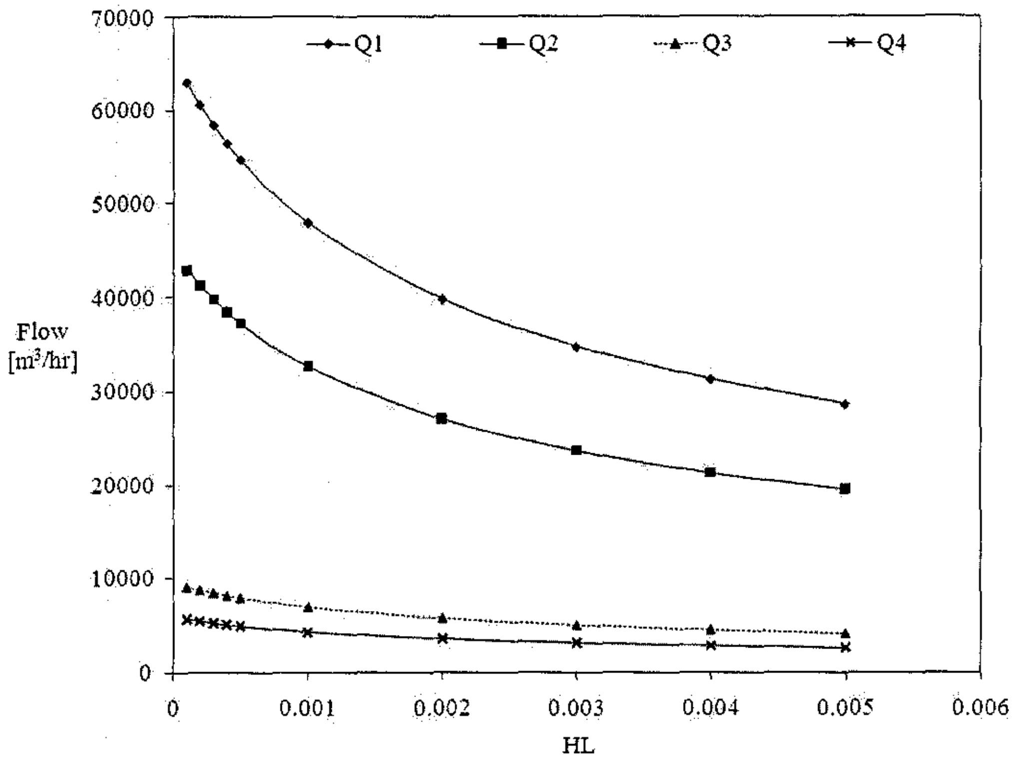


Figure 4.32 Effect of liquid holdup on flow through main pipes

4.4.2 The Effect of Internal Corrosion

The analyses conducted in this section for the gunbarrel and branched network configurations were based on the methodology discussed in section 3.5.2 on page 96.

i) Case 3C: Gunbarrel Pipeline Network Module

The gunbarrel pipeline network shown in Figure 3.19 on page 77 was also analyzed with the aid of the enhanced Newton-Raphson based TPNS simulation model by considering the effect of corrosion. The same specifications of compressors were used as in section 4.3.1. The age of the pipes could vary to give the corresponding friction coefficient which results different pressure drop. The results of the unknown nodal pressures and flow variable were obtained for the first ten iterations for ten years old pipes. Based on these results, the convergence of nodal pressures and flow variables for the network system are shown in Figure 4.33 and Figure 4.34, respectively.

The comparison of the convergence graphs obtained by neglecting the effect of corrosion in Figure 4.7 is identical to the convergence graph obtained considering the effect of corrosion shown in Figure 4.33. However, for the case of corrosion large shootings are observed on each graph from the initial estimation. This is resulted from the behavior of the convergence in Newton-Raphson solution technique where the graphs always tend towards the solution depending on the initial estimations. Initial estimations less than the final solutions are always resulted the convergence graphs to shoot upward before going stable at the solution. On the other hand, an initial estimation which are greater than the final solution resulted the convergence graphs to shoot downward before coming to stable at the final solutions.

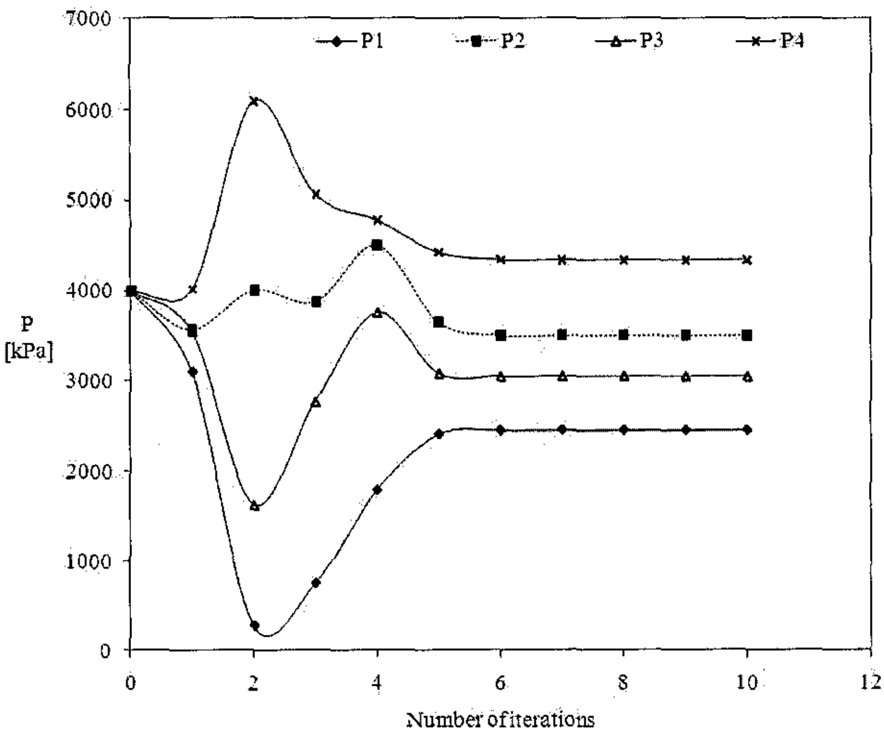


Figure 4.33 Convergence of pressure variables with corrosion (Case 3C)

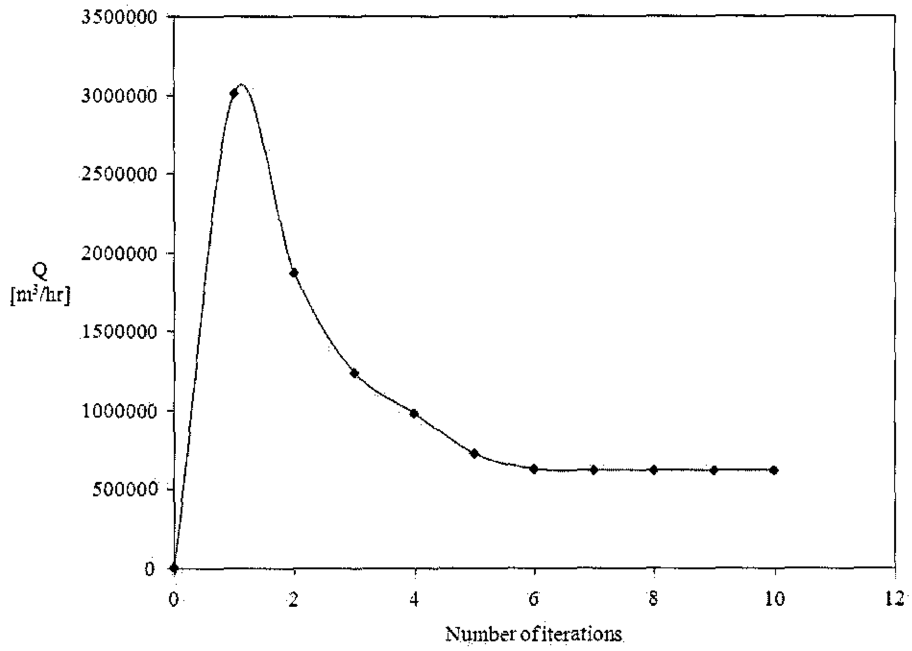


Figure 4.34 Convergence of flow variable with corrosion (Case 3C)

The results shown in Table 4.1 on page 115 were compared with the results obtained by considering the effect of corrosion for various ages of the pipe. The pressures at node 0 and 5 were constant throughout the various ages. This is because the pressures at these nodes are the given conditions. The speed of the compressor is assumed to be 8000 rpm for both cases. For the case of neglecting the effect of corrosion, only the natural frictional coefficient of the pipe was considered which is constant throughout the service of the pipes. However, for the case of pipes where carrions is taken into account, the friction factor varied with service life of the pipe based on the relationships developed in section 3.5.2 on page 96. The frictional coefficient had an effect on the pressure drop, flow capacity, compression ratio and power consumption.

Table 4.9 shows the comparison of the pressure variables at different nodes for various ages of the pipes. As indicated in the table, higher pressure drops were observed as the ages of the pipe increased. For instance, for pipe joining node 0 and

1, the pressure drop for the 20 years old pipe was higher than the pressure drop for 10 years old.

Table 4.9 Comparison of nodal pressures for different pipe ages

Nodes	Pressure [kPa] for various ages		
	New pipe	10 years old pipe	20 years old pipe
0	3000.00	3000.00	3000.00
1	2472.77	2460.22	2447.55
2	3505.01	3504.79	3504.51
3	3065.90	3055.53	3045.02
4	4345.73	4352.85	4359.99
5	4000.00	4000.00	4000.00

The flow capacity of the system was also studied for various ages of the pipes. The variation of the flow capacity of the pipe with age of the pipe is shown in Figure 4.35. From the figure, it is observed that the capacity of the pipe is reduced as the ages of the pipe increased. This is because, as the age of the pipes increase the roughness of the pipe increases due to corrosion and accumulation of various elements. As a result, the friction factors for the pipes increased which increase the pipe flow resistance. An increase in flow resistance of the pipe decreases the flow capacity of the system.

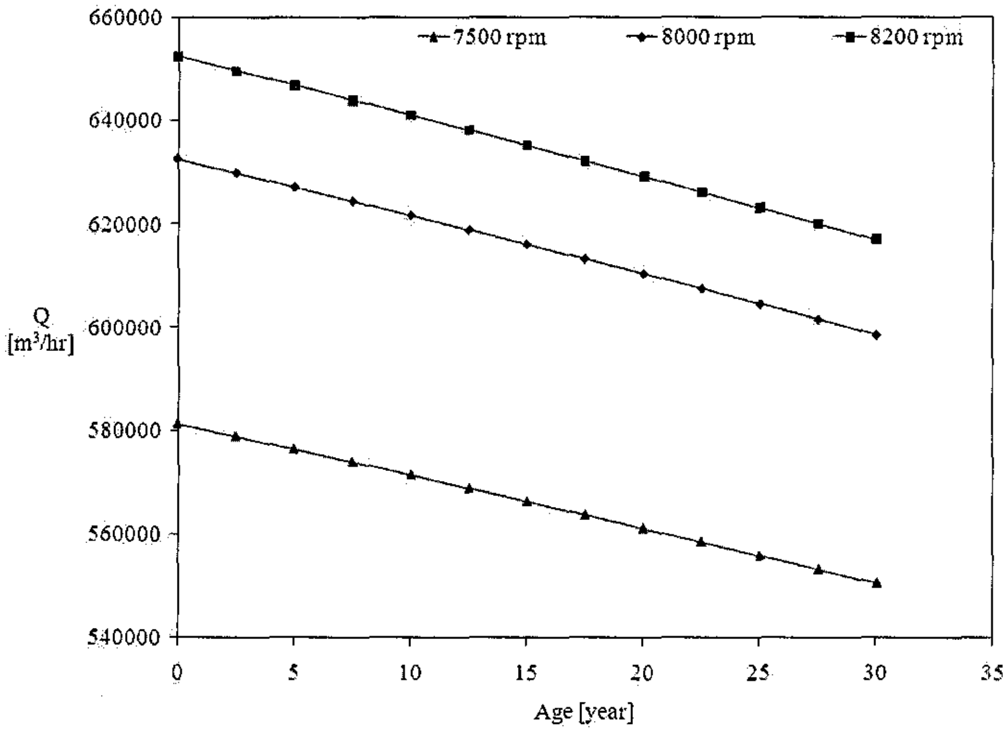


Figure 4.35 Variation of flow with age of the pipe

The variation of CR with ages of the pipe is shown in Figure 4.36. CR increased as the age of the pipe increased. This is due to the fact that, an increase in ages of the pipe could result in an increase in roughness of the pipe which leads to increase in friction factor. As a result, the pressure drop increased which cause higher CR.

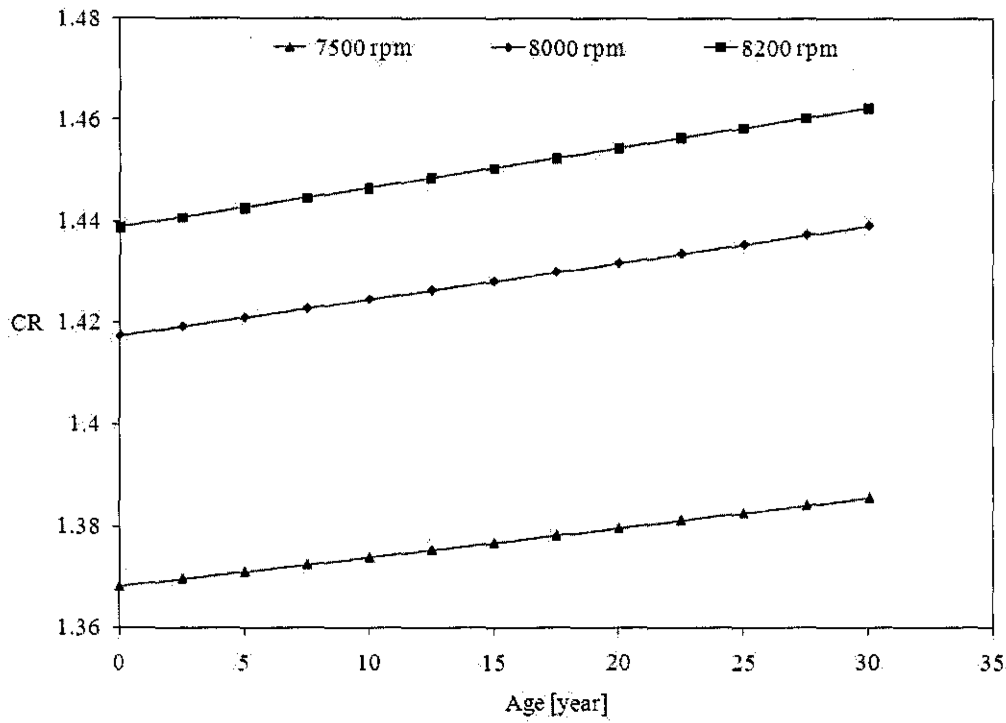


Figure 4.36 Variation of compression ratio with age of the pipe

The variation of the power consumption by the system with age of the pipe is shown in Figure 4.37. As it is observed from the figure, for constant speed operation, power consumption decreases with an increase in age of the pipes. As shown in equation (3.62), power consumption of the system is mainly function of the flow rate, CR and properties of the gas. From Figure 4.35, it is observed that an increase in age of the pipe caused a decrease in flow capacity of the system. Moreover, it is observed in Figure 4.36, CR increased with age of the pipes. Therefore, the trend of power consumption with age of the pipes depends on either flow rate or CR. From Figure 4.37, it is observed that the trend of power consumption followed the same trend as that of Q_1. This showed that the effect of flow variation was more dominant than the effect of CR variations with age of the pipes on power consumption.

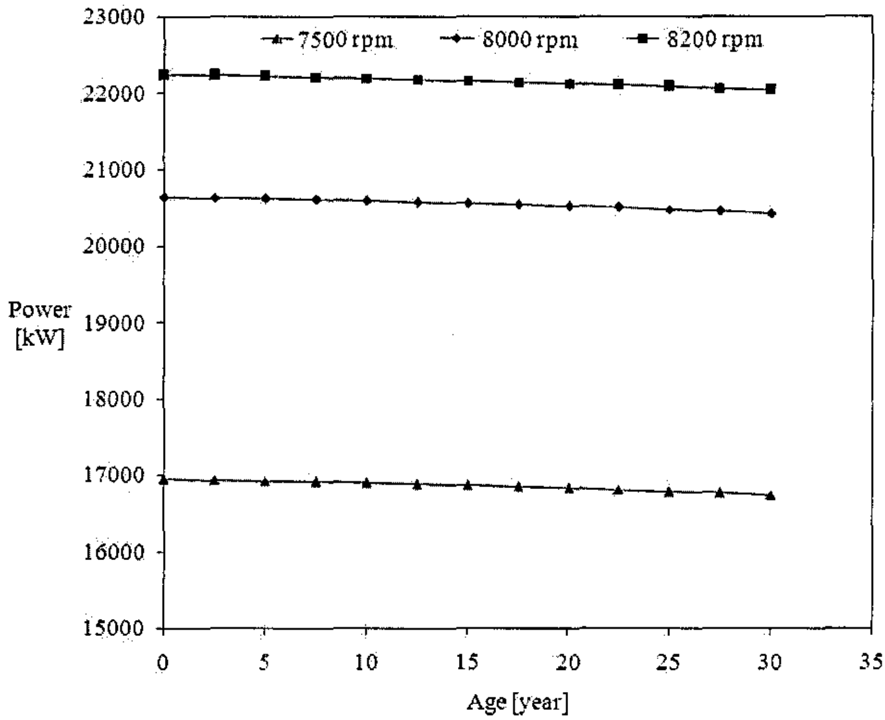


Figure 4.37 Variation of the power consumption with age of the pipes

ii) Case 4C: Branched Pipeline Network Module

The branched pipeline network shown in Figure 3.20 on page 79 was also analyzed with the aid of the enhanced Newton-Raphson based TPNS simulation model by considering the effect of corrosion. The same specifications of compressors were used as in section 4.3.2. The age of the pipes could vary to give the corresponding friction coefficient. The convergences of the pressure and flow variables were also studied based on ten years old pipes. The convergence of some of nodal pressure variables is shown in Figure 4.38. It is observed from the graph that the solutions for the nodal pressures were obtained after the third iterations. The maximum error at the end of the 10^{th} iterations was 1.92×10^{-15}. Figure 4.39 shows the convergence of flow variables through main pipes. As it is observed from the graph, the TPNS simulation nearly arrived to the final solution at the 4^{th} iteration. At the end of the 4^{th} iteraion, the maximum relative error was 0.045935.

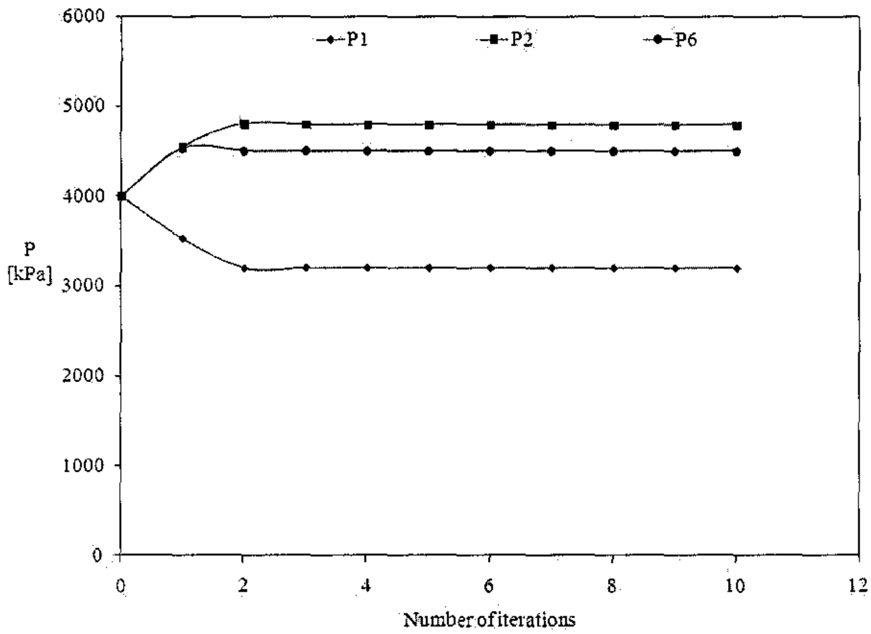


Figure 4.38 Convergence of pressure variables (Case 4C)

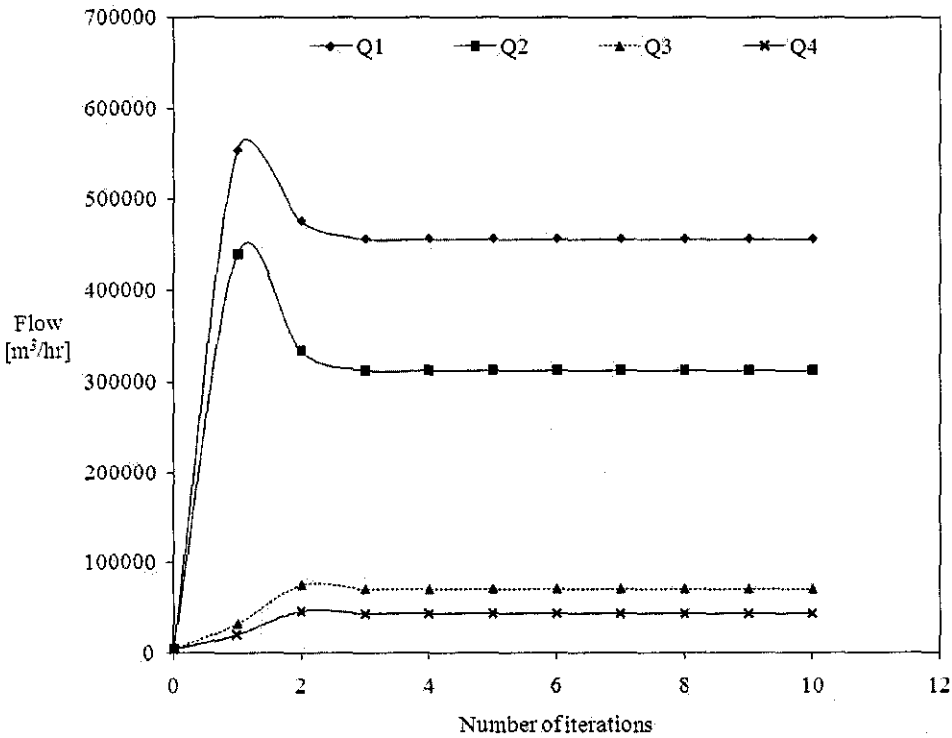


Figure 4.39 Convergence of flow through main pipes (Case 4C)

The convergence of flow variables through the branch pipes is shown in Figure 4.40. Similar to the convergence of the nodal pressures and flow variables through main pipes, the TPNS simulation converged almost to the final solution at the end of the 4th iteration for the flow variables through lateral pipes.

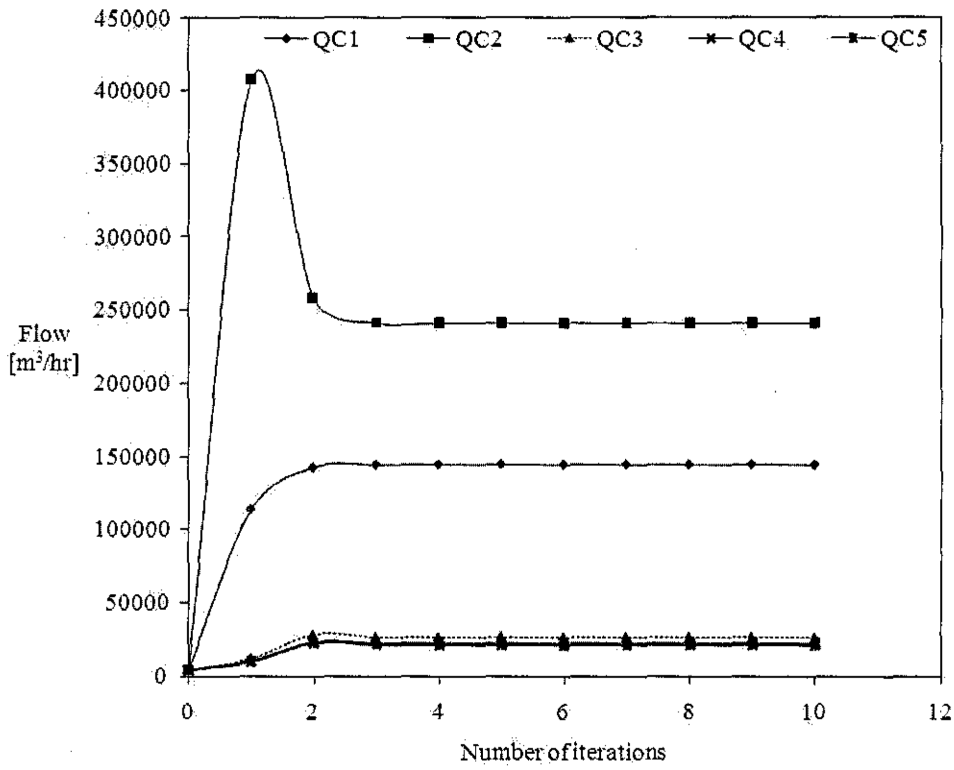
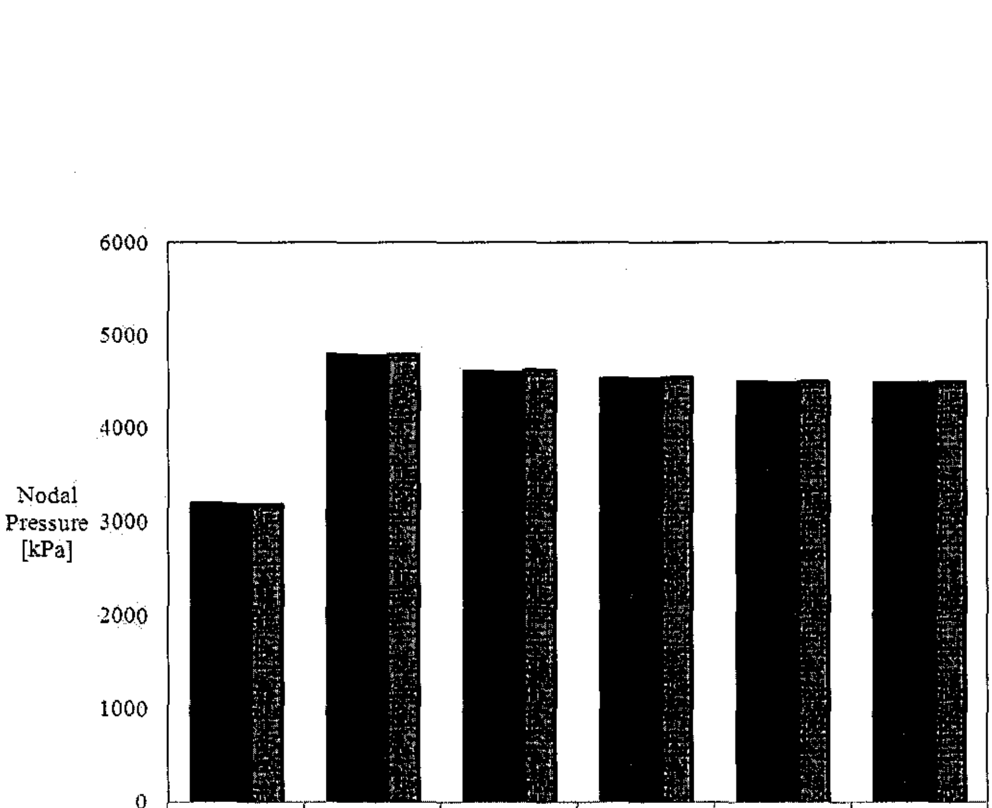


Figure 4.40 Convergence of flow through lateral pipes (Case 4C)

The results obtained in section 4.3.2 were compared with the results obtained by considering the effect of corrosion for various ages of the pipe. Three groups of pipes i.e. pipes with ages of 0, 10 and 20 years old were considered for comparison. Pipes with 0 years old are considered to be as new pipe. For this pipe, only the natural roughness of the pipe was considered during the analysis. Figure 4.41 shows the values of the pressure variables for different ages of the pipe. Since the customer requirement should have to be satisfied in terms of pressure in all groups of pipes, the nodal pressures remain nearly the same for different ages of pipes. However, slight increment in pressure drop is observed when the ages of the pipes increased.



	P1	P2	P3	P4	P5	P6
New	3207.31	4789.15	4622.27	4542.4	4504.83	4503.02
10 years old	3203.5	4792.71	4623.85	4542.96	4504.89	4503.06
20 years old	3199.64	4796.32	4625.45	4543.54	4504.95	4503.1

Figure 4.41 Nodal pressures for different ages of pipes

The variation of flow variables with ages of pipes is shown in Figure 4.42. It is observed that corrosion had a significant effect on flow capacity of the pipes. The results of the simulation analysis showed that a decrease in flow capacity of 2.16% and 4.35% were observed for the 10 and 20 years old pipes, respectively.

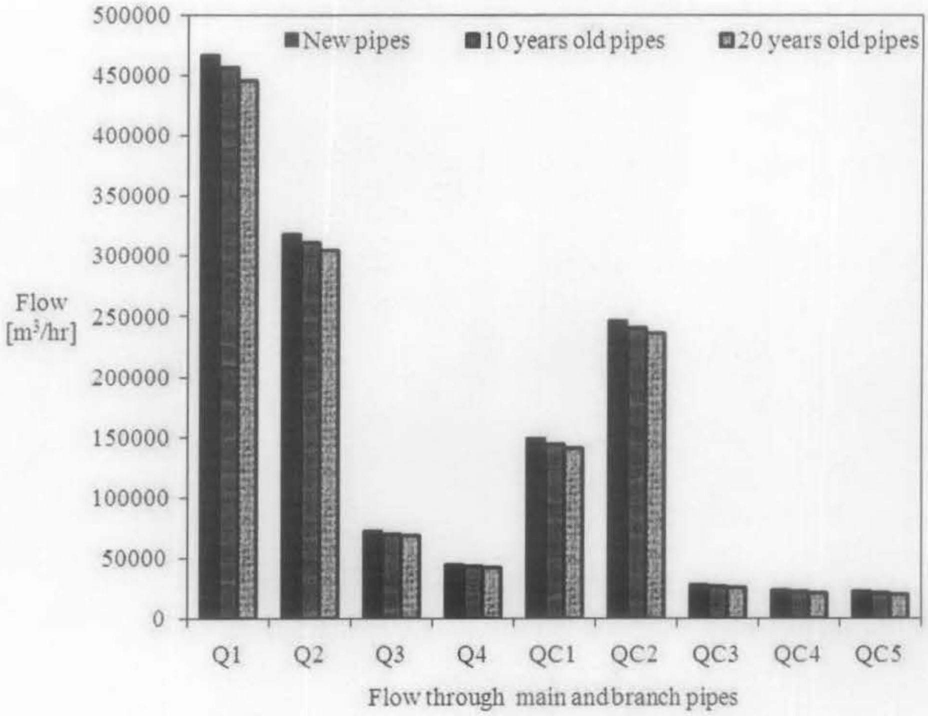


Figure 4.42 Flow through pipes for different ages of pipes

Table 4.10 shows the results of the simulation study conducted on pipe joining node 0 and 1 of the pipeline network system. The friction factor, pipe flow resistance and the flow through the pipe were studied under three age groups. As the age of the pipes increased, the friction factor and pipe flow resistance increased. Based on flow equations, for fixed pressure at the start and end node of the pipe, an increase in flow resistance of the pipe reduced the flow capacity.

Table 4.10 Variation of flow with ages of pipes

Years in service	Friction	Pipe flow resistance	Flow[m^3/hr]
New pipe	0.007003	9.01E-06	466683.00
10	0.007407	9.53E-06	456596.00
20	0.007847	1.01E-05	446371.00

4.4.3 Non-isothermal Flow Analysis

The analyses conducted in this section were based on the methodology discussed in section 3.5.3 on page 101. The gunbarrel pipeline network shown in Figure 3.19 on page 77 was also analyzed with the aid of the enhanced Newton-Raphson based TPNS simulation model for non-isothermal conditions. The same compressors data as in section 4.3.1 was used for the analysis. The source temperature was assumed to be 310 K. The results for the unknown pressure, flow and temperature variables were obtained with less than ten iterations. The unknown temperature variables for the first ten iterations are shown in Table 4.11. Note that temperature is measured in K.

Table 4.11 Results of temperature variables for the first 10 iterations

Iteration	T_1	T_2	T_3	T_4	T_5	Max. error
0	4000.00	4000.00	4000.00	4000.00	4000.00	
1	360.576	466.115	97337.9	97443.5	98018.4	0.998674
2	309.982	237.188	237.263	-16406.9	-16538.2	0.602838
3	309.972	827.606	822.405	-40046.9	-39564.5	0.504891
4	309.961	581.863	575.621	13105.1	13051.8	0.310895
5	309.948	430.935	426.949	-2749.02	-2753.84	0.351659
6	309.939	362.365	360.53	926.084	917.115	0.107755
7	309.938	358.562	357	408.03	404.835	0.006933
8	309.938	358.469	356.91	412.797	409.561	2.79E-05
9	309.938	358.468	356.91	412.795	409.559	3.02E-09
10	309.938	358.468	356.91	412.795	409.559	1.52E-14

The convergence of the pressure variables and flow variables are shown in Figure 4.43 and Figure 4.44, respectively.

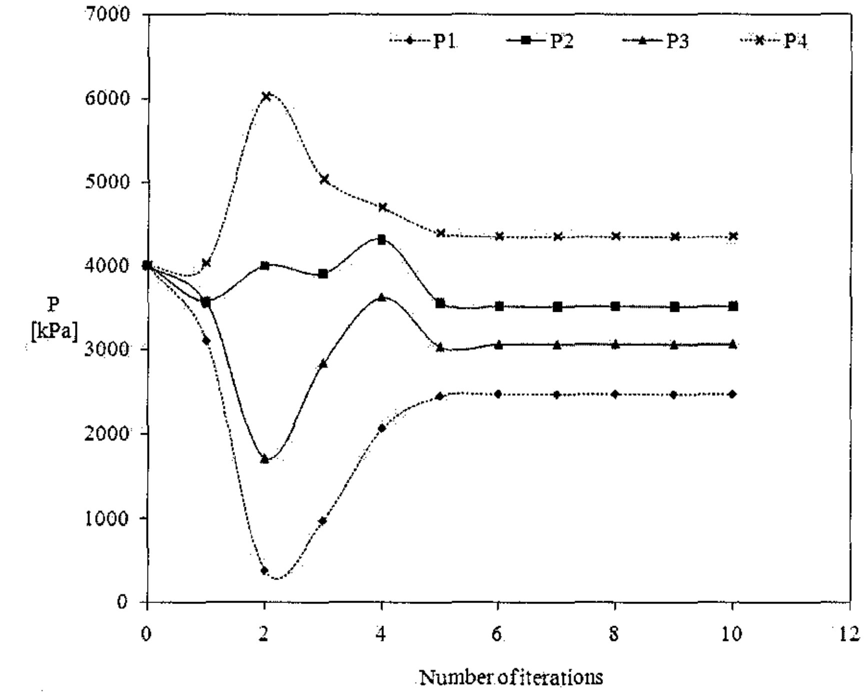


Figure 4.43 Convergence of pressures for non-isothermal conditions

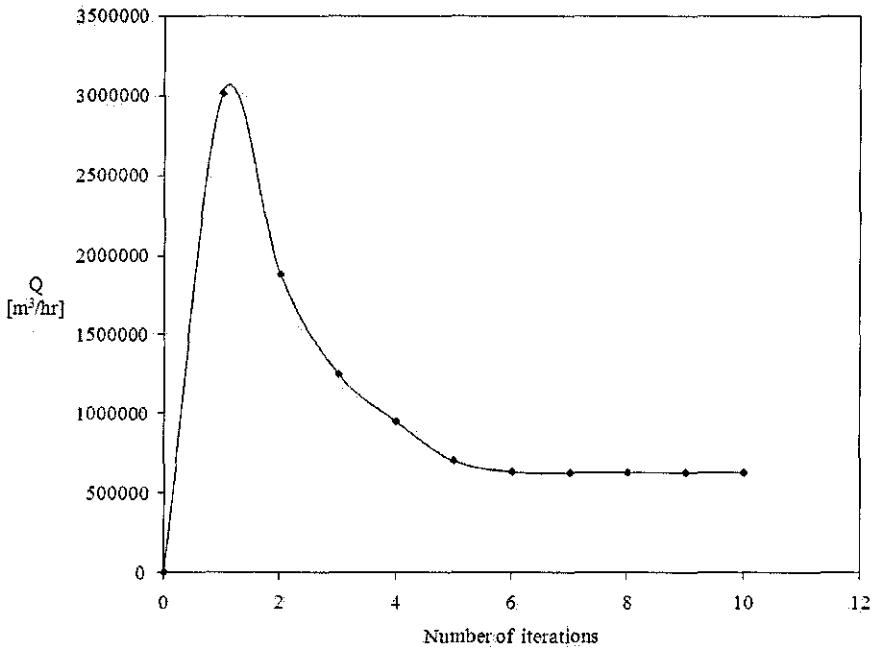


Figure 4.44 Convergence of flow variables under non-isothermal conditions

Based on the results obtained in Table 4.11, the convergence of some of the nodal temperature variables for the network system is shown in Figure 4.45. The convergences of the remaining nodal temperatures follow the same trends as T_1. It required a minimum of 6 iterations for the error to be stable. This is mainly due to the initial estimations which were far from the final solution of temperature variables.

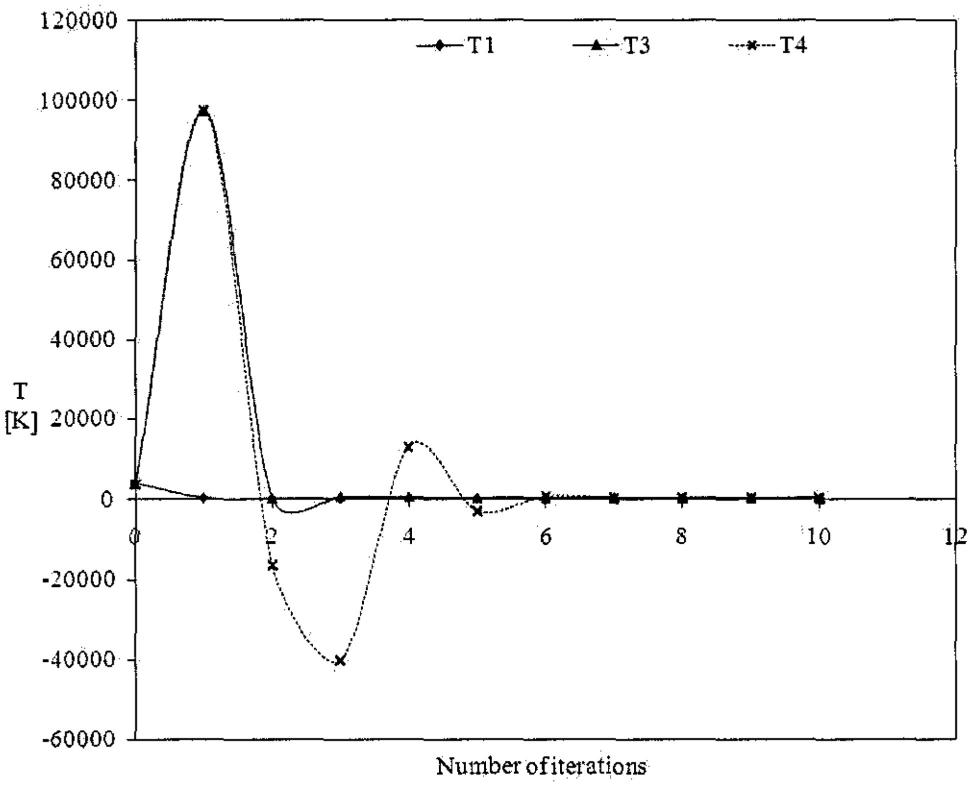


Figure 4.45 Convergence of some of the temperature variables

4.5 Verification and Validation of the TPNS Simulation Model

The developed TPNS simulation model provided the required operational variables of the pipeline network for various configurations. The results from the simulation model needs simulation verification and validation for accuracy and reliability. According to [94], model validation is usually defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". Model verification is often defined as "ensuring that the computer program of the computerized model and its implementation are correct". These definitions of validation and verification are adopted in this thesis.

Since simulation models are increasingly being used in problem solving and in decision making in various areas of interest, the verification and validation techniques also varies depending on the types and nature of the model. The different techniques on simulation model verification and validation are presented in [95]-[97].

The availability of real system data gives more rooms to implement the various verification and validation techniques on the simulation model. As presented in [98], there are three situations concerning the data availability which includes, the case of no data, the case of only output data, and the case of both input and output data availability. Various model validations and verifications were suggested based on the nature of the availability of the data.

The TPNS simulation model case is different and could not be categorized as the situations reported in [98]. This is because, the TPNS simulation model is developed based on the actual performance of the compressors, gas properties, pipe information, and source and exit pressure requirements. As a result, some of the input parameters are known. Even though the output data from the real system are available, some data were considered to be confidential by the company. Hence, it would be difficult to categorize the situations of the TPNS simulation model as one of the classifications discussed based on the data availability.

Simulation model validation and verification are not considered as an end process. They are integrated with the modeling process. Sargent [95] presented how the simulation verification and validation process are integrated with the modeling process. Sargent framework for modeling process is used as a basis in this research work. Figure 4.46 shows the simplified framework for simulation modeling process.

By referring to Figure 4.46, the problem entity is the system (real or proposed), idea, situation, policy, or phenomena to be modeled; the conceptual model is the mathematical/logical/verbal representation (mimic) of the problem entity developed for a particular study; and the computerized model is the conceptual model implemented on a computer. The conceptual model is developed through an analysis and modeling phase, the computerized model is developed through a computer programming and implementation phase, and inferences about the problem entity are obtained by conducting computer experiments on the computerized model in the experimentation phase [95].

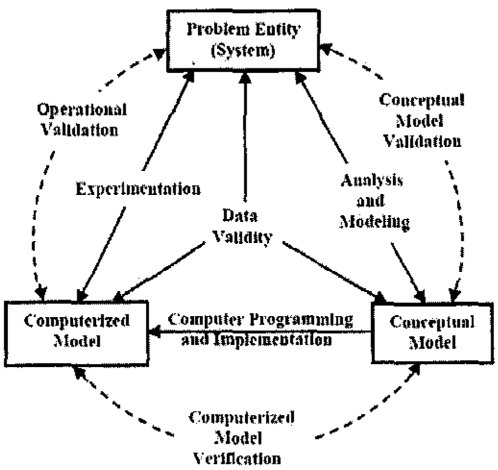


Figure 4.46 Simplified version of the modeling process [95]

4.5.1 TPNS Conceptual Model Validation and Verification

Conceptual model validation is one of the fundamental steps that were included during the development of the TPNS simulation model. This phase of the model development process includes the determination of the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is reasonable for the intended purpose of the model.

The various assumptions, theories and the relationships between parameters were studied carefully in order to insure the conceptual model validity. Some of the procedures conducted consist of thorough discussion with expert on the basic principles for model development and studying the basic relationships between the flow, pressure, temperature and performance measurements. Furthermore the whole model was divided into sub-models and studied if appropriate structure, logic, and mathematical relationships have been used. For instance, the pipe flow equations which is one of the governing simulation equations was divided into various sub groups in order to make sure that the mathematical relationships and basic principles were properly implemented.

Proper examination of the flowchart of the model and plotting of the basic relationships of the parameter were also conducted on the TPNS conceptual simulation model. The general flow equation was plotted based on pressure versus length of pipe for various flows in order to study the pressure drop profile. A comparison with the known flow equations is also performed. The compressor equation was derived by using some of the compressor data. The remaining data was used to validate the compressor equations as shown in Figure 3.9.

The model verification procedures ensure that the computer programming and implementation of the conceptual model are correct. There are various techniques suggested in [95] for simulation model verification. Two types of tests were conducted on the developed TPNS simulation model in order to ensure that the computer program is properly implemented. The first test was done based on static testing principles. This test consists of analyzing the computer program to determine if it is correct by using correctness proofs, structured walk-through and examining the structure properties of the program. The second test was conducted based on dynamic testing principles. In dynamic testing, the computerized TPNS simulation model was executed under different conditions like single phase flow analysis, two-phase flow analysis, and single phase with no corrosion effect. Furthermore, the TPNS model was tested for gunbarrel, branched and looped pipeline networks which are the most commonly used configurations. The resulting values from the dynamic analysis of the TPNS simulation model have shown that the computer program and its implementations were correct. The techniques commonly used in dynamic testing suggested in [94] are traces, investigations of input-output relations using different validation techniques, internal consistency checks, and reprogramming critical components to determine if the same results are obtained.

4.5.2 Operational Validation

One of the techniques applied for validation of TPNS simulation is the operational validation techniques. This technique ensures whether the TPNS simulation model's output behavior has the required accuracy for the application of the model to real system. This is where much of the validation testing and evaluation take place. There are various simulation validation techniques suggested in literatures [95], [97] and [99]. The type of validation techniques applied for the simulation model depends on the nature of the simulation model and the availability of data. The following sections discuss the detail of the operational validation techniques applied on the TPNS simulation model.

4.5.2.1 Comparison to Other Models

One of the techniques used in order to validate the TPNS simulation model was comparison with the previous models. The lack of data from literatures with the same problem instances make difficult to validate the simulation model based on model comparison. However, there were various types of pipeline networks analyzed for determination of optimal parameters or determination of the nodal pressure and pipe flow parameters for the given conditions. Two cases were taken from the available literatures in order to validate the results of the developed TPNS simulation model.

As discussed in sections 4.3.1 and 4.3.3, the results of the TPNS simulation model were compared with two other models based on various pipeline network configurations. Even though complete data regarding the type of compressors used were not mentioned in the cases considered, the TPNS simulation was able to provide solutions in both instances. In the first case, the TPNS simulation model was compared to an exhaustive optimization technique based on gunbarrel pipeline networks system. As discussed in detail in section 4.3.1, TPNS simulation yielded close solutions of nodal pressures and flow variables to the exhaustive technique. The comparison based on looped pipeline network discussed in section 4.3.3 also showed that the TPNS simulation model was able to provide solutions to nodal pressures and flow variables which were close to previous model.

4.5.2.2 Validation based on Operational Graphics

As presented in [94], this type of validation techniques consists of showing graphically the values of performance measures as the model moves through time or subjected to variations. The dynamical behavior of performance indicators are visually displayed as the simulation model runs with variations to ensure they behave correctly.

The operational validation technique was demonstrated based on the pipeline network shown in Figure 3.22. The performance of the compressor for the pipeline network was presented in section 4.3.4. The performance analyses of the compressor include the flow capacity, power consumption and compression ratio. The performance characteristics maps generated using the developed simulation model was similar to the one available in the literatures.

4.5.2.3 Model Parameter Variability - Sensitivity Analysis

One of the techniques used in order to validate the simulation model was sensitivity analysis. This technique consists of changing the values of the input and internal parameters of the model to determine the effect upon the model's behavior and its output. As presented in [100]-[102], performing sensitivity analysis on simulation model is one of the key elements in studying the effect of the input parameters variations on the output data.

Sensitivity analysis was conducted on the TPNS simulation model by varying the input parameters like compressor speed, number of compressors working within the compressor station and age of the pipe. The effect of the variation of these parameters on the TPNS output parameters and model behavior was studied.

Sensitivity analysis was conducted on the part of the existing pipeline network (Figure 3.22) which was used to demonstrate the application of the TPNS simulation model for real system. The pipeline data shown in Table 4.7 was used for the analysis. It was assumed that the demand pressure at various customer stations to be 4000kPa. The analysis was done based on single compressor data obtained from [59]. The details of the sensitivity analysis conducted for the TPNS by varying the input parameters are discussed as follows.

i) Variation in number of compressors working within the station

The variations of the number of compressors on the performance of the system were studied based on constant speed operations of the compressors. Compressors speed of 7500, 8000, 8250, and 8500rpm were taken as constant speed operations. The maximum compression ratio of the system was limited to 1.5. Furthermore, the source pressure for the pipeline network was 3000kPa and the age of the pipes was assumed to be ten years.

Figure 4.47 shows the variation of main flow variable of the pipeline network system (Q_l) with number of compressors working within the station for different speed operation of the compressors. When the number of compressors working within the station is increased, it is observed that the flow capacity of the system increased. As it is seen from equation (3.10), an increase in number of compressor improves the flow capacity of the system. There will be more compressors to work and satisfy the requirements. However, significant increment in flow rate capacity of the system was observed when the number of compressors working within the station increased to maximum of 4. The effect of the addition of a compressor to the existing compressors became less as the number of compressors increased from 5. Therefore, flow rate capacity of the system is more sensitive to increase in number of compressors only at lower number of compressors.

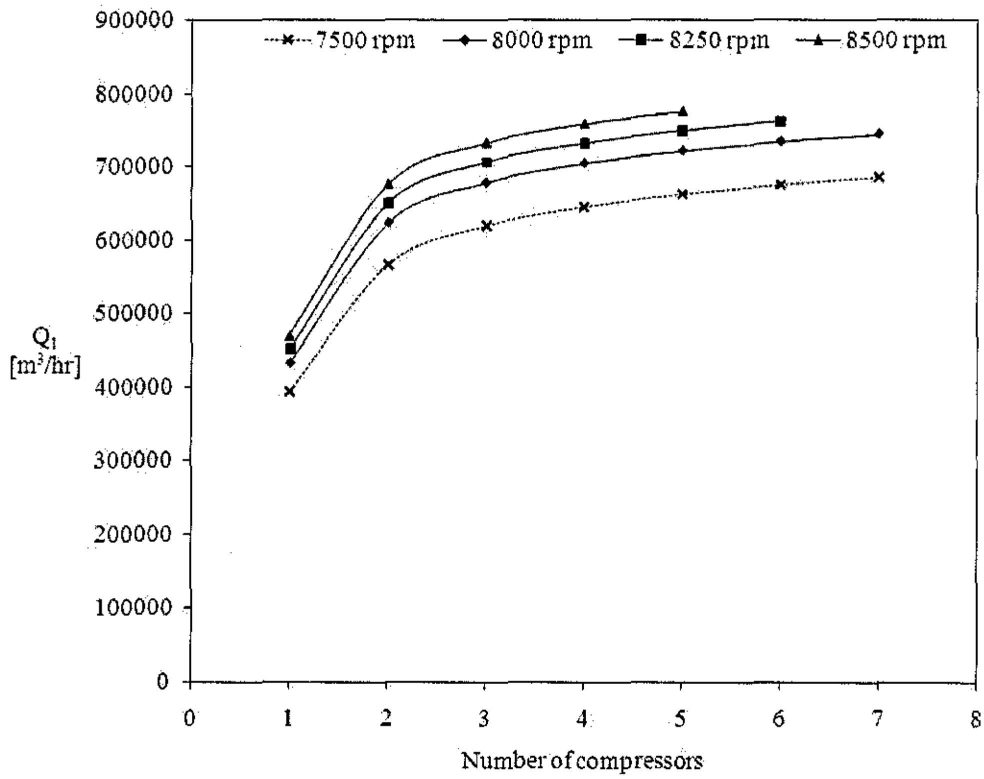


Figure 4.47 Variations of flow rate with number of compressors

Figure 4.48 shows the compression ratios when the number of compressors working within compressor station varies for different speed operations. An increase in number of compressors working within the compressor station caused an increase in compression ratio of the system for various speed operations. As seen from Figure 4.47, an increase in number of compressors enhanced the flow capacity Q_1. Hence, based on equation (3.1), an increase in flow capacity leads to higher pressure drop which increase the CR. Significant changes in CR was observed for all speed operations when the number of compressor changed from 1 to 2. Even though an increase in number of compressors increased the compression ratio of the system, their effect reduced as the number of compressors increased.

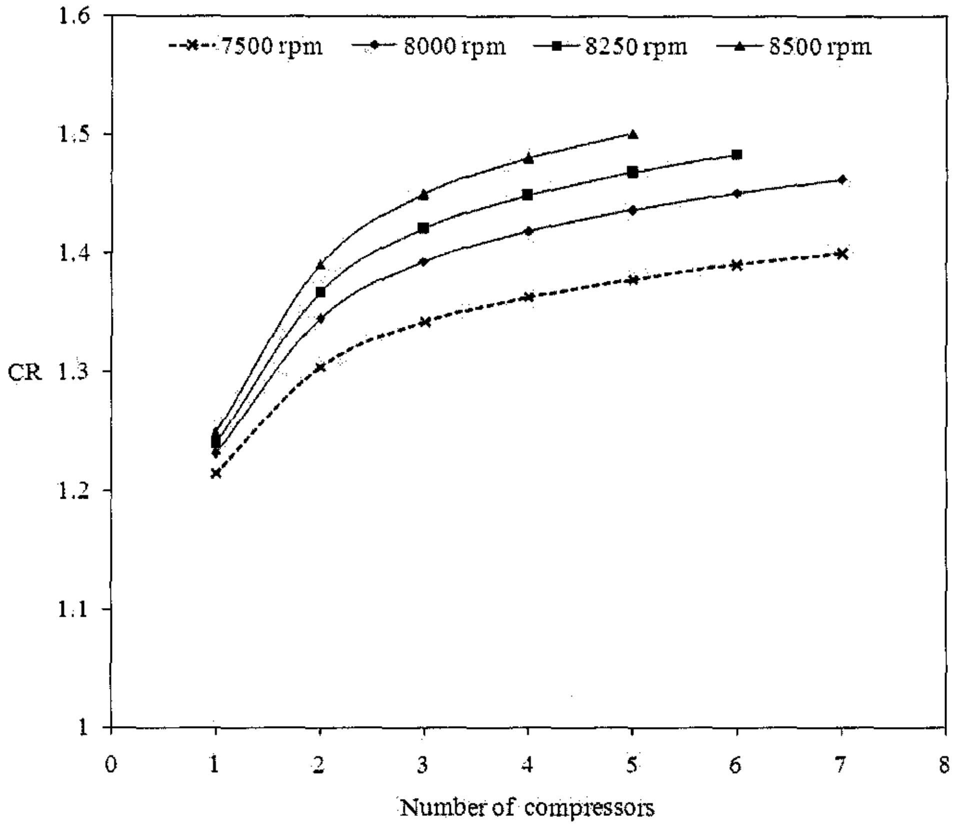


Figure 4.48 Variation of compression ratio with number of compressors

The magnitude of the variation of CR for various constant speed operations became more sensitive to change in number of compressors. For instance, when the number of compressor working within the system was 1, CR for compressor speed of 7500 rpm and 8500 rpm was 1.21459 and 1.24845, respectively. However, an increase in number of compressors working within the system to 5 gave CR of 1.37902 and 1.50166 for compressor speed of 7500rpm and 8500rpm, respectively. It is observed from Figure 4.48 that, compression ratio is more sensitive at lower number of compressors and the deviations among the constant speed operations increased with increase in number of compressors.

Figure 4.49 shows the variation of the power consumption with number of compressors at various speed operations. In the case of the power consumptions with number of compressors working, almost the same scenarios were observed as that of the compression ratio variations.

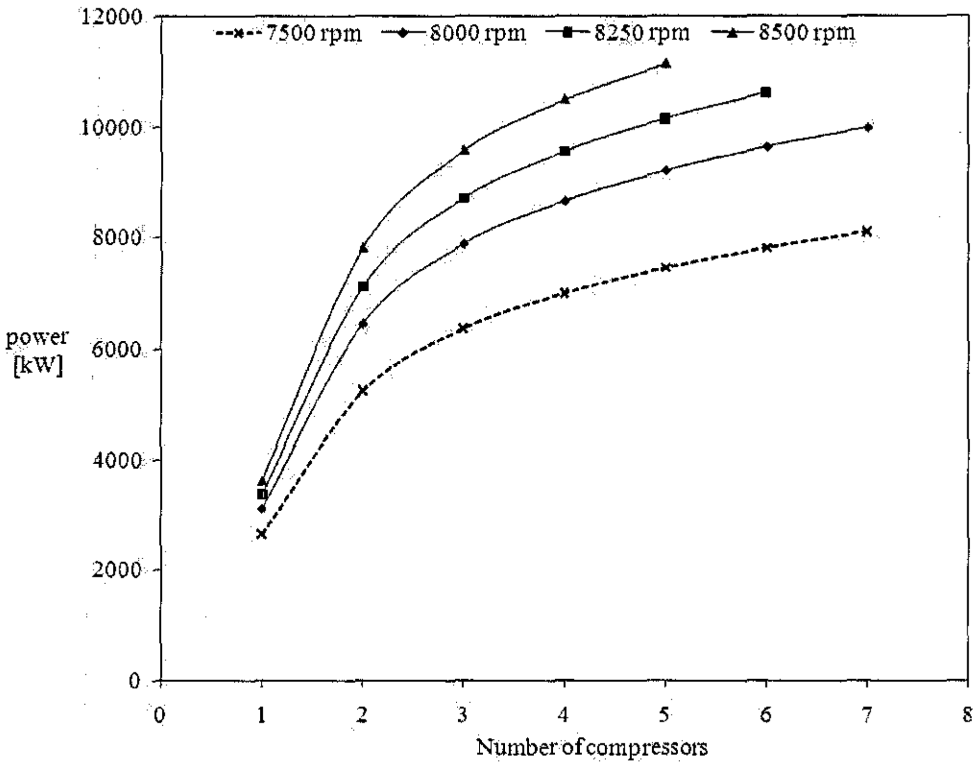


Figure 4.49 Variation of power consumption with number of compressors

At lower number of compressors working within the station, power consumption was more sensitive compared to high number of compressors working within the system. The deviations in power consumption at various speed operations were increased with increase in number of compressors working within the system.

ii) Variation in speed of the compressors working within the station

For performing the sensitivity analysis based on the variation in speed of the compressors, the number of compressors working within the station was assumed to be two. The source pressure for the pipeline network was 3500 kPa and the required demand pressures were assumed to be 4000, 4250 and 4500kPa. The age of the pipes was assumed to be ten years. The variation of flow capacity of the system, compression ratio and power consumption with speed were studied and presented in section 3.4.4.

iii) Variation in source pressure

For performing the sensitivity analysis based on the variation in source pressure, three constant speeds operations of compressor were identified, i.e. 8000rpm, 8500rpm and 8750 rpm. The simulation can be performed any arbitrary speed provided that the speed selected are within the working limit of the compressor. The demand pressure for the system was 4500kPa. The age of the pipes was assumed to be ten years. The number of compressors working within the compressor station was two. The working range of source pressures for each speed is bounded by the maximum CR and speed of the compressor. For instance, at source pressure of 3200kPa and compressor speed of 8750 rpm, the CR was 1.51074. Any source pressures less than 3200kPa could result higher CR which is beyond the working limit.

Figure 4.50 shows the variation of main flow rate (Q_l) with variation in source pressure (P_0). For fixed compressor speed and demand pressure requirement, an increase in source pressure increased Q_l and vice versa. For high speed operation of the compressors, high increment in the main flow was observed compared to low speed operations.

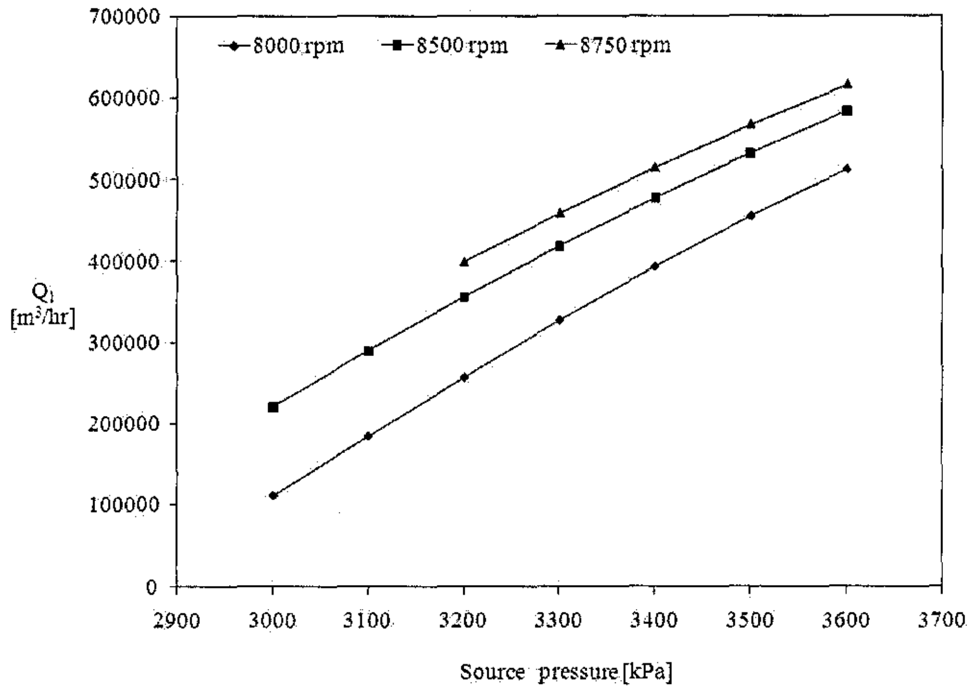


Figure 4.50 Variation of main flow rate with source pressure

As it is shown in Figure 4.51, an increase in source pressure decreased the compression ratio of the system for constant speed operation and demand requirement. In real system operation of the compressors, in order to meet fixed demand pressure requirement at constant speed, an increase in source pressure makes the system to move downward on the performance map of the compressor following the trace of constant speed line. This causes an increase in flow rate capacity and a decrease in compression ratio of the system. Thus, both the main flow Q_l and the compression ratio of the system are highly sensitive to change in source pressure.

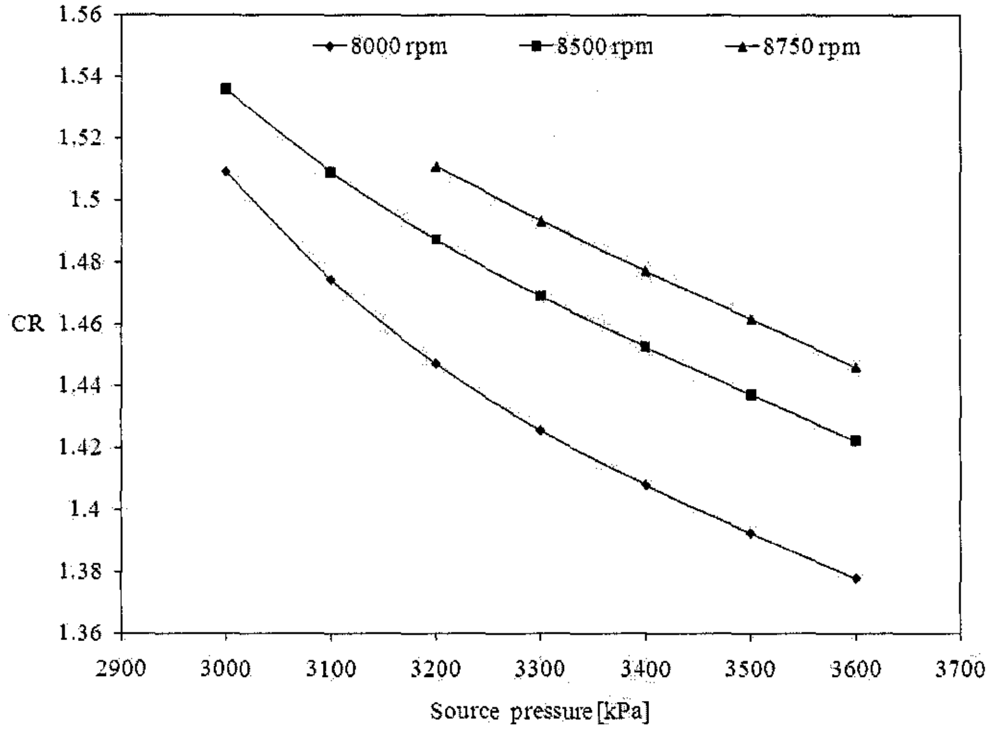


Figure 4.51 Variation of compression ratio with source pressure

Figure 4.52 shows the variation of power consumption of the pipeline network system for various source pressures. An increase in source pressure increased the power consumption the system. Power consumption by the system is mainly dependent on the flow rate capacity of the system, compression ratio and properties of the gas as presented in [23]. As shown in Figure 4.50 and Figure 4.51, an increased in source pressure increased the flow capacity and decreased the compression ratio of the system. Therefore, the overall effect of change in source pressure is either to increase or decrease the power consumption of the system depending on which factor is dominating. From Figure 4.52, it is observed that an increase in source pressure increased the power consumption of the system which indicates that the flow capacity of the system is the dominating factor over the compression ratio.

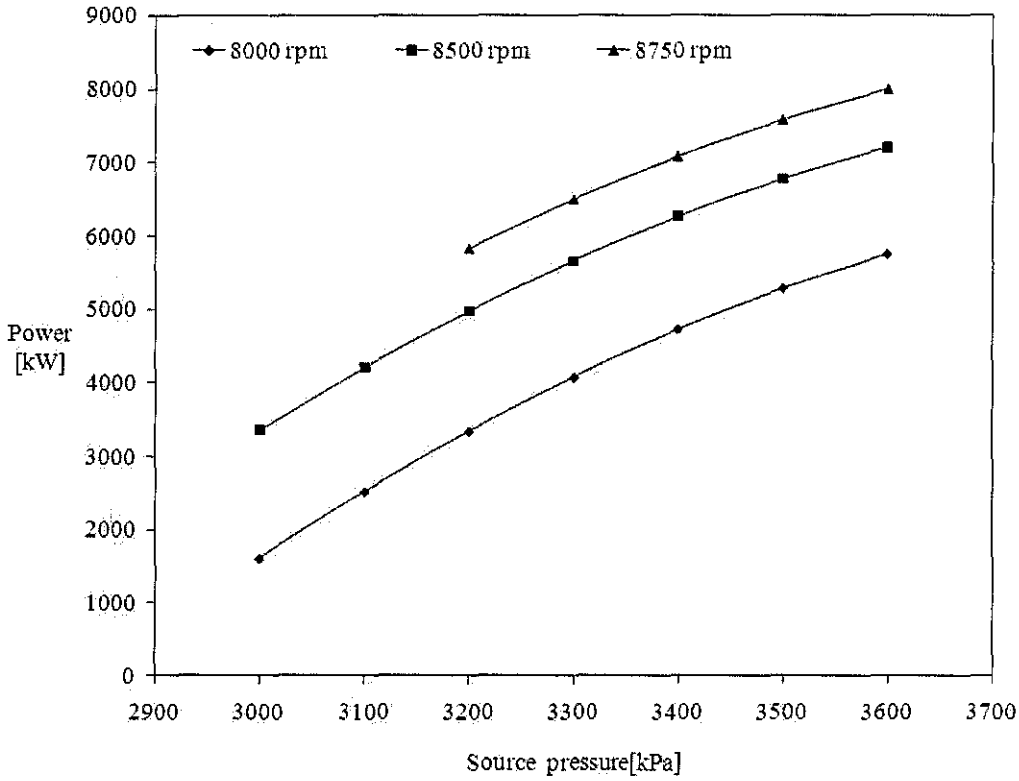


Figure 4.52 Variation of power consumption with source pressure

iv) Variation in the age of the pipes

The variations of the flow capacity, compression ratio and power consumption of the system with the age of the pipes were also studied. For performing the sensitivity analysis based on the variation in the age of the pipes, the speed of the compressor, source pressure, and the number of compressors working within the system were assumed to be constant. The details of the effect of the age of the pipes on the performance measures of the system were presented in section 4.4.2.

4.6 Summary

The simulation studies based on successive substitution and Newton-Raphson method showed that the TPNS simulation model produced solutions to nodal pressures and flow variables for various pipeline network configurations. Successive substitution scheme was limited to simple pipeline network configurations as the method is highly dependent on information flow diagram which is a difficult task to produce when the number of unknowns increased. The applications of successive substitution scheme on two different pipeline network configurations showed that, it took many iterations to arrive at specified tolerance.

The simulation experiments were conducted on TPNS simulation model based on Newton-Raphson solution scheme for the three most commonly found configurations, i.e. gunbarrel, branched and looped pipeline network system. It took less than ten iterations to arrive at reasonable error tolerance limit. Usually, it took a maximum of 4 iterations for the TPNS simulation model for the error to arrive at the stable solutions.

As discussed in sections 4.3.1 and 4.3.3, the results of the Newton-Raphson based TPNS simulation model were compared with two other models based on various pipeline network configurations. Even though complete data regarding the type of compressors used did not mentioned in the cases considered, the Newton-Raphson based TPNS simulation was able to provide solutions in both instances. In the first case, the simulation model was compared to an exhaustive optimization technique based on gunbarrel pipeline networks system. As discussed in detail in section 4.3.1, simulation model yielded close solutions of nodal pressures and flow variables to the exhaustive technique. The comparison of TPNS simulation model based on looped pipeline network configuration was discussed in section 4.3.3. The model produced solutions to nodal pressures and flow variables which were close to previous model.

The application of the Newton-Raphson based TPNS simulation model for real pipeline network system was also conducted based on existing pipeline network system in sections 3.4.4. Three modules of TPNS simulation model which includes input parameter analysis, function evaluation and network evaluation module were evaluated using the data taken from the real system. Analyses of the performance of compressor for existing pipeline network system which includes discharge pressure, compression ratio and power consumption were also conducted using the developed Newton-Raphson based TPNS simulation model. The performance characteristics maps generated by the simulation model showed the variation of discharge pressure, compression ratio, and power consumption with flow rate as similar to the one available in the literatures.

The enhanced Newton-Raphson based TPNS simulation model was also applied for analyzing branched and gunbarrel network configurations considering two-phase gas-liquid flow analysis, single phase with corrosion effect and single phase with temperature variations. In all cases, the results for the required nodal pressures, temperature and flow variables were achieved with less than ten iterations to the reasonable relative percentage errors. For instance, for two phase flow analysis discussed in section 4.4.1 on page 144 for case 2C, the relative percentage error at the end of the 10^{th} iteration was obtained to be $8.16639x10^{-17}$.

As discussed in section 4.5, the TPNS simulation model was verified and validated using the various techniques. The model verification and validation was integrated with the TPNS modeling process. Conceptual model validation and verification and operational validations were conducted on the TPNS simulation model based on the available data and simulation experiment.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In order to evaluate the performance of natural gas pipeline transmission network systems with non-pipe elements, a TPNS simulation model was developed. The developed TPNS simulation model was able to provide solutions to nodal pressure and flow variables for the given pipeline network systems. The performances of the system were analyzed based on the variables obtained. The TPNS simulation model was also enhanced to analyze pipeline network systems under two-phase gas-liquid flow, variable ages of pipes, and variable temperature.

The developed TPNS simulation model incorporated detailed parameters of the compressors into the governing simulation equations as discussed in section 3.2.3 on page 52. Compressor stations should not be considered as a black box or represented with few parameters during simulation. Speed of the compressor, flow rate, suction pressure and discharge pressure were the critical elements which affected the performance of the system as presented in section 3.4.4.

The TPNS simulation model proposed in this thesis based on the iterative successive substitution and Newton-Raphson algorithm were tested for different network configurations. The implementation of TPNS simulation model based on successive substitution scheme discussed in section 4.2 showed that the model is more suitable to simple network configurations. Simulation experiments were conducted on TPNS simulation model based on Newton-Raphson solution scheme for the three most commonly found configurations, i.e. gunbarrel, branched and looped pipeline network system as presented in section 4.3. In all the investigations, the solutions to the unknown variables were obtained with a wide range of initial estimations. A maximum of 10 iterations were required to get solutions to nodal pressure and flow variables with relative percentage errors less than 10^{-11}.

The results of the Newton-Raphson based TPNS simulation model were compared with two other models based on various pipeline network configurations. In the first case, the simulation model was compared to an exhaustive optimization technique based on gunbarrel pipeline networks system. The model yielded close solutions of nodal pressures with less than 1.8% absolute parentage errors. The comparison based on looped pipeline network also showed that, the Newton-Raphson based TPNS simulation model was able to provide solutions to nodal pressures and flow variables with mean absolute error of 5.10 % between the two methods.

The application of the Newton-Raphson based TPNS simulation model for real pipeline network system was also implemented based on the existing pipeline network system as discussed in section 3.4.4. Three modules of TPNS simulation model which includes input parameter analysis, function evaluation and network evaluation module were evaluated using the data taken from the real system. Analyses of the performance of compressor for existing pipeline network system which included discharge pressure, compression ratio and power consumption were also conducted using the developed TPNS simulation model. The performance characteristics maps generated by the developed TPNS simulation model show the variation of discharge pressure, compression ratio, and power consumption with flow rate similar to the one available in the literatures.

Simulation analysis was conducted using the enhanced Newton-Raphson based TPNS simulation model to investigate the effect of the ages of pipes on the performance of the system based on gunbarrel and branched network configuration as discussed in section 4.4.2. Pressure drop and flow rate of the gas were affected as the age of the pipe increases. The comparison of the performances of the three groups of pipes based on new, 10 years old, and 20 years old having branched network configurations showed that a decrease in flow capacity of 2.16% and 4.35% was observed for the 10 and 20 years old pipes, respectively. Since the customer requirement have to be satisfied in terms of pressure in all groups of pipes, the nodal pressures remain nearly the same for different ages of pipes as shown in Figure 4.41. For instance the nodal pressure at node 1 increased by only 0.119% when the years in service of the pipe increased to 10 years. The nodal pressure also increases by 0.239% when the years in service increased to 20 years.

The proposed enhanced Newton-Raphson based TPNS simulation model consists of module to analyze pipeline network systems with two-phases by incorporating modified homogeneous flow equation into the governing simulation equations. As presented in section 4.4.1 on page 144 , the simulation analysis conducted on branched TPNS configuration revealed that liquid holdup has a significant effect on flow capacity of the system. For instance, for the main flow rate Q_1, the flow capacity reduced by 54.56% when the liquid holdup increased from 0.0001 to 0.005. The corresponding nodal pressure at node 1 increased by 0.73%. Even though small amount of liquid holdup, usually less than 0.005 [24], is found in transmission pipeline network systems, the existence of the liquid had effect on pressure drop and flow capacity of the system.

5.2 Contributions of the Research

The main contributions of the research are summarized as follows.

1. *Performance analysis:* The developed TPNS simulation model is able to create alternative scenarios. There are two levels of creating alternative TPNS scenarios. The first level of creating alternative scenarios involves varying

TPNS configurations. This includes varying the number of pipes involved, number of compressor stations, the number of loops and the number of junction points within the TPNS. The second level of generating alternative networks involves varying the diameter of the pipes, the length of the pipes, the number of compressors working within the stations, the type of compressors, and the range of the speed of the compressors. The former method is used to evaluate possible TPNS configurations in order to guide for the selection of optimal network. The later method is used for evaluating the operation of the existing system. Hence, the developed TPNS simulation model could be used as tool for assisting decisions in designing and operating TPNS.

2. *Addressing the non-pipe elements*: Investigation on various literatures on TPNS simulation indicated that the overall operating cost of the system is highly dependent upon the operating cost of the compressor stations in a network [5, 6]. Hence, the detail incorporation of all its parameters, namely: speed, suction pressure, discharge pressure, flow rates, and suction temperatures are essential for a complete simulation of gas networks. The proposed TPNS simulation model incorporated compressor stations by integrating the characteristics map of compressor and energy equation as seen in equation (3.10). Thus, this can provide more details for the analysis of TPNS as presented in 4.3.4 on page 132.

3. *Effect of age of the pipe*: As discussed in section 4.4.2 on page 150, pressure drop and flow rate of the gas are affected as the age of the pipe increases. However, no known studies on the relationships between the age of the pipe and its effect on pressure drop and flow were reported in the literatures. The ability of the proposed enhanced Newton-Raphson based TPNS simulation model to incorporate the age of the pipes in its flow equations as presented in section 3.5.2 contributes for analyzing the effect of the age of pipes on

performance of the system. This could be useful for assisting decision in maintenance and pipe replacement during the operation of TPNS.

4. *Two phase flow analysis*: When liquid exists in TPNS, single phase flow modeling approach might not be adequate to predict the pressure drop, flow capacity, and power consumption for the system. The proposed enhanced Newton-Raphson based TPNS simulation model consists of module to analyze pipeline network systems with two-phase by incorporating modified homogeneous flow equation into the governing simulation equations as presented in 3.5.1 on page 88. This could help to predict the transport capabilities of the TPNS transporting two-phase gas-liquid mixtures.

5.3 Recommendations

The developed TPNS simulation model is mainly focused on natural gas transmission pipeline network system. However, the principles used in TPNS simulation model could be easily extended to be applied for the analysis of pipeline network systems for other petroleum products with multiple sources.

The developed TPNS simulation model is able to make performance analysis for the networks involving flow capacity, compressor ratio and power consumption for the system. The addition of cost evaluation module to the current TPNS simulation model could make the simulation model to analyze and evaluate the various network configurations and operational scenarios based on the cost.

Pipeline network system mainly consists of pipes and many other non-pipe devices such as compressor stations, valves and regulators. Although compressor station is the key characteristics in the network, the TPNS simulation model takes into account other non-pipe elements such as valves, regulators, and scrubbers could be one area of research which needs further investigation.

In a pipeline network system problem, the system can be modeled as steady state or transient model depending on how the gas flow changes with respect to time. Transient analysis requires the use of partial differential equations to describe the relationships between parameters. In case of transient simulation, variables of the system, such as pressures and flows, are function of time. Transient TPNS simulation model could be one of the problems to be addressed from the simulation perspective.

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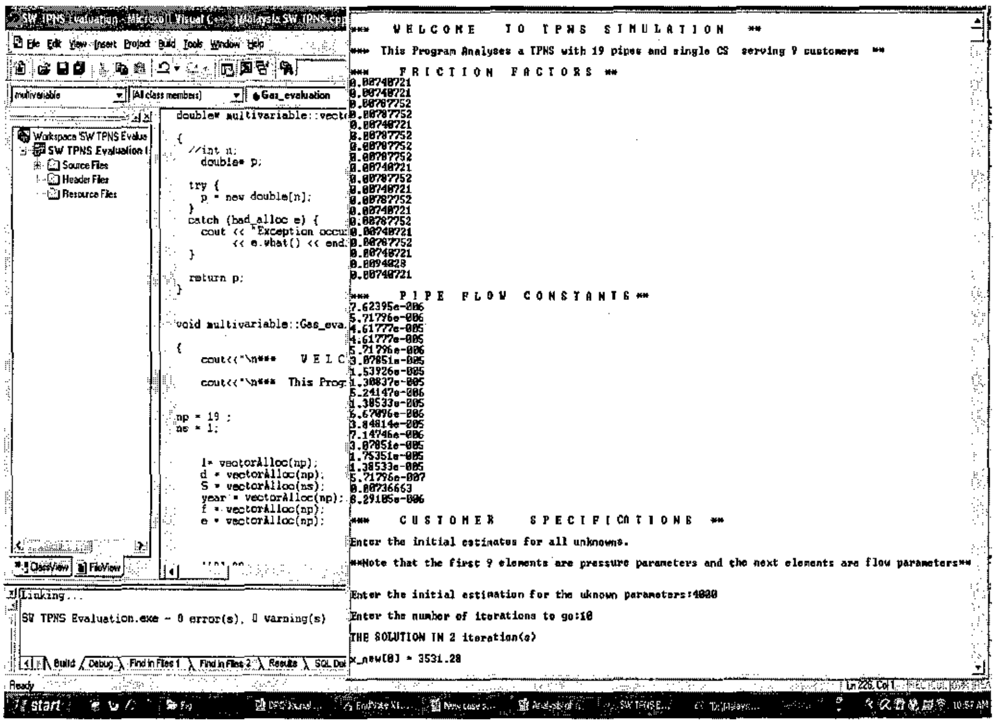
APPENDIX A

SNAPSHOT OF THE DEVELOPED TPNS SIMULATION CODE USING VISUAL C++

SNAPSHOT OF THE DEVELOPED TPNS SIMULATION CODE USING VISUAL C++



APPENDIX B

RESULTS OF TPNS SIMULATION MODEL FOR GUNBARREL NETWORK

RESULTS OF TPNS SIMULATION MODEL FOR GUNBARREL NETWORK

```
***  W E L C O M E   T O  T P N S  S I M U L A T I O N  **
***  This Program Analyses a TPNS with 3 pipes and two CSs  serving single customer**
***   P I P E L I N E    D E T A I L S **
Input the Length of the pipes [km]
80
80
80
Input the diameter of the pipes[mm]
900
900
900
Input the service life of the pipes [year]
0
0
0
***   P I P E L I N E   F R I C T I O N   F A C T O R **
0.00700345
0.00700345
0.00700345
***   P I P E L I N E   F L O W   C O N S T A N T S **
7.21113e-006
7.21113e-006
7.21113e-006
***   C O M P R E S S O R   S T A T I O N   D E T A I L S **
Input the number of the compressors within the station 1:1
Input the number of the compressors within the station 2:1
Input speeds of the compressors
8000
8000
***   C U S T O M E R   S P E C I F I C A T I O N S **
Input demand pressure requirements at customer each station
 PD1 =4000
Enter the initial estimates for all unknowns:
**Note that the first 4 elements are pressure parameters and the next element is flow parameters**
Enter the initial estimation for the unknown parameters:4000
Enter the number of iterations to go:10
THE SOLUTION IN 2 iteration(s)
x_new[0] = 3103.27
x_new[1] = 3573.37
x_new[2] = 3551.63
x_new[3] = 4021.73
x_new[4] = 3.01569e+006
The tolerance in 2 iterations =0.998674
THE SOLUTION IN 3 iteration(s)
x_new[0] = 383.496
x_new[1] = 3994.87
x_new[2] = 1709.82
x_new[3] = 6020.34
x_new[4] = 1.88147e+006
The tolerance in 3 iterations =0.602838
THE SOLUTION IN 4 iteration(s)
x_new[0] = 976.174
x_new[1] = 3902.12
x_new[2] = 2849.15
x_new[3] = 5036.5
x_new[4] = 1.25024e+006
```

```
The tolerance in 4 iterations =0.504891
THE SOLUTION IN 5 iteration(s)
x_new[0] = 2062.99
x_new[1] = 4313.44
x_new[2] = 3620.2
x_new[3] = 4694.88
x_new[4] = 953728
The tolerance in 5 iterations =0.310895.THE SOLUTION IN 6 iteration(s)
x_new[0] = 2450.26
x_new[1] = 3550.52
x_new[2] = 3036.26
x_new[3] = 4386.49
x_new[4] = 705598
The tolerance in 6 iterations =0.351659. THE SOLUTION IN 7 iteration(s)
x_new[0] = 2471.58
x_new[1] = 3505.17
x_new[2] = 3064.83
x_new[3] = 4346.65
x_new[4] = 636963
The tolerance in 7 iterations =0.107755. THE SOLUTION IN 8 iteration(s)
x_new[0] = 2472.77
x_new[1] = 3505.01
x_new[2] = 3065.89
x_new[3] = 4345.74
x_new[4] = 632577
The tolerance in 8 iterations =0.00693339. THE SOLUTION IN 9 iteration(s)
x_new[0] = 2472.77
x_new[1] = 3505.01
x_new[2] = 3065.9
x_new[3] = 4345.73
x_new[4] = 632559
The tolerance in 9 iterations =2.78791e-005
x_new[0] = 2472.77
x_new[1] = 3505.01
x_new[2] = 3065.9
x_new[3] = 4345.73
x_new[4] = 632559
The tolerance in 10 iterations =4.48679e-010
THE SOLUTION IN 11 iteration(s)
x_new[0] = 2472.77
x_new[1] = 3505.01
x_new[2] = 3065.9
x_new[3] = 4345.73
x_new[4] = 632559
The tolerance in 11 iterations =1.02997e-015
The solution within the specified number of iteration is :
x_new[0] = 2472.77
x_new[1] = 3505.01
x_new[2] = 3065.9
x_new[3] = 4345.73
x_new[4] = 632559
The compression ratio for the first station is  = 1.41744
The compression ratio for the second station is  = 1.41744
The energy consumption in KW  for the system is = 15855.6 :  Press any key to continue
```

SUCCESSIVE SUBSTITUTION BASED SIMULATION RESULTS (CASE 1A)

Intr. No	P_1	P_2	P_3	Q_1	Q_{C2}	Q_{C1}
0	-	-	6000.00	100.00	-	-
1	3678.87	6000.04	3666.79	6291.69	12899.49	-12799.49
2	2434.75	3910.86	1814.21	12715.58	7199.71	-908.02
3	2216.57	3293.23	3538.23	13340.78	510.76	12204.81
4	3106.64	4564.45	2419.12	10095.38	6865.21	6475.57
5	2107.34	3257.87	2415.34	13622.00	3642.51	6452.87
6	2605.59	3808.31	3075.67	12159.87	3629.74	9992.26
7	2697.67	4045.72	2429.77	11833.15	5620.64	6539.23
8	2339.99	3527.85	2717.10	12998.04	3678.31	8154.84
9	2643.73	3908.45	2765.30	12026.99	4587.10	8410.94
10	2525.27	3795.38	2560.44	12428.92	4731.16	7295.84
11	2485.71	3711.21	2749.06	12556.30	4103.91	8325.01
12	2593.01	3863.06	2664.90	12202.98	4682.82	7873.48
13	2501.94	3749.52	2646.67	12504.45	4428.83	7774.15
14	2536.94	3782.87	2712.73	12390.72	4372.96	8131.49
15	2551.62	3812.07	2654.48	12342.23	4573.96	7816.76
16	2517.00	3763.40	2678.15	12455.83	4396.93	7945.30
17	2544.66	3797.50	2685.79	12365.29	4469.23	7986.60
18	2535.14	3789.06	2664.78	12396.63	4492.46	7872.83
19	2529.74	3779.00	2682.37	12414.33	4428.47	7968.16
20	2540.62	3794.13	2675.73	12378.60	4482.09	7932.24
21	2532.30	3783.98	2672.87	12405.94	4461.89	7916.71
22	2534.91	3786.13	2679.53	12397.39	4453.15	7952.79
23	2536.82	3789.53	2674.20	12391.11	4473.44	7923.95
24	2533.39	3784.81	2676.04	12402.37	4457.22	7933.89
25	2535.89	3787.83	2677.08	12394.17	4462.81	7939.56
26	2535.20	3787.31	2674.98	12396.44	4466.00	7928.16
27	2534.53	3786.17	2676.58	12398.63	4459.59	7936.85
28	2535.61	3787.64	2676.08	12395.10	4464.48	7934.15
29	2534.86	3786.75	2675.71	12397.55	4462.96	7932.14
30	2535.04	3786.86	2676.38	12396.96	4461.83	7935.73
31	2535.27	3787.24	2675.89	12396.21	4463.85	7933.12
32	2534.93	3786.78	2676.03	12397.32	4462.38	7933.84
33	2535.15	3787.05	2676.16	12396.59	4462.78	7934.54
34	2535.11	3787.03	2675.95	12396.73	4463.18	7933.41
35	2535.03	3786.90	2676.09	12396.99	4462.54	7934.19

36	2535.14	3787.04	2676.06	12396.64	4462.98	7934.00
37	2535.07	3786.96	2676.01	12396.86	4462.88	7933.77
38	2535.08	3786.97	2676.08	12396.83	4462.74	7934.12
39	2535.11	3787.01	2676.04	12396.74	4462.94	7933.88
40	2535.07	3786.96	2676.04	12396.85	4462.81	7933.93
41	2535.09	3786.99	2676.06	12396.78	4462.84	7934.01
42	2535.09	3786.99	2676.04	12396.79	4462.88	7933.90
43	2535.08	3786.97	2676.05	12396.82	4462.82	7933.97
44	2535.09	3786.99	2676.05	12396.79	4462.86	7933.96
45	2535.09	3786.98	2676.04	12396.80	4462.85	7933.93
46	2535.09	3786.98	2676.05	12396.80	4462.84	7933.97
47	2535.09	3786.98	2676.05	12396.79	4462.86	7933.95
48	2535.09	3786.98	2676.05	12396.80	4462.85	7933.95
49	2535.09	3786.98	2676.05	12396.80	4462.85	7933.96
50	2535.09	3786.98	2676.05	12396.80	4462.85	7933.95

DIVERGENT CASE IN TPNS SIMULATION (CASE 2C)

```
"D:\Malaysia\Research\Gas Transportaion\PhD\Thesis\Draft 07_Enhanced model\VIVA CODES\CSTIE08 two phase flow...
*** This Program Analyses a TPNS with 10 pipes and single CS  serving 5 customers  **

***     P I P E L L N E      D E T A I L S **
Input the liquid hold up in the system
0.005

***     D E N S I T Y   A N D   V I S C O C I T Y   O F   T H E   M I X T U R E   **
5.046
2.99e-005

***     P I P E L L N E      F L O W C O N S T A N T S   **
4.26007e-006
3.40805e-006
2.08811e-005
3.40805e-006
2.68471e-005
2.98205e-006
2.38641e-005
3.83406e-006
2.08811e-005
2.38641e-005

Enter the initial estimation for the uknown parameters:100

Enter the number of iterations to go:10

THE SOLUTION IN 2 iteration(s)

x_new[0] = 3646.91

x_new[1] = 3718.37

x_new[2] = 3835.9

x_new[3] = 3926.65

x_new[4] = 3981.24

x_new[5] = 3986.04

x_new[6] = -481181

x_new[7] = -371554

x_new[8] = -28333.2

x_new[9] = -17408.3

x_new[10] = -109627

x_new[11] = -343220

x_new[12] = -10924.9

x_new[13] = -9287.4

x_new[14] = -8120.92

The tolerance in 2 iterations  =1.00021

SORRY SOLUTION DIDN'T CONVERGE. PLEASE ENTER NEW GUESS
Press any key to continue
```