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Compressible Natural Gas Flow study For Vehicle Refueling Equipment

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UNIVERSITI TEKNOLOGI PETRONAS

Compressible Natural Gas Flow Study For Vehicle Refueling Equipment

By

NOR AZIZAH HISAM

A THESIS
SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME
AS A REQUIREMENT FOR THE
Degree of Masters of Science
In Chemical Engineering

BANDAR SERI ISKANDAR,
PERAK,

APRIL , 2006

I, hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Date: 28th APRIL 2006

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ABSTRACT

There is considerable interest in Malaysia for the use of natural gas as the fuel for transportation. Natural Gas Vehicles (NGV) are known to be more environmentally friendly, safer and of lower fuel cost. To encourage the public to use natural gas, more NGV stations would have to be built. A major constraint in providing this facility is the high construction and operating cost of the stations. This is mainly due to the high cost of the metering system (cost of metering system is RM 80,000 while cost of refueling equipment is RM120, 000) and the compression power needed. The present research is undertaken to find a solution to these problems by developing a new low cost metering system and a new operating system approach which will lower the overall compression power needed at the refueling station by RM 0.89 millions per year.

To understand the reasons for the high compression cost, the compressible gas dynamics model of the refueling system is required. The flow of natural gas between the storage and the receiver has been modeled as Fanno Flow. In the event where the storage pressure is significantly higher than the automotive fuel tank, Mach number increases along the dispensing hose and ultimately become one at the tip of the hose. The Mach number cannot become higher than one under the Second Law of Thermodynamic, causing a pressure discontinuity between dispenser tip and automotive fuel tank. Due to the pressure discontinuity, the gas will experience sudden expansion and the expansion experienced by the gas at the pipeline exit was found to be significant thus resulting in high energy loss.

To avoid this high energy loss, the study conducted indicates that by utilizing several sources placed at different pressure levels and by gradually changing

over from the lower to the higher pressure source, the energy losses could be reduced. From the compressible gas flow model study, a new cascaded storage system which consists of 3 different levels of pressure banks i.e. 2MPa, 10MPa and 24.8MPa as low, medium and high pressure bank respectively has been proposed. This new cascaded storage system will help to reduce the operation cost by 17.5% by reducing the compression energy required and also the energy loss during refueling.

For developing a simple and cost effective measurement technique, a study on the properties relationship of natural gas is important. From the consideration of several equations of state (EOS) which are available in literature, it is important to find one which can represent the natural gas system with sufficient accuracy. For finding the most suitable equation for the system the approach used was analyzing the relationship between pressure and mass for different types of equations with assistance of HYSYS Software. These theoretical values were then compared with the actual measured experimental values. For natural gas system, the Peng Robinson equation was found to be the most accurate equation for the system with average error of 0.19%.

Besides the high compression cost in the filling stations, high metering cost is also an obstacle to the growth of NGV refueling facility. The flow meter used in the metering system namely Coriolis Flow Meter represents about 33.3% of the total typical 2 hose CNG dispenser cost. This project is believed to contribute in reduction of at least 30% (from RM120,000 to RM80,000) of current CNG dispenser capital expenditure (CAPEX) value. From the study of the EOS, a new concept of metering system has been developed, which is based only on measuring the pressure and temperature. This new metering system eliminated the dependency on currently used Coriolis Flow Meter which is a very expensive mass flow meter.

ABSTRAK

Di Malaysia terdapat pelbagai tarikan bagi penggunaan gas asli sebagai bahan bakar sektor pengangkutan. Kenderaan Gas Asli atau NGV terkenal sebagai lebih mesra alam, lebih selamat dan lebih menjimatkan kos bahan bakar. Bagi menggalakkan orang ramai menggunakan gas asli, lebih banyak stesen gas asli patut dibina. Penghalang utama bagi menyediakan lebih banyak kemudahan ini ialah kerana kos pembinaan dan kos pengendaliannya yang tinggi. Ini berpunca daripada kos sistem penyukatan yang mahal dan keperluan terhadap kuasa pemampatan yang tinggi (kos system penyukatan ialah RM 80,000 manakala ks dispenser gas asli ialah RM120,000). Kajian kali ini dijalankan bertujuan untuk mencari penyelesaian bagi masalah-masalah ini dengan menghasilkan sistem penyukatan baru yang lebih rendah harganya dan sistem pengendalian baru yang akan mengurangkan keseluruhan kuasa pemampatan yang diperlukan di stesen gas asli sebanyak RM0.89 juta setahun..

Bagi memahami mengapa kos pemampatan sangat tinggi, model gas boleh mampat bagi stesen gas asli diperlukan. Aliran gas asli dari tangki simpanan ke tangki bahan bakar NGV telah dimodelkan sebagai Aliran Fanno. Pada keadaan dimana tekanan dalam tangki simpanan jauh lebih tinggi daripada tangki penerima, nombor Mach meningkat disepanjang paip dan akhirnya menjadi satu di hujung paip tersebut. Nombor Mach tersebut tidak boleh melebihi satu dibawah Hukum Termodinamik Kedua, menyebabkan ketidaksinambungan tekanan diantara hujung paip dan tangki bahan bakar kenderaan. Disebabkan ketidaksinambungan tekanan tersebut, gas akan mengalami pengembangan yang sangat ketara dan menyebabkan kehilangan banyak tenaga.

Bagi mengelakkan kehilangan tenaga ini, kajian yang dijalankan menunjukkan bahawa dengan menggunakan beberapa tangki simpanan yang bertekanan

berbeza dan dengan bertukar dari tekanan rendah ke tinggi, kehilangan tenaga dapat dikurangkan. Dari kajian aliran gas boleh mampat, sistem simpanan berlata baru yang terdiri daripada 3 tahap tekanan berbeza iaitu 2MPa, 10MPa dan 24.8MPa sebagai tangki simpanan bertekanan rendah, rederhana dan tinggi telah dicadangkan. Sistem simpanan berlata baru ini akan membantu mengurangkan kos pengendalian dengan mengurangkan kuasa pemampatan yang diperlukan sebanyak 17.5% dan juga mengurangkan kehilangan tenaga semasa pengisian semula gas.

Bagi menghasilkan teknik pengukurunan yang ringkas dan ekonomi, kajian terhadap pertalian antara sifat-sifat bahan adalah penting. Daripada beberapa Persamaan Keadaan (EOS) yang ada, adalah penting untuk memilih satu persamaan yang boleh mewakili sistem ini dengan tepat. Pendekatan yang digunakan bagi mencari persamaan bagi sistem ini adalah dengan cara menganalisa pertalian diantara tekanan dan jisim bagi pelbagai persamaan dengan bantuan perisian HYSYS. Keputusan ini kemudiannya dibandingkan dengan nilai yang diperolehi melalui eksperimen. Bagi sistem gas asli, persamaaan Peng Robinson didapati memberikan ketepatan yang tertinggi dengan purata ralat 0.19%.

Selain kos pemampatan yang tinggi, kos penyukatan yang tinggi juga menjadi halangan kepada pertumbuhan stesen gas asli. Meter aliran yang digunakan mewakili 33% daripada harga keseluruhan dispenser gas asli 2 hos. Projek ini dipercayai dapat menyumbang kepada penurunan sekurang-kurangnya 30%, (dari RM120,000 ke RM80,000) daripada perbelanjaan modal dispenser gas asli waktu ini. Daripada kajian EOS, konsep sistem penyukatan baru telah dihasilkan. Sistem penyukatan baru ini menyahkan pergantungan terhadap Meter Aliran Coriolis yang terkenal dengan harganya yang tinggi, yang sedang diguna pakai waktu ini.

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NOMENCLATURE

A	:	Area, m^2
c	:	Speed of sound, ms^{-1}
C_P	:	Specific heat capacity at constant pressure, $kJkg^{-1}K^{-1}$
C_v	:	Specific heat capacity at constant volume, $kJkg^{-1}K^{-1}$
E_p	:	Potential energy, kJ
f	:	Friction factors
G	:	Mass velocity, $kgm^{-2}s^{-1}$
H	:	Enthalpy, kJ
L	:	Length of pipe, m
L_{max}	:	Maximum length of pipe, m
M	:	Mach number
m	:	Mass, kg
M_a	:	Upstream Mach number
M_b	:	Downstream Mach number
M_o	:	Pipe entrance Mach number

M_w	:	Molecular weight
ν	:	Specific volume, m^3kg^{-1}
n	:	Number of moles, mole
P	:	Pressure, kPa
P_a	:	Upstream pressure, kPa
P_b	:	Downstream pressure, kPa
P_c	:	Critical pressure, kPa
P_r	:	Reduced pressure, kPa
Q	:	Heat, kJ
R	:	Gas constant, $kPam^3kmol^{-1}k^{-1}$
r_H	:	Hydraulic radius, m
s	:	Isentropic restrain
S	:	Entropy, kJ
T	:	Temperature, K
t	:	Time, s
T_a	:	Upstream temperature, K
T_b	:	Downstream temperature, K
T_c	:	Critical temperature, K
T_r	:	Reduced temperature, K
T_s	:	Stagnation temperature, K
u	:	Speed of fluid, ms^{-1}
U	:	Internal energy, kJ

V	:	Volume, m^3
V_m	:	Density of molecules, $kgm^{-3}mole^{-1}$
ω	:	Eccentric factor
W	:	Work, kJ
Z	:	Compressibility factor
γ	:	Isentropic exponent
ρ	:	Density, kgm^{-3}
$\dot{m}$	:	Mass flow rate, kgs^{-1}

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Background of Study

1.1.1 Natural Gas Demand in Malaysia

The overall demand for energy between the years 2001 to 2005 in Malaysia is expected to increase at 7.8 % per annum. In line with the increased planned capacity in the power sector, the demand for natural gas is expected to grow at 9.0 % per annum. In the electricity generation mix, the share of natural gas was 71.8 % in 2001 compared with 74.9 % in 2000. However, the share of natural gas to the power generation mix is expected to reduce to 61 percent of the fuel generation mix by 2005. By year 2005, 1,687 mmscfd of gas is expected to be used for electricity generation. [1]

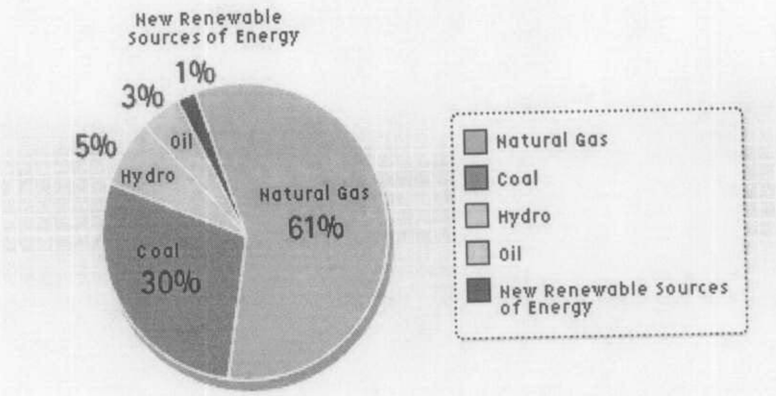


Figure 1.1 Fuel of Choice for Power Generation

1.1.2 Natural Gas for Transportation

There is considerable interest in Malaysia for the use of natural gas as the fuel for transportation. Natural Gas Vehicles (NGV) are more environmentally friendly [2-4], safer and of lower fuel cost. Natural gas used as fuel for NGVs is a clean energy source free from impurities, such as sulfur. Exhaust gas purification is easy, and no black smoke is generated. From a study conducted at VTT Technical Research Centre of Finland [5], NGV was found to give Nitrogen Oxides (NO_x) emission of about 75% less, compared to gasoline powered vehicle. This statement is further supported by an emission study at Argonne National Laboratory [6] that showed natural gas with CO_2 emissions of 140 gm CO2 eq/km, gasoline at 176 gm CO_2 eq/km, and diesel at 147 gm CO_2 eq/km.

Natural gas reserves are abundant and widely distributed throughout the world. There are large reserves of natural gas in Malaysia and in the surrounding offshore basins. The percentage breakdown according to various locations is shown in Figure 1.2. In January 2004, Malaysia has the 12th largest gas reserves in the world, which contains about 97.6 trillion cubic feet. This translates to about 66.8 years of natural gas availability based on the current production rate. The natural gas reserves under the Malaysia-Thailand Joint Development Area (JDA) are estimated to be around ten trillion cubic feet [7].

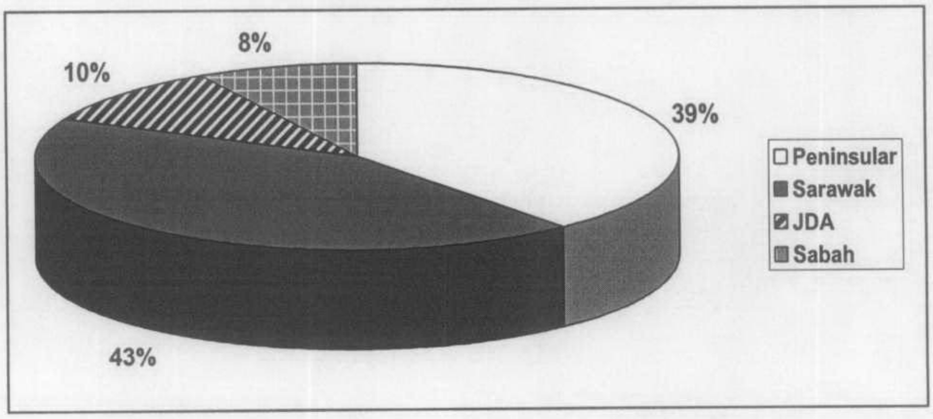


Figure 1.2 Malaysian Offshore Natural Gas Reserve

Daud, 2005 [8] reported that in Malaysia presently, more than 15,600 NGV is running on the road and by the year 2006, Malaysia will have about 40,000 NGVs . This number is expected to increase rapidly as Malaysian Government is actively promoting the use of NGV, as it is environmental-friendly with lower emissions and it is the government's policy to make the country less dependent on petroleum. Malaysian Transportation Ministry is planning to increase the number of public vehicles using natural gas by about 10% and the use of NGVs for public transport also is among the proposals of the Cabinet Committee to study the impact of the price increase of fuel and petroleum products on the economy.

1.1.3 Natural Gas Vehicle

The transportation sector is a major contributor to greenhouse gas emissions in the United States and the rest of the world. Worldwide, motor vehicles emit over 900 million metric tons of CO_2 each year, accounting for more than 15 percent of global fossil fuel derived CO_2 emissions [9]. In the industrialized world, 20-25 percent of greenhouse gas emissions come from the transportation sector and the share continues to grow [10].

NGV has many overwhelming advantages against traditional means of transportation using gasoline and diesel. Firstly, it brings environmental benefits because the usage of NGV has been proved to give a significant lowering of emissions of total polycyclic aromatic hydrocarbons and formaldehyde, and a reduction of global warming potential [2]. Secondly, the natural gas resource is more abundant, which makes the fuel cost lower than gasoline. Besides, it is the safer fuel; NGV emit less toxic emission [5]. As natural gas is lighter than air, in the case of leakage, it dissipates into the atmosphere, thereby reducing the risk of explosions and fires.

Since they started operating in Malaysia, the natural gas public vehicles have clocked an accumulated mileage of more than 600,000 kilometers with no major problems encountered [8]. The exhaust emission was also below the EURO II limits. The NGVs can travel up to 450 kilometers per filling of NGV, making its performance equivalent to a petrol-powered vehicle [8]. However, as NGV is substantially cheaper than petrol as Malaysian Government set regulations saying that natural gas price should always be at least 50% lower than petrol's price [8], its usage can generate significant savings on fuel cost.

1.2 Problem Statement

To date, there are only 40 NGV stations to cater the 15,600 NGVs in Malaysia [8]. To encourage public transport operators to use natural gas, more NGV stations would have to be built. Lack of refueling facility is the major obstacles to the growth of NGV usage. This problem is not only faced in Malaysia but also people of other countries in the world. For example, in Italy, though the relative price after taxes (in caloric equivalents) of natural gas is about 30% against gasoline and 40% against diesel fuel [11] but the usage of NGV is still very low. This is believed to be due to inadequate refueling network. The major constraint in expanding the network is the very high construction and operating cost of the stations.

The existing refueling stations in Malaysia are based on cascaded storage systems that have three storage banks operating at same pressure of 24.8 MPa (3600psi). Compression cost of the natural gas as well as the fixed charges on the capital investment represents a significant part of the natural gas cost to the customer. It has been estimated that the capital expenditure for setting up a refueling station with capacity to refuel 736 vehicles per day will be around USD 300,000 excluding the land cost [12]. The fixed charge on the capital investment is approximately 6 US cents per Gasoline Liter Equivalent (GLE) where 1 GLE, defined by international standards, provides an equivalent amount of energy to 0.678 kg (1.495 lb) of natural gas. Similarly the compression cost has been estimated at 2.5 USD cents per gasoline liter equivalent. The total dispensing cost is about 6% of the natural gas cost based on US data. This figure is approximately equal to 10% under Malaysian conditions.

A vehicle that comes to the station for filling will have its storage tank at a very low pressure. When this tank is connected to the dispenser tank maintained at nearly 3600 psig, sonic flow takes place in the refueling hose, and there will be pressure discontinuity at the tip of the dispenser. This is an irreversible energy loss that contributes considerably to the high compression cost in the filling stations.

Other than high compression cost in the filling stations, high metering cost is also an obstacle to the growth of NGV refueling facility. The flow meter used in the metering system namely Coriolis Flow Meter represents about 33.3% of the total typical dual hose CNG dispenser cost. By the survey that has been conducted at one of NGV stations in Shah Alam, Selangor, [13] one vehicle has to wait for at least half an hour to refuel due to a long queue and this long queue is continuous from morning to midnight. This scenario is due to the insufficient refueling facility for NGV in our country.

Based on these scenarios, this research study aims to model the compressible gas flow dynamics of natural gas in the filling stations, so that an improved understanding on the factors leading to the high operating cost of the process can be established, and solutions for future optimization could then be made. This research study also aims to understand the relationship between natural gas properties to help in developing a new metering system for NGV refueling equipment without using the Coriolis principles.

1.3 Objectives and Scope of Study

The main objectives of the study are:

i. Development of a process model to simulate the flow of natural gas in the NGV refueling system.

ii. Determination of gas properties relationship through an Equation of State (EOS) for natural gas.

iii. Suggest suitable methods to reduce operating expenditure (OPEX) of NGV refueling equipment based on the developed process model.

iv. Develop a suitable method based on an EOS to reduce capital expenditure (CAPEX) of NGV refueling equipment.

The scope of this research project is:

i. Development of a process model to simulate the Adiabatic Frictional Flow (Fanno Flow) of natural gas in the NGV refueling system and validate the process model with experiment data using NGV refueling equipment test rig.

ii. Study on EOS that is the most accurate for NGV refueling system; test on different EOS using HYSYS and validate the results using test rig.

iii. Conceptualization of improved method of gas compression method based on item (i).

iv. Conceptualization of alternative NGV refueling equipment's metering system based on item (ii).

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.0 LITERATURE REVIEW and THEORY

2.1 Literature Review

Literature review for present research is divided into four parts, each part is to complement all the four objectives mentioned in previous chapter. The first part is focused at literature review on natural gas flow studies. The second part is focused at EOS that is suitable for natural gas filling system. The third part of the literature review is focused at the method to reduce OPEX of NGV refueling equipment and the last part is focused at the methods that were studied by others to reduce the CAPEX of NGV refueling equipment.

2.1.1 Compressible Gas Flow

Comprehensive review of accurate methods for the numerical solution of compressible fluid flow, specifically for natural gas flow is presented in Gato [14]. The Runge–Kutta discontinuous Galerkin (RKGD) method was used as this method has an important advantage over other methods which is the discontinuous Galerkin space-discretization permits simple generalization of the degree of approximation to *n*th-order, since no special treatment of the boundary conditions is required to achieve uniform high-order accuracy. Gato considered gradually varying cross sectional area along the duct to study the occurrence of rapid disturbances in high-pressure natural gas flow in pipelines, using the a high-order RKDG method, developed at Instituto Superior Te´cnico, for the calculation of rapid transients in gas pipelines.

The pipeline used in NGV refueling equipments connecting the high pressure source to the vehicle fuel tank has a constant cross sectional area, therefore in present research other method or model need to be developed to suit the NGV refueling system.

2.1.2 EOS for Prediction of Natural Gas Properties' Relation

Compressibility, density and viscosity of natural gas are the necessary properties in most petroleum and natural gas engineering calculations such as metering, compression, design of processing units, and others. Properties of natural gas are also important in the calculation of gas flow rate through reservoir, material balance calculations, evaluation of gas reserves and reservoir simulations.

Usually the gas properties are measured in laboratory but occasionally experimental data is unavailable and prediction using an equation becomes necessary. For heavy natural gas, the methods available in literatures for the calculation of the properties of heavy gases such as condensates and sour gases produce unsatisfactory results. These methods can be classified into three groups. The first group uses gas composition or gas gravity to calculate pseudo-critical properties of gases and predicts gas properties from empirical correlations. The second group uses gas composition to estimate gas properties using the method of corresponding states. The third group is based on an EOS and this group has the advantage of using single equation to calculate k-values, compressibility, density, and viscosity [15].

EOS method has created great interest among researchers to apply it in various systems. Li and Guo [16] modified the original Peng-Robinson (PR) equation of state to predict properties of sour gases by introducing 33 constants. Mohsen-Nia et al. [17] presented a two constants EOS, based on theoretical background of statistical mechanics, designed specially to predict properties of sours natural gases. The equation has several constants for each of the pure components forming the gas mixture. Huron et al. [18] and Evelein and Moore [19] used Soave–Redlich–Kwong (SRK) equation to study the hydrocarbon system containing hydrogen sulfide and carbon dioxide.

Lee et al. [20] in his study of measurement of bubble point pressures and critical points of Carbon Dioxide and Chlorodifluoromethane mixtures using the variable-volume view cell apparatus has used PR equation to estimate the corresponding dew point compositions at equilibrium with the bubble point compositions. Orye [21] in his research has used Benedict-Wed-Rubin equation to predict and correlate phase equilibria and thermal properties of methane, ethylene, ethane, propylene, propane, 2-methylpropane, 2-methylpropene, n-butane, 2-methylbutane, n-pentane, n-hexane, n-heptane, n-octane, n-nonane, n-decane, benzene, hydrogen, nitrogen, carbon dioxide, and hydrogen sulfide.

Elsharkawy [22] suggested two different methods; one is to calculate compressibility factor and density while the other one is to calculate viscosity of natural gas. The new models are designed to be simpler and more efficient than EOS. They eliminate the numerous computations involved in EOS calculations. These models also eliminate the characterization of the heptanes plus fraction and estimation of binary interaction number or BIN needed for EOS calculations. The new methods account for the presence of heptanes plus, hydrogen sulfide, and carbon dioxide in natural gas. However, no literature proofing this method has been applied by any researchers to any system yet.

From the above literature review, it is learnt that EOS method has created great interest among researchers and EOS has been widely used for prediction of hydrocarbon system's properties. Therefore in present research EOS method is selected to predict natural gas properties' relation.

2.1.3 Method to Reduce OPEX of NGV Refueling Equipment

Natural gas coming from distribution pipeline is compressed to a very high pressure before it is dispensed into individual NGV. In particular, gas compressed and transported at high pressure begins to lose pressure as soon as it passes the outlet valve and enters into the high-pressure line leading to the next component. Without recompression, or some other method of maintaining the pressure of the gas, the transfer of gas from one vessel to another will stop as soon as the pressure differential drive force for the gas to flow between the two vessels ceased. Options for alleviating the pressure drop problem are install a complete duplicate compressor system at the daughter station, with cascade storage and controls to manage the cascade and the dispensing process or install a booster compressor system, which is a variable inlet pressure compressor designed to compress gas over a fairly wide range of inlet pressures. But both options result in high compression energy demand that lead to high OPEX.

NEOgas System [23] was developed by XinAo Group of China and Neogas Houstan of USA to maintain the pressure inside the storage vessel by using water to act as liquid piston that offers constant high flow rate and minimum compression energy needed. It is based on the principal that gas and liquids always resist mixing, with gas staying on top of the fluid so long as there is no barrier between them. The advantages of this system are lower overall system cost, maintenance cost and operating cost, more complete storage utilization of the gas, faster and more complete refueling for NGV.

The NGVs coming for refueling have various initial fuel tank pressures ranging from as low as 0.1MPa to as high as 21MPa while the source pressure is 24.8MPa. This very wide range of initial pressure if fed with single source pressure will cause a pressure discontinuity at the tip of the dispenser. Pressure discontinuity causes internal energy of gas to reduce and the lost energy will be dissipated into heat causing temperature rise to the fuel tank system that lead to reduction in filling efficiency. One of the objectives of the present research is to suggest some improvements in the cascaded storage system to further reduce the compression energy and improve the filling efficiency.

2.1.4 Method to Reduce Metering Cost of NGV Refueling Equipment

Current technology used in NGV refueling equipment's metering system is a Coriolis mass flow meter [24]. This meter uses the Coriolis effect to measure the amount of mass moving through the element. The substance to be measured runs through a U-shaped tube that is caused to vibrate in a perpendicular direction to the flow (Figure 2.1). Fluid forces running through the tube interact with the vibration, causing it to twist. The greater the angle of the twist, the greater is the flow based on momentum change that is related to mass.

Being the only flow meter that gives readings in mass per unit time for gas application, Coriolis Flow Meter is a very expensive flow meter compare to other flow meter such as volumetric flow meter which available in market. Compare to other flow meters, the difference on the unit price is very significant. The other objective of the present research is to develop an alternative metering system to eliminate dependency on Coriolis flow meter.

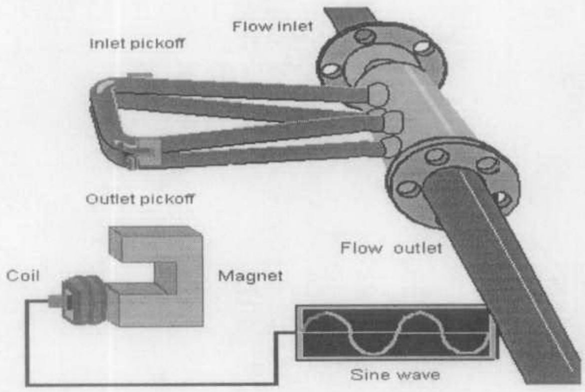


Figure 2.1 Coriolis Flow Meter

2.1.5 Natural Gas Measuring Method

The most commonly used method to measure natural gas is by using a flow meter. The two most commonly used flow meters are volumetric which gives reading in volume over time and mass flow meter that gives reading in mass over time. For large scale of natural gas dispensing system such as natural gas distribution to residential area, volumetric flow meter is more commonly used but for NGV refueling system, mass flow meter is used.

In the world so far, only Coriolis flow meter can give accurate measurement in natural gas refueling system [24]. High dependency on this flow meter makes this flow meter very expensive. There have been attempts to eliminate dependency on Coriolis flow meter by introducing new measuring method for natural gas by utilizing its P,V,T (pressure, volume, temperature) properties [25].

The amount of natural gas dispensed into NGV fuel tank maybe closely approximated without the use of flow meter. An initial standardized volume is calculated based upon the ambient temperature, the initial pressure level and an approximate compressibility of the gas. Gas is dispensed into a desired pressure that is confirmed with a pressure gauge. A final standardized volume of gas contained within the fuel tank is calculated based upon the final pressure level and assuming no change in the compressibility of the gas. The initial standardized volume of gas is subtracted from the final standardized volume of gas to yield an actual volume of gas dispensed from the storage vessel. Empirically derived temperature correction factors may be used to generate an even more accurate approximation of natural gas dispensed.

2.2 Theory

Study of theories related to the research work is very important to develop the mathematical modeling. The theories were extracted from popular chemical engineering reference books. The study of theories for present research is also divided into four major parts to complement all the objectives.

2.2.1 Natural Gas Flow in NGV Refueling Equipment

2.2.1.1 Introduction to Compressible Flow

For incompressible flow, the basic parameter is the Reynolds number. However, in compressible flow, at ordinary densities and high velocities, a more fundamental parameter is the Mach number. The Mach number, denoted by M, is defined as the ratio of u, the speed of the fluid, to a, the speed of sound in the fluid under conditions of flow.

$$M \equiv \frac{u}{a}$$

By definition, the Mach number is unity when the speed of fluid equals that of sound in the same fluid at the pressure and temperature of the fluid. Flow is called subsonic, sonic, or supersonic, according to whether the Mach number is less than unity, at unity, or greater than unity, respectively.

The following basic relations [26] are used:

1. The continuity equation

$$\rho . u . A = \dot{m} = constant \tag{2.1}$$

2. The steady flow total energy balance

$$\frac{dQ}{m} = dH + d\left(\frac{u^2}{2}\right) \tag{2.2}$$

3. Mechanical energy balance

$$\frac{dP}{P}+\frac{\rho}{P}(u.du)+\frac{\rho u^2}{2P}\frac{fdL}{r_H}=0 \tag{2.3}$$

4. Expression for velocity of sound in any median

$$a=\sqrt{\left(\frac{dP}{d\rho}\right)_s} \tag{2.4}$$

Where subscript s represents the isentropic restraint

ρ = Density	Q = Heat
u = Velocity	H =Enthalpy
A = Area	p = Pressure
$\dot{m}$ = Mass Flow Rate	f = friction
t = Time	r_H =Hydraulic Radius
a = Velocity of Sound	$_s$ = Isentropic restrain

2.2.1.2 Isentropic Flow

Isentropic flow occurs in the flow of ideal gas through nozzles, which is usually located at the pipe entrance.

The conditions of the gas at the pipe entrance are given by the following equations [27]

Pressure: $$\frac{P}{P_O}=\frac{1}{\{1+[(\gamma-1)/2]M^2\}^{1/(1-1/\gamma)}} \tag{2.5}$$

Temperature: $$T=T_O\left(\frac{P}{P_O}\right)^{1-1/\gamma} \tag{2.6}$$

Velocity: $$u=\sqrt{\frac{2\gamma RT_O}{M_W(\gamma-1)}\left[1-\left(\frac{P}{P_O}\right)^{1-1/\gamma}\right]} \tag{2.7}$$

P = Pressure

γ = Isentropic Exponent

T = Temperature

u = Velocity

M_w = Molecular Weight

P_o = Pressure at Source

M =Mach number

T_o = Temperature at Source

R = Gas Constant

2.2.1.3 Adiabatic Frictional Compressible Flow

Definition

Adiabatic frictional compressible flow, or Fanno flow, is the flow of a compressible fluid with frictional pressure drop and negligible heat transfer through the pipe wall. The process of natural gas flow through a dispenser can be approximated to such a system. Figure 2.2 shows a conceptual diagram of a natural gas dispenser system.

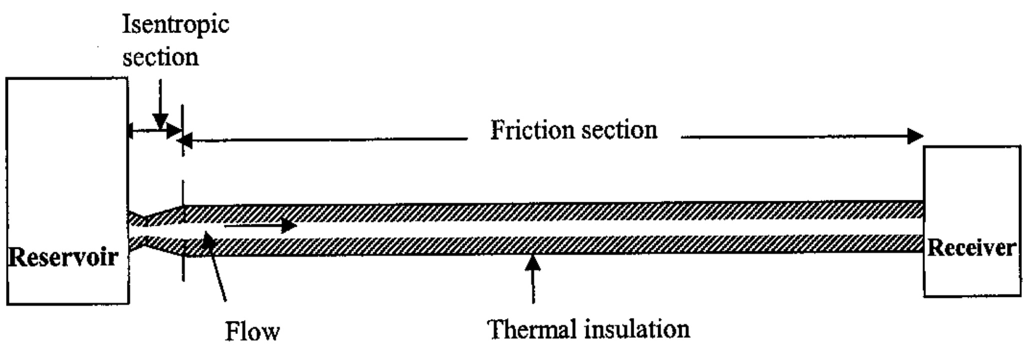


Figure 2.2 Adiabatic Frictional Flow Diagram

This is the typical situation where gas enters a long pipe at a given pressure, temperature and flows at a rate determined by the length and diameter of the pipe with a constant pressure at the outlet.

Since the cross-sectional area of the high-pressure source is significantly larger than that of the pipe, the initial Mach number can be assumed to be very small. However, in a long line, with a very high pressure at the pipe entrance, and very low pressure at the pipe exit, the speed of the gas at a point within the pipe may reach the sonic velocity. Nevertheless, it is not possible for a gas to pass through the sonic barrier from the direction of either subsonic or supersonic flow. In other words, if the gas enters the pipe at a Mach number of less than 1, as the gas flows along the line, the Mach number will increase but will not exceed one [27]. If an attempt is made to force the gas to change from subsonic to supersonic flow (or vice versa), the gas flow rate will reach a maximum limit, and the effect is called "choking".

The Friction Parameter

The basic quantity that measures the effect of friction is the friction parameter fL/r_H. In adiabatic frictional flow, temperature of the gas change. The viscosity also varies, and the Reynolds number and friction factor are, in fact, not constant. Nevertheless, in gas flow, the effect of temperature on viscosity is small, and the effect of Reynolds number on the friction factor is not so important. Therefore, it is satisfactory to use an average value for f as a constant in calculations [26].

From the Mechanical Energy Balance equation [27],

$$\frac{dp}{p}+\frac{\rho}{p}(u.du)+\frac{\rho u^2}{2p}\frac{fdL}{r_H}=0 \tag{2.8}$$

Substituting relationship between the pressure, velocity and the Mach number

$$\frac{dp}{p}=-\frac{1+(\gamma-1)M^2}{1+[(\gamma-1)/2]M^2}\frac{dM}{M} \tag{2.9}$$

And $$\frac{du}{u}=\frac{dp}{p}+2\frac{dM}{M} \tag{2.10}$$

Will result in the following differential equation

$$f\frac{dL}{r_H}=\frac{2(1-M^2)dM}{\gamma M^3\{1+[(\gamma-1)/2]M^2\}} \tag{2.11}$$

Integration of (2.4) between an entrance station a and exit station b, assuming the friction factor, f, to be constant, produces a final relationship

$$\frac{f.\Delta L}{r_H}=\frac{1}{\gamma}\left(\frac{1}{M_a^2}-\frac{1}{M_b^2}-\frac{\gamma+1}{2}\ln\frac{2M_b^2\{1+[(\gamma-1)/2]M_a^2\}}{M_a^2\{1+[(\gamma-1)/2]M_b^2\}}\right) \tag{2.12}$$

p = Pressure	ρ = Density
u = Velocity	f = Friction
L = Length of Conduit	r_H = Hydraulic Radius
M =Mach number	γ = Isentropic Exponent
M_a =Upstream Mach number	M_b =Downstream Mach number

Property Equations

The ratio of the inlet and outlet pressure is found by direct integration of Eq. (2.9) between the limit P_a, P_b , M_a and M_b to give [27]

$$\frac{P_a}{P_b}=\frac{M_b}{M_a}\sqrt{\frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}}} \tag{2.13}$$

Similarly, the temperature ratio will be

$$\frac{T_a}{T_b}=\frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}} \tag{2.14}$$

P_a = Upstream Pressure	P_b =Downstream Pressure
M_a = Upstream Mach number	M_b =Downstream Mach number
T_a = Upstream Temperature	T_b =Downstream Temperature

Maximum Conduit Length

To ensure that the conditions of a problem do not create the impossible phenomenon of crossing the sonic barrier, an equation is needed giving the maximum value of $\overline{f}L/r_H$ consistent with a given entrance Mach number. Such an equation is found by choosing the entrance to the conduit as station a and identifying station b as the asterisk condition, where $M_b = 1$. Then the length $L_b - L_a$, denoted by L_{max} represents the maximum length of conduit that can be used for a fixed value of M_a^2. Equation (2.12) then gives [27]

$$\frac{fL_{max}}{r_H} = \frac{1}{\gamma}\left(\frac{1}{M_a^2} - 1 - \frac{\gamma+1}{2}\ln\frac{2\left\{1+\left[(\gamma-1)/2\right]M_a^2\right\}}{M_a^2(\gamma+1)}\right) \quad (2.15)$$

f = Friction $\quad$ r_H =Hydraulic Radius

L_{max} = Maximum Length of Conduit $\quad$ M_a = Upstream Mach number

Stagnation Temperature

The stagnation temperature of a high-speed fluid is defined as the temperature that the fluid would attain when it is to rest adiabatically without the development of shaft work. The relationship between actual fluid temperature, the actual fluid velocity, and the stagnation temperature is found as [26]

$$T_S = T + \frac{u^2}{2c_P} \quad (2.16)$$

T_s = Stagnation Temperature $\quad$ T = Temperature

u = Velocity $\quad$ C_p = Specific Heat Capacity at Constant Pressure

For adiabatic process, the stagnation temperature is constant. Therefore, the faster the fluid in the pipe flows, the more temperature drop will occur.

2.2.2 EOS for Prediction of Natural Gas Properties' Relation

An equation of state (EOS) [28] is a formula describing the interrelation between various macroscopically measurable properties of a system. For physical states of matter, equation of state usually relates the thermodynamic variables of pressure, temperature, volume and number of moles of material.

2.2.2.1 Ideal Gas Law

The simplest EOS is the ideal gas law given by,

$$P V = n R T \tag{2.17}$$

P = Pressure	V = Volume
n = Number of moles	R = Gas constant
T = Temperature	

All substances behave according to this simple equation at sufficiently high specific volume (low density). This is because, at extremely low density, the individual molecules are essentially "point particles", occupying zero volume and never colliding with one another [29]. In engineering applications, which are most often at atmospheric pressure or higher, no fluid is truly an ideal gas. However in many cases the assumption is within a few percent to be exact.

Real gas laws try to predict the true behavior of a gas better than the ideal gas law by putting in terms to describe attractions and repulsions between molecules. These laws have been determined empirically, based on a conceptual model of molecular interactions or derived from statistical mechanics.

2.2.2.2 Van der Waals Equation

A well-known real gas law is the Van Der Waals equation [28]:

$$(P + a / V_m^2)(V - b) = R T \tag{2.18}$$

P = Pressure $\quad$ V = Volume

R = Gas constant $\quad$ T = Temperature

V_m = Density of molecules

where a and b are either determined empirically for each individual compound or estimated from the following relations.

$$a = (27 R^2 T_c^2)/ 64 P_c \tag{2.19}$$

$$b = (R T_c)/ 8 P_c \tag{2.20}$$

The first parameter, a, is dependent upon the attractive forces between molecules while the second parameter, b, is dependent upon repulsive forces. Followings are the other equation of state used for real gas application.

2.2.2.3 Soave-Redlich-Kwong (SRK) Equation

The SRK equation by Soave [30] was the first modification of the simple Redlich-Kwong equation where the parameter *a* was made temperature dependent in such a way that the vapour pressure curve could be reproduced well. The EOS requires three input parameters per pure compound: T_c, P_c and ω.

$$P = \frac{RT}{v - b} - \frac{a(T)}{v(v - b)} \tag{2.21}$$

P = Pressure $\qquad$ v = Specific volume

R = Gas constant $\qquad$ T = Temperature

Pure component parameters:

$$a_c = 0.42747 \frac{R^2 T_c^2}{P_c} \tag{2.22}$$

where,

$$a(T) = a_c \cdot a(T) \tag{2.23}$$

with,

$$a(T) = \left(1 + m\left(1 - \sqrt{T_r}\right)\right)^2 \tag{2.24}$$

with,

$$m = 0.48 + 1.574\,\omega - 0.176\,\omega^2 \tag{2.25}$$

$$b = 0.08664 \frac{RT_c}{P_c} \tag{2.26}$$

2.2.2.4 Peng-Robinson (PR) Equation

The PR equation [31] is the most widely used equation in chemical engineering thermodynamics. It is known to give slightly better predications of liquid densities than the SRK equation by Soave. The equation requires three inputs per compound: T_c, P_c and the eccentric factor ω.

$$P = \frac{RT}{v - b} - \frac{a(T)}{v^2 + 2bv - b^2} \tag{2.27}$$

P = Pressure $\qquad$ v = Specific volume

R = Gas constant $\qquad$ T = Temperature

V_m = Density of molecules

Pure component parameters: $$a(T_c) = 0.45724 \frac{R^2 T_c^{\ 2}}{P_c} \tag{2.28}$$

where,

$$a(T) = a(T_c) \cdot a(T_r, \omega) \tag{2.29}$$

with,

$$a(T_r, \omega) = (1 + \kappa(1 - \sqrt{T_r}))^2 \tag{2.30}$$

$$\kappa = 0.37464 + 1{,}54226\ \omega - 0{,}26992\ \omega^2 \tag{2.31}$$

with

$$b = 0.0778 \frac{RT_c}{P_c} \tag{2.32}$$

2.2.2.5 Lee-Kesler-Plocker Equation

The Lee-Kesler-Plocker equation is an accurate general method for non-polar substances and mixtures. Plocker et al [32] applied the Lee-Kesler equation to mixtures, which itself was modified from the Benedict-Web-Rubin (BWR) equation.

BWR equation:

$$P = \frac{RT}{v} + \frac{1}{v^2}\left(B_o RT - A_o - \frac{C_o}{T^2}\right) + \frac{1}{v^3}(bRT - a) + \frac{a\alpha}{v^6} + \frac{C}{v^3 T^2}\left(1 + \frac{\gamma}{v^2}\right)e^{-\gamma / v^2} \tag{2.33}$$

$$z = z^{(o)} + \omega / \omega^{(r)} (z^{(r)} - z^{(o)}) \tag{2.34}$$

P = Pressure	v = Specific volume
R = Gas constant	T = Temperature
z = Compressibility factor	ω = Acentric factor

The compressibility factors are determined as follows:

$$z = \frac{Pv}{RT} = \frac{P_r v_r}{T_r} = z(T_r, v_r, A_\kappa) \tag{2.35}$$

$$z = 1 + \frac{B}{v_r} + \frac{C}{v_r^2} + \frac{D}{v_r^5} + \frac{C_4}{T_r^3 v_r^2}\left[\beta + \frac{\gamma}{v_r^2}\right]\exp\left[\frac{-\gamma}{v_r^2}\right] \tag{2.36}$$

where,

$P_r v$

$$C = c_1 - \frac{c_2}{T_r} + \frac{c_3}{T_r^2} \tag{2.37}$$

$$B = b_1 - \frac{b_2}{T_r} - \frac{b_3}{T_r^2} - \frac{b_4}{T_r^3} \tag{2.38}$$

$$D = d_1 - \frac{d_2}{T_r} \tag{2.39}$$

$$\omega^{(o)} = 0 \tag{2.40}$$

$$\omega^{(r)} = 0.3978 \tag{2.41}$$

Mixing rules for pseudo critical properties are as follows:

$$T_{cm} = \left(\frac{1}{V_{cm}^{\eta}}\right)\sum_i \sum_j x_i x_j v_{cij} \tag{2.42}$$

Where,

$$T_{cij} = (T_{c_i} T_{c_j})^{1/2} \tag{2.43}$$

$$T_{c_{ii}} = T_{c_i} \tag{2.44}$$

$$T_{c_{jj}} = T_{c_j} \tag{2.45}$$

2.2.2.6 Peng-Robinson-Stryjek-Vera (PRSV) Equation

The PR equation was modified by several researchers. Stryjek et. al [33] proposed new alpha functions, introducing a new temperature dependence of the parameter a(T). The only differences between the different modifications are the different alpha functions with a different number of adjustable parameters.

$$P = (RT/(v - b)) - (a/(v^2 + 2bv - b^2)) \tag{2.46}$$

P = Pressure	v = Specific volume
R = Gas constant	T = Temperature

$$v_{c_{ij}} = \frac{1}{8}(v_{c_i}^{1/3} + v_{c_j}^{1/3})^3 \tag{2.47}$$

$$v_{cm} = \sum_i \sum_j x_i x_j v_{c_{ij}} \tag{2.48}$$

where P is in kPa, T is in K, v is in m^3/mole, and R = 0.008314 kJ/(mole) (K). The constants a and b is calculated as follows:

$$z_{c_i} = 0.2905 - 0.085\,\omega_i \tag{2.49}$$

$$a = \Sigma\,\Sigma\, x_i\, x_j\, a_{ij} \tag{2.50}$$

$$b = \Sigma\, x_i\, b_i \tag{2.51}$$

$$z_{c_m} = 0.2905 - 0.085\,\omega_m \tag{2.52}$$

where,

$$a_{ij} = (a_i\, a_j)0.5\ (1 - k_{ij})\ b_i = 0.077796\ RT_{ci}/\ P_{ci} \tag{2.53}$$

$$P_{c_m} = z_{c_m} \frac{RT_{c_m}}{v_{c_m}} \tag{2.54}$$

$$\omega_m = \sum_i x_i \omega_i \tag{2.55}$$

$a_i = (0.457235\ R^2\ T_{ci}^2/P_{ci})\ \alpha_i$ (2.56)

$a_j = (0.457235\ R^2\ T_{cj}^2/P_{cj})\ \alpha_j$ (2.57)

k_{ij} = binary interaction parameter for components i and j

$\alpha_i = [1 + \kappa_i\ (1 - T_{ri}^{0.5})]^2$ (2.58)

$\kappa_i = \kappa_{0i} + \kappa_{1i}\ [(1 + T_{ri}^{0.5})\ (0.7 - T_{ri})]$ (2.59)

$\kappa_i = \kappa_{0i}$ for $T_r > 0.7$ (2.60)

$\kappa_{0i} = 0.378893 + 1.4897153\omega_i - 0.17131848\omega_i^2 + 0.019655\omega_i^3$ (2.61)

κ_{1i} = adjustable parameter for component i

$T_{ri} = T_i/T_{ci}$ for component i (2.62)

Values for R, T_{ci}, P_{ci}, ω_i, κ_{1i}, x_i, and k_{ij} are needed to calculate constants a and b. R = 0.008314 kJ/(mole) (K).

2.2.2.7 Zudkevitch Joffee Equation

The Zudkevitch Joffee model [34] is a modification of the Redlich Kwong equation. This model has been enhanced for better prediction of vapour liquid equilibrium for hydrocarbon systems, and systems containing H_2. The major advantage of this model over the previous version of the Redlich Kwong equation is the improved capability of predicting pure component equilibrium, and the simplification of the method for determining the required coefficients for the equation.

2.2.2.8 Kabadi-Danner Equation

This Kabadi-Danner model [35] is a modification of the original SRK equation, enhanced to improve the vapour-liquid-liquid equilibrium calculations for H_2O-hydrocarbon systems, particularly in the dilute regions. The model is an improvement over previous attempts that were limited in the region of validity. The modification is based on an asymmetric mixing rule, whereby the interaction in the water phase (with its strong H_2 bonding) is calculated based on both the interaction between the hydrocarbons and the H_2O, and on the perturbation by hydrocarbon on the H_2O-H_2O interaction (due to its structure).

2.2.2.9 Application of EOS

EOS can be used to predict properties of mixtures ranging from well-defined light hydrocarbon systems to complex oil mixtures and highly non-ideal (non-electrolyte) chemical systems. Enhanced EOS such as PR and PRSV can be used for rigorous treatment of hydrocarbon systems; semi empirical and vapour pressure models for the heavier hydrocarbon systems; steam correlations for accurate steam property predictions; and activity coefficient models for chemical systems. Table 2.1 lists some typical systems and recommended correlations. From the table it is learned that EOS is widely used in hydrocarbon system therefore it is proofed that EOS is suitable for natural gas system.

Table 2.1 Recommended EOS for Various Applications

Type of System	**Recommended Equations**	**Reference**
Sour Gas	PR	Li and Guo [16]
Hydrocarbon with Hydrogen Sulfide and Carbon Dioxide	SRK BWR	Huron et al. [18] Evelein and Moore [19] Orye [21]
Carbon Dioxide and Chlorodiflouromethane Mixtures	PR	Lee et al. [20]
Non-aqueous Binary Mixtures	SRK, PR, PRSV	Lee and Yung [36]
Pure Alkanes, Ethers and Their Mixtures	GCEOS	Hofman [37]
Oil Extraction Process	Zudkevitch-Joffee, SRK	Boss [38]

2.2.3 Method to Reduce OPEX of NGV Refueling Equipment

This section focused at theories related to the development of the method to reduce OPEX of NGV refueling equipment that inclusive of study of calculation of energy loss and calculation of compression energy.

2.2.3.1 Energy Loss

When the source pressure is high and sink pressure is low the pipe exit pressure is much higher than the sink pressure. This leads to the pressure discontinuity between end of the pipe and sink. If gas is thermally isolated from its surroundings and if the gas is allowed to expand quasi-statically under these so called adiabatic conditions then it does work on its environment, and, hence, its internal energy is reduced. So the highly compressed gas will expand into the lower pressure of receiver and this will result to energy loss.

The system considered is the gas inside the tank at any point of time. Therefore, the system will be an open, unsteady-state system.

Energy balance [39]:

$$d(nU) = U_{final} dn_{final} - U_{initial} dn_{initial}$$

$$= H_{in} dn_{in} - H_{out} dn_{out} + dQ + dW_s + dE_k + dE_p \qquad (2.63)$$

The energy balance equation is derived based on the following assumptions:

1. Negligible potential energy change → $dE_p = 0$
2. Negligible heat transfer to the environment → $dQ = 0$
3. Size of the tank remain unchanged → no shaft work ($dW_s = 0$)
4. No outlet → $dn_{out} = 0$
5. Gas inside the tank has insignificant velocity.

Hence, the equation is reduced to

$$U_{final} dn_{final} - U_{initial} dn_{initial} = H_{in} dn_{in} + (-mu^2)/2 \quad (2.64)$$

From the equations 2.64, energy loss, is defined as enthalpy of gas flowing into sink plus kinetic energy change of gas when flowing into sink.

Properties changes of natural gas flowing into sink can be obtained from the following correlations.

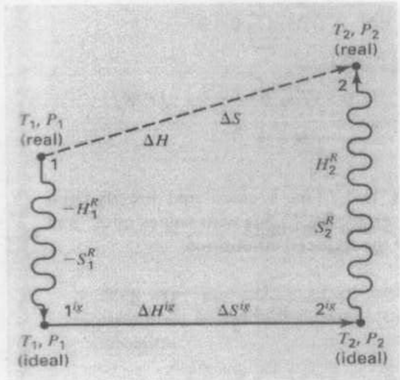


Figure 2.3 Calculational Path for Property Changes (enthalpy and entropy) [40]

The actual path from state 1 to state 2 of a real gas (dashed line) can be replaced by a three-step calculational path, illustrated in Figure 2.3 [40].

- Step $1 \rightarrow 1^{ig}$: A hypothetical process that transforms a real gas into an ideal gas at (T_1, P_1). The enthalpy and entropy changes for this process are:

$$\Delta H = H_1^{ig} - H_1 \quad (2.65)$$

$$\Delta S = S_1^{ig} - S_1 \quad (2.66)$$

- Step $1^{ig} \rightarrow 2^{ig}$: Changes in the ideal-gas state from (T_1, P_1) to (T_2, P_2). For this process,

$$\Delta H^{ig} = H_2^{ig} - H_1^{ig} = \int_{T1}^{T2} C_P^{ig} dT \tag{2.67}$$

$$\Delta S^{ig} = S_2^{ig} - S_1^{ig} = \int_{T1}^{T2} C_P^{ig} \frac{dT}{T} - R\ln\left(\frac{P_2}{P_1}\right) \tag{2.68}$$

- Step $2^{ig} \rightarrow 2$: Another hypothetical process that transforms the ideal gas back into a real gas at (T_2, P_2).

$$\Delta H = H_2^{ig} - H_2 \tag{2.69}$$

$$\Delta S = S_2 - S_2^{ig} \tag{2.70}$$

When state 1 (P_1, T_1) is the reference state, properties of the gas will be calculated as

- ***Enthalpy***:

$$H - H_{ref} = (H - H^{ig})_{T,P} + \int_{Tref}^{T} C_p dT - (H - H^{ig})_{ref} \tag{2.71}$$

$$\text{Where } \frac{H - H^{ig}}{RT} = \left[\int_0^{\rho} -T\left(\frac{\partial Z}{\partial T}\right)_{\rho} \frac{d\rho}{\rho}\right] + Z - 1 \tag{2.72}$$

- ***Internal energy***:

$$U - U_{ref} = (U - U^{ig})_{T,P} + \int_{Tref}^{T} C_V dT - (U - U^{ig})_{ref} \tag{2.73}$$

$$\text{Where } \frac{U - U^{ig}}{RT} = \left[\int_0^{\rho} -T\left(\frac{\partial Z}{\partial T}\right)_{\rho} \frac{d\rho}{\rho}\right] \tag{2.74}$$

- ***Entropy***:

$$S - S_{ref} = (S - S^{ig})_{T,P} + \int_{Tref}^{T} \frac{C_P}{T} dT - R\log(P/P_{ref}) - (S - S^{ig})_{ref} \tag{2.75}$$

Where $$\frac{S - S^{ig}}{R} = \left[\int_0^{\rho} \left[-T\left(\frac{\partial Z}{\partial T}\right)_{\rho} - (Z-1) \right] \frac{d\rho}{\rho} \right] + \ln Z$$

(2.76)

2.2.3.2. Compression Processes versus Energy Requirement

The process of compressing gas from low pressure to high pressure can be isothermal or isentropic. Energy requirement is calculated using the basic First Law of Thermodynamics, $\Delta H = Q + W_S$.

In *isothermal* compression process, as temperature is constant, Q=TΔS, work required for compression will be $W_S = \Delta H - Q = \Delta H - T\Delta S$. This amount of work is proven to be the minimum, which makes isothermal process the most desirable path. However, it can only be obtained if ideal cooling is continuous, which is very difficult during normal operation.

In *isentropic* compression, heat transfer to the environment is negligible, Q=0, hence, work requirement is $W_S = \Delta H$. The energy requirement is much greater than the isothermal case, which makes the process the least desirable form of compression. Besides, large temperature increment can affect the equipment's lifetime.

The actual form of compression in industrial applications is *multistage adiabatic compression,* in which the gas is cooled isobarically by an intercooler after it is adiabatically compressed to a certain intermediate pressure. If intercooling is complete, the gas will enter the next stage at the same temperature at which it entered the previous one. Work required for the process is the sum of work required for adiabatic compression and isobaric cooling, and is proven to be in between the work requirement by isothermal compression and one required by single stage adiabatic compression.

The diagram of multistage compression with intercooling is shown in Figure 2.4 [41].

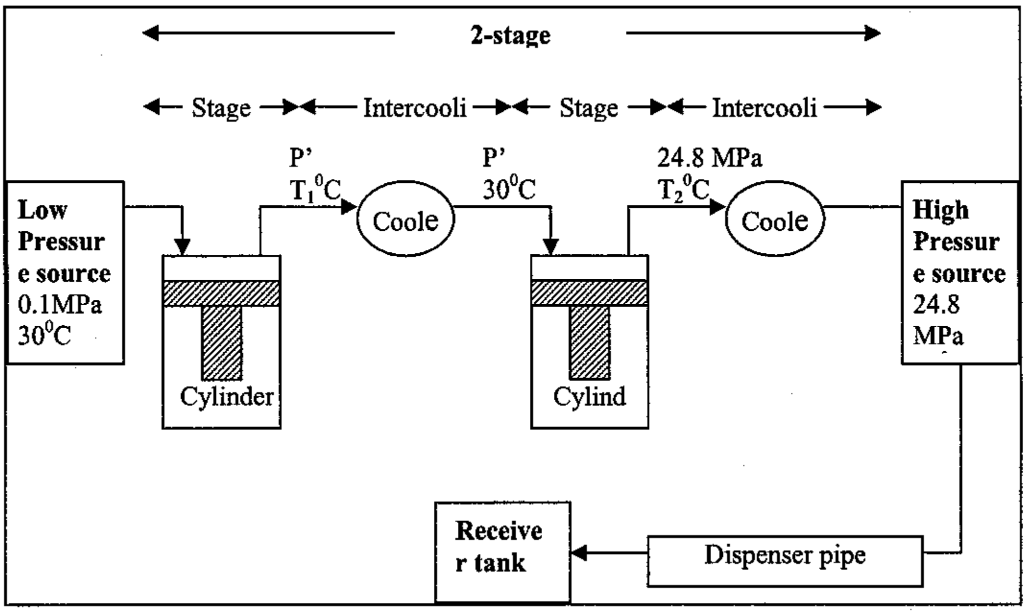


Figure 2.4: Diagram of Multistage Adiabatic Compression

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

Chapter 2 discussed literature review and theories those related to all the four research components of the present project. The present chapter will discuss the methodology of each research's component.

3.1 Natural Gas Flow in NGV Refueling Equipment

The methodology of this project work is summarized in Figure 3.1

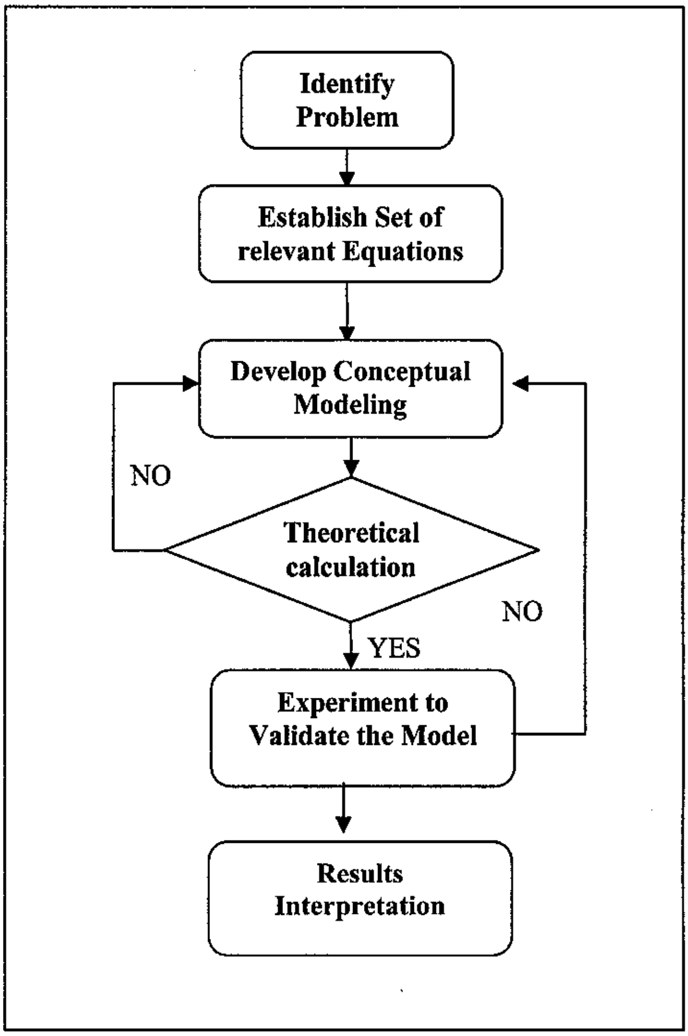


Figure 3.1: Methodology of Project Work

3.1.1 Establish Set of Relevant Equations

It is important to identify appropriate mathematical equations and correlations to help develop a suitable mathematical modeling. From literature review and theory identification stage, mathematical relations from (2.1) to (2.16) are believed to be the most accurate relations to simulate the compressible flow phenomena, which are the important elements of the model.

To develop equations for compressible flow in a natural gas dispenser, the following assumptions have been made.

1. One-dimensional flow.
   - Diameter of the pipe is relatively small compared to the overall length of the pipe.
2. Velocity gradients within a cross-section are neglected, so that $\overline{V} = u$
   - The result of interest is mass flow rate and it's not a priority to look at the actual velocity gradient across the diameter.
3. Friction is restricted to wall shear.
   - Head loss only calculated for the friction along the pipe.
4. Zero shaft work.
   - No work is done by the fluid
5. Negligible gravitational effects.
   - Height variation is very small to have significant effect on the flow.

3.1.2 Identify Problem

Thoroughly understanding the project title and its background is very important and the identification of problem statement can help narrow the scope and specify clear objectives.

3.1.3 Develop Conceptual Diagram

From the theory, the simplified model for the study of an existing NGV refueling system has been developed [42] (Figure 3.2).

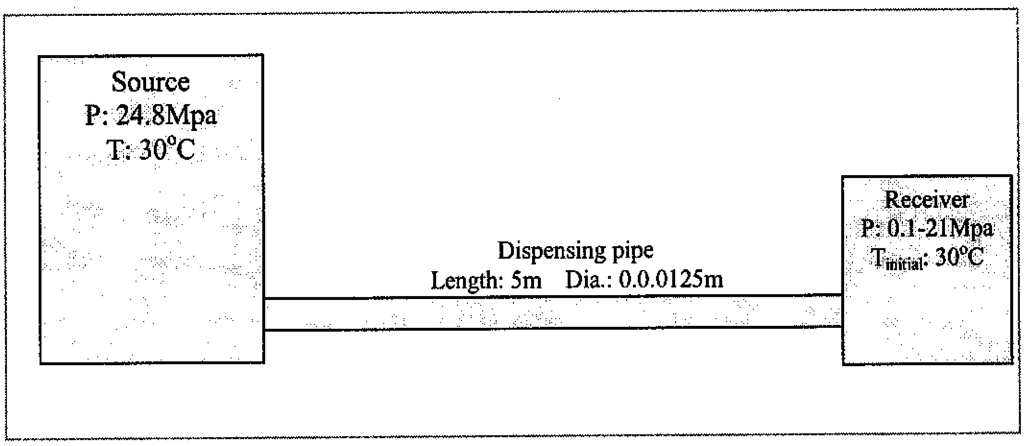


Figure 3.2 Conceptual Model of NGV Refueling Equipment

From the conceptual diagram, the assumptions for important process parameters are summarized in Table 3.1.

Table 3.1: Important Parameters of the Refueling System

Elements	**Conditions**
High Pressure Source (to discharge gas to the automobile storage tank)	24.8 MPa (3600 psig) 30^0C
Dispenser Pipe (the piping system from refueling station)	Straight, horizontal, constant cross-sectional area Length = 5m Diameter = 0.0125m
Receiver Tank (the vehicle storage tank)	Volume = $0.055m^3$ Initial (empty tank): 101.325kPa (14.7psig) 30°C Final (full tank) : 21 Mpa (3000 psig) 30°C

Figure 3.2 shows the simplified model for process modeling study to duplicate existing NGV refueling system. It consists of a reservoir, a straight horizontal pipeline and a receiver. The reservoir's pressure is 24.8MPa (3600psi) and its temperature is 30°C and both are assumed to be constant. The pipeline is horizontally straight with length of 5 meters and diameter of 0.0125 meters; these are the actual size of the piping system of the NGV refueling equipment. The cross sectional area of the pipe is constant. Friction effect along the pipeline is taken into account since the flow is irreversible. It is assumed that an automobile with an empty tank (pressure=101.33 kPa) is being filled. The automobile tank varies from the initial value of 101.33kPa (14.7 psi) that equal to 1 atm to full fill pressure of 21MPa (3000 psi). These sets of conditions are chosen as the extreme values. Depending on the initial quantity of gas inside the tank and the final required fill pressure other conditions may apply and can be easily substituted. . The volume of tank is 0.055 m^3, the standard value in the existing NGV. The initial temperature of the tank is assumed to be 30°C and temperature changes is expected due to gas expansion and compression effects.

3.1.4 Malaysian Natural Gas Composition

Natural gas composition varies depending on the location where it is collected. For the purpose of this project, composition of natural gas is provided by Petronas Research and Scientific Service (PRSS). The composition was obtained from a study conducted by PRSS between Jun 1999 to January 2000 at various NGV dispensers as well as at Petronas Gas Berhad (PGB) Kapar. The natural gas studied was the one that had gone through treatment process where impurities such as sulfur, carbon dioxide and nitrogen were removed. The main component of the natural gas is methane. Other longer chain hydrocarbons such as ethane, propane, iso-butane and n-butane only presents in small amount. Although impurities had been extracted from the natural gas, some nitrogen and carbon dioxide still exist in very small amount.

Table 3.2 shows the result of the study by categorizing the composition into the richest and the leanest. In present research, the average composition that is calculated by adding richest composition and leanest composition and dividing this with two (2) is taken into the calculation.

Table 3.2 Composition of Natural Gas

Component	**Symbol**	**Composition**	
		Leanest	**Richest**
Methane	C1	96.42	89.04
Ethane	C2	2.29	5.85
Propane	C3	0.23	1.28
i-Butane	iC4	0.03	0.14
n-Butane	nC4	0.02	0.10
i-Pentane	iC5	-	-
n-Pentane	nC5	-	-
n-Hexane	nC6	-	-
Nitrogen	N_2	0.44	0.47
Carbon dioxide	CO_2	0.57	3.09
Gross heating value		38.13	38.96

3.1.5 Theoretical calculation

The theoretical calculation predicts the changes along the pipeline and inside the vehicle fuel tank in terms of pressure, temperature and gas content.

The problem solving is carried out by MATLAB Simulink Program using two levels of looping: the inner loop is to simulate filling during choke flow, and the outer one is to simulate a filling during non-choke flow or normal flow. The detail program is attached as Appendix A.

A set of relevant equations has been identified to develop the Fanno model. The full set of the equations is attached as Appendix B. These equations constitute the model for the filling. The solution of these equations is however not straight forward. A nested iterative approach has to be followed to solve these equations. Source pressure, initial sink pressure, initial sink temperature are the known variables. For a fixed source pressure and initial receiver pressure. Firstly entrance Mach number is assumed, and for the given length of pipe, exit Mach number is calculated. And then exit pressure, temperature and density is calculated. Next, based on exit Mach number, pressure and density, mass velocity at exit of pipe is calculated. From mass velocity, the mass of gas that has been filled into the tank is calculated. And then the pressure and temperature of the receiving tank is calculated. The theoretical calculation is preceded until exit pressure of the pipe equals to tank pressure. If the two pressures are equal, a new entrance Mach number needs to be assumed. Then exit Mach number and exit pressure are calculated. If the exit pressure is greater than tank pressure then another assumption of entrance Mach number is necessary. The theoretical calculation proceeds until the tank pressure reach 21MPa. Figure 3.4 and 3.5 show the problem-solving algorithm. Table 3.3 enlists all the variables and its value used in the calculations.

Table 3.3 Variables Used in Algorithm

Variables	**Value used in calculation**
f	0.00365
L_{max}	5m
γ	1.3
P_o	24,800kPa
T_o	303.15K
ρ_o	209.7kg/m^3
M	17.46
A	1.2272 x 10^{-4} m^2
t	0.1s
Z	0.819
R	8.3143kPam^{3}kmol^{-1}k^{-1}
V	0.055m^3

Set: Source (P_{source}, T_{source})
Sink (P_{sink}, T_{sink})
Filling time: t=0s

↓

Pipe-exit Mach No. is known, M_b=1

↓

Calculate pipe-entrance Mach No., M_a

$$\frac{fL_{max}}{r_H} = \frac{1}{\gamma}\left(\frac{1}{M_a^2} - 1 - \frac{\gamma+1}{2}\ln\frac{2\{1+[(\gamma-1)/2]M_a^2\}}{M_a^2(\gamma+1)}\right)$$

↓

Calculate pipe-entrance properties; P_a, T_a, ρ_a

$$\frac{P}{P_o} = \frac{1}{\{1+[(\gamma-1)/2]M^2\}^{1/(1-1/\gamma)}}$$

$$T = T_o\left(\frac{P}{P_o}\right)^{1-1/\gamma}$$

$$\rho^\gamma = \frac{p\rho_o^\gamma}{p_o}$$

↓

Calculate pipe-exit properties; P_b, T_b, ρ_b

$$\frac{P_a}{P_b} = \frac{M_b}{M_a}\sqrt{\frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}}}$$

$$\frac{T_a}{T_b} = \frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}}$$

$$\frac{\rho_a}{\rho_b} = \frac{M_b}{M_a}\sqrt{\frac{\{1+[(\gamma-1)/2]M_a^2\}}{\{1+[(\gamma-1)/2]M_b^2\}}}$$

↓

Calculate mass velocity, G

$$G = M\sqrt{\rho\gamma p}$$

↓

Figure 3.3a Algorithms for Choke Flow Condition -1

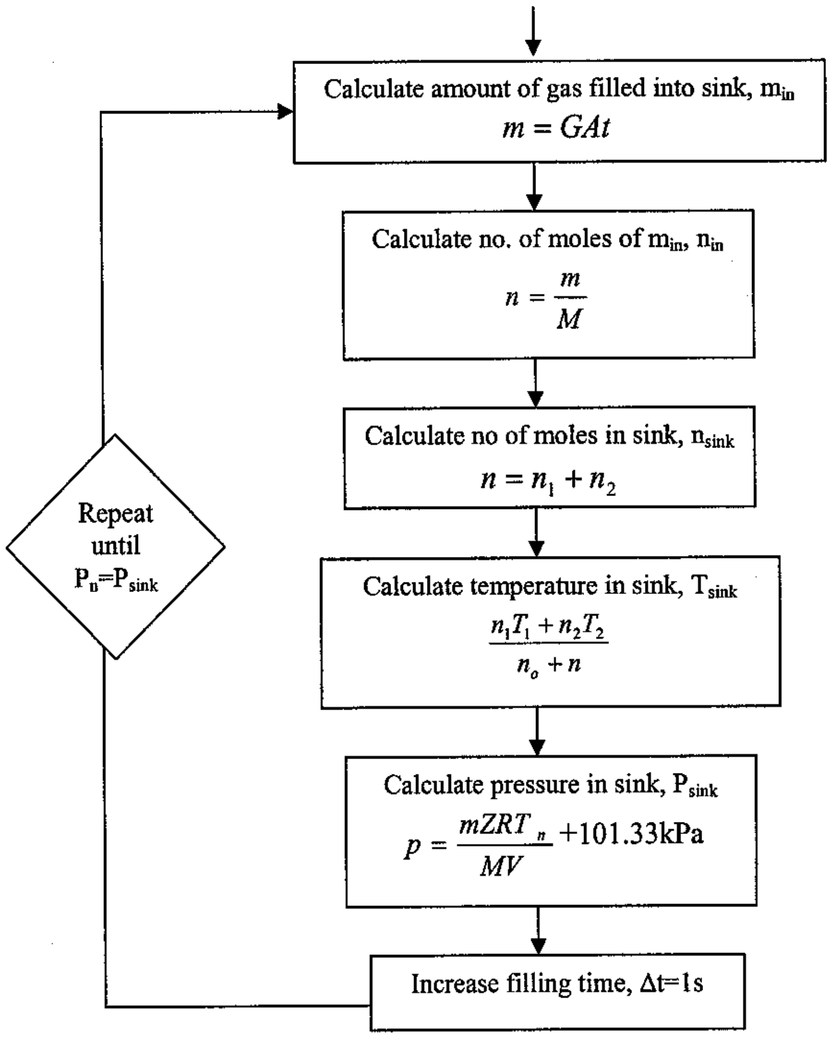


Figure 3.3b Algorithms for Choke Flow Condition -2

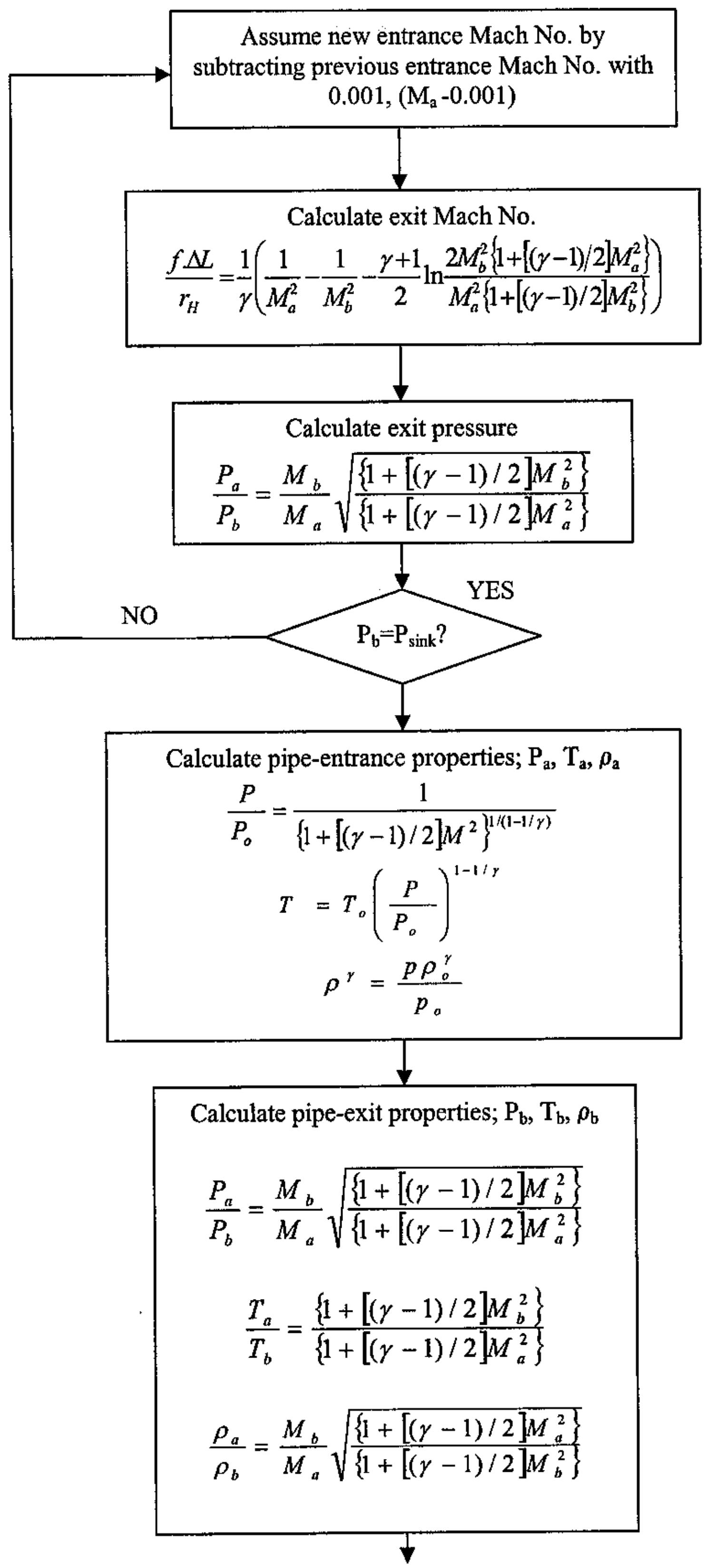


Figure 3.4a Algorithm for non-Choke Flow Condition-1

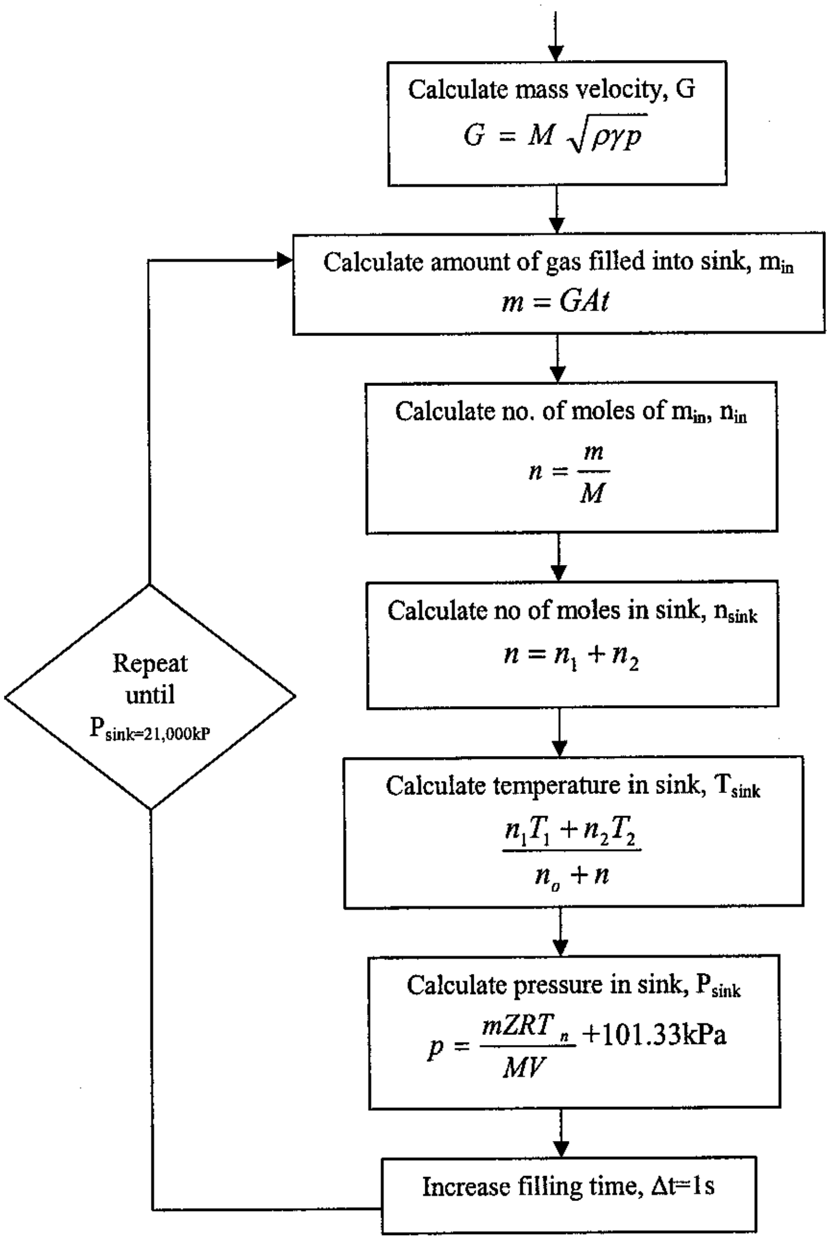


Figure 3.4b Algorithm for non-Choke Flow Condition-2

3.1.6 Experiment to Validate the Model

To study the phenomenon of compressible gas flow in NGV refueling equipment, an NGV Refueling Equipment test rig has been set up at UTP.

3.1.6.1 Experimental Set-up

The NGV test rig was conceptualized and designed at UTP. It was designed in such a way that it shall be able to replicate the actual filling condition of the existing refueling equipment. The test rig was fabricated by one of the vendor who has licensed from Petronas to supply natural gas dispenser in Malaysia that has many years experience in this field. It consists of three major components that are Cascaded Storage System; storage cylinders horizontally stacked in metal frame, Metering System and a Receiver that has the same capacity as the actual NGV fuel tank. It also has a Recycling System to recycle the gas that has been filled into the receiver back to the cascaded storage. It helps to maintain volume of the gas for other experiments.

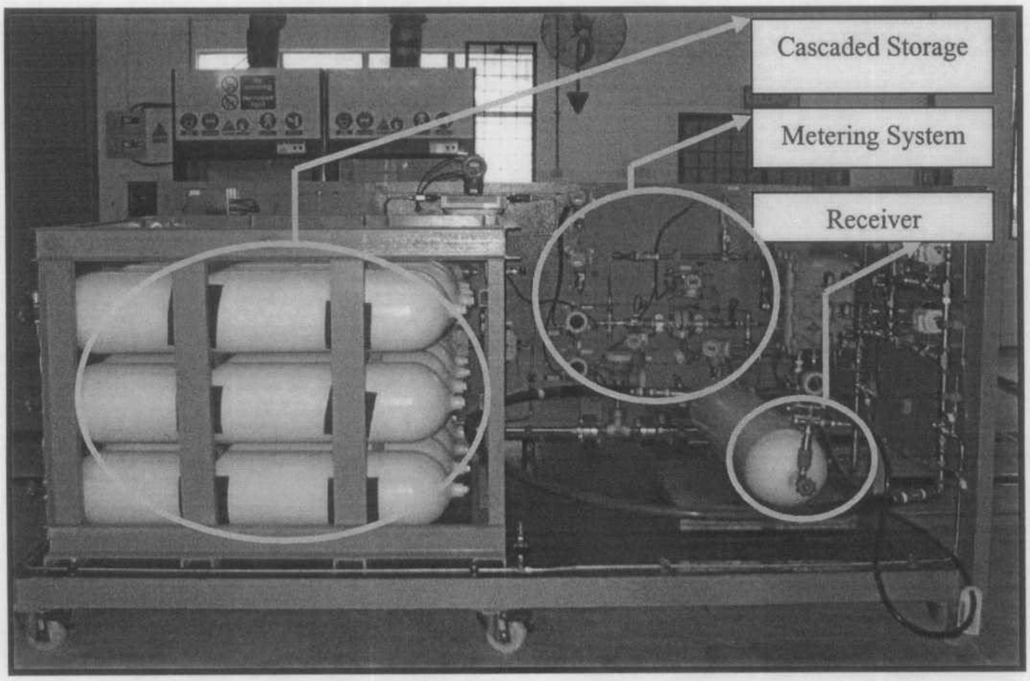


Figure 3.5 NGV Refueling Equipment Test Rig

The high-pressure natural gas is stored inside cascaded storage at pressure of 24.8MPa. After the dispenser start button is switched on, the gas flows from the storage cylinders to the dispenser and finally to a receiver tank. The sequencing is done automatically via dispenser control and the total amount of gas flow to the vehicle tank is registered on a display panel. While dispensing gas to the receiving tank, all process parameters such as pressures, temperatures and flow rates are being transmitted to a data acquisition system (DAQ). DAQ will then process the data and produces table and charts.

Recycling system is used to empty the receiving tank by transferring the gas to the storage cylinders. This is done via slow-filled compressor that has the inlet and discharge pressure of 1.25 psig and 3600psig respectively. Once empty, the compressor will stop and the next sampling process could take place. Figure 3.6 shows the front view of the test rig.

3.1.6.2 Process Flow/ Technical Drawing

To have better understanding on the process flow of the natural gas dispensing system, a Process and Instrumentation Diagram is included. Figure 3.6 shows the process flow in detail technical drawing of the test rig. As can be observed from the figure, materials or equipments are presented by tag numbers. These tag numbers will be defined individually in the process explanation.

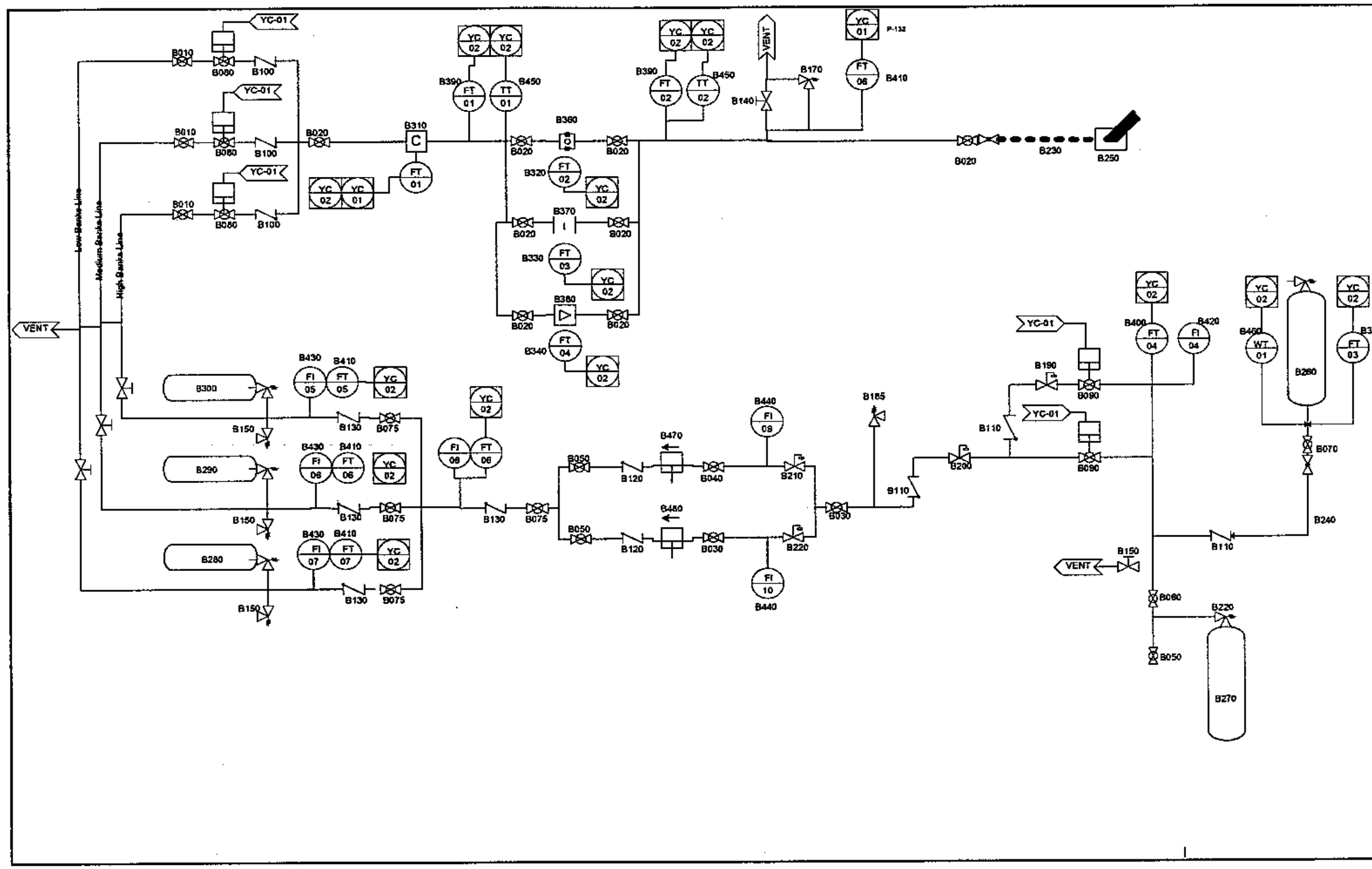


Figure 3.6 Process Flow of NGV Refueling Equipment

To dispense natural gas to vehicle tank, which is Tank B260, nozzle (B250) is connected to tank vehicle via receptacle that is located at the cylinder's neck. After that, the start switch on the display panel is switched on. Next, the nozzle valve is turned to 180 degree to 'ON' position. Having done this, the gas will then flow to vehicle tank from the storage tanks. However, it is important to understand that when the dispensing occurs, the B240 hose should not be connected to the vehicle tank as shown in the figure. The hose is only connected to B070 and B110 valves when recycling system is operated. It means that, for dispensing system, while the first end of the vehicle tank is connected to nozzle, the other end is not connected to any other equipment. The natural gas flow goes into the vehicle tank where it accumulates. In this tank, pressure, temperature and mass of natural gas are measured using transmitters (B390, B450, and B460) as shown in the diagram. These transmitters will then send input signal to the data acquisition system (YC02). DAQ system will stores and displays all the data captured when requested by users.

There are three types of storage tank systems that consist of low bank, medium bank and high bank, designated as B280, B290, and B300 respectively. All of these tanks have the same pressure of 3600 psig when they are full.

The natural gas dispensed from the low, medium or high bank will flow through a Coriolis meter (B310). As shown in the diagram, the Coriolis measured the flow of natural gas and using flow transmitter (B350) sends the measured value to the data acquisition system (YC-02). The natural gas then passes through three flow meters that are vortex, differential pressure and turbine meters. Since the meters are installed in a parallel arrangement, the natural gas is allowed to flow only through any one of these meters at a time. These volumetric flow meters are actually set for other projects and do not related to present project. After flowing through the flow meters the natural gas finally flows through the flexible hose (B230) and nozzle (B250) into the vehicle tank.

Recycling process will take place to empty the vehicle tank that is filled with natural gas from the dispensing process. To operate the recycling system, flexible hose (B240) is used to connect vehicle tank to the temporary storage tanks (B270). One end of the high pressure flexible hose is coupled to a ball valve (B070) located at the bottom neck of the vehicle tank while the other end is connected to the inlet of a check valve (B110). Both valves B070 and B060 are then turned to 'ON' position. Gas will then flow into the temporary storage tanks that are also known as the recycling tanks. The start switch is then turned on which will start the recycling process. The gas from the recycling tanks flows to the compressor, usually B480. The other compressor (B470) acts as backup when B480 is under maintenance. Compressor is used to compress the gas that in turn provides the pressure different between the recycling tanks and the storage tanks. This is to ensure the flow from the recycling tanks to the storage tanks occur smoothly throughout the recycling process.

3.1.6.3 Dispensing Flowchart

Figure 3.8 shows the dispensing flow chart of the test rig. The dispensing system duplicates the existing natural gas dispensing system.

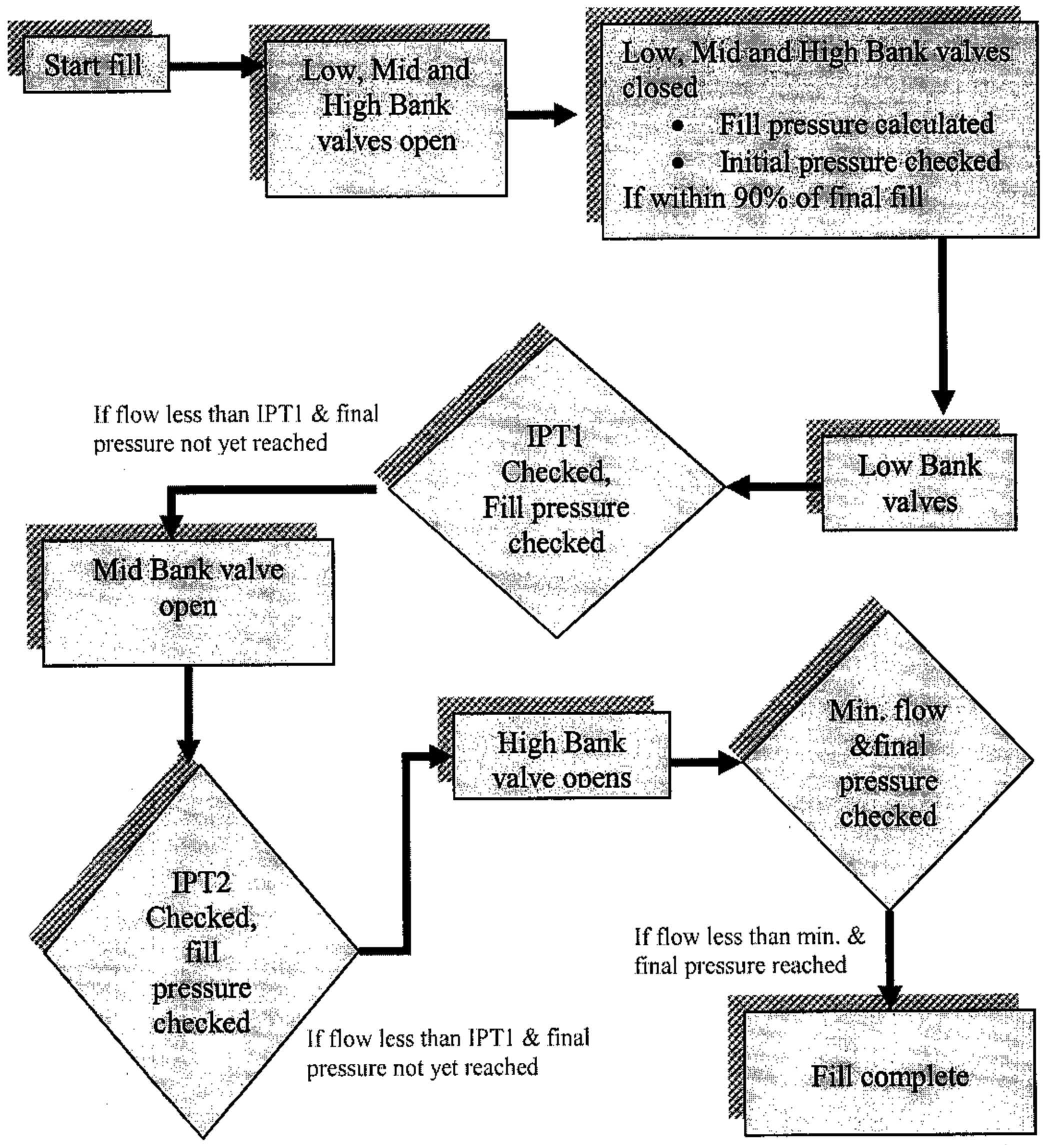


Figure 3.7 Dispensing Flowchart

3.1.6.4 Test Rig's Data Acquisition System

The test rig has a data acquisition system that capable to record data of pressure, temperature, flow rate and others in every 1 second. Figure 3.8 shows Memo Graph Data Acquisition System complete with the specification.

- Model : Memo Graph
- 90 … 253V power supply
- 16 universal inputs; 4..20 mA, thermocouple, 0.10 V,
- 7 digital inputs
- 5 SPST relays
- Provide real time data and storage
- Produce graphs, tables and charts

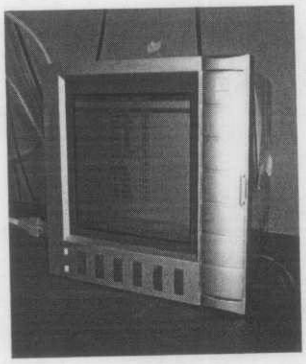


Figure 3.8 Specifications of Data Acquisition System

3.1.6.5 Experimental Procedure

The NGV Dispenser test rig is designed in such that it shall be able to replicate the actual filling condition of a commercial filling station. The high-pressure natural gas is stored inside storage cylinders at 24.8MPa. After the dispenser start button is switched on, the gas flows from the storage cylinders to the dispenser and finally to a tank which is considered as a vehicle tank. The sequencing is done automatically via dispenser control and the total amount of gas flow to the vehicle tank is registered on a display panel. There is a flow meter installed in the dispensing system that is Coriolis Flow Meter to give flow rate reading of natural gas during filling process. While dispensing gas to the vehicle tank, all process parameters such as pressures, temperatures and flow rates are being transmitted to a data acquisition system (DAQ). DAQ will then process the data and produce tables and charts.

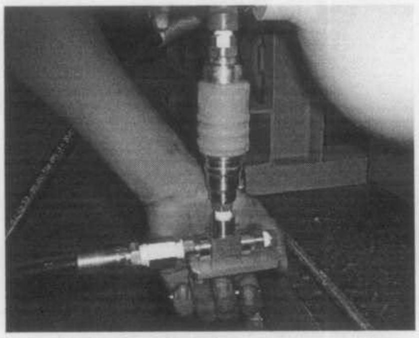
Recycling system is used to empty the vehicle tank by transferring the gas to the storage cylinders. This is done via slow-filled compressor that has the inlet and discharge pressure of 1.25 psig and 3600 psig respectively. Once empty, the compressor will stop and the next sampling process could take place.

The detailed procedure can be explained by step-by-step procedure as below:

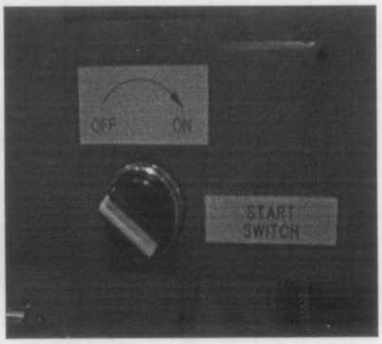
1. The power source of the test rig as well as of the DAQ is turned "on".
2. Data acquisition system is prepared to collect data. A new data collection file is opened, named and saved.
3. Initial properties such as pressure, temperature, are noted.
4. Filling process is started following the Test Rig Operating Procedure in section 3.1.5.6.
5. After filling has been completed, the collected data is transmitted from Memo graph to computer for data analysis work.
6. The data collected were:
   i. Time
   ii. Receiver's pressure
   iii. Flow rate
   iv. Mass of gas dispensed (from weighing scale)
   v. Source pressure at high bank, medium bank and low bank.
7. Recycling hose is connected from receiver to recycling line to recycle the gas back to the source for other sampling.

3.1.6.6 Test Rig Operating Procedure

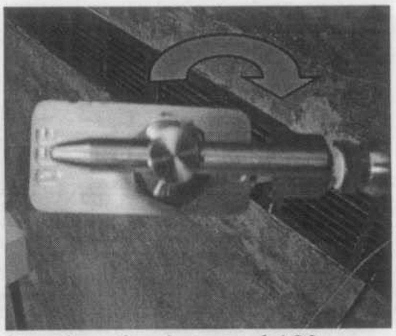
Figure 3.9 shows the detailed operating procedure for the test rig. The procedure is exactly same with the actual NGV refueling operating procedure.



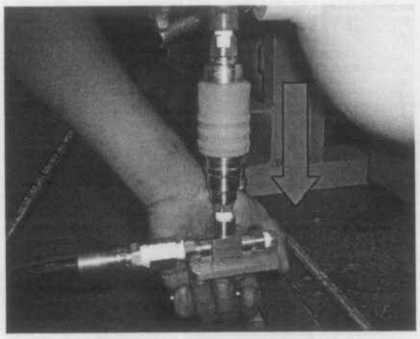
Nozzle is pushed into receptacle located at cylinder neck. A 'click' sound should be heard.



Switch located on display panel is turned to 'ON' position.



Nozzle valve is turned 180 degree to 'ON' position. Gas will then flow to cylinder.



When filling has completed, turn nozzle valve is turned back to 'OFF' position. Nozzle is uncoupled from receptacle by pulling blue collar.

Figure 3.9 Test Rig Operating Procedure

3.1.6.7 Data Acquisition System's Operation

Prior to running the experiment, data acquisition system should first be opened, and create a new data file; the details of the file, such as date and time of experiment are keyed-in.

The data acquisition system is fully automated; during experiment, the experiment data is automatically recorded and can be retrieved easily.

After the experiment completed, transmit the experiment data from monograph to computer. Depends on the size of the data, the transmission time may vary. The transmitted data can be saved in spreadsheet for easy analysis work.

3.1.7 Results Interpretation

Results interpretation is important to conclude whether the project has successfully achieved its objectives, and to provide recommendations for further improvement.

3.2 EOS for Prediction of Natural Gas Properties

The methodology of this section of project work is summarized in Figure 4.1

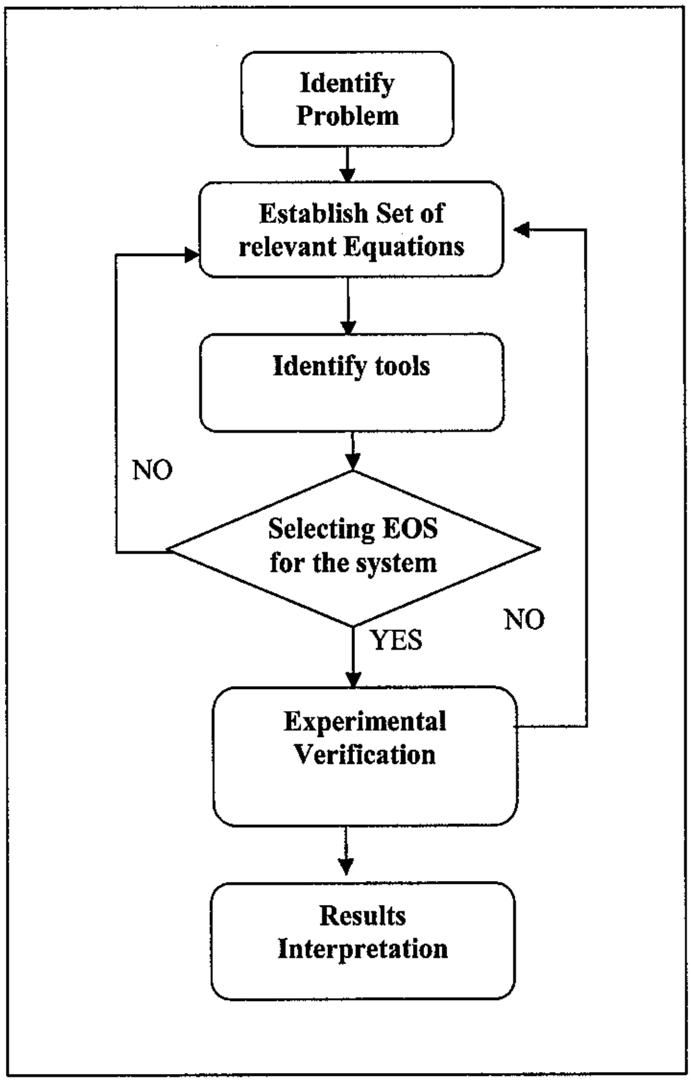


Figure 3.10 Methodology of Project Work

3.2.1 Identify Problem

Thoroughly understanding the sub-project title and its background is very important and the identification of problem statement can help narrow the scope and specify clear objectives.

3.2.2 Establish Set of Relevant Equations

It is important to identify appropriate equations to relate the properties of natural gas. From literature review and study on HYSYS, the appropriate equations for the system have been identified.

3.2.3 Identify Tools

The equations available in HYSYS (Figure 3.11) can be used to predict properties of mixtures ranging from well-defined light hydrocarbon systems to complex oil mixtures and highly non-ideal chemical systems. HYSYS provides enhanced equations of state for rigorous treatment of hydrocarbon systems; semi empirical and vapour pressure models for the heavier hydrocarbon systems; steam correlations for accurate steam property predictions; and activity coefficient models for chemical systems. HYSYS is used in present research not only because it has embedded EOS for reliable calculation but it is also very user-friendly.

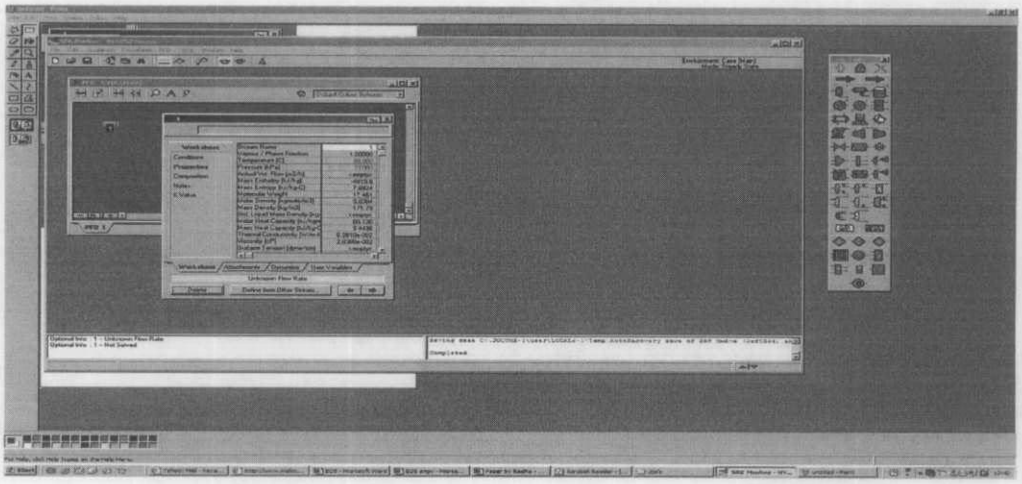


Figure 3.11 EOS Embedded Software -HYSYS

3.2.4 Selecting EOS for NGV Refueling Equipment System

From several equations of state that are available, it is important to find one that can represent the system with sufficient accuracy. The approach used to find the accurate equation for the system was done by analyzing the relation between pressure and mass at certain temperature for different types of equations. The equations tested were Peng-Robinson, Soave-Redlich-Kwong, Lee-Kesler-Plocker, Kabadi-Danner, GCEOS, Peng-Robinson-Stryjek-Vera and Zudkevitch-Joffee equations. These equations were selected based on literature review and pre-theoretical calculation performed using HYSYS. In HYSYS, for certain compositions of hydrocarbon, only certain EOS respond to it, in present research, only these EOS responded to the composition of natural gas keyed-in.

Natural gas composition, temperature and pressure were the only inputs for the software. The composition of natural gas with the exact mole fraction was keyed-in into 'Composition' window that is shown in Figure 3.12. With these 3 data, the software will give outputs such as the molecular weight, molar density, mass density, viscosity, compressibility factor and others. These data could be viewed in 'Properties' Window that is shown in Figure 4.4. Using mass density value, the mass of gas was calculated by multiplying mass density to volume of the vehicle fuel tank. It was repeated for various values of pressure till the pressure reach 21MPa. To determine the most accurate equation for NGV refueling equipment application, the calculation was performed at average composition of natural gas for every equation of state.

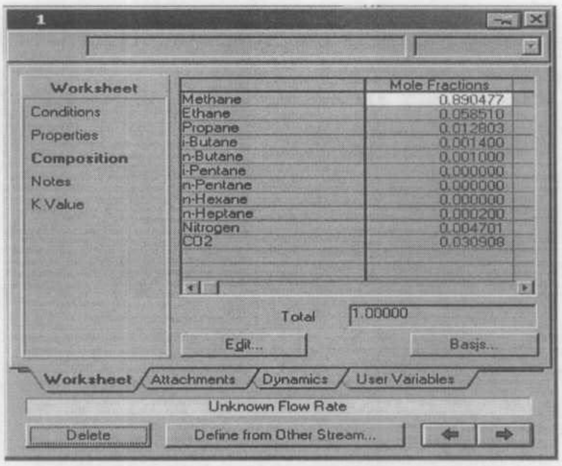


Figure 3.12 'Composition' Window

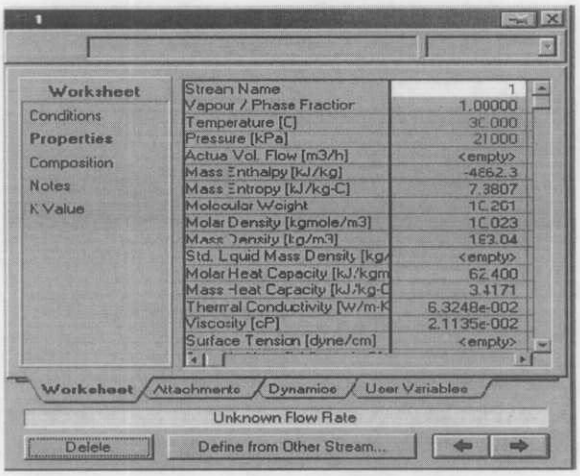


Figure 3.13 'Properties' Window

3.2.5 Experimental Verification

A static experiment was performed using the NGV refueling equipment test rig to validate the theoretical calculation. The filling of gas was done little by little, meaning that the gas is filled into the receiver little by little (approximate receiver's pressure increment of 1000kPa) until receiver's pressure reach 21000kPa to study the properties relation under steady state condition between mass, temperature and pressure. The gas was allowed to settle for at least ten minutes before the mass, temperature and pressure data were collected. The data was recorded manually to ensure high accuracy.

3.2.5.1 Experimental Procedure

The detail procedure can be easily explained by step by step procedure as below:

a. The power source of the test rig is turned "on".
b. Initial properties such as pressure of receiver, temperature of receiver and mass of the dispensed gas (from Coriolis Flow Totalizer) are noted. The pressure and temperature readings were taken from the pressure and temperature indicator attached to the receiver. The pressure and temperature sensor detect properties of gas inside the receiver.
c. Filling process is started by turning the "start button" to "ON" position (Refer to section 3.1.5.6 for Test Rig Operating Procedure). The filling is stopped when the receiver's pressure has increased 4MPa of initial pressure. However, it's not possible to increase the pressure exactly to the desired value because there is no dedicated control system to control the pressure increment inside the receiver. The gas inside the receiver is allowed to settle, the pressure and temperature of the receiver is recorded after steady state condition has been achieved. The steady state condition is achieved when the pressure and temperature reading stop changing.
d. After the gas has reached steady state condition, pressure and temperature of the receiver are recorded. The mass of gas dispensed is also recorded. All the readings are recorded manually.
e. Then the filling process is started once again until the pressure of receiver increased another 4MPa. After the steady state condition has been achieved, pressure, temperature and mass of gas dispensed are recorded manually.

f. Step c, d, and e were repeated until the maximum pressure is achieved.

g. After filling completed, the recycling hose was connected from receiver to recycling line to recycle the gas back to the source for other sampling.

3.3 Method to Reduce OPEX of NGV Refueling Equipment

The methodology of this section of project work is summarized in Figure 4.1

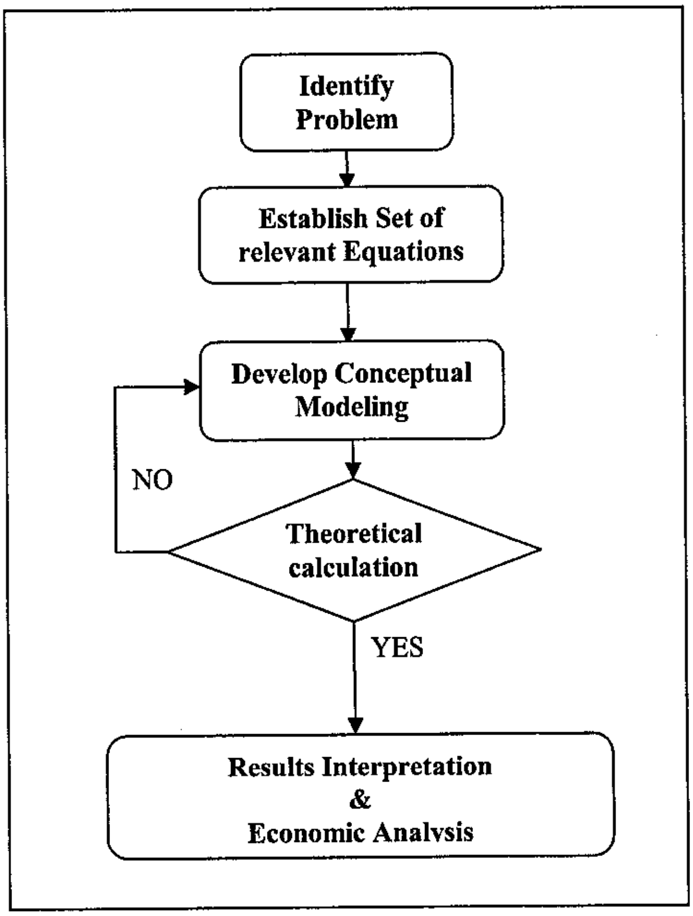


Figure 3.14 Methodology of Project Work

3.3.1 Identify Problem

Thoroughly understanding the sub-project title and its background is very important and the identification of problem statement can help narrow the scope and specify clear objectives.

3.3.2 Establish Set of Relevant Equations

It is important to identify appropriate equations to relate the properties of natural gas. From literature review and study of related theories, the appropriate equations for the system have been identified.

3.3.3 Develop Conceptual Modeling

From literature review, the simplified model for the study of an existing NGV refueling system has been developed (Figure 3.15). In section 3.1, the modeling focused at filling process which takes place from high pressure source to vehicle fuel tank. In present section, the modeling focused at compression of gas from low pressure source to high pressure source via a compressor.

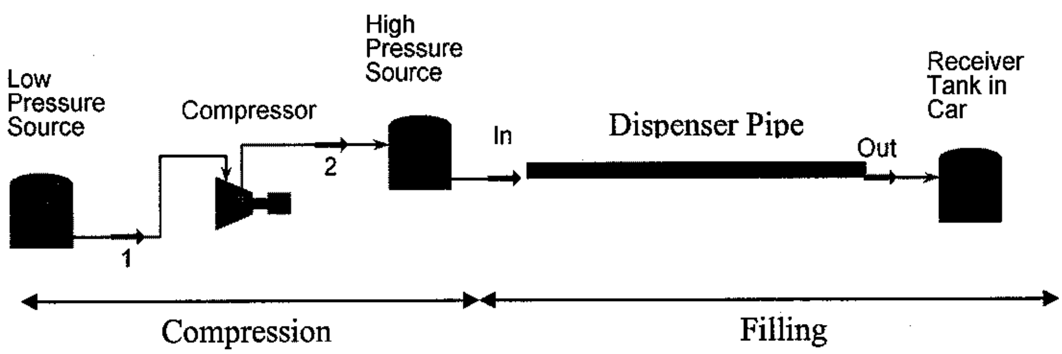


Figure 3.15: Conceptual Model of the Refueling System

From the conceptual diagram, the assumptions for important process parameters are summarized in Table 3.4.

Table 3.4: Important Parameters of the Refueling System

Elements	**Conditions**
Low Pressure Source (to contain gas provided by the supplier)	101.325kPa (14.7psig) 30^0C
Compressor (to compress gas from low pressure source to high pressure source)	Compressor Efficiency =0.75 Three-stage compressor
High Pressure Source (to discharge gas to the automobile storage tank)	24.8 MPa (3600 psig) 30^0C
Dispenser Pipe (the piping system from refueling station)	Straight, horizontal, constant cross-sectional area Length = 5m Diameter = 0.0125m
Receiver Tank (the vehicle storage tank)	Volume = $0.055m^3$ Initial (empty tank): 101.325kPa (14.7psig) 30^0C Final (full tank): 21 MPa (3000 psig) 30^0C

3.3.4 Theoretical calculation

The theoretical calculation is carried out to calculate the energy required for compression of gas. The problem solving is carried out by MATLAB software to simulate a series of sources with increasing pressure as outer loop while Fanno Model is used as inner loop to predict amount of gas discharged into vehicles. Figure 3.16 shows the problem-solving algorithm.

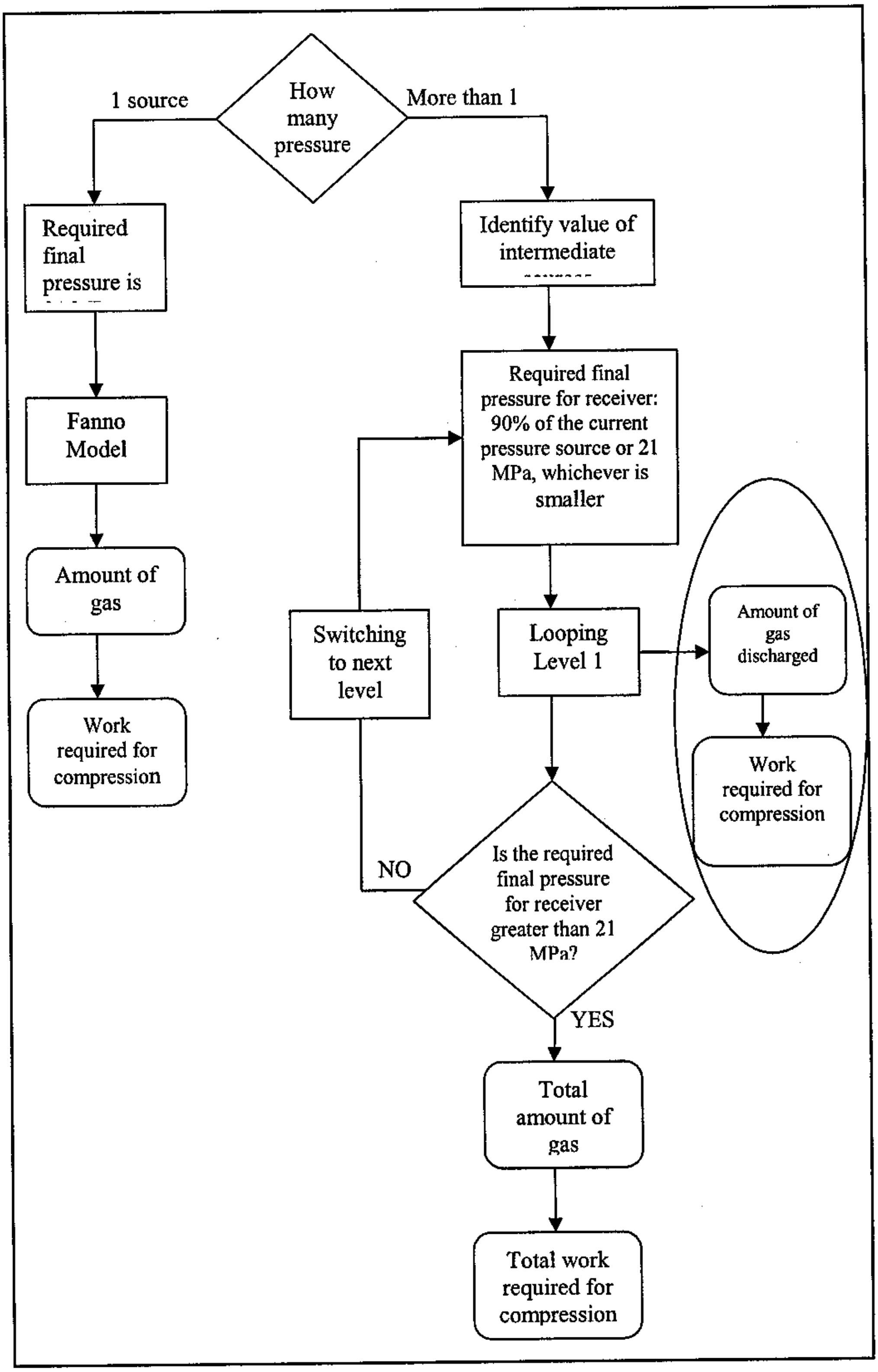


Figure 3.16 Algorithm

3.3.5 Result Interpretation

Results interpretation is important to conclude whether the project has successfully achieved its objectives, and to provide recommendations for further improvement. An economic analysis is important to measure the worth of the project's outcome.

3.4 Method to Reduce CAPEX of NGV Refueling Equipment

The methodology of this section of project work is summarized in Figure 3.16

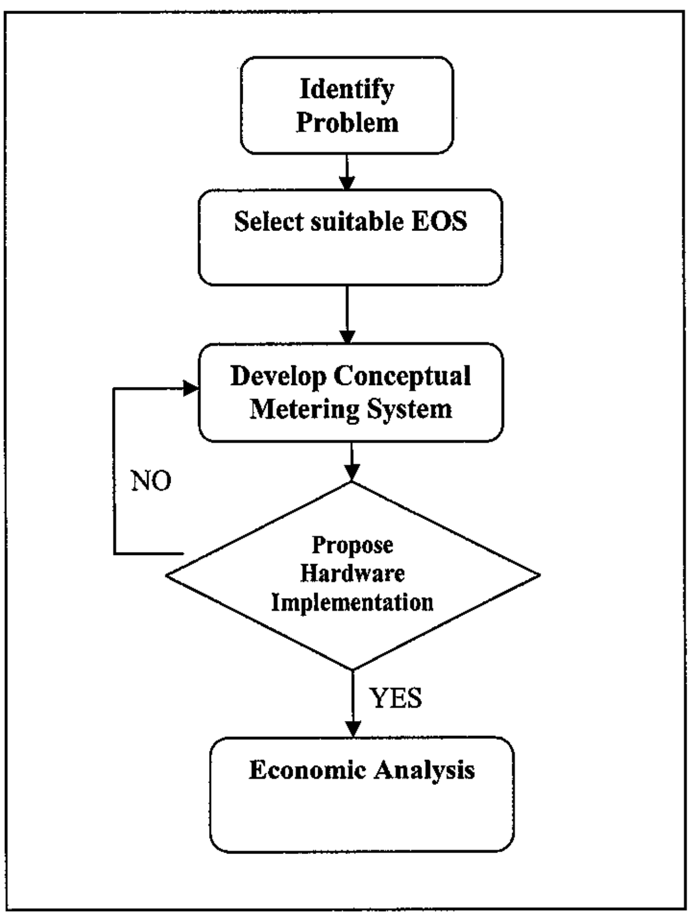


Figure 3.16 Methodology of Project Work

3.4.1 Identify Problem

Thoroughly understanding the sub-project title and its background is very important and the identification of problem statement can help narrow the scope and specify clear objectives.

3.4.2 Select Suitable EOS

Based on the study of EOS, the result is used in this section in development of conceptual metering system for NGV refueling equipment.

3.4.3 Develop Conceptual Metering System

Based on literature review, a conceptual metering system based on an EOS is developed.

3.4.4 Propose Hardware Implementation

Implementation of the conceptual metering system is important to give clearer idea to others on how the metering system works and it will be very useful for commercialization purpose.

3.4.5 Economic Analysis

Economic analysis is important to measure the worth of the project's outcome and to attract industrialist to commercialize it.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 RESULTS AND DISCUSSION

The result has been divided into four components for four different studies that have been carried out in present research. Methodology for each study has been discussed in Chapter 3.

4.1 Natural Gas Flow in NGV Refueling Equipment

This section will discuss the results obtained from theoretical calculation of natural gas flow modeling and experimental results obtained from experiments that meant for verification of the model.

4.1.1 Effect of Entrance Mach Number of Pressure Distribution along the Pipeline of Constant Source Pressure

Since the cross-sectional area of the high-pressure source is significantly larger than that of the pipe, the initial Mach number can be assumed to be very small. However, in a long line, with a very high pressure at the pipe entrance, and very low pressure at the pipe exit, the Mach number is increasing along the line, however the maximum it can goes is one and this can only occur at the tip of the pipe.

Table 4.1 Conditions of Theoretical Calculation 1

Parameters	**Value**
Length of pipe, L	5 m
Friction factor, f	0.00365
Isentropic coefficient, γ	1.3
Source pressure, P_o	24,800 kPa
Source temperature, T_o	303.15 K
Receiver's pressure, P_b	101.33 kPa
Receiver's temperature, T_b	303.15 K
Entrance Mach number, M_o	0.01, 0.05, 0.1, 0.2, 0.3, 0.38, 0.3811
Exit Mach number, M_b	1

To determine the effect of different operating conditions, the system was simulated under various conditions of source and sink pressures. This corresponds to customers coming with different initial conditions of their vehicle fuel tank. A set of theoretical calculation runs with constant source pressure of 24,800 kPa, sink pressure of 101.33 kPa, length of pipe of 5 meters, source and sink initial temperature of 303.15K were conducted assuming different values of entrance Mach numbers. Table 4.1 listed the conditions used in calculation and the result is as shown in Figure 4.1.

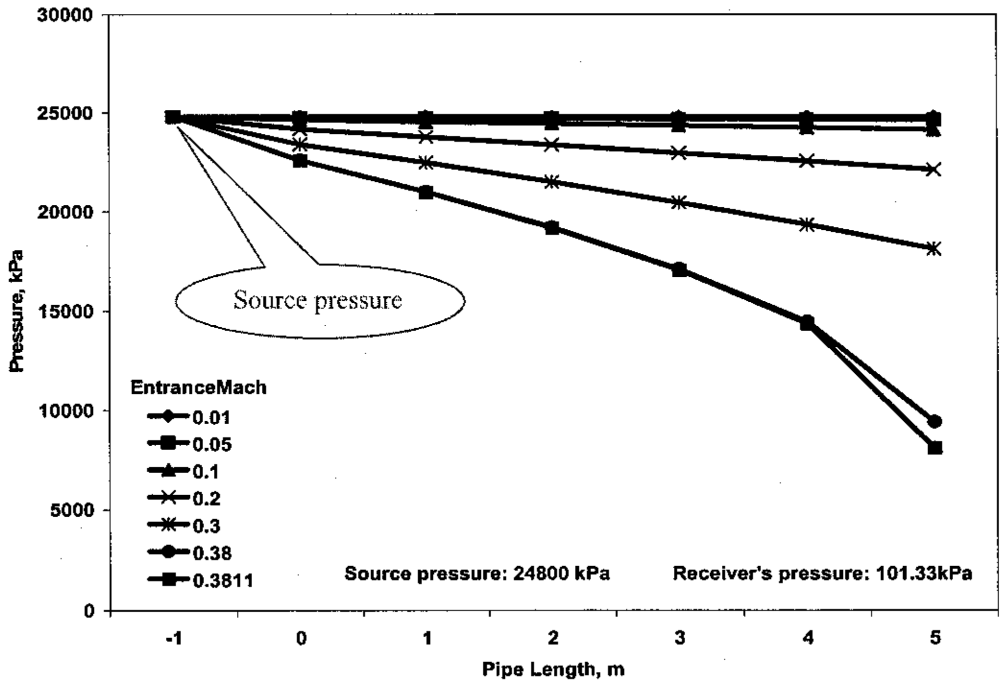


Figure 4.1 Pressure Changes along the Pipeline

At x-axis, '-1'represent the source, while the pipeline starts from '0', which is the pipe entrance, and up to '5' which is the end of the pipe. The pressure decreases along the pipeline, and at higher mass velocities that correspond with the higher entrance Mach number the pressure drops is higher. However in all the cases the exit pressure is much higher than the tank pressure and there will be a pressure discontinuity. In all these cases the exit Mach number is less than one but becomes higher as the entrance Mach number is higher. Ultimately at an entrance Mach number of 0.3811 the exit Mach number is exactly equal to 1. We cannot have a higher entrance Mach number since that will make the exit Mach number higher than 1 that is against the thermodynamic law. Hence the maximum entrance Mach number is 0.3811 to give the exit Mach number exactly equal to 1. With exit Mach number equal to 1, the exit pressure is 8114kPa and if the receiver pressure is less than 8114kPa then choking flow has to take place. The isentropic coefficient, γ value used in the calculation was 1.3.

4.1.2 Effect of Source Pressure on Pressure Distribution along the Pipeline

With the entrance Mach number fixed at 0.3811 a series of theoretical calculations were conducted to determine the pressure at the exit of the pipe. The sink pressure was again assumed constant at a value of 101.33 kPa. Table 4.2 listed the conditions used in calculation and Figure 4.2 shows the exit pressure corresponding to various source pressures.

Table 4.2 Conditions of Theoretical Calculation 2

Parameters	**Value**
Length of pipe, L	5 m
Friction factor, f	0.00365
Isentropic coefficient, γ	1.3
Source pressure, P_o	24,800 kPa, 14000kPa, 7000kPa, 3500kPa, 700kPa
Source temperature, T_o	303.15 K
Receiver's pressure, P_b	101.33 kPa
Receiver's temperature, T_b	303.15 K
Entrance Mach number, M_o	0.3811
Exit Mach number, M_b	1

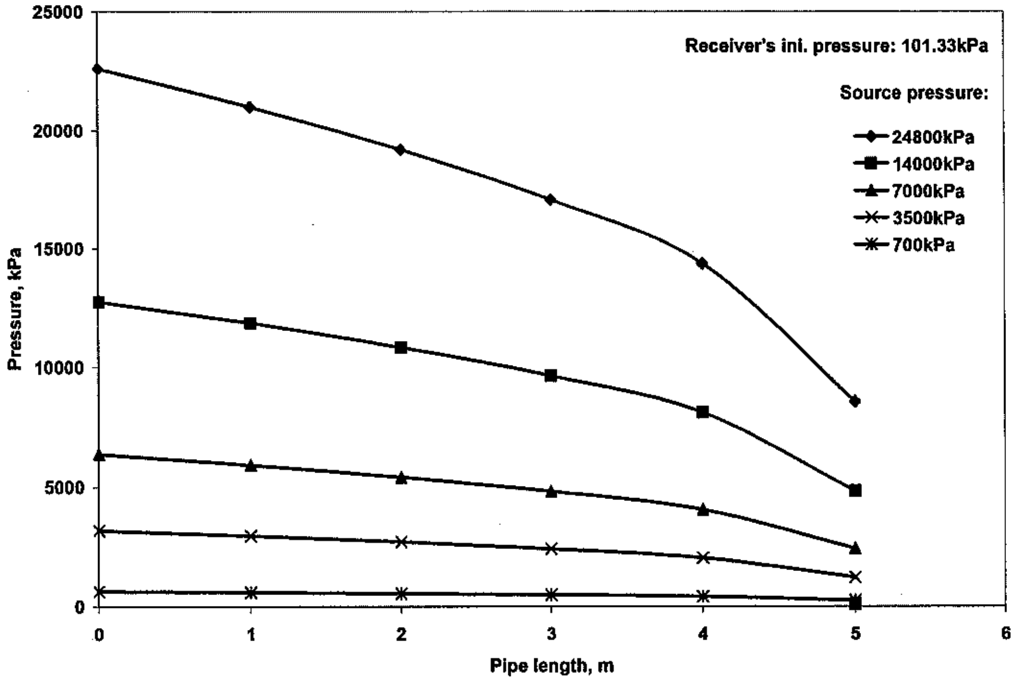


Figure 4.2 Pressure Changes along Conduit for Various Source Pressure

It can be seen that the pressure at the end of the pipe is much higher than the sink pressure. The difference between the two pressures is more for the higher source pressures. This results to increment of the pressure discontinuity between the end of the pipe and the vehicle fuel tank.

4.1.3 Pressure Discontinuity at End of Conduit

When the source pressure is high and sink pressure is low the pipe exit pressure is much higher than the sink pressure. This leads to the pressure discontinuity as shown in Figure 4.3. The pressure discontinuity between the end of the pipe and the vehicle fuel tank allows the highly compressed gas to expand. If gas is allowed to expand adiabatically, it will do work on its environment, and hence its internal energy is reduced. But in this system the work done by the gas is unnecessary work thus this phenomenon results to an energy loss.

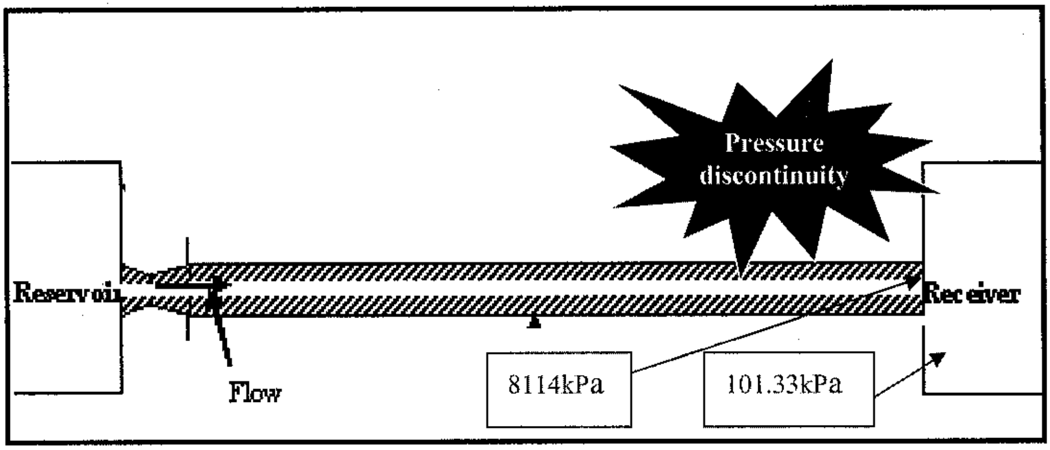


Figure 4.3 Pressure Discontinuities between End of Conduit and Receiver

Energy loss is defined as the internal energy reduction of the compressed gas between two points: starting point at the mother source, and destination point, at the vehicle fuel tank. Energy loss occurs due to friction along the dispensing line during normal flow (Mach number at the pipe exit is less than one). But during choke flow (when Mach number at the pipe exit equals to one) energy loss occurs not only due to friction but also due to sudden expansion of the gas at the pipe exit, causing abrupt changes in its pressure and kinetic energy. The energy loss increases with respect to time; but in contrast to the pressure rate of change, the rate of energy loss is initially constant, then reduced abruptly, as soon as choking condition is overcome by normal flow.

4.1.4 Theory and Experimental Comparison

Validation of the model was carried out based on the comparison between theoretical calculation and experiment for parameters of flow rate and pressure build-up in receiver as shown in Figure 4.4, 4.5, 4.6 and 4.7.

Some changes to the model's variables were made to follow the actual conditions of the test rig. Length of pipe was changed to the actual length of test rig's pipeline and the minor losses due to joints and fittings were included. Due to small scale of the test rig, the source pressure was not constant as assumed. The actual source pressure that was tapped from pressure meter at the source line was fed into the model. Since the source pressure has changed due to the switching from one bank to another, the experimental conditions changed at this point. The sudden increase in flow at 34 second (Figure 4.7) is caused by the switching from one pressure to another, and the model is able to follow this trend faithfully.

Table 4.3 Conditions of Theoretical Calculation vs. Experiment

Parameters	**Value**
Length of pipe, L	10.7 m
Friction factor, f	0.00365
Isentropic coefficient, γ	1.3
Source pressure, P_o	24,800kPa, kPa
Source temperature, T_o	303.15 K
Receiver's Initial Pressure, P_b	7000kPa, 5000 kPa
Receiver's initial temperature, T_b	303.15 K
Initial Entrance Mach number, M_o	0.3811
Initial Exit Mach number, M_b	1

4.1.4.1 Pressure Changes in Vehicle Fuel Tank

Pressure changes inside the vehicle fuel tank are an important parameter to help in verifying the validity of the model. The pressure indicator located at the bottom neck of the tank gave instantaneous pressure readings of the tank during filling. Figure 4.4 and 4.5 shows the comparison between pressure changes obtained from theoretical calculation and experiment for receiver's initial pressure of 7000kPa and 5000kPa respectively.

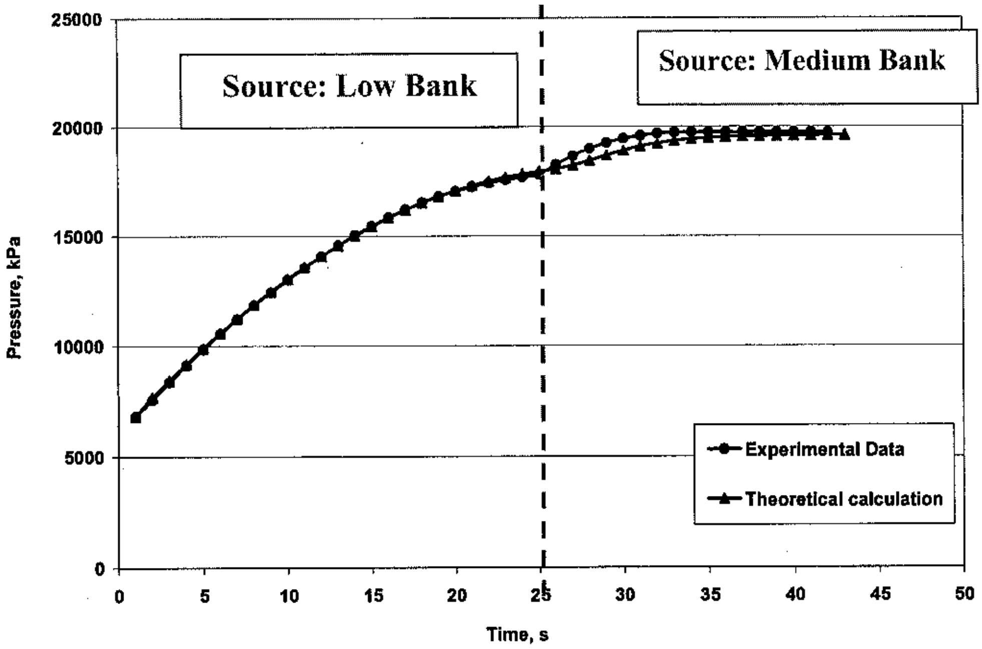


Figure 4.4 Comparisons of Pressure Changes in Vehicle Fuel Tank between Theoretical Calculation and Experimental Data

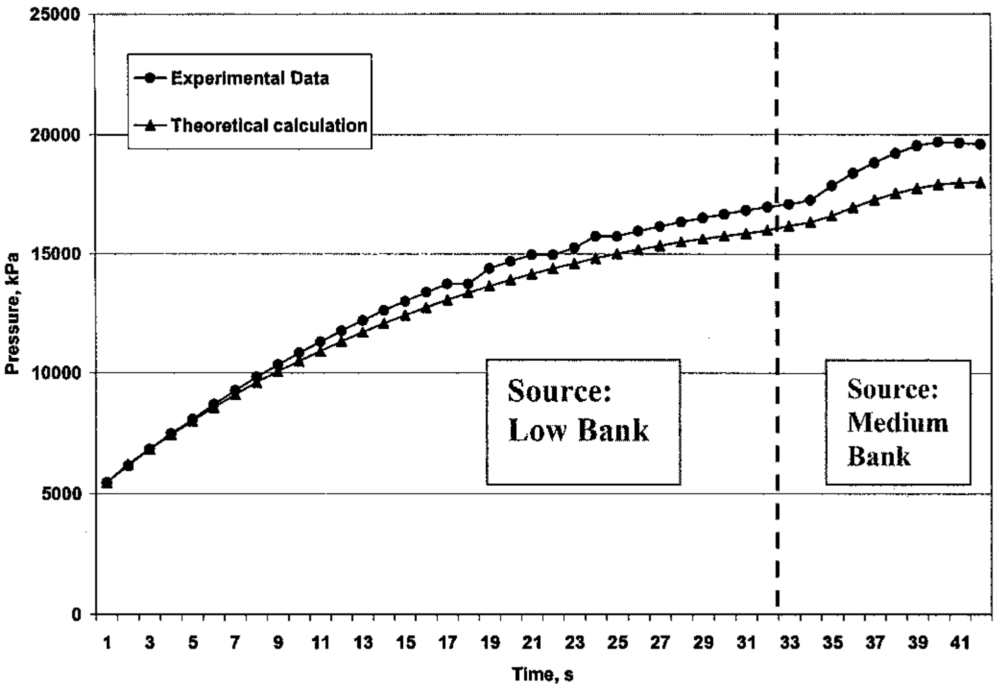


Figure 4.5 Comparisons of Pressure Changes in Vehicle Fuel Tank between Theoretical Calculation and Experimental Data

Due to small scale of the test rig, the source pressure was not constant as assumed. The filling was done starting by filling the gas from low bank. As the filling takes place, the source pressure is decreasing while the receiver pressure is increasing causing a decrease in pressure differential between source and receiver. The pressure changes inside the receiver during this time can be seen from 0 to 26 seconds for experiment with receiver's initial pressure of 7000kPa and from 0 to 34 seconds for experiment with receiver's initial pressure of 5000kPa. After the flow rate has dropped to certain value due to decreasing of differential pressure, the filling of gas was switched to medium bank. At this time, a greater gradient can be seen from the line showing that the pressure built up rate inside the tank is higher than the previous second.

Comparison of pressure changes inside the vehicle fuel tank between experimental data and theoretical calculation results shows a close relation and agreement of the two. Error analysis shows an average error of 0.9% for receiver's initial pressure of 7000kPa and 4.4% for receiver's initial pressure of 5000kPa. Detail comparison is provided in Appendices.

4.1.4.2 Flow Rate Changes

The fact that the source pressure was not constant as assumed can clearly be seen in flow rate changes graph as shown in Figure 4.6 and 4.7. Same as in pressure changes study, the filling was done starting by filling the gas from low bank, when the flow rate has drop to a very low value due to small differential pressure between source and sink, the filling was switched to medium bank to give more drive force for the gas to flow at higher flow rate. The 'spikes' that can be seen inside the graph is caused by the sudden increase of source pressure (switching from low bank to medium bank). Filling with Low Bank can be seen between 0 to 24 seconds while filling with Medium Bank starts at 25 seconds until the filling completed for experiment with receiver's initial pressure of 7000kPa. For experiment with receiver's initial pressure of 5000kPa, filling with Low Bank can be seen from 0 to 34 seconds while filling with Medium Bank can be seen from 35 seconds until the filling completed.

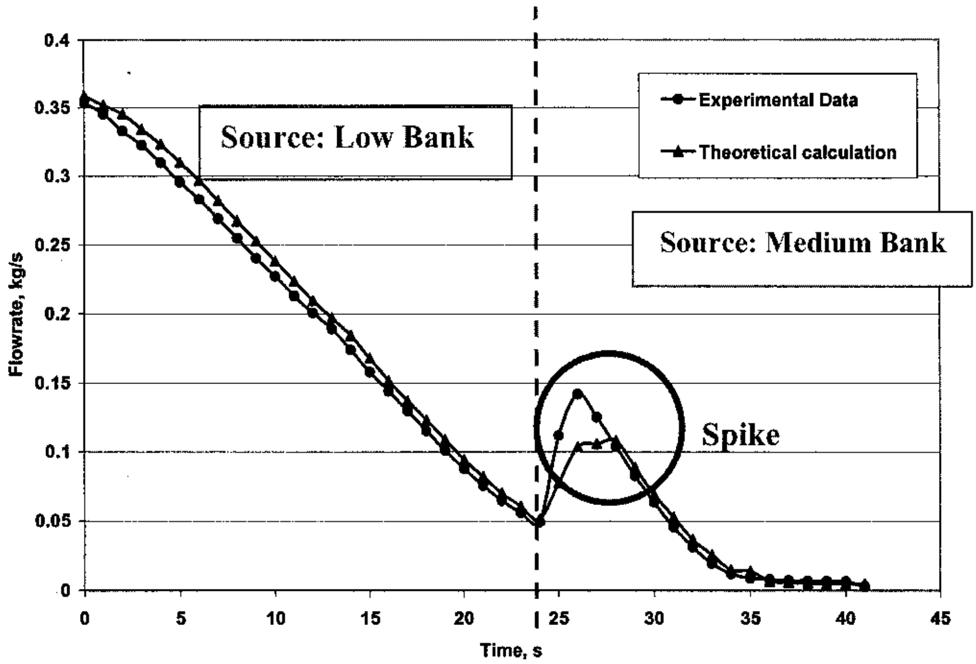


Figure 4.6 Comparisons of Flow Rate Changes during Filling between Theoretical Calculation and Experimental Data

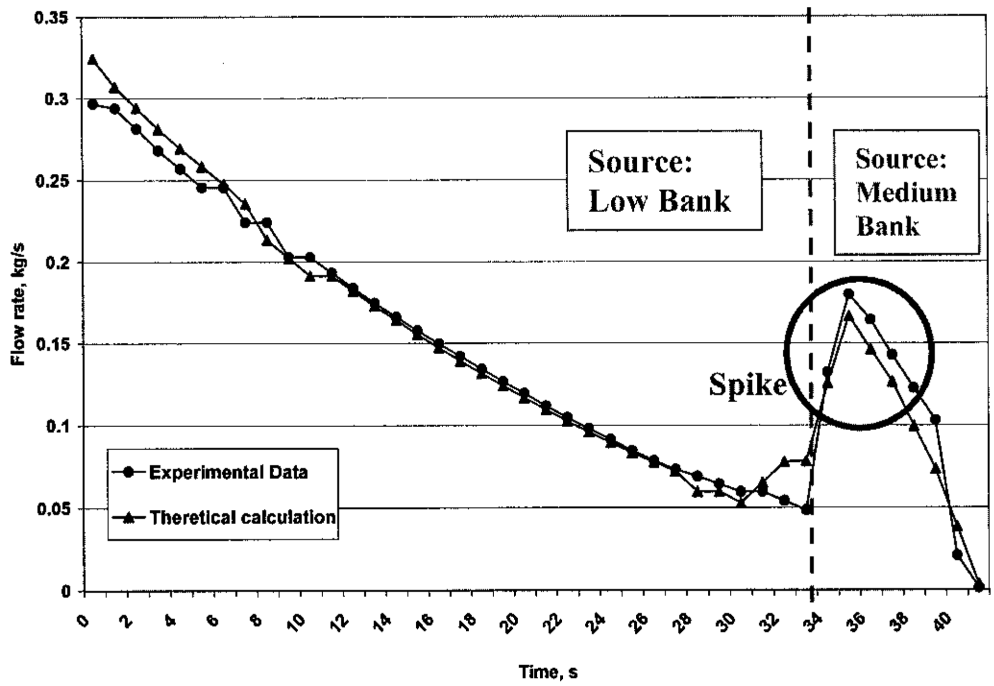


Figure 4.7 Comparisons of Flow Rate Changes during Filling between Theoretical Calculation and Experimental Data

Comparison of flow rate changes inside the vehicle fuel tank between experimental data and theoretical calculation results shows an agreement of the two. Error analysis shows an average error of 13% for both experiments with receiver's initial pressure of 7000kPa and 5000kPa. Detail comparison can be found in Appendix C.

From the above comparisons for the parameters of flow rate and pressure changes during filling, it is clear that the model that has been developed capable to simulate the pressure and flow rate changes of compressible gas inside NGV Refueling Equipment System. The application of this model and the results obtained from this study is capable to help in improving the operation and reducing the operational cost of NGV refueling facility and is further discussed in Section 4.3.

4.2 EOS for Prediction of Natural Gas Properties' Relation

This section will discuss the results obtained from theoretical calculation of prediction of natural gas properties' relation and experimental results obtained from experiments that meant for verification of the selected EOS.

4.2.1 Pressure vs. Mass for Different EOS

A set of calculation was done for every equation of state at constant temperature. The pressure was ranging between atmospheric pressure assuming empty vehicle fuel tank to 21MPa that represent a full natural gas powered car fuel tank. These pressure values are actually the readings that would be obtained from the pressure indicator attached to the fuel tank in actual scenario. Table 4.4 listed the conditions of the theoretical calculations and the same conditions are used throughout the study of this section. Figure 4.8 shows the mass changes in respect with temperature built up in fuel tank.

Table 4.4 Conditions of Theoretical Calculation

Parameters	**Value**
Sink Initial Pressure	101.33kPa
Sink Final Pressure	21,000kPa
Natural Gas Molecular Weight	17.46
Sink Temperature	30°C
EOS Tested	Lee-Kesler-Plocker, Kabadi-Danner, GCEOS, Peng-Robinson, Soave-Redlich-Kwong , Zudkevitch-Joffee and PRSV

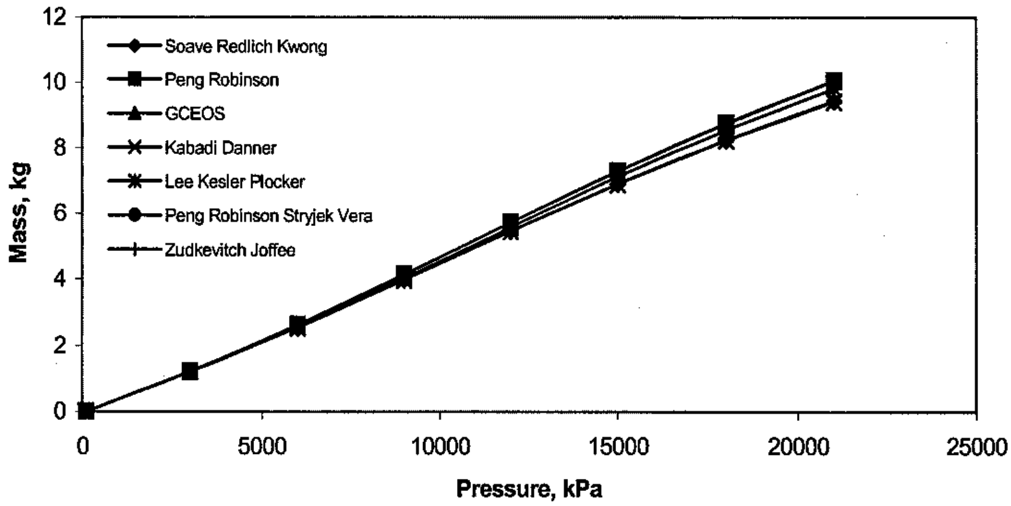


Figure 4.8 Pressures vs. Mass for Different EOS

As shown in the graph, the mass increases with pressure for all equations. Gap between the lines is nearly zero for the first 5MPa and the gap increases as the pressure increases. It shows that at low pressure, all the equations give the same results, but at higher pressure the difference between equations become significant. It can be seen that Peng-Robinson gave the most number of mass accumulated while Kabadi-Danner gave the least. From the graph it can be said that all equations are giving the same pressure – mass relation pattern with small difference between each other. Therefore it can be concluded that all the equations tested is applicable to the system and selection of the most suitable equation can be preceded.

4.2.2 Pressure vs. Mass at Different Temperature

Another set of calculation was performed at 25°C, 30°C and 40°C to see the temperature effect to the system. Figure 4.9 shows the temperature effect for Peng-Robinson equation.

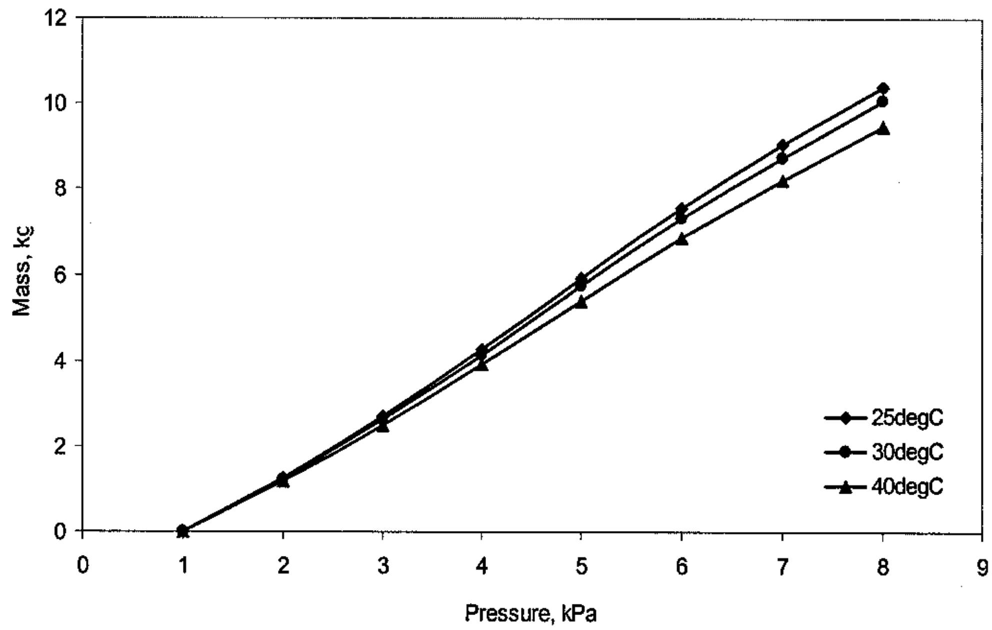


Figure 4.9 Pressures vs. Mass at Different Temperature for Peng-Robinson EOS

At 25°C the amount of gas at final pressure, 21,000kPa was the highest compared to the results for calculation performed at 30°C and 40°C. For Peng-Robinson equation, the difference of mass calculated at 25°C and mass calculated at 40°C is 0.92kg. Table 4.5 summarized the temperature effect to the mass of gas for Peng-Robinson equation.

Table 4.5 Summary of Temperature Effect on Peng-Robinson's Equation

Temperature, °C	**Difference of mass, kg**
25-40	0.92
30-40	0.59
25-30	0.32

It is can be summarized that for temperature difference of -15°C, the mass is less by 0.92kg and for temperature difference of 5°C the mass is less 1/3 of it. From here, it is known that temperature is not a negligible variable and individual temperature for each pressure increment should be taken into account in the calculation.

4.2.3 Theory and Experimental Comparison

To determine the most accurate EOS for natural gas application, a series of experiments were conducted using the test rig. Table 4.6 listed the conditions of experiment and theoretical calculations used to obtain the result showed in Figure 4.10. The results are then compared with theoretical calculation using the EOS.

Table 4.6 Conditions of Experiments and Theoretical Calculation

Parameters	**Value**
Sink Initial Pressure	475.61kPa
Sink Final Pressure	18624.50kPa
Natural Gas Molecular Weight	17.46
Sink Initial Temperature	29.2°C
Sink Final Temperature	33.8°C
EOS Tested	Lee-Kesler-Plocker, Kabadi-Danner, GCEOS, Peng-Robinson, Soave-Redlich-Kwong , Zudkevitch-Joffee and PRSV

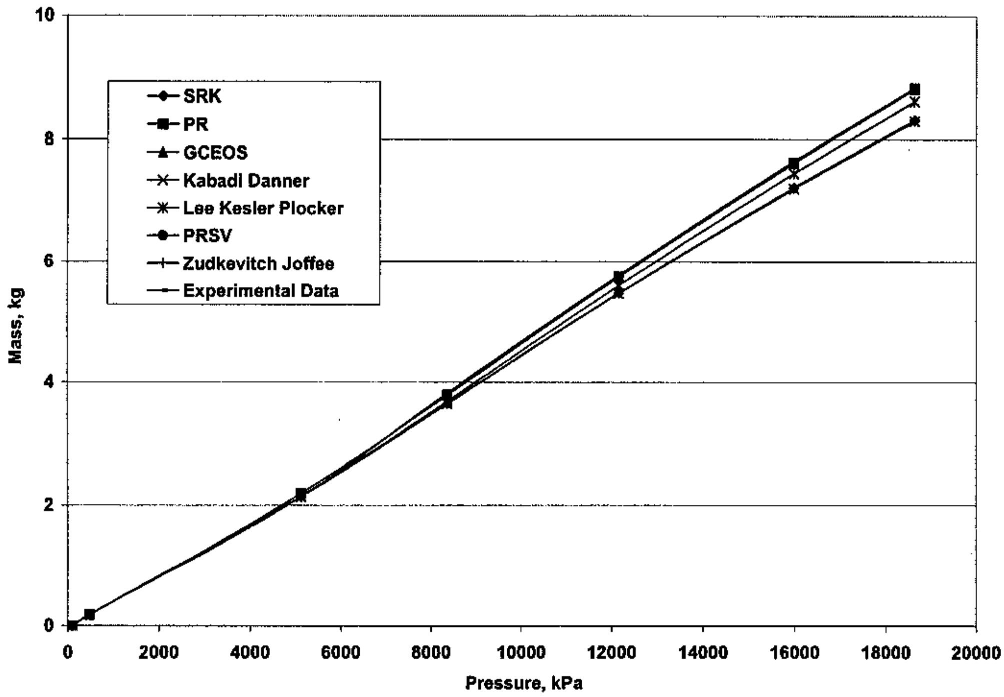


Figure 4.10 Pressures vs. Mass for Different EOS

Comparison between experimental data and results calculated by different equations was carried out and the result is shown in Figure 4.7. From the graph, it can be seen that Peng-Robinson gave the closest result to experimental data compared to other equations.

An error analysis was conducted to find the equation that gives the closest value to the experimental data. 'Error' was defined as:

$$Error = Abs(m_{calculated\ by\ EOS} - m_{experimental\ data})/\ m_{experimental\ data}\ x\ 100\%$$

To find the best equation, mean error for every equation was compared; the equation that gives smallest mean error is chosen as the best equation for the system.

Mean Error =Total error/ number of readings

Table 4.7 Comparison between Experimental data and Calculations Results

Pressure kPa	Absolute Error, %						
	SRK	PR	GCEOS	KABADI	LEE	PRSV	ZUD
475.61	0	0.24	0.24	0.01	0.01	0.24	0
5114.50	0.04	2.53	2.49	0.02	0.33	2.49	0.04
8354.14	4.54	0.93	1.00	4.65	3.55	1.00	4.53
12152.11	5.12	0.45	0.55	5.27	2.97	0.55	5.09
15977.64	5.65	0.25	0.37	5.83	2.58	0.37	5.60
18624.50	5.88	0.08	0.20	6.06	2.43	0.20	5.82

From Table 4.7, the error was found to be fluctuating for all equations. Some equations gave smaller error at low pressure but the error becomes greater as the pressure increases. The Peng-Robinson equation of state gave the smallest average error and thus the best results among all the equations tested with maximum error of 2.5%. Peng-Robinson's error is significantly less at pressure of 18,624MPa that is only 0.08%. From here it can be said that Peng-Robinson equation can represent the system with sufficient accuracy compared to other equations. The detail error for each equation is listed in Table 4.8 below.

Table 4.8 Error between Experimental Data and Calculated Value by EOS

Pressure, kPa	**Error, %**						
	SRK	**PR**	**GCEOS**	**Kabadi Danner**	**Lee-Kesler-Plocker**	**PRSV**	**Zudkevich Joffee**
475.607	0	0.243	0.24	-0.006	-0.012	0.24	0
5114.5	0.042	2.532	2.488	-0.023	0.333	2.488	0.044
8354.14	-4.543	0.929	1.002	-4.652	-3.551	-1.002	-4.530
12152.11	-5.116	0.446	0.551	-5.272	-2.972	-0.551	-5.088
15977.64	-5.649	0.252	0.374	-5.829	-2.576	-0.374	-5.600
18624.5	-5.884	0.08	0.204	-6.065	-2.434	-0.205	-5.822
Mean Error							
	0.432	***0.019***	0.029	0.446	0.197	0.029	0.428

4.3 Method to Reduce OPEX of NGV Refueling Equipment

From the results of the study of Compressible Gas Flow Modeling that has been discussed in Section 4.1, it was found that energy loss occurs during filling of gas from 24.8MPa source to atmospheric pressure of NGV assuming the vehicle comes with an empty tank. To minimize the effect of energy loss, the pressure discontinuity that occurs at the tip of dispenser prior to entering the vehicle fuel tank should be eliminated by either lowering the source pressure or increasing the receiver pressure. As the vehicle tank's pressure depends on the customers' side, it is more reasonable to focus at lowering the source pressure at the filling station. However, there is a constraint in the effort of minimizing the pressure source, because the pressure level must always be ensured to provide sufficient driving force for the gas to flow, especially when the vehicle tank is almost full. Therefore, instead of simply reducing the pressure, it is more practical to divide the single source pressure into a series of pressures, from low to the standard value of 24.8MPa. By having this multilevel pressure source, not only energy loss can be minimized but the compression energy could also be reduced thus contribute to reduction in NGV refueling facility's OPEX.

4.3.1 Minimization of Energy Loss and Compression Energy

To study how energy loss can be minimized by using multiple-pressure sources, a set of theoretical calculation was carried out with a series of different number of intermediate sources by calculating the energy required for compressing the amount of gas, from the gas supplier's source to the high-pressure source by using multi-stage adiabatic with intercooling. In the current NGV refueling stations in Malaysia, only one level, 24.8 MPa, is used for gas discharging. Therefore, for this project, a single source at 24.8 MPa is taken as the reference case for optimization. Following task aims to add intermediate sources between the low and high-pressure source. Figure 4.11 shows the energy loss reduction in a gas filling system with two, three, and four sources respectively.

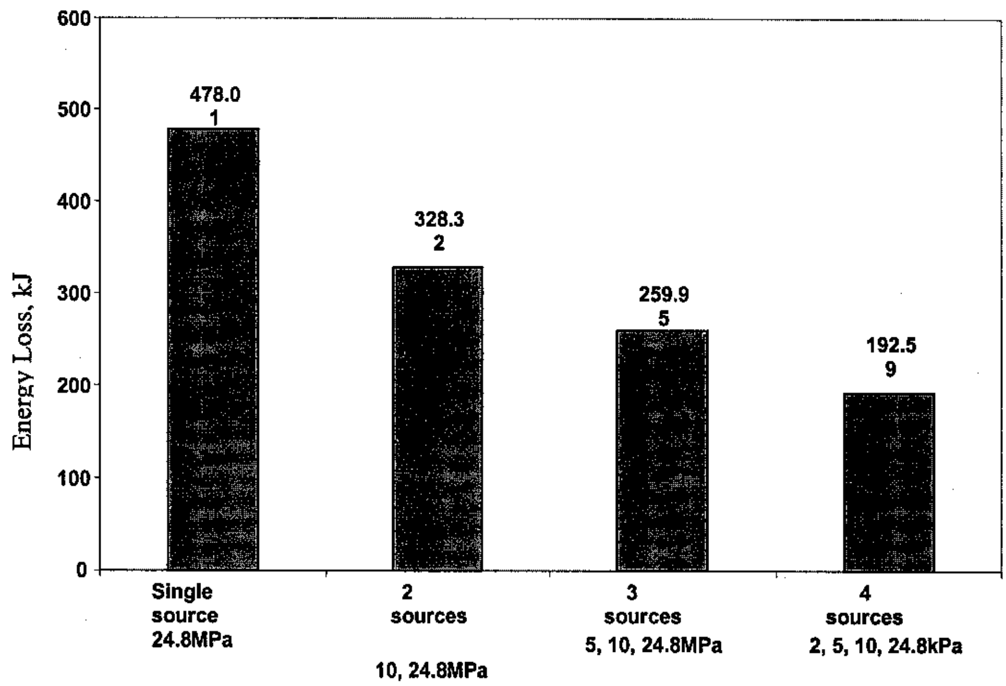


Figure 4.11 Energy Loss vs. Multi pressure level Sources

When the pressure source is lower, the pressure gap between the source and the receiver is lessened; which helps eliminate choked flow condition. Consequently, the energy loss reduces significantly. In short, as the pressure of the source is lower, or the number of sources increases, the energy loss will reduces.

From the previous part, the total amount of gas filled into the vehicle tank, from different sources, are identified. This section continues to calculate the amount of energy required for compression of gas, from the initial supply condition. Theoretically, there are three different compression paths namely isothermal, adiabatic only, and adiabatic with inter-cooling. By using various ways of compression, the corresponding work requirement is different. As expected, the work required for isothermal compression is the lowest, which makes the process very attractive, yet almost infeasible in normal operation. The highest amount of work is demanded by adiabatic compression without inter-cooling process. Two-stage adiabatic compression with inter-cooling offers a better option, in which the energy requirement is reduced by 31.3 % (shown in Figure 4.12). The result has also shown that the more intermediate stages a compressor has, the smaller amount of work input it requires. However, economic trade-off must be taken into consideration as the capital cost of the compressor also increases when the number of stages increases. Thus in present project, the existing compression system which applying 3 stage compression is maintained to avoid major additional capital cost.

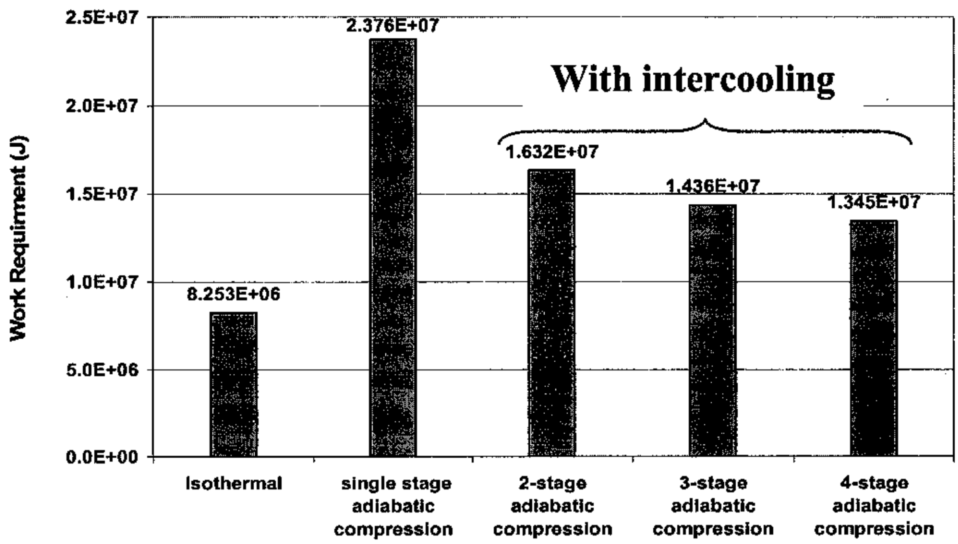


Figure 4.12 One Source (24.8 MPa)-Energy Requirement versus Compression Paths

The current compressing system utilizes a three-stage compressor, which compresses gas completely to 24.8 MPa before discharging to individual vehicles. Even though the compressor is optimized by using multistage compression, the gas is still being compressed to very high pressure. As highly compressed gas associates with great amount of energy requirement, the total energy cost for compression will still be significant; making the process uneconomical.

For an energy improvement, the project proposes that when an empty vehicle comes for filling, instead of receiving gas from one single source at 24.8 MPa, it will first be filled from the lower pressure source and when the automobile receiver tank reached a certain value, i.e. 90% of the low pressure source, the filling will be automatically switched to a medium source pressure. Ultimately, it will be topped up with the highest one, 24.8 MPa.

There is no need to build up separate medium sources and install new compressors. Instead, the system can extract compressed gas from the cylinders at each stage of the compressor to be intermediate sources, to make full use of the available pressurized gas. To enable that, a new system of pipeline connected from the compressor's cylinder directly to the receiver should be implemented.

To determine the optimum value of intermediate pressure for the multiple source pressure system, another set of theoretical calculation was conducted. The theoretical calculation was performed to study the energy requirements for different source pressures. The source pressure was varied from 1MPa to 14MPa and the results are as shown in Figure 4.13.

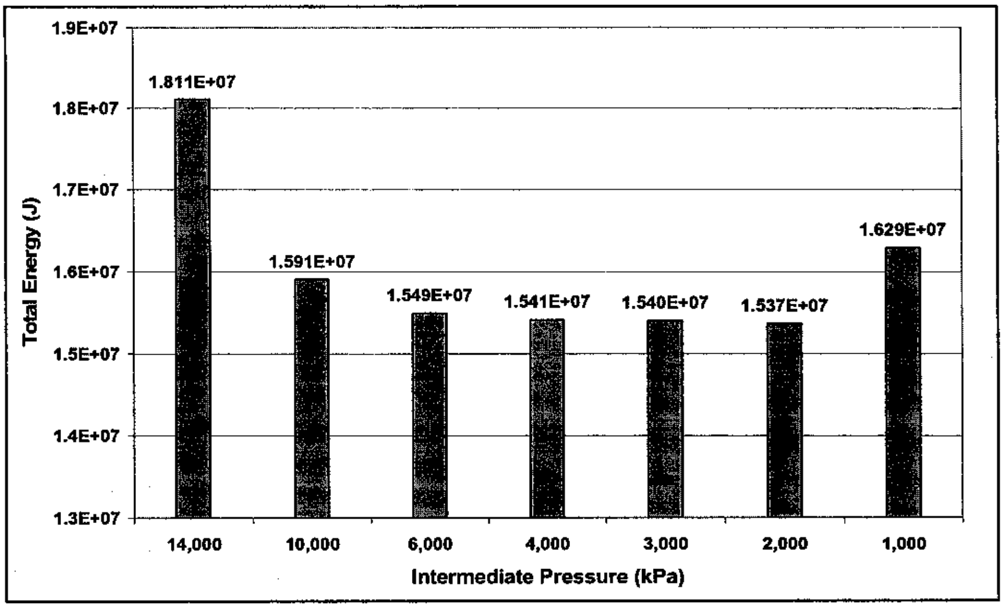


Figure 4.13 Energy Requirements vs. Source Pressure

Based on the current compressing system (three-stage adiabatic compression), the energy requirement for potential alternatives was compared (Figure 4.14). It is clear that when the number of sources increases, there is a significant reduction in work requirement. While a series of two sources result in a higher energy requirement than the base case (107.05%), increasing two sources to three and four sources results in a paramount reduction (24.56% and 29.16% respectively). Although four-source interconnected system achieves a higher energy saving, its drawback is the capital cost of the compressor will increases as the number of stages increase. Therefore, when making decision in whether or not further increasing the number of compression stages to four and above, economic analysis must be considered carefully to balance the energy cost saving with the increments of the capital cost.

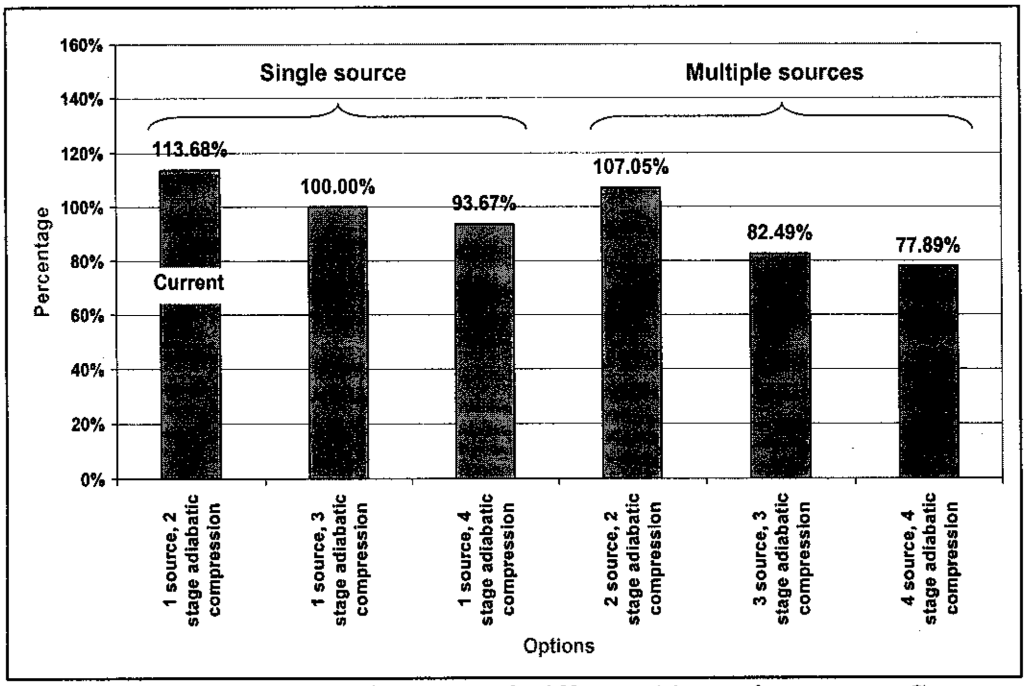


Figure 4.14 Energy Requirements of Different Alternatives versus Current System

As mentioned in the previous part, energy loss is an important parameter to be considered. The analysis result is shown in Figure 4.15. For single-source filling system, irrespective of the number of compression stages, the energy loss is constant, as it is a function of the number and the pressure level of sources filling gas to vehicles. When the number of intermediate sources increases, energy loss reduces. The energy loss reduction when increasing from one source to two, three and four sources is 5.2%, 39.6%, and 41.2% respectively. The sudden drop in energy loss, when increasing from 2 to 3 sources, is explained by the choked flow concept. As two sources are fixed at 2 and 24.8 MPa, which still have relatively large pressure difference, choked flow occurs again when the filling is switched. For three sources of 2, 10 and 24.8 MPa, choked flow does not reoccur, due to the introduction of the intermediate source, 10 MPa, acting as a buffer. Further increasing from three to four sources continues lowering the energy loss, but the reduction is not as significant.

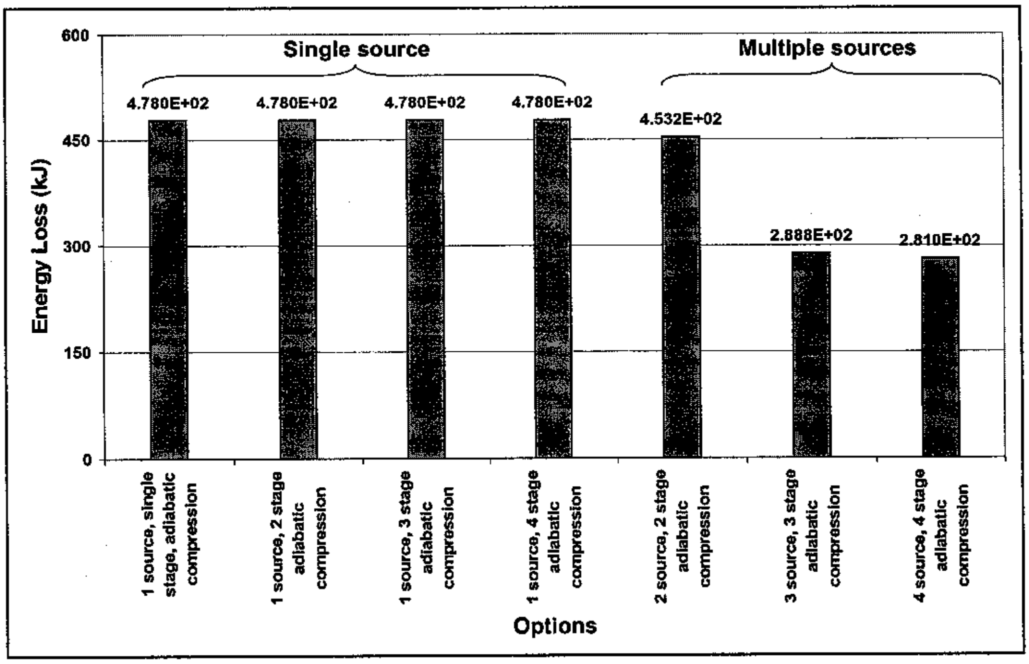


Figure 4.15 Energy Losses versus Alternatives

In short, after analyzing both energy demand and energy loss associated with different alternatives, it is suggested the three-source filling system be implemented.

4.3.2 Conceptual Diagram of the Three-source Filling System

The modification of the gas flow scheme from the current system to a new system using a series of three different sources is shown in Figure 4.16 and 4.17. The current system which using three stage compression is maintained. The new system is designed in such a way to enable the system to extract compressed gas from the cylinders at each stage of the compressor to be intermediate sources, to make full use of the available pressurized gas by installing new piping system which connecting the first and second stage of compressor's cylinders directly to the vehicle tank. By implementing the new system, the compression cost is reduced with very minimal additional capital investment involved.

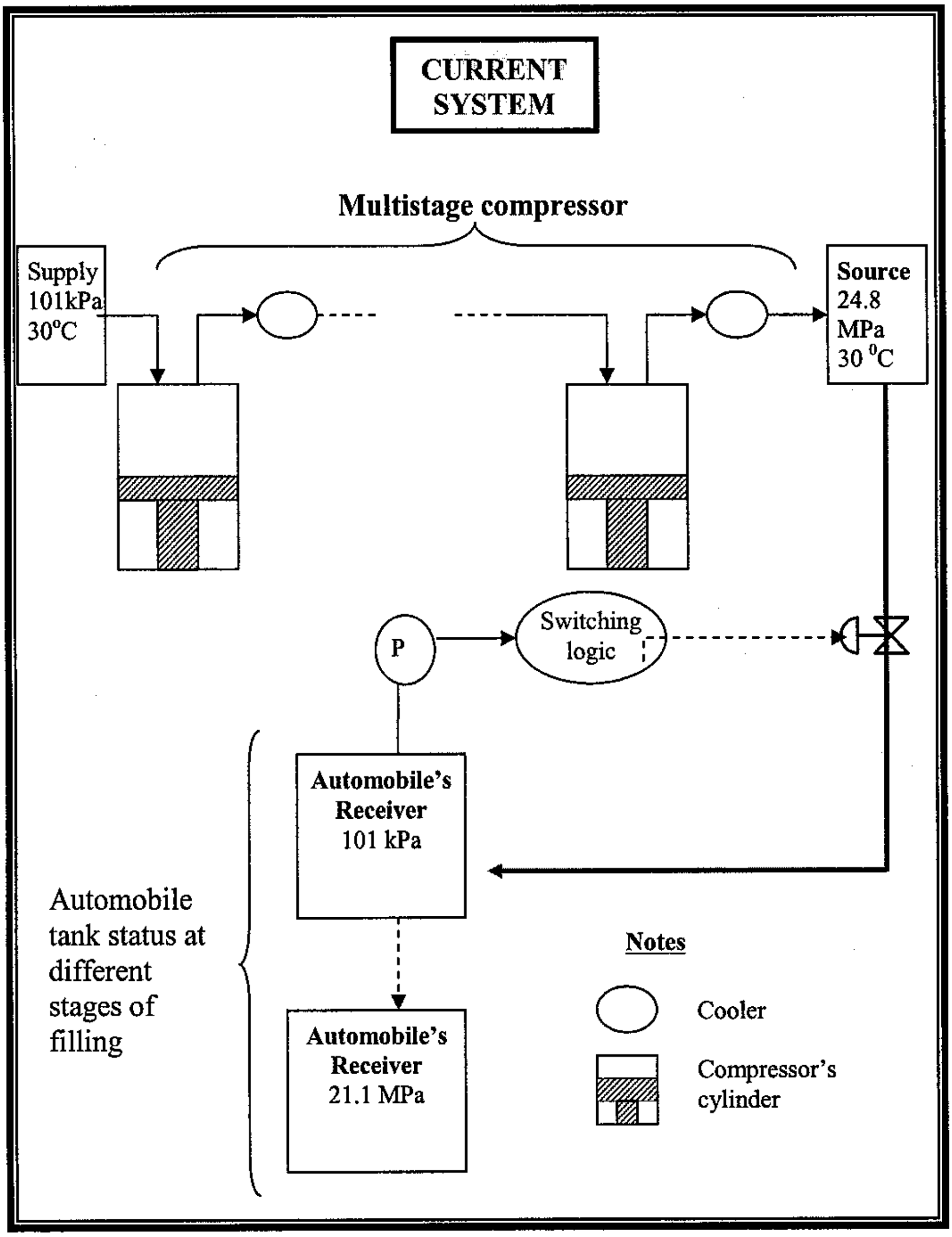


Figure 4.16 Conceptual Diagram for Three-Source-Filling System (Current System)

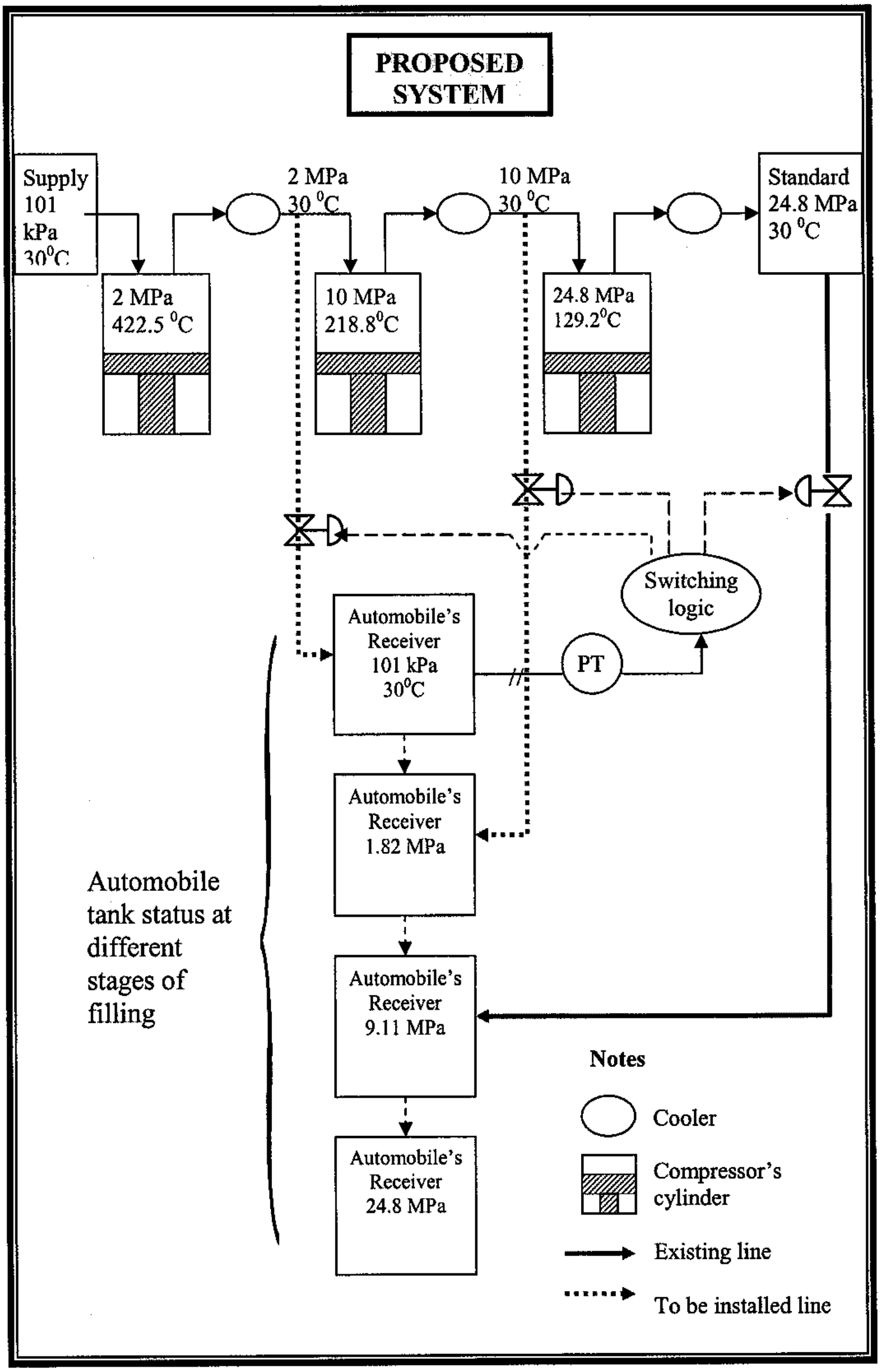


Figure 4.17 Conceptual Diagrams for Three-Source-Filling System (Proposed System)

4.3.3 New Filling System: Work Requirement versus Initial Condition of Receiver

All of the energy above used the assumption of empty vehicle tank. In fact, at the start of the filling process, the receiver's pressure could have different values, which sometimes can be up to 75% full. The energy requirement for different initial pressures in the tank has been studied in another set of theoretical calculation. In this study, under a series of constant source tank pressures, different initial automobile storage pressures are considered. The sources are set at 2 MPa, 10MPa, 24.8 MPa sequentially, obtained from the previous result, and whereas the automobile tank initial pressure are varied from empty tank up to 75% full tank.

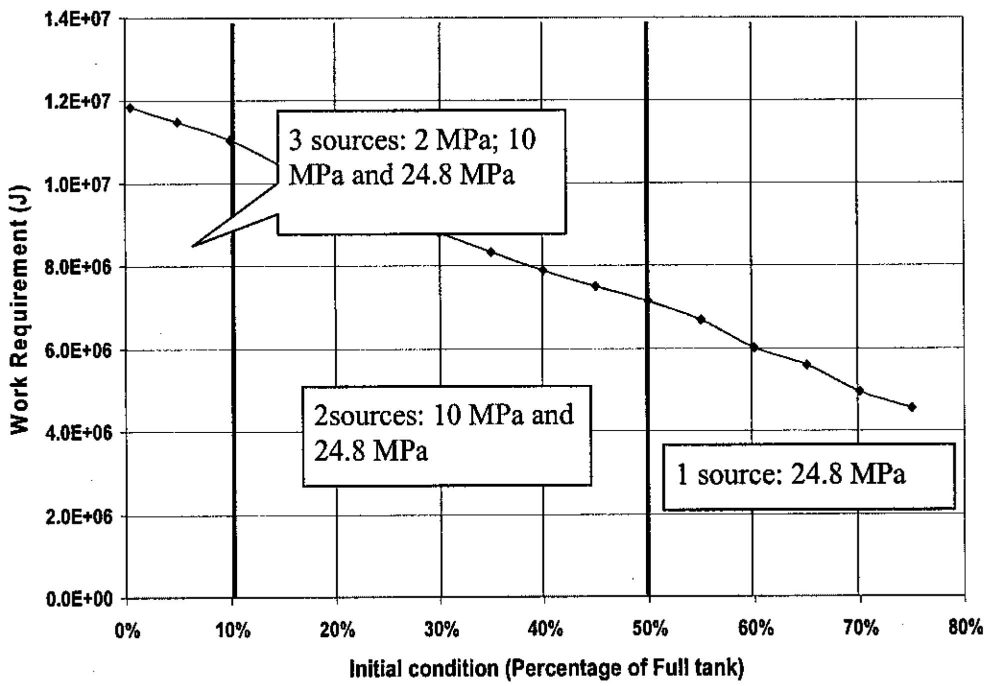


Figure 4.18 Work Requirement for Compression with Respect to Different Initial Receiver's Content

As shown in Figure 4.18, the work required reduces as the initial content of automobile's tank increases. When the initial content of the automobile's tank is less than 10% of its capacity, the filling should start with the lowest source, 2 MPa. However, when the automobile contains equal or more than 10% of its full capacity ($P \gtrapprox 2.1$ MPa), 2 MPa source does not have sufficient pressure energy, hence, the refueling should start from the second stage 10 MPa source. Similarly, when the automobile's content is equal or more than 50% of its full capacity ($P \lessapprox 10.5$ MPa), the refueling process only need to use the highest source of 24.8 MPa.

4.3.4 Malaysian NGV Fuel Tank Initial Condition

An automobile coming for refueling to an NGV station will have different conditions with respect to pressure and temperature in its fuel storage tanks. To determine initial pressure and temperature condition of Malaysian NGVs, a survey has been conducted at one of NGV refueling station at Shah Alam, Selangor [13]. The survey was conducted with the help of Gas Emas Corporation Sdn. Bhd., the contractor who installed the dispenser.

When the first taxi comes for refueling, the driver is informed about the survey that's being conducted to get their corporations. They are requested to open the vehicle's trunk where the fuel storage tank is located to detect tank's temperature. The cascaded storage pressure was collected from the control panel room. To detect pressure inside the fuel tank, first the dispenser nozzle was connected to the vehicle fuel tank receptacle, then by using a 'communicator', a device that's similar as remote control that capable to communicate with dispenser's display panel was used to change the 'liter equivalent' to 'pressure inside the tank' display. The pressure that's displayed at the display panel would give the fuel tank initial pressure. Simultaneously, initial temperature of the fuel tank is detected using portable surface temperature detector. The initial pressure, initial storage pressure as well as the initial temperature were then recorded. Before filling switch is turned to "ON", stopwatch is set to record the refueling time. The stopwatch and refueling switch is turned on simultaneously. After the filling completed, the final temperature, final pressure, final storage pressure and filling time were recorded. The survey was conducted from morning to midnight for 1000 number of vehicles that consisted of NGV taxis and personal vehicles. Figure 4.19 shows the initial pressure distribution for Malaysian NGVs in Klang Valley for 1000 number of vehicles. It can be seen that the most vehicles those come for filling has initial pressure of 100psi and below. From further analysis on the data, it was found that average initial pressure of Malaysian NGVs that comes for refueling is 60psi or 413.6kPa (1.97% of full tank).

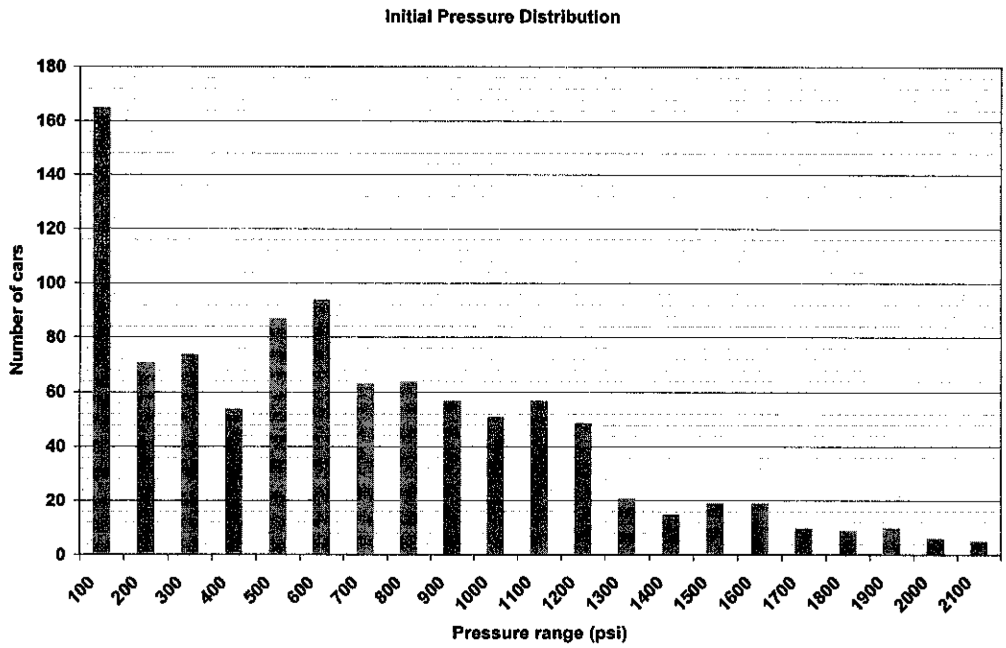


Figure 4.19 Frequency Distribution of Initial Tank Pressure of NGV Vehicles Coming to NGV Stations for Refueling

From this survey, it shows that with existing refueling system, lots of energy has been lost during filling and the proposed three-stage-pressure-source is necessary to minimize energy losses.

4.3.5 Economic Analysis

From the literature study in the previous section, the cost of compressing 1 GLE of gas is estimated at 2.5 cents US. Estimated by NGVs, the total natural gas consumption by NGVs in Malaysia per day is 100,000 GLE. Therefore, by saving 17.5 % energy consumptions from the new filling system, the estimated saving on operating cost will be 0.89 millions ringgit per year, without any further increment in capital cost. (Detailed estimation is provided in the Appendix D). This figure at the present time may not be so important; as it is estimated on the current 15,600 NGVs in Malaysia. However, the expecting number of NGVs in year 2006 will increase to 40,000 while in year 2010, it is estimated that Malaysia will have about 54,000 NGVs [8] and it will continue to rise strongly years after. As shown in Figure 4.20, the annual savings is increasing from RM 0.89 millions in 2005 to RM 2.29 millions in 2006 and RM3.09 millions in 2010. As the number of NGV in Malaysia increases, the annual savings also increases significantly. As a result, the economic potential of this project cannot be ignored, as it promises to reduce the operating cost of NGVs filling stations significantly.

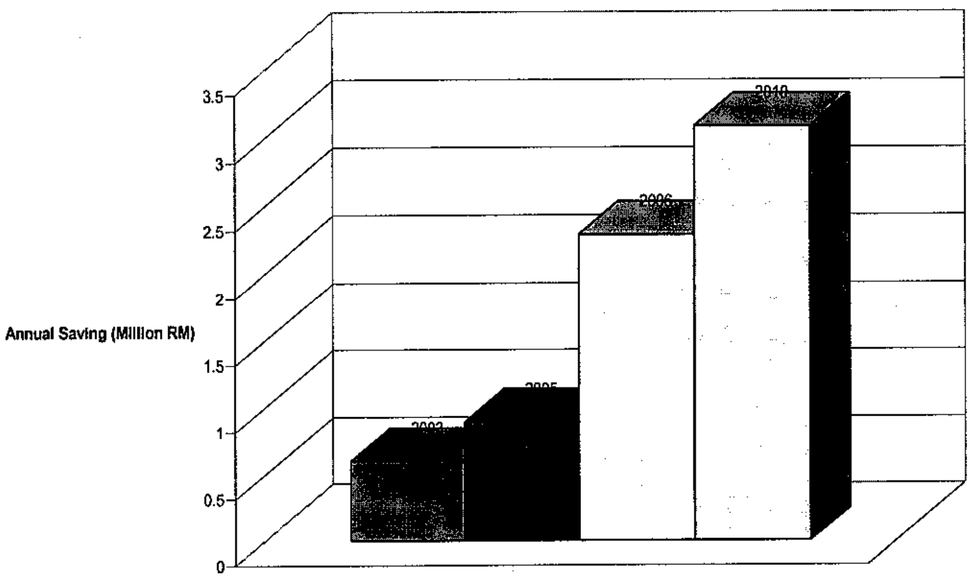


Figure 4.20 Estimation of Annual Savings on NGV Station OPEX

4.4 Method to Reduce CAPEX of NGV Refueling Equipment

From the results of study of equation of state which has been discussed in Section 4.2, it is expected that some reduction in CAPEX specifically in its metering system can be achieved by introducing a new metering system based on an equation of state. This EOS Metering System is a metering system which uses no flow meter but only an EOS to calculate the amount of gas dispensed into the vehicle by utilizing gas's pressure and temperature values.

4.4.1 Concept of EOS Metering System

The concept of this EOS metering system is without the use of any flow meter, the mass of gas filled to the NGV fuel tank, is calculated by utilizing its pressure and temperature by an equation of state [43].

The calculation of mass of gas in fuel tank was made using HYSYS Program. The car fuel tank has a volume of $0.055m^3$ with a temperature and pressure indicator attached to it. These indicators would give readings of the temperature and pressure inside the tank as the inputs of the software.

4.4.2 Varying Natural Gas Composition Effect

The amount of gas dispensed into a vehicle may vary with different composition of gas. Variation in composition of gas gives different value of molecular weight. From the simplest equation of state i.e. Ideal Gas Law it is known that at certain pressure, higher molecular weight gives higher mass. From the natural gas composition data collected from PRSS, the richest composition gives molecular weight of 18.3 while the leanest composition gives molecular weight of 16.7. The difference in mass that affected by molecular weight is about 1.32kg for Peng-Robinson equation at 21MPa.

In NGV industry, this difference would clearer if seen in terms of calorific energy instead of mass. Calorific energy is defined as calorific values multiply by mass and has a unit of kilojoules (kJ). Calorific value in the other hand is defined as the heat energy evolved by the combustion of unit quantity of fuel. From this definition, it is known that calorific energy is directly dependant to mass and is affected by natural gas composition variation. To minimize the composition effect, the average value was taken in present calculation. An error analysis due to natural gas composition was carried out to see the impact that may affect the calorific value of natural gas dispensed into a vehicle. Figure 4.21 shows the error analysis on natural gas composition.

Positive error was defined as the calorific value gained by the customer when the actual calorific value is a higher than the average value. Similarly negative error was defined as the loss to the customer when the actual calorific value is less than the average value. By taking the average value, the loss that NGV refueling equipment's operators would face in case of natural gas composition at that time is 'rich' is about 15100.3kJ while, the loss that NGV drivers would face in case of natural gas composition at that time is 'lean' is about 14402.7kJ. Compared to the loss that NGV refueling equipment's operators or NGV drivers would face if the calculation were done based on richest or leanest composition only, but the actual composition at that time is the opposite is about 29503kJ which is about double of previously calculated loss. From this analysis, it is learnt that this new measurement system is giving a very fair measurement for both natural gas retailers and the customers.

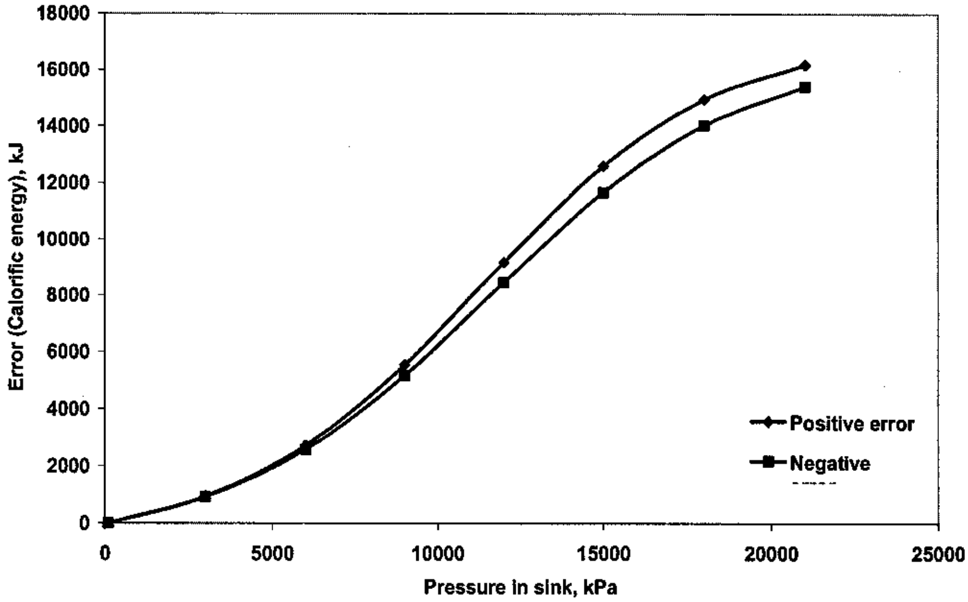


Figure 4.21 Error Analysis on Natural Gas Composition

4.4.3 Proposed Implementation of EOS Metering System

The concept of the hardware implementation of the EOS Metering system is as in Figure 4.22. The car fuel tank must come with pressure and temperature sensor to detect the pressure and temperature of the gas that has been filled into the tank. These pressure and temperature data is then transmitted to EOS software through Fieldpoint system for calculation of mass. The mass will then be displayed at the dispenser's display panel.

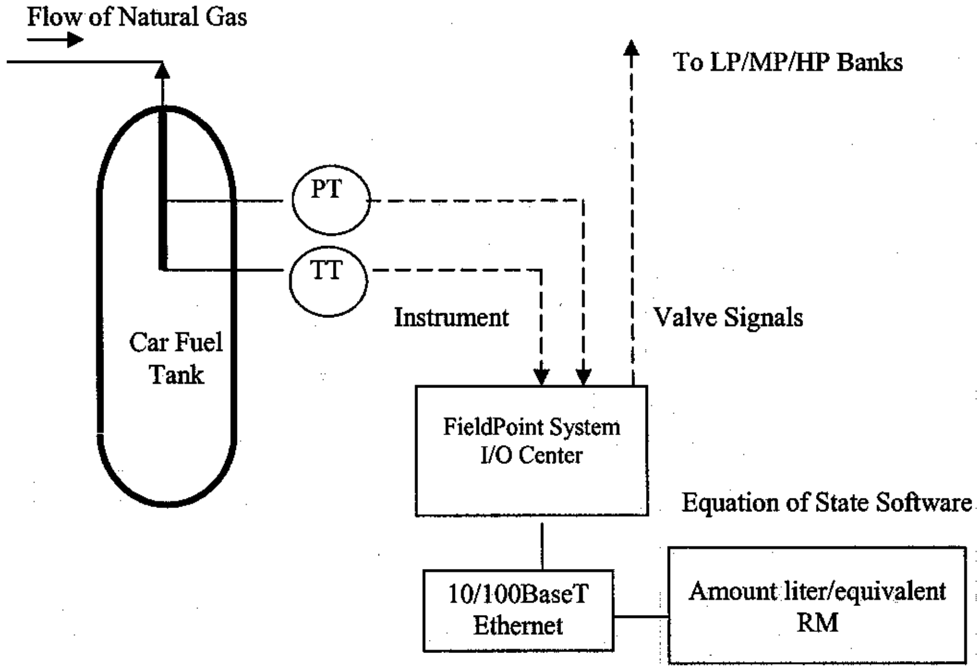


Figure 4.22 Hardware Implementation of EOS Metering System

4.4.4 Economic Analysis

The market unit price for Coriolis Flow Meter ranges between RM 20,000 to RM50, 000. The typical 2 hose dispenser that has 2 units of Coriolis Flow meter inside it cost about RM 120, 000. From total cost of NGV dispenser, 33.3% of it is calculated for the cost of flow meters. The proposed EOS Metering System is believed to reduce the cost of NGV Dispenser from RM120, 000, which is the current market price to RM80, 000.

CHAPTER 5

CONCLUSIONS AND RECCOMMENDATIONS

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The mathematical Fanno Flow Model developed is able to predict the changes along the pipeline and the vehicle fuel tank in terms of pressure, temperature, density, gas content and the energy loss associated. Based on this study, an optimized gas filling schedule, which aims to reduce the energy requirement for compressing natural gas, has also been successfully developed. With the assumption of empty vehicle tank as the initial condition, the best option is using a series of three different sources, with the sequential pressurized level at 2 MPa, 10 MPa and 24.8 MPa. By using the new schedule, the energy saving will be able to achieve 17.5% reduction compared with the current compression system.

The EOS study enables easy prediction of natural gas properties by using Peng-Robinson Equation of State. From this study, a conceptual metering system that uses no flow meter at all has been achieved. The implementation of the meter-less metering system is believed to reduce the cost of natural gas dispenser by at least 30% compared to the current market price.

In conclusion, this project has provided the basis for the future optimization study of NGV Refueling Station.

5.2 Recommendations for Future Work

In the course of conducting the research, a number of challenges are encountered. These challenges can be pragmatically seen as potential areas to be further explored and developed. A number of extension work based on the framework can also be pursued to further promote this concept. These issues are summarized here to stimulate research interests.

5.2.1 Multi-Level-Pressure Storage System

The present research work has been developed to bring forward the concept of multi-level-pressure storage in Cascaded Storage System for NGV Refueling Equipment. Due to the limited capability of the test rig, experimental filling process with multi-level-pressure storage couldn't be conducted. A modification to the test rig control system is necessary to implement multi-level- pressure storage to the test rig in order to conduct the experiment. From the experiment, further optimization could be planned to further improve the filling efficiency and further reduce the compression energy.

5.2.2 EOS Metering System

The present research work has been developed to bring forward the concept of EOS Metering System. Selection of the EOS for the system was limited to the equations that are available in HYSYS. Further exploration to the other equations or some modifications to the selected EOS is necessary to further reduce the error between experimental value and calculated value.

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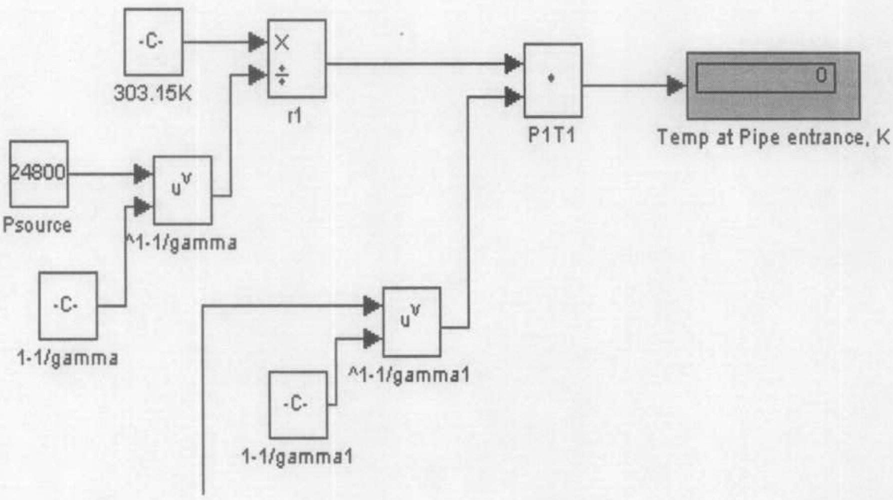
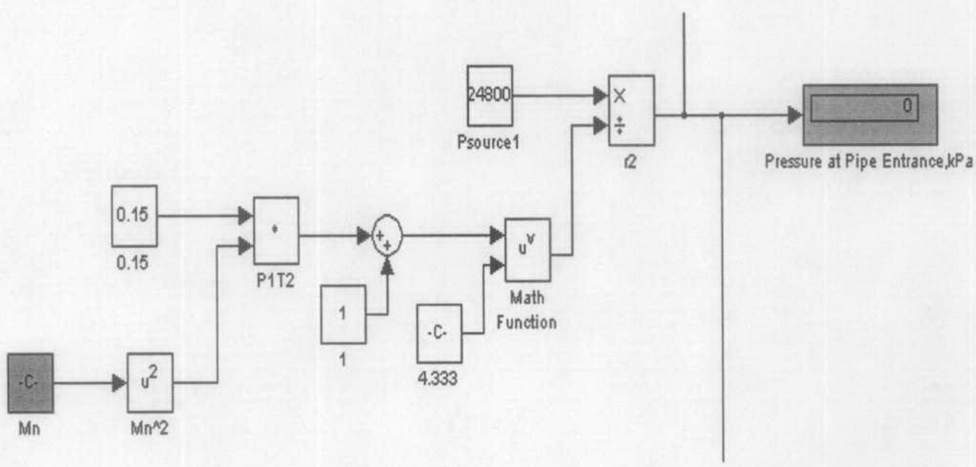
7.0 APPENDICES

Appendix A: Matlab-Simulink Programming

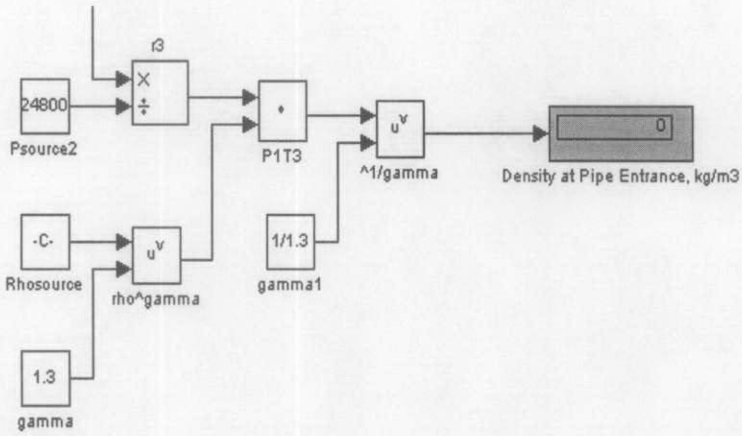
1) Calculation of temperature of gas at pipe entrance; after flowing out from source tank.



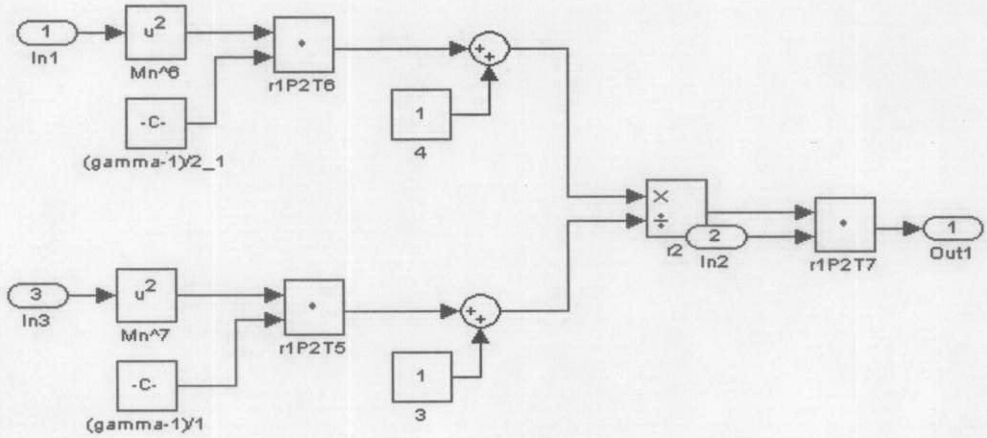
2) Calculation of pressure of gas at pipe entrance; after flowing out from source tank.



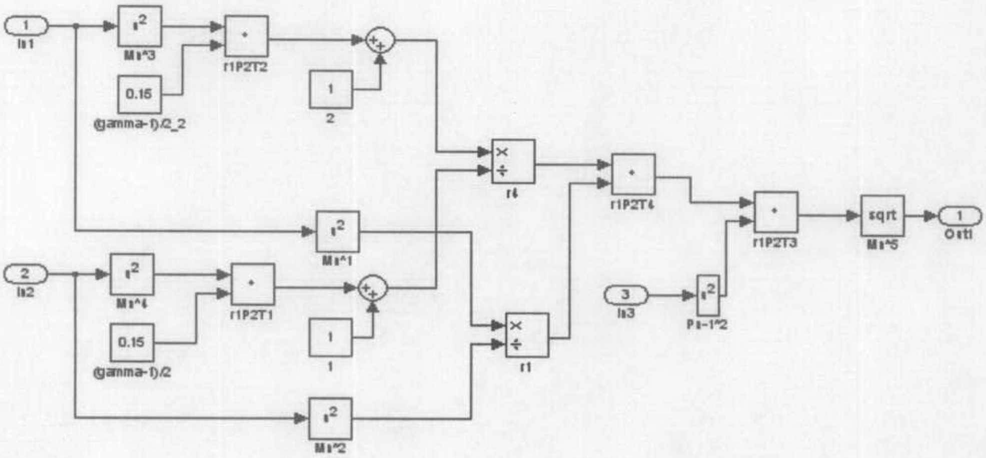
3) Calculation of density of gas at pipe entrance; after flowing out from source tank.



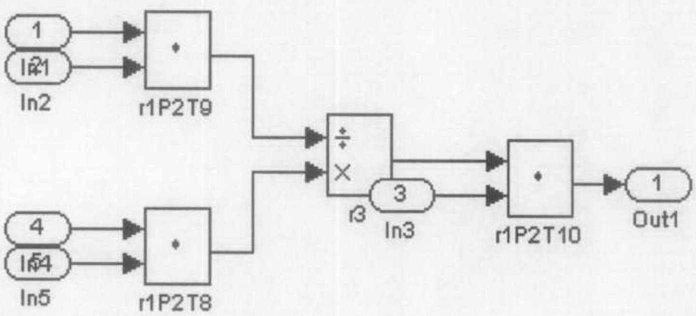
4) Calculation of temperature of gas at pipe exit; after flowing through the pipe and before entering receiver



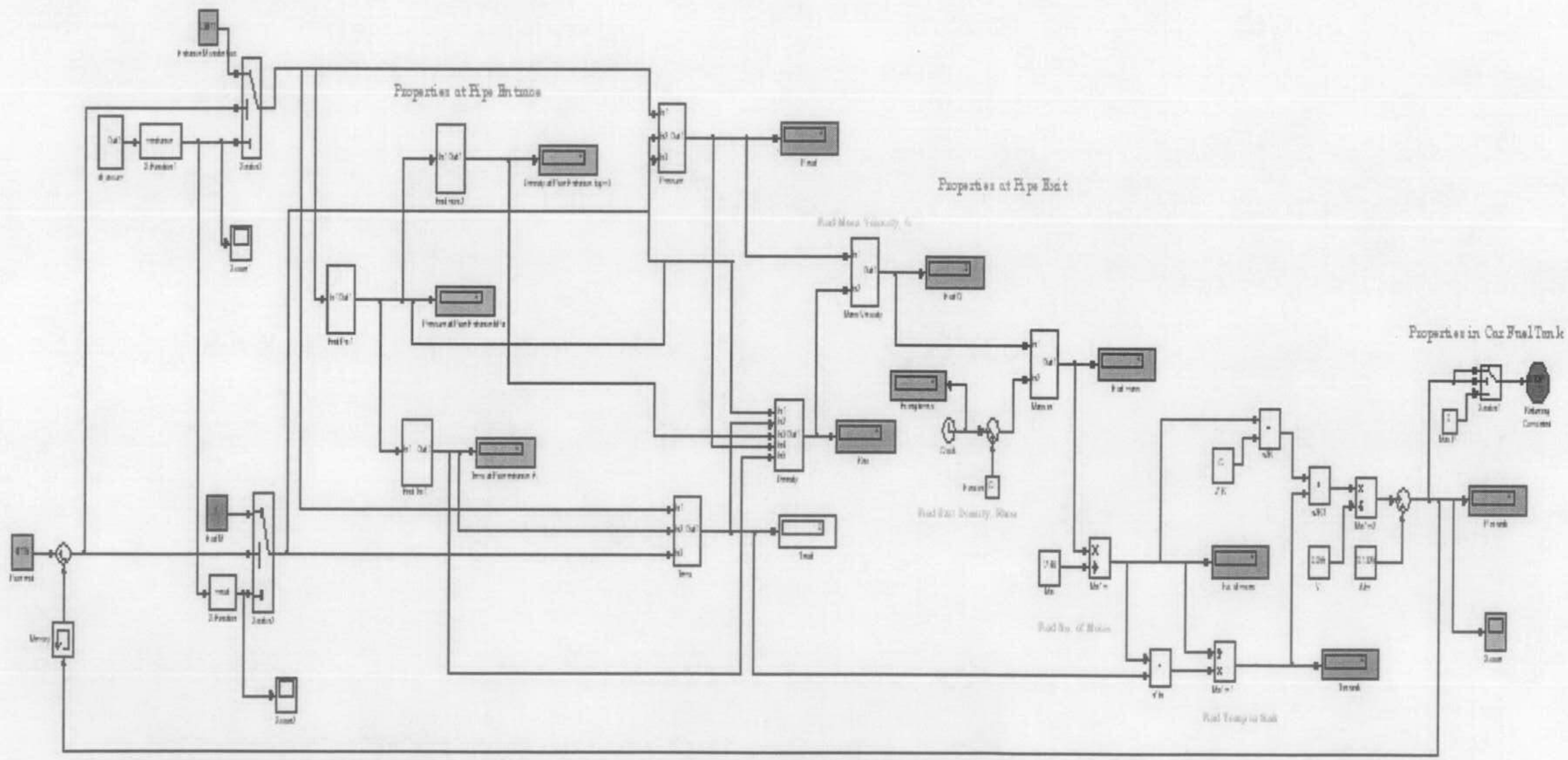
5) Calculation of pressure of gas at pipe exit; after flowing through the pipe and before entering receiver



6) Calculate density of gas at pipe exit; after flowing through the pipe and before entering receiver



7) Full Filling Process; dispensing process of gas from source tank into the receiver until maximum receiver's pressure is reached. The filling is stopped automatically when receiver's pressure reach 21,000kPa



Appendix B: Full Set of Equations to develop Fanno Model

The following equation is used to develop Fanno Model together with algorithms discussed in Section 3.1.5.

Calculate pipe-entrance Mach No., M_{n-1}	$\frac{fL_{max}}{r_H} = \frac{1}{\gamma}\left(\frac{1}{M_a^2} - 1 - \frac{\gamma+1}{2}\ln\frac{2\{1+[(\gamma-1)/2]M_a^2\}}{M_a^2(\gamma+1)}\right)$
Calculate pipe-entrance properties; P_{n-1}, T_{n-1}, ρ_{n-1}	$\frac{P}{P_o} = \frac{1}{\{1+[(\gamma-1)/2]M^2\}^{1/(1-1/\gamma)}}$ $T = T_o\left(\frac{P}{P_o}\right)^{1-1/\gamma}$ $\rho^\gamma = \frac{p\rho_o^\gamma}{p_o}$
Calculate pipe-exit properties; P_n, T_n, ρ_n	$\frac{P_a}{P_b} = \frac{M_b}{M_a}\sqrt{\frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}}}$ $\frac{T_a}{T_b} = \frac{\{1+[(\gamma-1)/2]M_b^2\}}{\{1+[(\gamma-1)/2]M_a^2\}}$ $\frac{\rho_a}{\rho_b} = \frac{M_b}{M_a}\sqrt{\frac{\{1+[(\gamma-1)/2]M_a^2\}}{\{1+[(\gamma-1)/2]M_b^2\}}}$
Calculate mass velocity, G	$G = M\sqrt{\rho\gamma p}$
Calculate amount of gas filled into sink, m_{in}	$m = GAt$
Calculate no. of moles of m_{in}, n_{in}	$n = \frac{m}{M}$

Calculate no of moles in sink, n_{sink}	$n = n_1 + n_2$
Calculate temperature in sink, T_{sink}	$\frac{n_1 T_1 + n_2 T_2}{n_o + n}$
Calculate pressure in sink, P_{sink}	$p = \frac{mZRT_n}{MV} + 101.33$

Following is the value of variables used in the theoretical calculation

Symbol	Value used in calculation
f	0.00365
L_{max}	5m
γ	1.3
P_o	24,800kPa
T_o	303.15K
ρ_o	209.7kg/m^3
M	17.46
A	1.2272 x 10^{-4} m^2
t	0.1s
Z	0.819
R	8.3143kPam^{3}kmol^{-1}k^{-1}
V	0.055m^3

Appendix C: Comparison between theoretical calculation results and experimental data

1) Receiver's initial pressure: 7000kPa

Flow rate

Simulation	Experimental Data	Error, %
0.36	0.35	1.36
0.35	0.35	1.93
0.35	0.33	3.73
0.33	0.32	3.55
0.32	0.31	4.32
0.31	0.30	4.90
0.30	0.28	4.86
0.28	0.27	4.86
0.27	0.25	4.99
0.25	0.24	5.22
0.24	0.23	4.85
0.22	0.21	5.07
0.21	0.20	4.39
0.20	0.19	4.23
0.18	0.17	6.02
0.17	0.16	6.39
0.15	0.14	5.21
0.14	0.13	5.75
0.12	0.12	7.00
0.11	0.10	7.75
0.09	0.09	7.44
0.08	0.08	8.54
0.07	0.06	8.29
0.06	0.06	8.07
0.05	0.05	4.18
0.08	0.11	30.84
0.10	0.14	27.03
0.11	0.13	15.52

0.11	0.10	4.13
0.09	0.08	7.15
0.07	0.06	8.99
0.05	0.05	15.50
0.04	0.03	16.88
0.03	0.02	32.00
0.01	0.01	22.06
0.01	0.01	55.67
0.01	0.01	15.93
0.01	0.01	19.14
0.01	0.01	22.83
0.01	0.01	23.69
0.00	0.01	24.61
0.00	0.00	76.70
	Average error	**13.13**

Pressure

Simulation	Experimental Data	Error, %
6817.00	6817.04	0.00
7683.46	7568.36	1.52
8434.01	8367.93	0.79
9170.93	9119.25	0.57
9883.71	9836.11	0.48
10573.19	10525.39	0.45
11234.43	11207.79	0.24
11867.81	11841.93	0.22
12469.86	12434.71	0.28
13040.89	13013.71	0.21
13580.62	13558.25	0.17
14088.97	14082.11	0.05
14566.27	14571.50	0.04
15012.98	15047.11	0.23
15433.06	15460.68	0.18
15826.44	15860.46	0.21
16184.83	16218.89	0.21
16508.21	16535.96	0.17
16801.26	16804.79	0.02
17063.89	17039.14	0.15
17295.78	17245.93	0.29
17496.81	17418.25	0.45
17671.72	17556.11	0.66
17820.41	17687.07	0.75
17949.19	17804.25	0.81
18058.52	18259.18	1.10
18223.61	18652.07	2.30
18444.52	18982.93	2.84
18670.20	19244.86	2.99
18900.60	19444.75	2.80
19089.28	19582.61	2.52
19236.23	19672.21	2.22

19348.80	19720.46	1.88
19426.97	19734.25	1.56
19481.90	19741.14	1.31
19513.60	19741.14	1.15
19543.50	19734.25	0.97
19557.56	19741.14	0.93
19570.22	19734.25	0.83
19581.47	19727.36	0.74
19592.33	19727.36	0.68
19602.79	19706.68	0.53
	Average error	**0.87**

2) Receiver's initial pressure: 5000kPa

Flow rate

Simulation	Experimental Data	Error, %
0.32	0.30	9.37
0.31	0.29	4.52
0.29	0.28	4.52
0.28	0.27	4.90
0.27	0.26	4.81
0.26	0.25	5.18
0.25	0.25	0.84
0.24	0.22	5.10
0.21	0.22	4.76
0.20	0.20	0.34
0.19	0.20	5.73
0.19	0.19	1.08
0.18	0.18	1.00
0.17	0.17	1.06
0.16	0.17	1.09
0.16	0.16	1.52
0.15	0.15	1.65
0.14	0.14	1.95
0.13	0.13	2.09
0.12	0.13	2.16
0.12	0.12	2.29
0.11	0.11	2.00
0.10	0.10	1.97
0.10	0.10	2.07
0.09	0.09	2.19
0.08	0.08	1.60
0.08	0.08	1.18
0.07	0.07	1.53
0.06	0.07	13.36
0.06	0.06	7.18
0.05	0.06	11.18
0.07	0.06	9.57

0.08	0.05	43.72
0.08	0.05	60.89
0.13	0.13	4.97
0.17	0.18	7.52
0.15	0.16	10.87
0.13	0.14	11.43
0.10	0.12	18.85
0.07	0.10	28.64
0.04	0.02	84.19
0.00	0.00	169.97
	Average error	**13.35**

Pressure

Simulation	Experimental Data	Error, %
5466.09	5466.09	0.00
6222.83	6166.13	0.92
6850.58	6856.97	0.09
7450.63	7489.14	0.51
8025.47	8086.80	0.76
8576.71	8704.01	1.46
9105.23	9274.06	1.82
9608.10	9829.15	2.25
10063.76	10340.52	2.68
10495.57	10838.66	3.17
10904.01	11302.86	3.53
11312.46	11754.99	3.76
11701.04	12192.73	4.03
12069.81	12616.67	4.33
12419.99	13007.25	4.51
12751.49	13385.17	4.73
13065.71	13738.35	4.90
13362.66	13738.35	2.73
13643.42	14386.63	5.17
13908.12	14693.80	5.35
14157.31	14960.70	5.37
14391.02	14960.70	3.81
14610.15	15260.39	4.26
14814.79	15738.40	5.87
15005.88	15738.40	4.65
15183.49	15960.44	4.87
15349.19	16163.49	5.04
15503.04	16347.56	5.17
15630.47	16517.83	5.37
15757.71	16675.44	5.50
15870.57	16834.20	5.72
16009.80	16973.40	5.68
16175.74	17092.47	5.36
16342.62	17259.86	5.31

16610.74	17865.57	7.02
16965.49	18383.85	7.72
17277.67	18818.72	8.19
17547.55	19215.62	8.68
17760.00	19543.50	9.13
17916.94	19686.73	8.99
17999.46	19647.61	8.39
18007.23	19591.24	8.09
	Average error	**4.43**

Appendix D: Economic Analysis on Energy Saving

Energy saving (compared with current compression system)	17.5%
Compression cost per liter equivalent	2.5 cents US
Daily natural gas consumptions by NGVs in Malaysia (based on 15, 600 NGVs running on road)	146,668 Liter equivalent
Daily Compression operating cost	0.025 USD/ Liter equivalent x 146,668 Liter equivalent / day = 3666 USD/ day = 13, 933 RM/ day
Annual compression cost	13,933 RM/ day x 365 days/ year = 5,08 millions RM/ year
Annual cost saving by reduction of energy requirement	5.08 millions RM/ year x 17.5% =0. 89milions ***RM/ year***