OPTIMIZATION OF THE REFUELLING SYSTEM OF COMPRESSED NATURAL GAS VEHICLES

by

Dinh Thi Hoang Lan

Dissertation submitted in partial fulfilment of
the requirements for the
BACHELOR OF ENGINEERING (Hons)
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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS
Tronoh, Perak
January 2005

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reverences and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

DINH THI HOANG LAN

ABSTRACT

Compressed Natural Gas (CNG) is increasingly becoming an important fuel for automobiles due to the considerable reduction of air pollution compared with gasoline and diesel, and reduction of oil dependence. However, its application has not become widespread in Malaysia yet mainly due to the high operating cost of developing the infrastructure for filling stations. The objective of the present study is to model the compression and flow mechanism in the storage and delivery system of natural gas in the filling stations, so that an improved understanding on the elements leading the high operating cost of the process can be established, and then solutions for future optimization could then be made.

This paper is based on theoretical modelling of the compressible gas flow using Fanno Flow concept, taking place in a dispenser unit i.e. from the cascaded CNG storage tanks (sources) at a filling station to the CNG storage tank of an automobile (receiver). The cascaded CNG storage tanks are held at a constant pressure of 24.8 MPa (3600 psig) and the maximum allowable pressure set for the car storage tank is 21 MPa (3000 psig). The mathematical model developed by using MATLAB software is able to simulate the pressure distribution along the dispenser unit, the Mach number at the pipe entrance and exit, and differential changes in the vehicle storage tank in terms of pressure, temperature and gas content. From this model, the energy required for compression of gas, which is necessary to produce high pressurized source, is calculated.

The results have shown that a new filling scheme, as a series of three sources, with increasing pressures of 2 MPa, 10 MPa and 24.8 MPa, is able to reduce 17.5% energy requirement for gas compression compared with the current compression system. This is based on the assumption of empty vehicle tank as initial condition. In short, all the objectives were achieved, which successfully makes the project the basis for the future optimization study on Natural Gas Vehicles.

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ABBREVIATIONS AND NOMENCLATURES

Nomenclatures

f	Fanning fraction factor	
L	Length, maximum length	[m]
r_H	Hydraulic Radius	[m]
u	Velocity	$[m.s^{-1}]$
m	Mass	[kg]
n	Moles of gas	[mol]
t	Time	[s]
A	Area	$[m^2]$
M	Mach number	
M_w	Molecular weight	[kg/kmol]
P	Pressure	[Pa]
T	Temperature	[K]
R	Gas constant	$[Pa.m^3.kg^{-1}K^{-1}]$
V	Volume	$[m^3]$
Z	Compressibility factor	
U	Internal Energy	[J/mol]
H	Enthalpy	[J/mol]
W	Work	[J/mol]
S	Entropy	[J/mol]
C_p	Heat Capacities at constant pressure	$J. kg^{-1}K^{-1}]$
C_v	Heat Capacities at constant volume	$[J. kg^{-1}K^{-1}]$
γ	Isentropic Coefficient	
ρ	Density	$[kg.m^{-3}]$

Abbreviations

NGV Natural Gas Vehicles

CNG Compressed Natural Gas

LNG	Liquefied Natural Gas
GLE	Gasoline Litre Equivalent
HP	High Pressure
LP	Low Pressure
o	Source
In	Pipe Entrance
Out	Pipe exit

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

1.1.1 Natural Gas Vehicles Overview

For nearly a century, the transportation sector has used petroleum-based fuels for almost 100 percent of its energy requirement. Unfortunately, the combustion products of gasoline and diesel vehicles and engines cause serious health and environmental problems. Although governments and authorities all over the world have worked closely to implement emission reduction regulations, and technology has achieved remarkable advancement in order to reduce the vehicle emission levels, the number of vehicles travelling still continues to increase significantly each year. In addition to the need for vehicle pollution reduction, the rapid depletion of crude oil resources, coupled with the continuous political instability of Middle East countries, continues to drive the urgent need of alternative fuels.

In transportation sector, natural gas is becoming more important. It may be used in two forms: compressed natural gas (CNG) and liquefied natural gas (LNG). Fundamentally, the difference between these two forms is energy density - a liquid fuel carries more energy per pound than a gaseous fuel.

Compressed Natural Gas Vehicle (CNGV) has many overwhelming advantages against traditional means of transportation using gasoline and diesel. Firstly, it brings environmental benefits because natural gas is completely burnt in comparison to gasoline, alcohol or diesel. This is why NGVs emit less pollutant, i.e. nitrous oxides (NOx), carbon dioxide (CO_2) and especially carbon monoxide (CO). Secondly, the natural gas resource is more abundant, which makes the fuel cost lower than gasoline. Besides, it is the safer fuel. 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.

1.1.2 Compressed Natural Gas Vehicles in Malaysia

Recently, there is a considerable interest in Malaysia for the use of natural gas as the fuel for transportation. As a first step in this direction, PETRONAS, the national oil company, has launched NGV taxis known as Enviro 2000. These taxis are operating successfully in Kuala Lumpur and Klang Valley. It is expected that, by the year 2006, Malaysia will have about 40,000 NGVs.

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 1.1. 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.

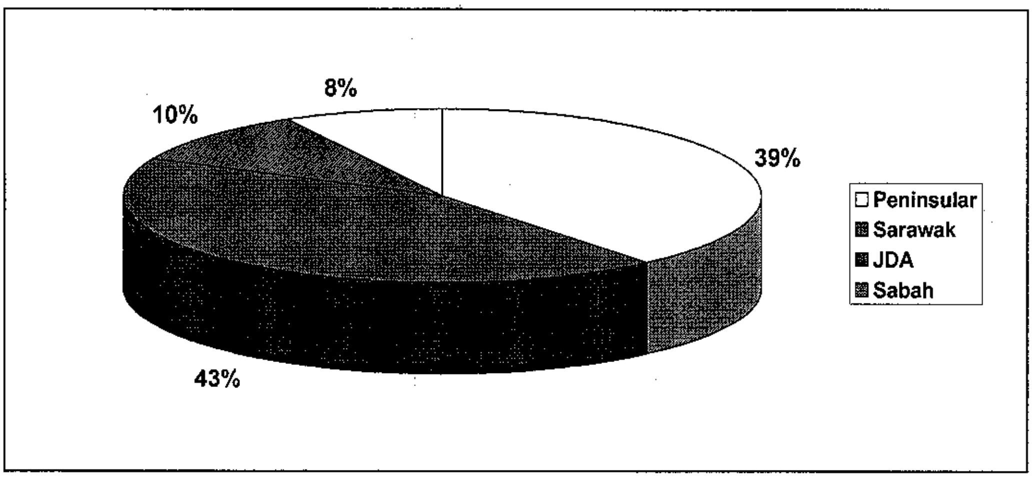

Figure 1.1 Malaysian Offshore Natural Gas Reserve [1]

PETRONAS NGV Sdn. Bhd. (PNGV), a wholly-owned subsidiary of PETRONAS, is a company that is dedicated to implement the program to commercialize and promote the use of natural gas as a cleaner fuel for the transportation sector. Thirty seven PETRONAS service stations have been equipped with facilities to retail natural gas. Most of these service stations are located in the Klang Valley to serve 10,500 NGVs.

At the present, six more NGV refuelling stations are being setup in different parts of the country such as Kuala Lumpur, Klang Valley, Penang and Johor Baru. Besides the national capital region, these locations include important urban and industrial centers in the country. Twenty nine units of NGV trailers are used to transport the natural gas to the various NGV stations around the country. These six new NGV refueling stations are scheduled to be completed by end of 2004.

1.2 PROBLEM STATEMENT

1.2.1 Problem Identification

Currently, Malaysia's existing refueling stations are using cascaded storage systems which have three storage banks operating at the same pressure of 24.8 MPa (3600psi). The compression cost of the natural gas as well as the fixed charges on the capital represent 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 [2]. The fixed charge on the capital investment is approximately 6 US cents per Gasoline Litre 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 as 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 [3].

One of the major causes of the high cost of the refueling operation is the high compression costs involved. An automobile which 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 end of the hose [4]. This is an irreversible energy loss and contributes considerably to the high compression cost in the filling stations.

1.2.2 Significance of the Project

Based on this scenario, this research study aims to model the compression and flow mechanism in the storage and delivery system of natural gas in the filling stations, so that an improved understanding on the elements leading the high operating cost of the process can be established, and solutions for future optimization could then be made. The successful results of the project will have an opportunity to participate in the ANGVA (Asia Pacific Natural Gas Vehicles Association) Conference and Exhibition, to propose a potential solution for the cost improvement of NGVs.

1.3 OBJECTIVES AND SCOPE OF STUDY

1.3.1 Relevancy of the Project

The project is relevant through the light of its objectives and scope of study. The main objectives of the study are:

1. To theoretically analyze the compressible gas flow phenomena during the filling of the vehicle tank from the station storage tank
2. To develop a simulation models for predicting the conditional changes in the vehicle tank with respect to time.
3. To develop alternate filling strategies to reduce the energy loss and energy requirement for compression, hence to increase the overall filling effectiveness.

The scope of this research project is limited to deriving and manipulating mathematical equations related to the adiabatic compressible flow and real gas behaviours, in order to model the gas filling and compressing processes without conducting experimental work.

1.3.2 Feasibility of the Project within the Scope and Time Frame

The project schedule is illustrated in Table A1 in the Appendix 1, which clearly exhibits the project milestone from July 2004 to November 2004. Based on the schedule, the time frame in completing the project has been divided into systematic and feasible tasks.

CHAPTER 2

LITERATURE REVIEW

2.1 FRICTIONAL ADIABATIC COMPRESSIBLE FLOW

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 N_{Ma}, 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.

$$N_{Ma} \equiv \frac{u}{a}$$

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 or near unity, or greater than unity, respectively.

To develop equations for compressible flow, the following assumptions are necessary [6].

1. Steady flow
2. One-dimensional flow
3. Velocity gradients within a cross-section are neglected, so that $\overline{V} = u$
4. Friction is restricted to wall shear
5. Zero shaft work
6. Negligible gravitational effects and mechanical-potential energy

The following basic relations are used:

1. The continuity equation

$$\rho.u.A = \dot{m} = cons\tan t \tag{2.1}$$

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. Velocity of sound

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

Where s represents the isentropic restraint

2.1.2 Isentropic Flow

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

The conditions of the gas at the pipe entrance are given by the equations

Pressure: $$\frac{P_{in}}{P_O} = \frac{1}{\left\{1 + [(\gamma - 1)/2]N_{Ma}^2\right\}^{1/(1-1/\gamma)}} \tag{2.5}$$

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

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

2.1.3 Adiabatic frictional compressible flow

2.1.3.1 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 is shown diagrammatically in Figure 2.1.

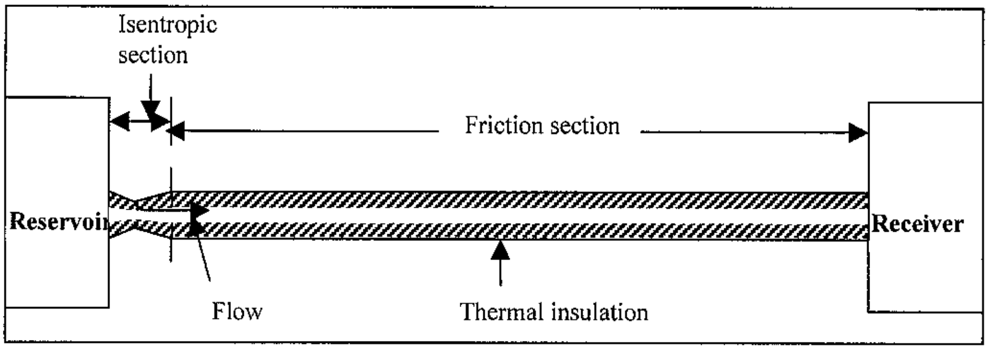

Figure 2.1: Adiabatic Frictional Flow Diagram

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 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 can not exceed 1 [7]. 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".

2.1.3.2 The Friction Parameter

The basic quantity that measures the effect of friction is the friction parameter fL/r_H. In adiabatic frictional flow, the temperature of the gas changes. 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 [6].

2.1.3.3 Equations for Adiabatic Frictional Compressible Flow

From the Mechanical Energy Balance equation,

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

Substituting relationship between the pressure, velocity and the Mach number

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

And $$\frac{du}{u}=\frac{dp}{p}+2\frac{dN_{Ma}}{N_{Ma}} \tag{2.10}$$

Will result in the following differential equation

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

Integration of (2.11) between an entrance station a and exit station b, assuming the friction factor, f, to be constant (part 2.1.3.2), the final relationship will be

$$\frac{f.\Delta L}{r_H}=\frac{1}{\gamma}\left(\frac{1}{N_{Ma,a}^2}-\frac{1}{N_{Ma,b}^2}-\frac{\gamma+1}{2}\ln\frac{2N_{Ma,b}^2\{1+[(\gamma-1)/2]N_{Ma,a}^2\}}{N_{Ma,a}^2\{1+[(\gamma-1)/2]N_{Ma,b}^2\}}\right) \tag{2.12}$$

Property equations

The ratio of the inlet and outlet pressure is found by direct integration of (2.9) between the limit p_a, p_b and $N_{Ma,a}$, $N_{Ma,b}$ to give

$$\frac{P_a}{P_b} = \frac{N_{Ma,b}}{N_{Ma,a}} \sqrt{\frac{\{1 + [(\gamma - 1)/2] N^2_{Ma,b}\}}{\{1 + [(\gamma - 1)/2] N^2_{Ma,a}\}}} \qquad (2.13)$$

Similarly, the temperature ratio will be

$$\frac{T_a}{T_b} = \frac{\{1 + [(\gamma - 1)/2] N^2_{Ma,b}\}}{\{1 + [(\gamma - 1)/2] N^2_{Ma,a}\}} \qquad (2.14)$$

Maximum conduit length

To ensure that the conditions of a problem do not create the impossible phenomenon of a crossing of 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* is the asterisk condition, where $N_{Ma,b} = 1$. 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 $N^2_{Ma,a}$. Equation (2.12) then gives

$$\frac{\overline{f}L_{max}}{r_H} = \frac{1}{\gamma}\left(\frac{1}{N^2_{Ma,a}} - 1 - \frac{\gamma + 1}{2}\ln\frac{2\{1 + [(\gamma - 1)/2] N^2_{Ma,a}\}}{N^2_{Ma,a}(\gamma + 1)}\right) \qquad (2.15)$$

Stagnation Temperature

The stagnation temperature of a high-speed fluid is defined as the temperature the fluid would attain were it brought 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

$$T_S = T + \frac{u^2}{2c_p} \qquad (2.16)$$

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 ADIABATIC FILLING OF GAS INTO THE RECEIVER TANK

The system considered is the gas inside the tank at any point of time. Therefore, the system will be an open, unsteady-state system [8].

Energy balance:

$$d(nU) = U_{final} dn_{final} - U_{initial} dn_{initial} = H_{in} dn_{in} - H_{out} dn_{out} + dQ + dW_s + dE_k + dE_p \tag{2.17}$$

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

$$U_{final} dn_{final} - U_{initial} dn_{initial} = H_{in} dn_{in} + (-mu^2)/2 \tag{2.18}$$

Final pressure and temperature of the receiver are determined by equation (2.18) and the equation of state, which will be derived in the next section.

2.3. EQUATION OF STATE AND REAL GAS PROPERTIES

2.3.1. Peng-Robinson Equations of State

To obtain P-V-T properties of real gases, many approximate equations of state have been proposed. Peng-Robinson model, one of the most successful approaches, has been applied throughout this project [8].

Generally, the empirical equations of state (EOS) is given by

$$P = \frac{RT\rho}{1 - b\rho} - \frac{a\rho^2}{1 + 2b\rho - b^2\rho^2} \tag{2.19}$$

$$Z = \frac{1}{1-b\rho} - \frac{a}{bRT} \times \frac{b\rho}{1+2b\rho-b^2\rho^2} \tag{2.20}$$

Where ρ = molar density=n/V

$a = a_c \alpha$

Where $\alpha = [1+\kappa(1-\sqrt{T_r})]^2$

$a_c = \psi R^2 T_c^{\,2} / P_c^{\,2}$

$b = \Omega R T_c / P_c$

The values of the parameters κ, ψ, Ω depend on the model that is applied. For Peng Robinson model, the parameters are given in Table 2.1.

Table 2.1: Parameters of Peng-Robinson Equation of State

K	Ψ	Ω
$0.37464 + 1.54226\varpi - 0.26992\varpi^2$	0.45724	0.07779607

If rewriting equation (2.20) as $Z = 1 + Z^{rep} + Z^{att}$ where Z^{rep} represents the deviations from the ideal gas law due to repulsive interactions; Z^{att} represents the deviations due to repulsive interactions, equation (12) will be

$$Z = 1 + \underbrace{\frac{b\rho}{1-b\rho}}_{Z^{rep}} \underbrace{- \frac{a}{bRT} \times \frac{b\rho}{1+2b\rho-b^2\rho^2}}_{Z^{att}} \tag{2.21}$$

The repulsive term accounts for the asymptotic divergence of the compressibility factor at the close-packed density. The divergence occurs because increasing the pressure can not further increase the density as close packing is approached. The role of attractive forces increases as the temperature decreases. At low temperature, kinetic energy can no longer overwhelm the potential attractions. This eventually leads to condensation.

2.3.2 Calculation for property changes ΔH and ΔS

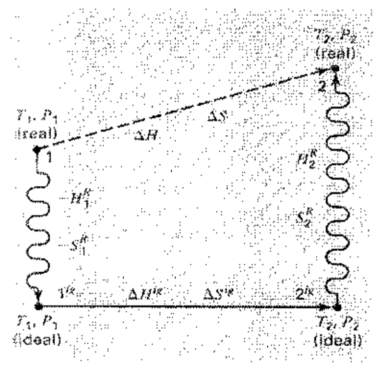

Figure 2.2: Calculational path for property changes (enthalpy and entropy) [9]

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 2.2 [9].

- 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:

$$\Delta H = H_1^{ig} - H_1 \tag{2.22}$$

$$\Delta S = S_1^{ig} - S_1 \tag{2.23}$$

- 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,

$$\Delta H^{ig} = H_2^{ig} - H_1^{ig} = \int_{T1}^{T2} C_P^{ig} dT \tag{2.24}$$

$$\Delta S^{ig} = S_2^{ig} - S_1^{ig} = \int_{T1}^{T2} C_P^{ig} \frac{dT}{T} - R\ln\left(\frac{P_2}{P_1}\right) \tag{2.25}$$

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

$$\Delta H = H_2^{ig} - H_2 \tag{2.26}$$

$$\Delta S = S_2 - S_2^{ig} \tag{2.27}$$

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

- ***Enthalpy***:

$$H - H_{ref} = (H - H^{ig})_{T,P} + \int_{Tref}^{T} C_p dT - (H - H^{ig})_{ref} \quad (2.28)$$

$$\text{Where } \frac{H - H^{ig}}{RT} = \left[\int_0^{\rho} -T\left(\frac{\partial Z}{\partial T}\right)_{\rho} \frac{d\rho}{\rho} \right] + Z - 1 \quad (2.29)$$

- ***Internal energy***:

$$U - U_{ref} = (U - U^{ig})_{T,P} + \int_{Tref}^{T} C_V dT - (U - U^{ig})_{ref} \quad (2.30)$$

$$\text{Where } \frac{U - U^{ig}}{RT} = \left[\int_0^{\rho} -T\left(\frac{\partial Z}{\partial T}\right)_{\rho} \frac{d\rho}{\rho} \right] \quad (2.31)$$

- ***Entropy***:

$$S - S_{ref} = (S - S^{ig})_{T,P} + \int_{Tref}^{T} \frac{C_P}{T} dT - R\log(P / P_{ref}) - (S - S^{ig})_{ref} \quad (2.32)$$

$$\text{Where } \frac{S - S^{ig}}{R} = \left[\int_0^{\rho} \left[-T\left(\frac{\partial Z}{\partial T}\right)_{\rho} - (Z - 1) \right] \frac{d\rho}{\rho} \right] + \ln Z \quad (2.33)$$

2.4 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 2.3 [5].

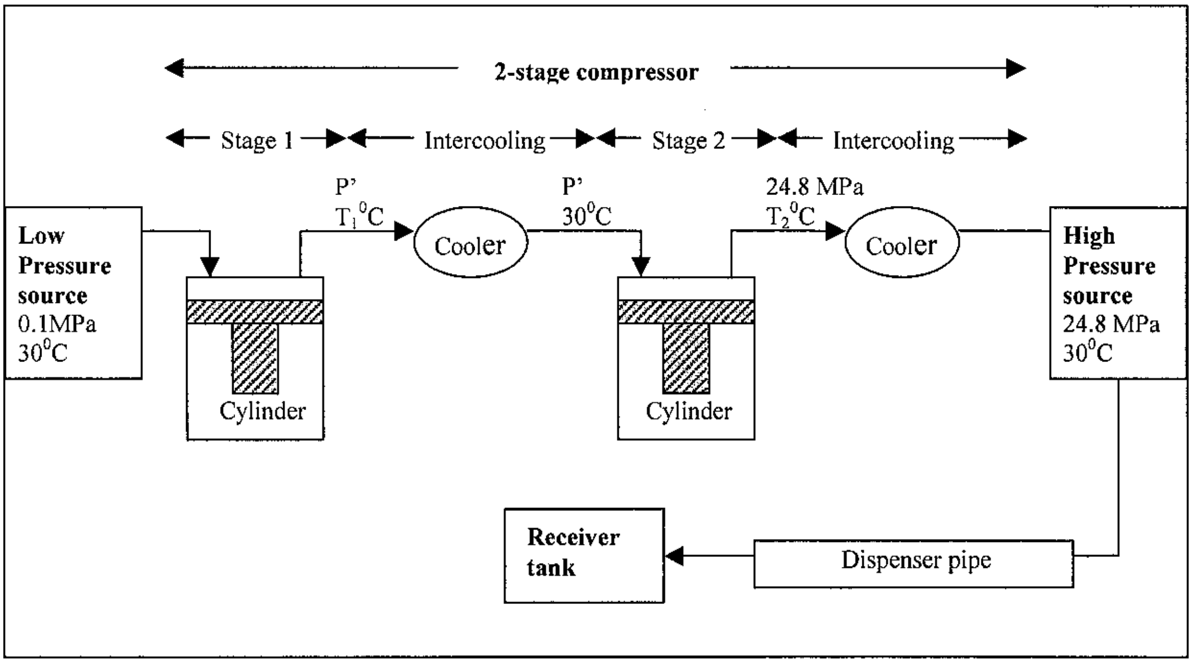

Figure 2.3: Diagram of multistage adiabatic compression

CHAPTER 3

METHODOLOGY

3.1. PROCEDURE IDENTIFICATION

The methodology of this project work is summarized in Figure 3.1.

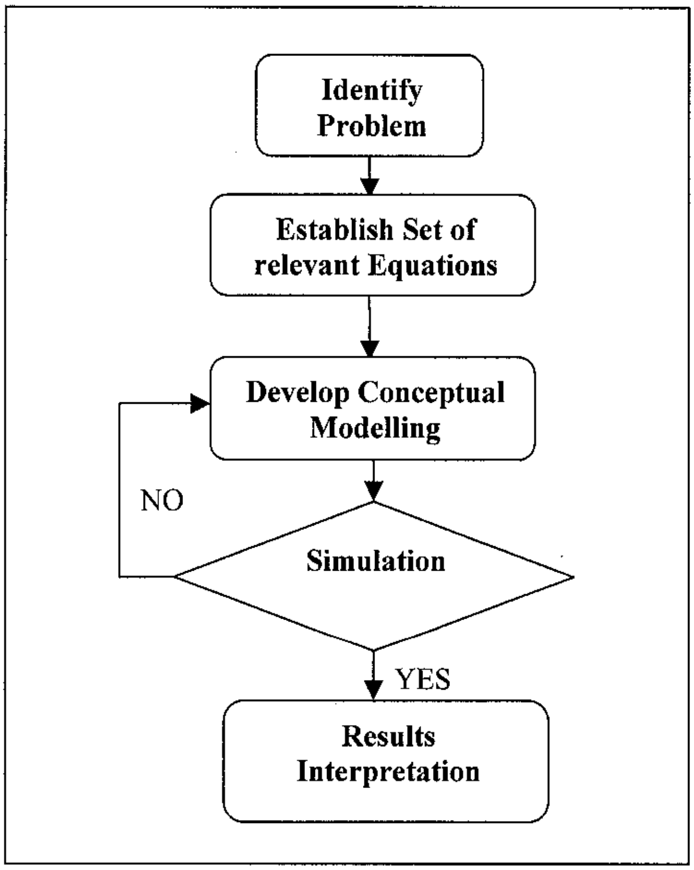

Figure 3.1: Methodology of project work

3.1.1. 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.

3.1.2. Establish Set of Relevant Equations

It is important to identify appropriate mathematical equations and correlations to help develop a suitable mathematical modelling. Mathematical relations from (2.1) to (2.33), obtained during the literature review stage, are able to simulate the compressible flow phenomena and the real gas behaviours, which are the important elements of the model.

3.1.3. Develop Conceptual Diagram

From literature review, the simplified model for the study of an existing NGV refuelling system has been developed (Figure 3.2).

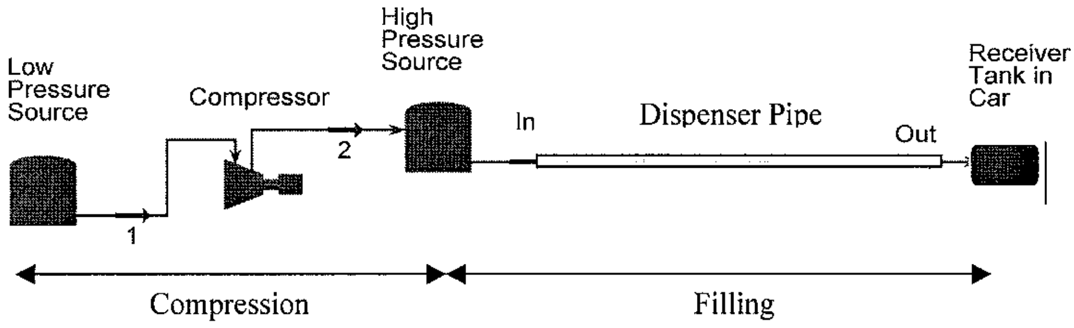

Figure 3.2: Conceptual Model of the Refuelling System

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

Table 3.1: Important Parameters of the Refuelling 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 refuelling 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

3.1.4. Simulation

The simulation consists of two parts, namely (i) predicting the differential changes in the vehicle storage tank in terms of pressure, temperature and gas content and (ii) calculating the energy required for compression of gas

In the first part, the problem solving is carried out by MATLAB software using two levels of looping: the inner loop is to simulate a single standard source, and the outer one is to simulate a series of sources with increasing pressure.

Figure 3.3 and 3.4 show the problem solving algorithm.

Figure 3.3: Programming Loop Level 1

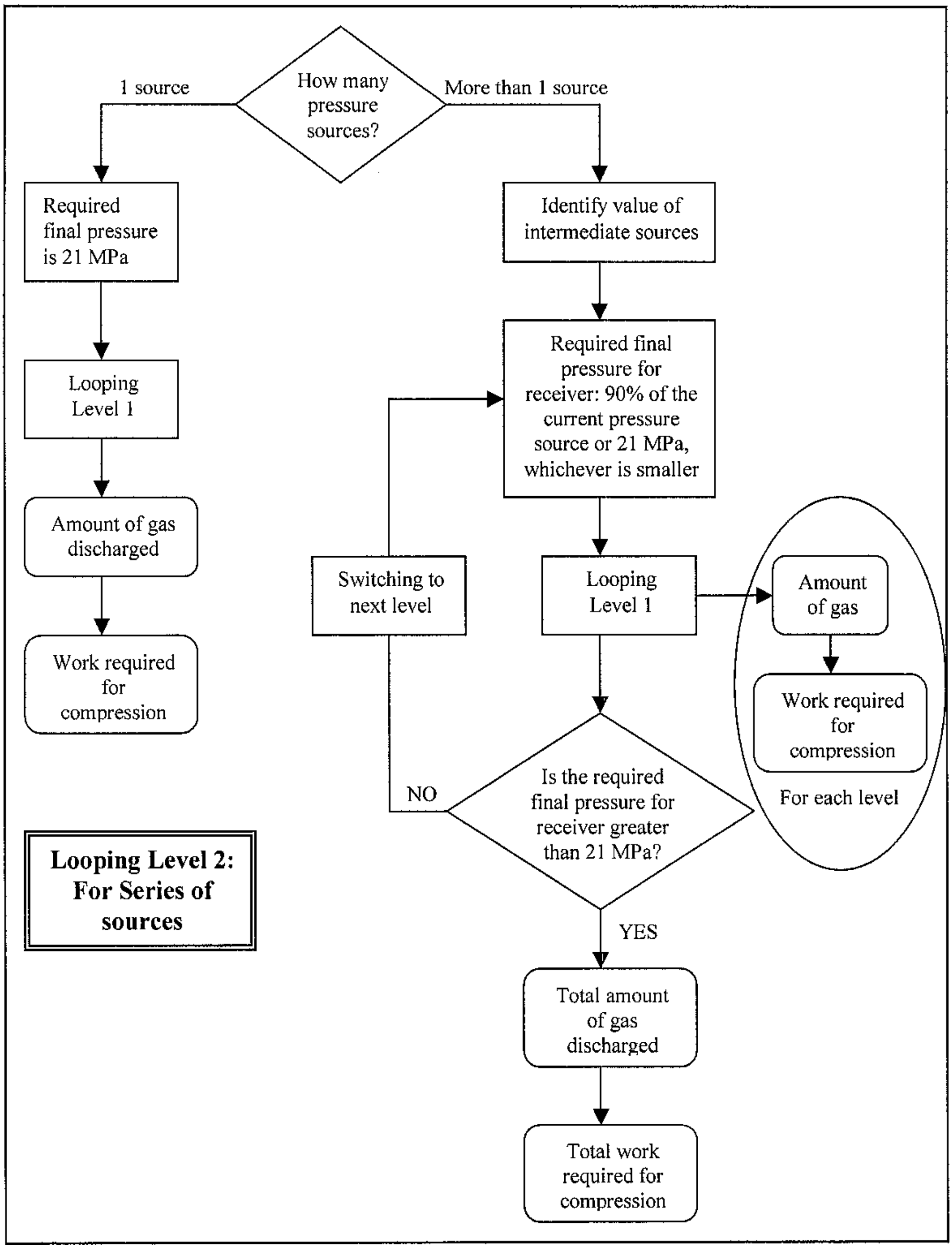

Figure 3.4: Programming Loop Level 2

In the second part, the task is to calculate the energy required for compressing the amount of gas, obtained from the previous part, from the gas supplier's source to the high pressure source by using different compression pathways, either isothermal, single-stage adiabatic or multi-stage adiabatic with intercooling. In the current NGV refuelling 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. Quantity and the pressurized level are varied to study the work requirement associated with different options (Figure 3.5).

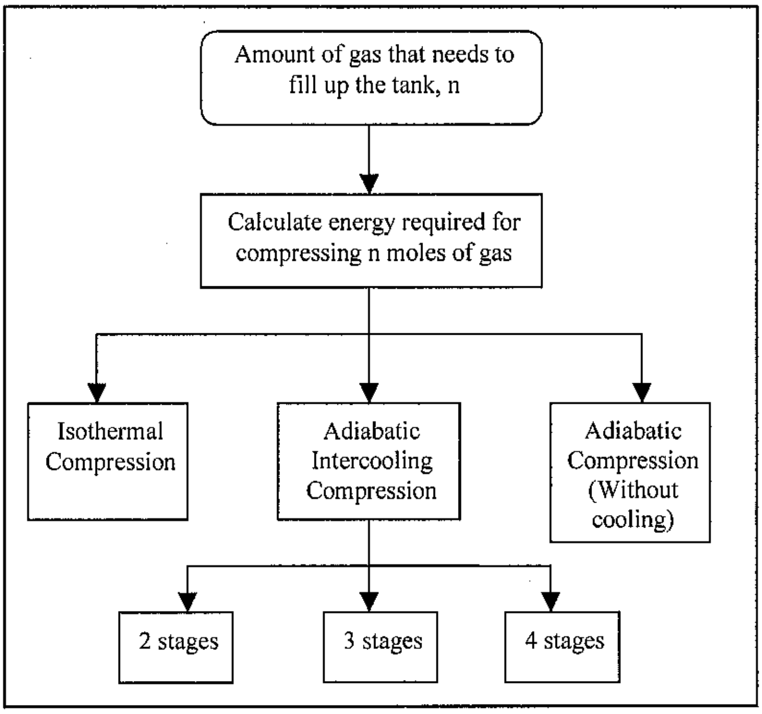

Figure 3.5: Calculation of Energy required for Compression

3.1.5 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 TOOL: MATHLAB

MATLAB software is in use throughout the project work. The MATLAB product family is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. In this project, it is the best choice in order to solve system of complex equations and to carry out multi-level iterations.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses three parts, namely (i) the energy loss occurring during the filling process, (ii) the energy required for compression of gas, and (iii) recommendation for an optimized gas filling schedule.

4.1 ENERGY LOSS DURING THE FILLING PROCESS

4.1.1 Single source at 24.8 MPa

A set of simulation runs with a single source pressure maintained at 24.8 MPa and initial vehicle tank pressure of 0.101 MPa (atmospheric pressure) were conducted. The simulation will terminate when the tank's pressure reaches 21 MPa.

Shown in four sub-plots in Figure 4.1, the results exhibit differential changes of five important parameters of the gas filling process:

Pressure and gas content: Due to very large potential difference between the mother source and the vehicle's tank, the gas quickly fills the vehicle tank and the pressure increases. However, as the initial tank's pressure is too low, for the first 2 seconds, the flow experiences choked flow condition, which causes great pressure energy drop between the pipe ending and the receiver. Therefore, the rate of pressure increment is less compared with the rate when the filling is no longer under choked flow (after 2 seconds). This is clearly shown in the slope change of the graph (pressure versus time).

Different from the pressure's behaviour, the gas content in the tank increases in a relatively constant manner as the tank receives an even amount of gas per unit of time. It is due to the fact that the amount of gas flowing into the tank is a function of the mass velocity of the gas flow, which is constant along the dispenser pipe and depends to a greater extent on the pressure of the starting point than the destination point. Therefore, despite of the conditional changes of the vehicle tank, the increment of gas content is almost steady over the filling time.

Temperature: As gas initially rushes in, the temperature reduces sharply because of two main reasons. Firstly, as a consequence of the Joule-Thomson effect, the compressed gas when expands in a fixed volume at lower pressure will experience a temperature drop. Secondly, it is due to the heat transfer effect between gas flowing in and gas inside the tank. As the gas flow develops its speed along the pipe, its associated temperature falls (refer to stagnation temperature section in 2.1.3.3), causing a significant temperature difference between the pipe exit (lower than ambient temperature) and the vehicle tank (assumed to be at ambient temperature).

Nevertheless, as more gas rushes into the tank, the compression effect overwhelms the expansion effect; as a result, the temperature increases again. This change is interpreted as a temperature minimum in the graph. The minimum temperature inside the tank is noted at -96^{0}C, which seems to be unusually low. However, all the formulae, based on the assumption of gas phase, are still valid. It is because at the condition of (-96^{0}C), the corresponding pressure (0.8 MPa) is much lower than the vapour pressure of natural gas, consisting mostly of methane (2.8 MPa); therefore, there is no phase change along the pipeline. To obtain a more accurate result, it is recommended that a statistical study on the average temperature of the station source should be conducted.

Energy loss and Mach number: 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 tank. Energy loss occurs due to friction along the dispensing line, sudden expansion of the gas at the pipe exit, causing abrupt changes in 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 (when Mach number at the pipe exit equals to 1) is overcome by normal flow (Mach number at the pipe exit is less than 1).

For single source at 24.8 MPa, total time at which choked flow exit is 2.1 seconds, which is almost 50% the total filling time. Long time of choked flow causing large energy loss; and as a result of that, a great amount of gas is required to be filled in, in order to maintain the same vehicle performance.

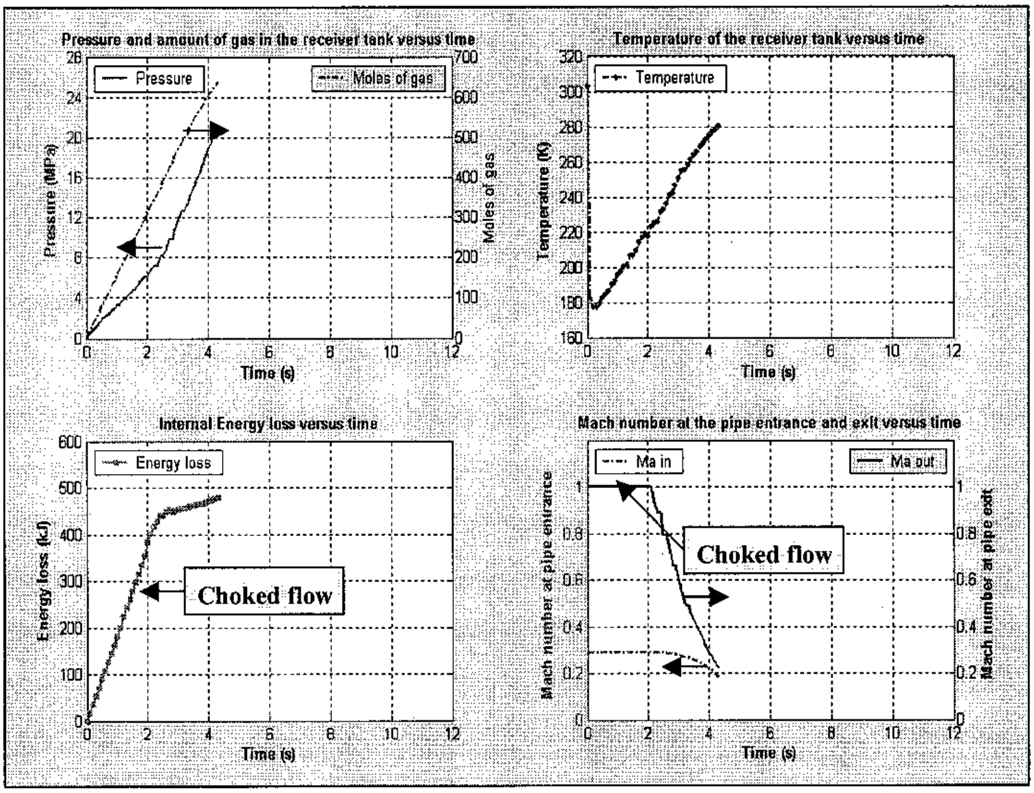

Figure 4.1: MATLAB Simulation of vehicle tank's condition with respect to time, with a single source of 24.8 MPa (base case)

To avoid choked flow, the pressure discontinuity between the pipe exit and the 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 mother 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 ensure to provide sufficient drive force for the gas to flow, especially when the vehicle tank is almost filled up (up to 21MPa). Therefore, instead of simply reducing the pressure, it is more feasible to divide the single source into a series of sources, of which step-wise pressure levels increase from moderately low to the standard value of 24.8 MPa.

4.1.2. Multiply Sources: A Strategy for Minimizing Energy Loss

To study how energy loss can be saved by using a multiple sources, a set of simulation was carried out with a series of different number of intermediate sources. Figure 4.2, 4.3, 4.4 shows the results of a gas filling system with two, three, and four sources respectively.

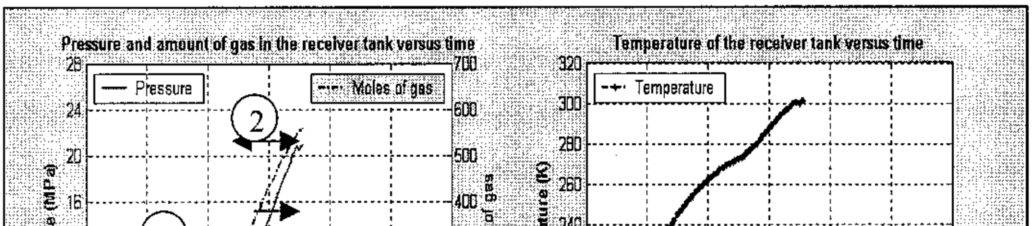

Figure 4.2: MATLAB Simulation of vehicle tank's condition with respect to time with 2 sources of 10 and 24.8 MPa

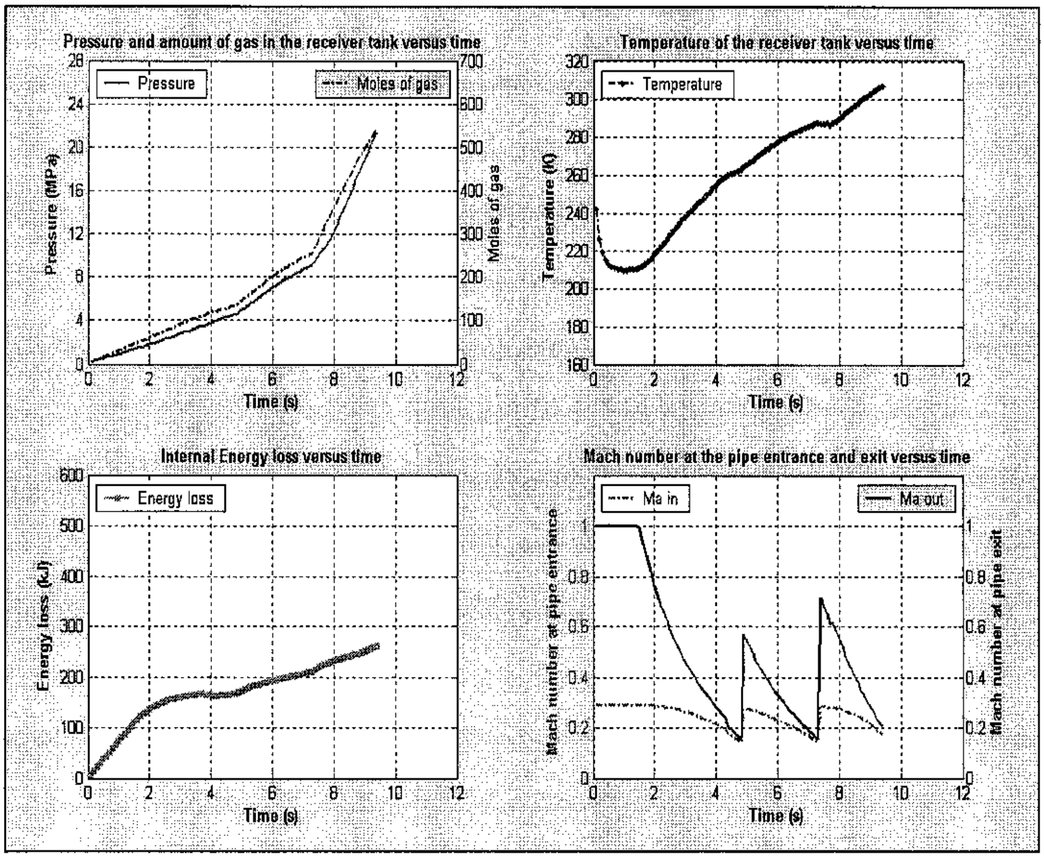

Figure 4.3: MATLAB Simulation of vehicle tank's condition with respect to time, with 3 sources of 5, 10 and 24.8 MPa

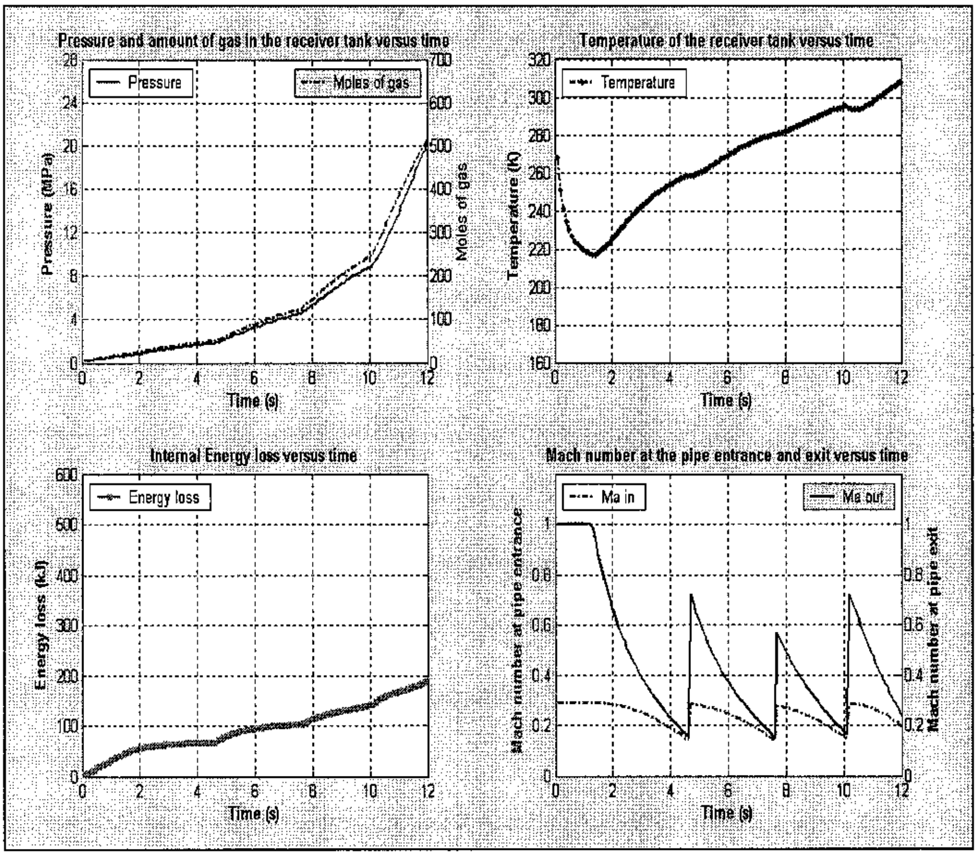

Figure 4.4: MATLAB Simulation of vehicle tank's condition with respect to time, with 4 sources of 2, 5, 10 and 24.8 MPa

When the vehicle tank is filled from a series of sources instead of a single source, there are noticeable changes in the gas's condition.

Pressure and Gas content: It is observed that the pressure and gas content increases more slowly compared with the single source case. The rate of pressure increment when the tank is topped up from a specific pressure source depends significantly on the driven force (pressure difference) between the starting point and destination point. On one hand, if the intermediate source is closer to the initial tank pressure, i.e. 10 MPa, the rate of pressure change at section 1 will be smaller than section 2 (refering to the slope change of the graph pressure versus time). On the other hand, if the intermediate source is closer to the source pressure, i.e. 17 MPa, the rate of pressure increment at section 1 will turn out to be larger. The gas content inside the vehicle tank behaves similarly.

Besides, because the filling rate reduces, the filling time extends accordingly. The more the number of sources increases or the greater the source pressure is reduced, the longer time it takes to fulfil the tank.

Temperature: The behaviour is similar to the single source of 24.8 MPa. However the average temperature obtained is higher than one in the case of single source. It is because the effect of heat transfer as well as gas expansion/compression is smaller; hence the temperature inside the tank is more closed to the initial condition.

Energy loss and Mach number: 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.

Table 4.1 summarizes the changes in the value of the parameters of the gas filling process.

Table 4.1: Summary of changes of process parameters with different pressure sources

	1 source 24.8MPa (Base case)	**2 sources 10 & 24.8 MPa**	**3 sources 5 , 10 & 24.8 MPa**	**4 sources 2 , 5, 10 & 24.8 MPa**
Energy Loss (kJ)	478.01	328.32	259.95	192.59
	Decreasing			
Energy Loss Reduction (%) (compared with base case)		31.3 %	45.6 %	59.7%
	Increasing			
Total amount of gas filled in	639.05	***563.96***	540.82	532.27
	Decreasing			
Filling time (s)	4.3	7.1	9.4	12.2
	Increasing			

In short, as the pressure of the source is lower, or the number of sources increases, the energy loss will reduces, the moles of gas needed to fulfil the tank also decreases, but the filling time increases. There is no attempt to optimize the pressure level yet, as the analysis for energy required for compression plays a more important role in optimizing.

4.2. ENERGY REQUIRED FOR GAS COMPRESSION

4.2.1. Single source at 24.8 MPa: Energy requirement versus different paths of compression

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, assumed at 101.325 kPa, to the standard one, at 24.8 MPa.

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 a ttractive, y et almost infeasible in normal operation. The h ighest a mount 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 4.5). 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.

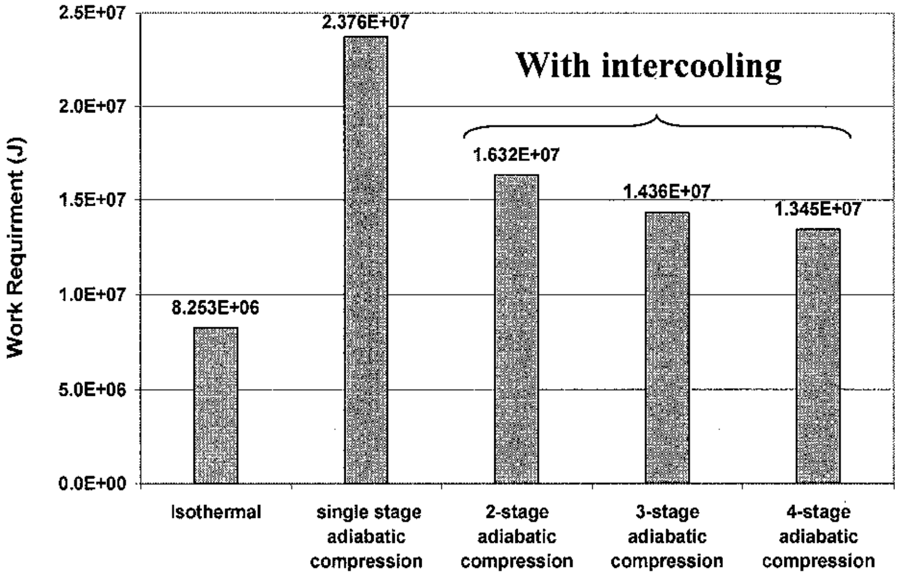

Figure 4.5: One source (24.8 MPa)-Energy requirement versus compression paths

4.2.2 Multiple sources-A Strategy for Minimizing Work Requirement

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 level. 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 automobile 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.

Figure 4.6 shows the new gas filling scheme with two sources.

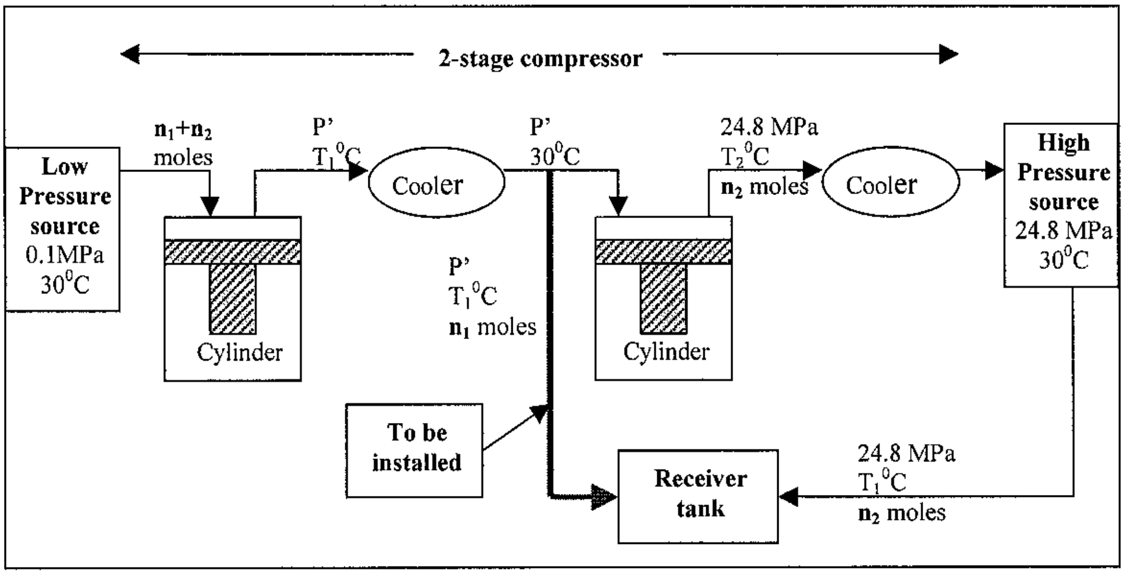

Figure 4.6: New scheme of gas flow

From the scheme shown above, the gas flowing out from the first cylinder will be divided into two portions: one portion will flow to the receiver tank, as a medium pressure source, and another one will continue to be compressed to a higher level in the next cylinder.

Another set of simulations were conducted to determine the optimum value of intermediate pressure P' in the case of two interconnected sources. Figure 4.7 shows that the optimum value for P' is 2 MPa.

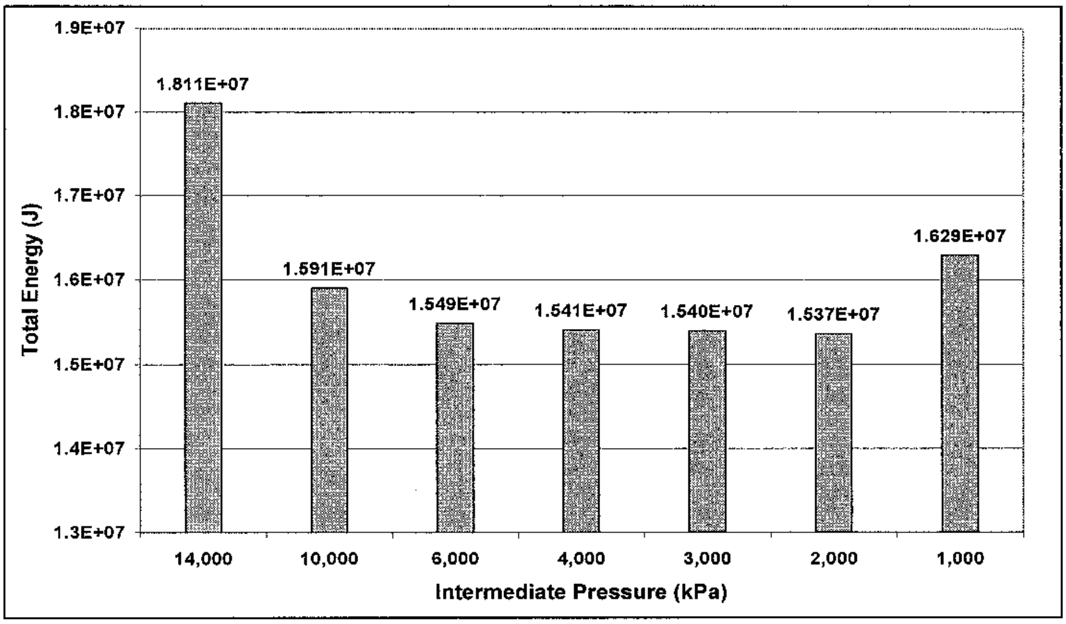

Figure 4.7: Two sources- Work requirements versus intermediate pressure

Still, there is room for improvement. Instead of two levels 2 MPa and 24.8 MPa, an additional source can be introduced between, to further reduce the work requirement. Some values of intermediate pressures were studied, and the optimum value is proven to be 10 MPa.

To achieve even more energy saving, the option of introducing a fourth one has also been considered. The optimum value is found to be 17 MPa. As the final pressure of the receiver is 21 MPa, there should not be any additional pressure source higher than 17 MPa. In Figure 4.8, the energy requirements for all alternatives have been summarized.

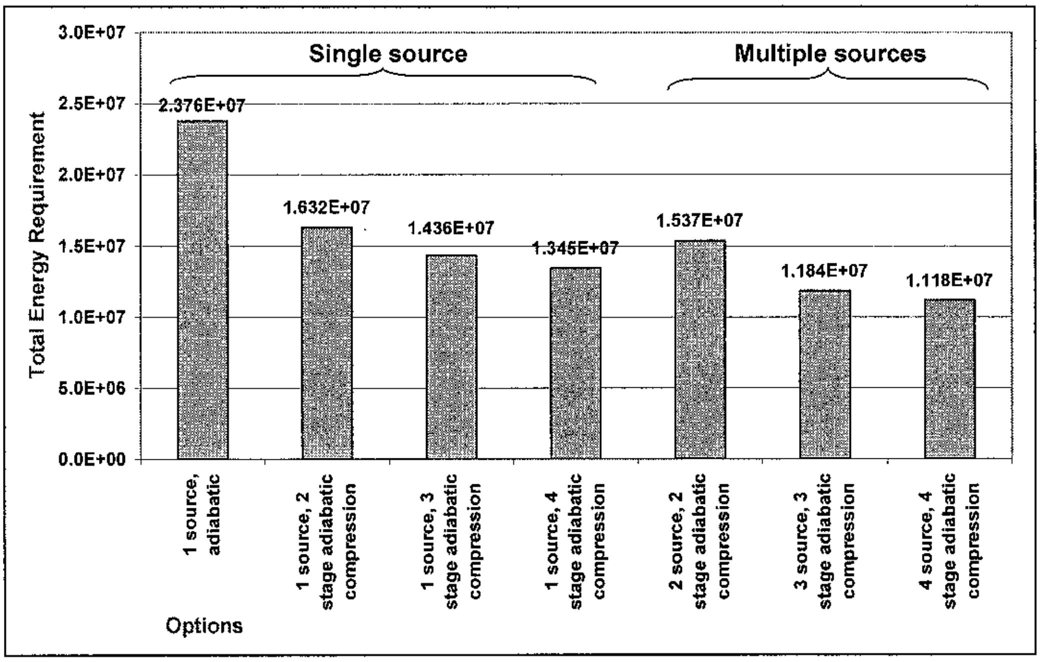

Figure 4.8: Total Energy Requirements versus different Alternatives

Based on the current compressing system (three-stage adiabatic compression), the energy requirement for potential alternatives was compared (Figure 4.9).

Current

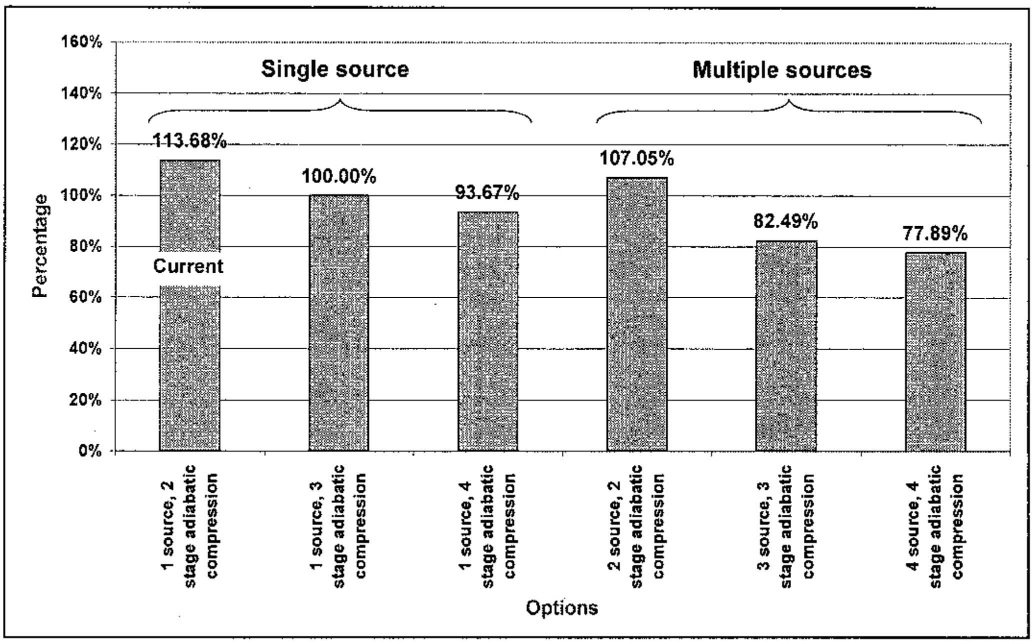

Figure 4.9: Energy Requirement of Different Alternatives versus Current system

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.

As mentioned in the previous part, energy loss is an important parameter to be considered. The analysis result is shown in Figure 4.10.

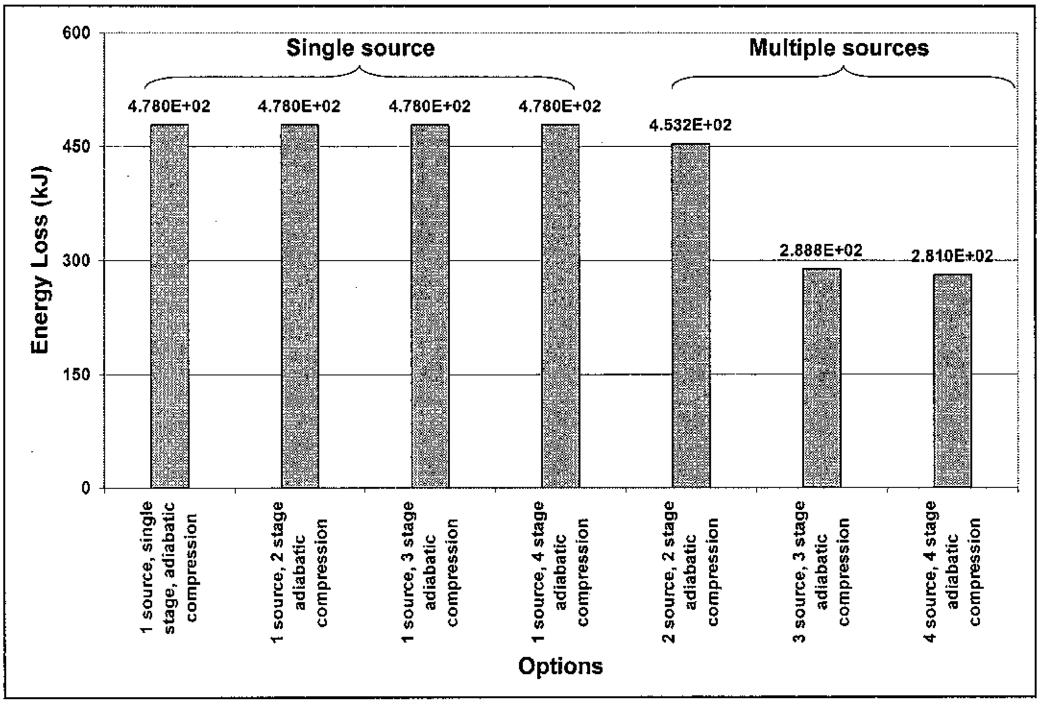

Figure 4.10: Energy loss versus Alternatives

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 (refer to 4.2.2). 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.

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 RECOMMENDATION FOR A NEW FILLING SYSTEM

4.3.1 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 4.11.

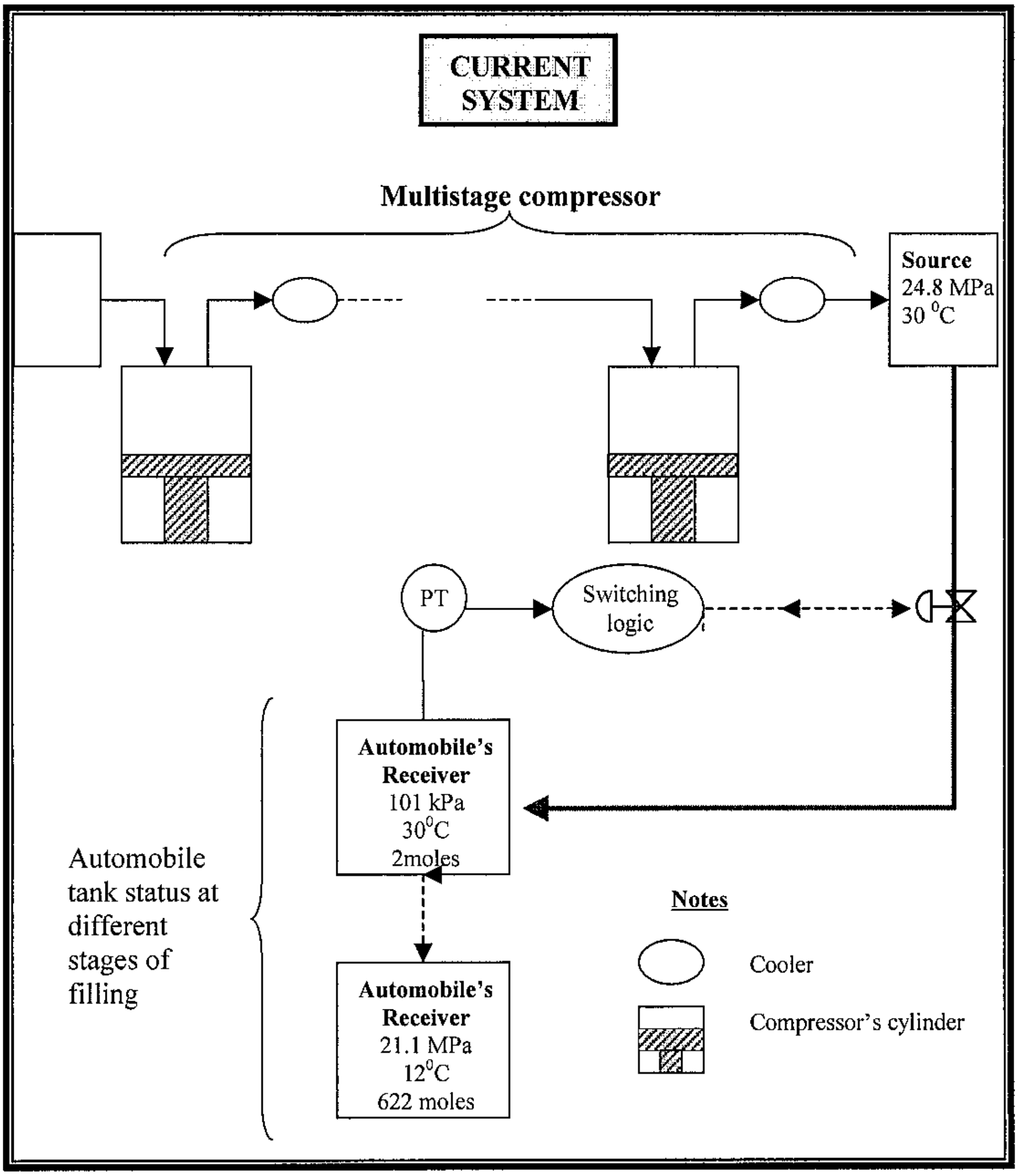

Figure 4.11a: Conceptual Diagram for Three-Source-Filling System (current system)

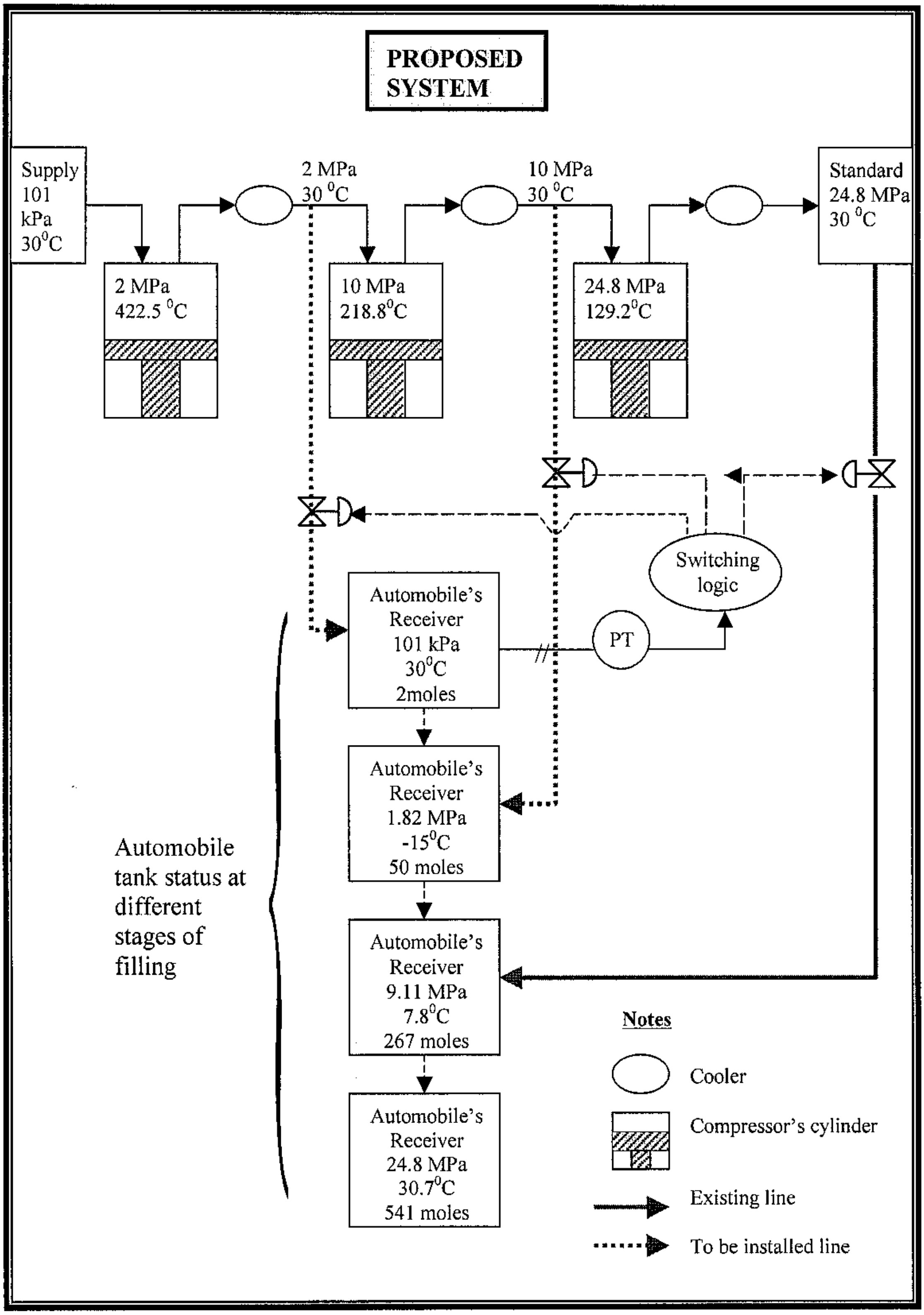

Figure 4.11b: Conceptual Diagram for Three-Source-Filling System (proposed system)

4.3.2. 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 will be studied in another set of simulation. 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; 10,000kPa; 24.8 MPa sequentially, obtained from the previous result, whereas the automobile tank initial pressure are varied from empty tank up to 75% full tank.

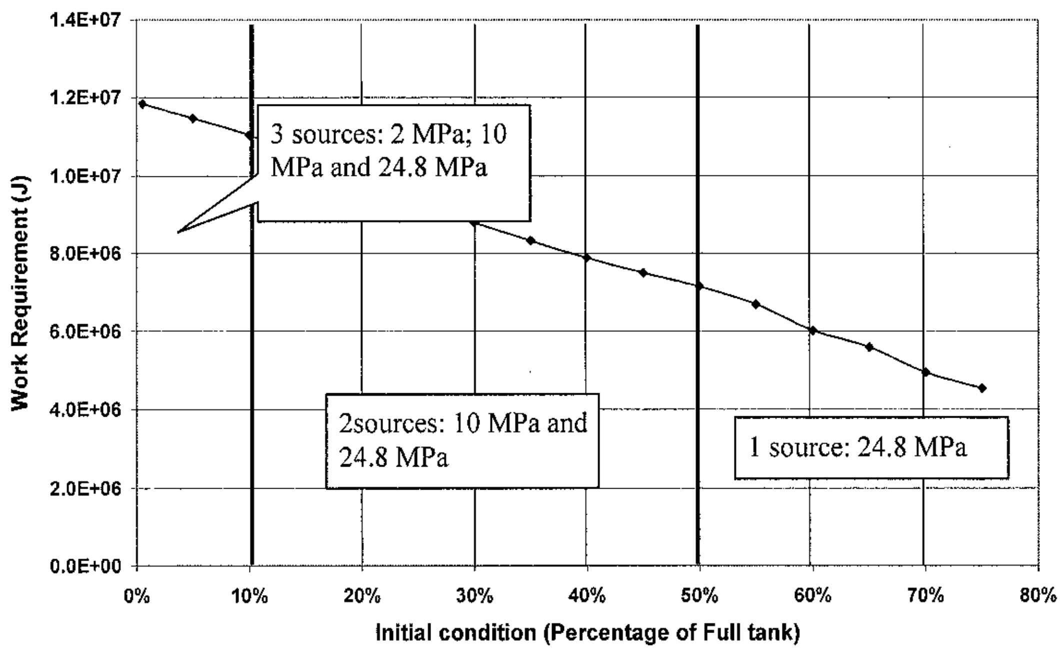

Figure 4.12: Work Requirement for Compression with respect to different initial receiver's content

As shown in Figure 4.12, 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≈2.1 MPa), 2 MPa source does not have sufficient pressure energy, hence, the refuelling 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≈10.5 MPa), the refuelling process only need to use the highest source of 24.8 MPa.

4.4 ECONOMIC ANALYSIS OF ENERGY SAVING

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 ***0.6 millions ringgit*** per year, without any further increment in capital cost. (Detailed estimation is provided in the Appendices). This figure at the present time may not be so important; as it is estimated on the current 10,500 NGVs in Malaysia. However, the expecting number of NGVs in year 2006 will increase to 40,000 and it will continue to rise strongly years after. As a result, the economic potential of this project can not be ignored, as it promises to reduce the operating cost of NGVs filling stations significantly.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

The mathematical model developed is able to predict the differential changes in the vehicle storage tank in terms of pressure, temperature, gas content and the energy loss associated. From this model, the energy required for compression of gas, which is necessary to produce high pressurized source, is calculated.

Based on this study, there are two significant conclusions:

1. The lower the pressure level in the source, the more energy saving on gas compression and less energy loss encountered during the filling. However, the time of filling increases.
2. Improvement in operating cost, without further investment in capital cost, can be carried out by modifying the gas flow scheme.

From this model, 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.

In conclusion, this project has provided the basement for the future optimization study of the refuelling system of Compressed Natural Gas Vehicles.

5.2 RECOMMENDATIONS

5.2.1 Statistical Study of Initial Tank Pressure of Vehicles

In the partial optimization reported in the present study, the basis was a receiver's pressure of 101.325 kPa. On this basis, the intermediate compressor pressures of 2; 10 and 24.8 MPa have been determined. These optimized values depend closely on the initial receiver's pressures. In real life, automobiles come with different initial gas content, or in other word, different initial gas pressure. Hence, a complete optimization has to be based on a statistical study of initial tank pressure of automobiles arriving for refuelling.

5.2.2 Modelling Validation

The validity of this project cannot be verified until experiments are conducted. Experimental work is in need to provide true data. For the justification and improvement, it is strongly recommended the project should be continued further by experiments so that simulation results can be compared and modified if necessary.

5.2.3 Consideration of all components in natural gas

It is assumed, for simplicity, in this study that natural gas is pure gas, 100 percent composed of methane. In fact, there are few other components, i.e. ethane, propane, etc. These components, though in minority, do slightly affect the real gas behaviours. Therefore, for a more accurate result, it is suggested that future work should take this effect into account.

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APPENDIX I
GANTT CHART

Table A1: Project Milestones for Final Year Research Project July 2004

No	Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Selection of Project Topic														
2.	Preliminary research on project														
	i. First meeting with Supervisor and project partner														
	ii. Do research from internet, reference book, professional journal														
	iii. Collect all relevant data														
3.	Writing Preliminary Report														
4.	Submission of Preliminary Report				•										
5.	Familiarization of MATLAB														
	i. Formulating program code														
	ii. Consulting with lecturers														
6.	Modelling with MATLAB														
	i. Constructing programme code														
	ii. Testing and Debugging														
	iii. Obtaining Results														
7.	Start Progress Report														
8.	Submission of Progress Report								•						
9.	Analysis and Discussion on Modelling Results														
10	Start Project Dissertation														
11	Submission draft of project dissertation													•	
12.	Oral Presentation														•
13.	Submission of Project Dissertation														•

APPENDIX II
MALAYSIAN NATURAL GAS COMPOSITION

Table A.2. Malaysian Natural Gas Specifications provided by PRSS

Component	Abbreviation	Moles Percentages	
		Leanest	Richest
Methane	C_1	96.42	89.04
Ethane	C_2	2.29	5.85
Propane	C_3	0.23	1.28
iso-Butane	i-C_4	0.03	0.14
n-Butane	n-C_4	0.02	0.10
n-Pentane	n-C_5		
n-Hexane ++	C_6 ++		
Condensate	C_5+	0.00	0.02
Nitrogen	N_2	0.44	0.47
Carbon Dioxide	CO_2	0.57	3.09
Total		100	100

APPENDIX III

MATLAB PROGRAMMING

A.3.1 Get Data

```
% Get data

function [P,T,Pi,Ti,Pf]=data_input

disp('Source')
n=input('Enter number of sources: ')
for i=1:n
   disp(['Source ' ])
   disp(i)
   P(i)=input ('Enter pressure: ');
   T(i)=input ('Enter temperature:');
end

disp ('Receiver')
disp ('Initial')
Pi=input ('Enter pressure: ');
Ti=input ('Enter temperature:');

disp ('Final')
Pf=input ('Enter pressure: ');
```

A.3.2. Process Variable Identification

```
% Identify variables

function globevar          % Identify global constants
global R                   % Gas Constant
global MW                  % Molecular Weight
global den                 % Density of gas
global Cp                  % Heat Capacity @ constant P
global Cv                  % Heat Capacity @ constant V
global gam                 % Ratio of Cp/Cv
global k,global a_c, global b,

global Pc                  % Critical Pressure
global Tc                  % Critical Temperature
global omega               % Critical acentric factor

global f                   % Friction factor
global L                   % Length of dispenser pipe
global D                   % Diameter of dispenser pipe
global r                   % Hydraulic Radius
global A                   % Area of the dispenser pipe
global Vt                  % Volume of vehicle tank

% Identify the gas properties at reference state
global Pref, global Tref,global Zref, global dHref, global dUref,global dSref,global Vref

R=8.314;
MW=17.45055637;
Cp=36.7194047;
Cv=Cp-R;

Pc=4590000;
Tc=190.564;
omega=0.011;

gam=Cp/Cv;
k=0.37464+1.54226*omega-0.26993*omega^2;
a_c=0.45723553*8.314^2*Tc^2/Pc;
b=0.07779607*8.314*Tc/Pc;

f=0.003654372;
L=5;
D=0.0125;
r=D/4;
A=pi*D^2/4;
Vt=0.055;
```

```
%calculate thermodynamic properties at reference state: 101325Pa and 303.15K
Pref=101325; Tref=303.15;
[Zref,dHref,dUref,dSref,Vref]=cal_prop(Pref,Tref);
```

A.3.3. Calculation of Thermodynamic Properties of Real Gas

```
% Calculate the thermodynamic properties of real gases

function [Z,H,U,S,v]=cal_prop(P,T)
global R, global MW, global Cp, global Cv,
global Pc, global Tc, global omega,
global gam, global k, global a_c, global b
global Pref, global Tref, global Zref,
global dHref, global dUref, global dSref, global Vref

% Calculate compressibility factor Z of gas at state of (P,T)
Tr=T/Tc;
alfa=(1+k*(1-sqrt(Tr)))^2;
a=alfa*a_c;
A=a*P/(R*T)^2;
B=b*P/(R*T);
f=[1 B-1 A-3*B^2-2*B -A*B+B^2+B^3];
t=(roots(f));
j=1;real(j)=0;
for i=1:1:3;
   if imag(t(i))==0
      real(j)=t(i);
      j=j+1; end
end
Z=max(real);

% Calculate residual properties of real gas at(P,T)
deltaH=R*T*(Z-1-log((Z+(1+sqrt(2))*B)/(Z+(1-sqrt(2))*B))*A/B/sqrt(8)*(1+k*sqrt(Tr/alfa)));
deltaU=R*T*(-log((Z+(1+sqrt(2))*B)/(Z+(1-sqrt(2))*B))*A/B/sqrt(8)*(1+k*sqrt(Tr/alfa)));
deltaG=R*T*(Z-1-log(Z-B)-log((Z+(1+sqrt(2))*B)/(Z+(1-sqrt(2))*B))*A/B/sqrt(8));
deltaS=(deltaH-deltaG)/T;

% Calculate compressibility factor Z of gas at reference state
Tr=Tref/Tc;
alfa=(1+k*(1-sqrt(Tr)))^2;
a=alfa*a_c;
A=a*Pref/(R*Tref)^2;
B=b*Pref/(R*Tref);
f=[1 B-1 A-3*B^2-2*B -A*B+B^2+B^3];
t=(roots(f));
Zref=max(t);

% Calculate residual properties at reference state
deltaH_ref=R*Tref*(Zref-1-log((Zref+(1+sqrt(2))*B)/(Zref+(1-sqrt(2))*B))*A/B/sqrt(8)*(1+k*sqrt(Tr/alfa)));
deltaU_ref=R*Tref*(-log((Zref+(1+sqrt(2))*B)/(Zref+(1-sqrt(2))*B))*A/B/sqrt(8)*(1+k*sqrt(Tr/alfa)));
deltaG_ref=R*Tref*(Zref-1-log(Zref-B)-log((Zref+(1+sqrt(2))*B)/(Zref+(1-sqrt(2))*B))*A/B/sqrt(8));
deltaS_ref=(deltaH_ref-deltaG_ref)/Tref;

% Calculate Thermodynamic properties of Real gases
H=deltaH+Cp*(T-Tref)-deltaH_ref;                 % Enthalpy
U=deltaU+Cv*(T-Tref)-deltaU_ref;                 % Internal Energy
S=deltaS+Cp*log(T/Tref)-R*log(P/Pref)-deltaS_ref; % Entropy
v=Z*R*T/P;                                       % Corresponding Volume
```

A.3.4. Calculate Pressure of Real Gases when Temperature and Volume is known

```
% Calculate corresponding pressure of real gases with known temperature and volume

function P=cal_P(T,V,n)
global R,global MW,global Cp,global Cv,
global Pc,global Tc,global omega,
global gam,global k,global a_c, global b,
```

```
global Pref, global Tref,global Zref,
global dHref, global dUref,global dSref,global Vref

%calculate ideal gas pressure
Tnew=T;P=n*R*Tnew/V;
[Z,H,U,S,v]=cal_prop(P,Tnew);
Pnew=n*Z*R*Tnew/V;
tol=abs((P-Pnew)/P);
i=0;small=0.03;

% The iteration starts with assumption of ideal gas, using the pressure found from
% Ideal Gas Equation of State
% to calculate the compressibility factor Z
% From Z calculated, the new pressure is found. The iteration will stop when the
% difference between two pressures is less than 3%

while tol>small
  P=Pnew;
  [Z,H,U,S,v]=cal_prop(P,Tnew);
  Pnew=n*Z*R*T/V;
  tol=abs((P-Pnew)/P);
  i=i+1;
  if i>5;
    small=small+0.005;
    i=0;
  end
end
```

A.3.5. Calculate pressure and temperature of gas by using Energy Balance equation and Equation of State

```
% Calculate pressure and temperature of gas by using Energy Balance equation
% and Equation of State

function [P,T]=cal_PT(ni,Pi,Ti,n_in,P_in,T_in,u_in)

global R,global MW,global Cp,global Cv,
global Pc,global Tc,global omega,
global gam,global k,global a_c, global b,
global Pref, global Tref,global Zref,
global dHref, global dUref,global dSref,global Vref
global Vt

%calculate internal energy of initial amount of gas
[Zi,Hi,Ui,Si,Vi]=cal_prop(Pi,Ti);
sumUi=ni*Ui;

%calculate enthalpy of gas flowing into tank
[Z_in,H_in,U_in,S_in,V_in]=cal_prop(P_in,T_in);
sumH_in=n_in*H_in;

%calculate kinetic energy change of gas when flowing into tank
Ek=-(n_in*MW*u_in^2)/2000;

% Calculate P, T propeties after gas has flown in
% P and T must satify both condition:
  % 1) Pv=ZRT
  %   energy change between the pipe exit and tank is zero
  %   (adiabatic process)

  % 2)d(Uf-Ui)=dHin+dEk
  %  where Uf:internal energy corresponding to (P,T) at equilibrium
  %       Ui:initial energy before gas flows in
  %       dHin:enthalpy of gas flowing in
  %       dEk: kinetic energy change

nf=ni+n_in;dT0=25;dT1=dT0;dT2=dT1;
T=(sumH_in+Ek+ni*Cv*(Ti-Tref))/(nf*Cv)+Tref;
P=cal_P(T,Vt,nf);
```

```
[Z,H,U,S,v]=cal_prop(P,T);
f1=(nf*U)-(sumUi)-sumH_in-Ek;
tol=0.05;
i=0;j=0;

% Solving Equation by using Secant Method
while abs(dT2)>tol
   T=T+dT1;
   P=cal_P(T,Vt,nf);
   [Z,H,U,S,v]=cal_prop(P,T);
   f2=(nf*U)-(sumUi)-sumH_in-Ek;
   dT2=-dT1*f2/(f2-f1);
   if abs(dT2)>1.e3;
      error('method diverging');end
   dT1=dT2;  f1=f2;
   i=i+1;
   if i>30;
      tol=tol+0.01;
      j=j+1;
      i=0;
   end
 end
j              % Show number of increment to make sure the tolerance is not too loose
```

A.3.6. Calculate corresponding Mach number at the pipe entrance, with known Mach number at pipe exit

```
% Calculate Mach number at pipe entrance with known Mach number at pipe exit

function Mi=Ma_in(Mo)
global gam, global f, global L,global r;

% Assume a reasonable value for Mach number
if Mo>0.6
   Mi=0.4;
elseif Mo>0.3
   Mi=0.2;
else Mi=0.05;end

dx0=0.005; dx1=dx0; tol=0.0001;
f0=Mi^(-2)-Mo^(-2)-(gam+1)/2*log(Mo^2*2*(1+(gam-1)/2*Mi^2)/Mi^2/(1+(gam-1)/2*Mo^2))-gam*f*L/r;
i=0;
while abs(dx1)>tol
   Mi=Mi+dx0;
   f1=Mi^(-2)-Mo^(-2)-(gam+1)/2*log(Mo^2*2*(1+(gam-1)/2*Mi^2)/Mi^2/(1+(gam-1)/2*Mo^2))-gam*f*L/r;
   dx1=-dx0*f1/(f1-f0);
   if abs(dx1)>30;
      error ('method diverging');end
   dx0=dx1;  f0=f1;
   i=i+1;
   if i>30;
      error ('30 iterations is too many');end
end
```

A.3.7. Calculate Mach number at the pipe entrance and exit, with known pressure at the pipe exit

```
% Calculate Much number at pipe entrance and exit with known pressure at
% the pipe exit

function [Mi,Mo]=cal_Ma(Psource,Po,Mo)
global gam, global f, global L,global r;

Mi=Ma_in(Mo);
```

```
dx0=0.0001; dx1=dx0; tol=0.00005;

% Using compressible flow equation
f0=(1+(gam-1)/2*Mi^2)^(-1/(1-1/gam))/((Mo/Mi)*sqrt((1+(gam-1)/2*Mo^2)/(1+(gam-1)/2*Mi^2)))-Po/Psource;
i=0;
while abs(dx1)>tol
  Mo=Mo+dx0;
  Mi=Ma_in(Mo);
  f1=(1+(gam-1)/2*Mi^2)^(-1/(1-1/gam))/((Mo/Mi)*sqrt((1+(gam-1)/2*Mo^2)/(1+(gam-1)/2*Mi^2)))-Po/Psource;
  dx1=-dx0*f1/(f1-f0);
  if abs(dx1)>30;
    error ('method diverging');end
  dx0=dx1;  f0=f1;
  i=i+1;
  if i>50;
    error ('50 iterations is too many');end
end
```

A.3.8. Predicting the properties of compressible flow

```
% Predicting the properties of the compressible flow phenomena

function [P1,T1,n_in,P2,T2,u2]=flow(Psource,Tsource,Mi,Mo,t)
global gam,global MW, global A, global R,global dref

Zsource=cal_prop(Psource,Tsource);
dsource=Psource*MW/(Zsource*1000*R*Tsource);                  % density of gas at source

% Entrance of pipe (position 1)
  P1=Psource/(1+(gam-1)/2*Mi^2)^(1/(1-1/gam));                % pressure at the pipe entrance (position 1)
  T1=Tsource*(P1/Psource)^(1-1/gam);                          % temperature
  d1=dsource*(P1/Psource)^(1/gam);                            % density
  u1=sqrt(2*gam*Zsource*1000*R*Tsource/(MW*(gam-1))*(1-(P1/Psource)^(1-1/gam))); % velocity
  G1=d1*u1;                                                   % mass velocity
  n_in=G1*A*t*1000/MW;                                        % moles of gas flowing into tank in t time

% Exit of pipe (position 2)
  P2=P1*(Mi/Mo)*sqrt((1+(gam-1)/2*Mi^2)/(1+(gam-1)/2*Mo^2));
  T2=T1*(1+(gam-1)/2*Mi^2)/(1+(gam-1)/2*Mo^2);
  Z2=cal_prop(P2,T2);
  u2=Mo*sqrt(gam*Z2*1000*R*T2/MW);
```

A.3.9. Simulation of compressible flow and properties changes in the vehicle tank with respect to time (single source)

```
% Simulation of compressible flow and properties changes
% in the vehicle tank with respect to time


function [t,Mi,Mo,Pf,Tf,nf,delta_u]=base(Psource,Tsource,Ptank,Ttank,moles,t,Ma,Pft,loss)

global R,global MW,global Cp,global Cv,  global Vt

global Pc,global Tc,global omega,
global gam,global k,global a_c, global b,
global Pref, global Tref,global Zref,
global dHref, global dUref,global dSref,global Vref, global dref

[Zo,Ho,Uo,So,vo]=cal_prop(Psource,Tsource);
[Zi,Hi,Ui,Si,vi]=cal_prop(Ptank,Ttank);

i=1;
t(i)=t;del_t=0.1;
Pf(i)=Ptank;
Tf(i)=Ttank;
```

```
nf(i)=moles;
delta_u(i)=loss;

% calculate minimum pressure at the pipe exit to prevent choked flow condition
Mo=1;Mi=Ma_in(Mo);
[P1,T1,n,P2,T2,u2]=flow(Psource,Tsource,Mi,Mo,del_t);
Pchoked=P2

% Simulating with time increment is 0.1 seconds
i=i+1;
Pi(i)=Pf(i-1);
Ti(i)=Tf(i-1);
ni(i)=nf(i-1);

% Choked flow condition, Mach number at pipe exit is unity
while Pi(i)<=Pchoked
    t(i)=t(i-1)+del_t;
    Mo(i)=1;
    Mi(i)=Ma_in(Mo(i));
    [P1(i),T1(i),n_in(i),P2(i),T2(i),u2(i)]=flow(Psource,Tsource,Mi(i),Mo(i),del_t);
    [Pf(i),Tf(i)]=cal_PT(ni(i),Pi(i),Ti(i),n_in(i),P2(i),T2(i),u2(i));
    nf(i)=ni(i)+n_in(i);
    [Zf(i),Hf(i),Uf(i),Sf(i),vf(i)]=cal_prop(Pf(i),Tf(i));
    delta_u(i)=loss+nf(i)*Uf(i)-(nf(i)-moles)*Uo-moles*Ui;
    Pi(i+1)=Pf(i); Ti(i+1)=Tf(i); ni(i+1)=nf(i);   % Pfinal@t(s) = Pinitial@(t+1)s
    i=i+1;
end
constraint=0.9*Psource;
if Ptank>Pchoked && i>2
  Mo(i-1)=Ma
end

% Normal flow condition, pressure inside the vehicle tank equals to one at the pipe exit

while Pi(i)>Pchoked && Pi(i)<Pft
  t(i)=t(i-1)+del_t;
  [Mi(i),Mo(i)]=cal_Ma(Psource,Pi(i),Mo(i-1));
  [P1(i),T1(i),n_in(i),P2(i),T2(i),u2(i)]=flow(Psource,Tsource,Mi(i),Mo(i),del_t);
  [Pf(i),Tf(i)]=cal_PT(ni(i),Pi(i),Ti(i),n_in(i),P2(i),T2(i),u2(i));
  nf(i)=ni(i)+n_in(i);
  [Zf(i),Hf(i),Uf(i),Sf(i),vf(i)]=cal_prop(Pf(i),Tf(i));
  delta_u(i)=loss+nf(i)*Uf(i)-(nf(i)-moles)*Uo-moles*Ui;     % Energy loss
  Pi(i+1)=Pf(i);
  Ti(i+1)=Tf(i);
  ni(i+1)=nf(i);   % Set Pfinal @ t(s) = Pinitial @ (t+1)s
  if Psource<2.4e7 && Pi(i+1)>=0.9*Psource
    break
  end
  i=i+1;
end
```

A.3.10. Simulation of compressible flow and properties changes in the vehicle tank with respect to time (series of sources)

```
% Simulation of compressible flow and properties changes in the vehicle tank
% with respect to time (series of sources)
% Plotting Results

function [result]=series
global R; global Vt;

[P,T,Pi,Ti,Pft]=data_input;          %obtain data from users
n=Pi*Vt/(R*Ti);                     %initial moles of gas in tank
n_i=n;
result=[0 0 0 0 0 0 0];
x=1;
time=0;del_t=0.1;
e_loss=0;
```

```
% For Single source
if length(P)==1
   if Pi>=(2*P(x)/3)
        Ma=0.3;
   elseif Pi>=P(x)/3
        Ma=0.6;
   else Ma=1;                        % Assume a reasonable initial Mach number at the pipe exit
   end
   [t,Mi,Mo,Pf,Tf,nf,delta_u]=base(P,T,Pi,Ti,n,time,Ma,Pft,e_loss);
   all=[t' Mi' Mo' Pf' Tf' nf' delta_u'];
   result=[result;all];
   L=size(result);
   delta_n=result(L(1),6)-n;          % Moles of gas inside the tank when the system is switched to new source
else

% For Series of sources
   while x<=length(P)
      if Pi>=2*P(x)/3
         Ma=0.3;
      elseif Pi>=P(x)/3
         Ma=0.6;
      else Ma=1;
      end
      [t,Mi,Mo,Pf,Tf,nf,delta_u]=base(P(x),T(x),Pi,Ti,n,time,Ma,Pft,e_loss);
      all=[t' Mi' Mo' Pf' Tf' nf' delta_u'];
      all(1,:)=[];
      result=[result;all];
      L=size(result);
      Pi=result(L(1),4);
      Ti=result(L(1),5);
      n=result(L(1),6);
      time=result(L(1),1);
      Ma=result(L(1),3);
      e_loss=result(L(1),7);
      x=x+1;
      n_switch(x)=n;                 % Amount of gas filled in at each stage
   end;

% Continue simulating until pressure inside the tank reaches 21 MPa
    if (Pi<Pft)
      [t,Mi,Mo,Pf,Tf,nf,delta_u]=base(P(x-1),T(x-1),Pi,Ti,n,time,Ma,Pft,e_loss);
      all=[t' Mi' Mo' Pf' Tf' nf' delta_u']
      L=size(all);
      all(L(1),:)=[];
      result=[result;all];
   end
   L=size(result);
   n_switch(1)=n_i;
   n_switch(x)=result(L(1),6)

   % Moles of gas from each different pressure soures
   for j=1:length(P)
      delta_n(j)=n_switch(j+1)-n_switch(j);
   end
   delta_n
end

result(1,:)=[];
for i=1:L(1)-1
   result(i,4)=result(i,4)/(1e6);
   result(i,7)=result(i,7)/(-1e3);
end

% Plotting graphs

figure

% Subplot 1: Graph of pressure and moles of gas versus time
subplot(2,2,1);
[t,P,n]=plotyy(result(:,1),result(:,4),result(:,1),result(:,6),'plot');
title('Pressure and amount of gas in the receiver tank versus time','Fontweight','bold')
axes(t(1))
ylabel('Pressure (MPa)','Fontweight','bold')
xlabel('Time (s)','Fontweight','bold')
ylim([0 2.8e1])
```

```
xlim([0 12])
set(gca,'ycolor','r','Ytick',0:4:28)
set(P,'LineStyle','-','Linewidth',2,'color','r')
legend('Pressure',2)

axes(t(2))
ylabel('Moles of gas')
ylim([0 700])
xlim([0 12])
set(gca,'ycolor','k','Ytick',0:100:700)
set(n,'LineStyle','-.','Linewidth',2,'color','k')
legend('Moles of gas',1)

% Subplot 2: Graph of temperature versus time
subplot(2,2,2);
plot(result(:,1),result(:,5),'-.b*','linewidth',2,'markersize',3)
title('Temperature of the receiver tank versus time','Fontweight','bold')
legend('Temperature',2)
ylabel('Temperature (K)','Fontweight','bold')
xlabel('Time (s)','Fontweight','bold')
set(gca,'xlim',[0 12],'xtick',0:2:12)
set(gca,'ylim',[160 320],'ytick',160:20:320)

% Subplot 3: Graph of Energy loss versus time
subplot(2,2,3);
plot(result(:,1),result(:,7),'-og','linewidth',2,'markersize',3)
title('Internal Energy loss versus time','Fontweight','bold')
legend('Energy loss',2)
ylabel('Energy loss (kJ)','Fontweight','bold')
xlabel('Time (s)','Fontweight','bold')
set(gca,'xlim',[0 12],'xtick',0:2:12)
set(gca,'ylim',[0 6e2 ],'ytick',0:1e2:6e2)

% Subplot 4: Graph of Mach number at the pipe entrance and exit versus time
subplot(2,2,4);
[t,Mi,Mo]=plotyy(result(:,1),result(:,2),result(:,1),result(:,3),'plot');
title('Mach number at the pipe entrance and exit versus time','Fontweight','bold')
axes(t(1))
ylabel('Mach number at pipe entrance','Fontweight','bold')
ylim([0 1.2])
xlim([0 12])
xlabel('Time (s)','Fontweight','bold')
set(gca,'ycolor','m','Ytick',0:0.2:1)
set(Mi,'LineStyle','-.','Linewidth',2,'color','m')
legend('Ma in',2)

axes(t(2))
ylabel('Mach number at pipe exit','Fontweight','bold')
ylim([0 1.2])
xlim([0 12])
set(gca,'ycolor','k','Ytick',0:0.2:1)
set(Mo,'LineStyle','-','Linewidth',2,'color','k')
legend('Ma out',1)
```

A.3.11. Calculation of Energy required for Gas Compression (using optimized compression pathway)

```
% To calculate the energy requirement by using optimized compression
% Optimized compression is multi-stage with intercooling compression,
% with pressure ratio of each state is set at optimized value

function [P,W,totalW]=opt_compression(Pi,Ti,Pf,n)

%MULTI-STAGED ADIABATIC COMPRESSION+ISOBARIC INTERCOOLING-
% SEPARATE COMPRESSORS
% each intermediate source providing gas to the reciever, is fed with gas
% compressed by SEPARATE compressors
% hence, n intermediate sources will require n compressors.

% For n-stage compression, the minimum work load is when the compression
```

```
% stages share the same load --> optimum pressure ratio in each stage is the
% same and equal to (Pf/Pi)^(1/n)

% Assume compressor efficiency = 0.75
eff=0.75;
[Zi,Hi,Ui,Si,vi]=cal_prop(Pi,Ti);

P_ratio=(Pf/Pi)^(1/n)     % Optimized pressure ratio
P(1)=Pi;
H0=Hi;S0=Si;
totalW=0;totalQ=0;
for i=1:n
    % Adiabatic Compression
    P(i+1)=P(i)*P_ratio;
    Tacs(i)=adiabatic(P(i),Ti,P(i+1));           % Adiabatic Temperature
    Tac(i)=Ti+(Tacs(i)-Ti)/eff;                 % Actual Temperature
    [Z1,H1,U1,S1,v1]=cal_prop(P(i+1),Tacs(i));
    Qac(i)=0;
    Wacs(i)=H1-H0;                              % Adiabatic work requirement
    Wac(i)=Wacs(i)/eff;                         % Actual work requirement

    % Isobaric Cooling
    Tc(i)=Ti;
    [Z2,H2,U2,S2,v2]=cal_prop(P(i+1),Tc(i));
    Wc(i)=0;
    Qc(i)=H2-H1;

    % Total Energy requirement
    W(i)=Wac(i)+Wc(i);
    Q(i)=Qac(i)+Qc(i);
    totalW=totalW+W(i);
    totalQ=totalQ+Q(i);
    H0=H2;S0=S2;
  end
```

A.3.12. Calculation of Energy required for Gas Compression (isothermal compression, single stage adiabatic compression, multi-stage adiabatic with intercooling compression)

```
% To calculate energy requirement for gas compression
% in isothermal, adiabatic only (single stage)
% and adiabatic with intercooling compression (multi-stage)
% The pressure at each intermediate stage of multi-stage compression
% is determined by user

function [Wis,Wad,Tad,result]=compression(P,T)

n=length(P);
% P(1)=Pinitial,P(n)=Pfinal

% 3 alternatives for compression
%   1.isothermal(ideal case)
%   2.single stage adiabatic
%   3.n-stage idiabatic +intercooling (n>=2)

% ISOTHERMAL COMPRESSION
[Zi,Hi,Ui,Si,vi]=cal_prop(P(1),T);
[Zf,Hf,Uf,Sf,vf]=cal_prop(P(n),T);
%use Q + W = delta_H; where Q = Tdelta_S (as T=const)
delta_Sis=Sf-Si;
Qis=T*delta_Sis;
delta_His=Hf-Hi;
Wis=delta_His-Qis;

%SINGLE-STAGED ADIABATIC COMPRESSION
% Assume compressor efficiency =0.75
eff=0.75;
Tfs=adiabatic(P(1),T,P(n));    % Adiabatic temperature
```

```
Tad=T+(Tfs-T)/eff;           % Actual temperature
[Zf,Hf,Uf,Sf,vf]=cal_prop(P(n),Tfs);
%use Q + W = delta_H; where Q = 0 (adiabatic)--> W=delta_H
Qa=0;
Wads=Hf-Hi;             % Adiabatic work requirement
Wad=Wads/eff;            % Actual work requirement

%MULTI-STAGE ADIABATIC COMPRESSION
if (n>1)
totalW=0; totalQ=0;
Pa(1)=P(1); Ta(1)=T;
for i=1:n-1

   % Adiabtic Compression
   Pa(i+1)=P(i+1);
   Tas(i+1)=adiabatic(P(i),T,Pa(i+1));      % Adiabatic temperature
   Ta(i+1)=T+(Tas(i+1)-T)/eff;             % Actual temperature
   [Z1,H1,U1,S1,v1]=cal_prop(Pa(i),T);
   [Z2,H2,U2,S2,v2]=cal_prop(Pa(i+1),Tas(i+1));
   Qa(i+1)=0;
   Was(i+1)=H2-H1;                       % Adiabatic work requirement
   Wa(i+1)=Was(i+1)/eff;                  % Actual work requirement

   % Isobaric Cooling
   Pc(i+1)=Pa(i+1);
   Tc(i+1)=T;
   [Z3,H3,U3,S3,v3]=cal_prop(Pc(i+1),Tc(i+1));
   Wc(i+1)=0;
   Qc(i+1)=H3-H2;

   %total energy requirement
   W(i+1)=Wa(i+1)+Wc(i+1);
   Q(i+1)=Qa(i+1)+Qc(i+1);
   totalW=totalW+W(i+1);
   totalQ=totalQ+Q(i+1);
 end
 result=[Pa' Ta'   Wa'  Qa'   Pc'   Tc'   Wc'   Qc'];
 end
```

APPENDIX IV
SIMULATION RESULTS

Table A.4.1. Single sources at 24.8 MPa

Time	Ma in	Ma out	P (Mpa)	T(K)	Moles	E loss (kJ)
0			0.101	303.15	2.2111	0
0.1	0.2880	1.0000	0.467	182.24	17.798	18.17
0.2	0.2880	1.0000	0.811	177.39	33.385	36.341
0.3	0.2880	1.0000	1.127	177.58	48.972	54.522
0.4	0.2880	1.0000	1.491	179.74	64.559	72.696
0.5	0.2880	1.0000	1.826	182.28	80.145	90.765
0.6	0.2880	1.0000	2.074	184.27	95.732	108.84
0.7	0.2880	1.0000	2.341	186.57	111.32	127.07
0.8	0.2880	1.0000	2.738	190.31	126.91	145.21
0.9	0.2880	1.0000	2.934	192.07	142.49	163.38
1	0.2880	1.0000	3.326	195.78	158.08	181.56
1.1	0.2880	1.0000	3.494	197.3	173.67	199.77
1.2	0.2880	1.0000	3.900	200.4	189.25	223.65
1.3	0.2880	1.0000	3.987	201.19	204.84	241.81
1.4	0.2880	1.0000	4.565	206.37	220.43	260.4
1.5	0.2880	1.0000	4.591	206.47	236.01	279.91
1.6	0.2880	1.0000	4.886	209	251.6	298.09
1.7	0.2880	1.0000	5.536	214.26	267.19	316.26
1.8	0.2880	1.0000	5.852	216.66	282.77	334.42
1.9	0.2880	1.0000	6.159	218.75	298.36	354.79
2	0.2880	1.0000	6.080	217.57	313.95	384.03
2.1	0.2880	1.0000	6.876	223.08	329.54	401.56
2.2	0.2879	0.9327	7.212	225.41	345.12	415.89
2.3	0.2877	0.8930	7.233	225.83	360.69	428.25
2.4	0.2876	0.8906	8.135	231.31	376.26	441.14
2.5	0.2866	0.7974	8.186	232.44	391.78	439.73
2.6	0.2865	0.7926	8.845	236.26	407.29	447.93
2.7	0.2851	0.7347	9.805	241.26	422.74	453.98
2.8	0.2825	0.6619	9.825	242.29	438.06	447.38
2.9	0.2824	0.6605	10.752	246.7	453.37	451.64
3	0.2791	0.6001	11.679	250.81	468.52	453.94
3.1	0.2748	0.5471	12.602	254.63	483.46	455.03
3.2	0.2698	0.5002	12.745	255.58	498.14	456.66
3.3	0.2689	0.4934	13.453	258.34	512.79	458.45
3.4	0.2644	0.4612	14.190	261.04	527.2	460.13
3.5	0.2590	0.4299	14.950	263.66	541.35	461.77
3.6	0.2528	0.3997	15.727	266.18	555.18	463.43
3.7	0.2457	0.3707	16.513	268.58	568.65	465.16
3.8	0.2376	0.3426	17.300	270.85	581.71	467
3.9	0.2288	0.3160	18.084	272.99	594.31	468.98
4	0.2190	0.2904	18.857	275	606.4	471.09
4.1	0.2082	0.2658	19.613	276.86	617.92	473.32
4.2	0.1965	0.2420	20.344	278.58	628.83	475.64
4.3	0.1837	0.2188	21.044	280.16	639.05	478.01

Table A.4.2. Series of two sources at 2 and 24.8 MPa

Time	Ma in	Ma out	P (Mpa)	T(K)	Moles	E loss (kJ)
0			0.101	303.15	2.2111	0
0.1	0.28797	1	0.13724	267.72	3.3911	3.1544
0.2	0.28797	1	0.17324	250.72	4.5711	6.3088
0.3	0.28797	1	0.20934	240.8	5.7511	9.4631
0.4	0.28797	1	0.24553	234.35	6.9311	12.618
0.5	0.28797	1	0.28182	229.85	8.1111	15.772
0.6	0.28797	1	0.31821	226.57	9.2911	18.926
0.7	0.28797	1	0.35469	224.08	10.471	22.081
0.8	0.28797	1	0.39127	222.16	11.651	25.235
0.9	0.28797	1	0.42794	220.64	12.831	28.389
1	0.28797	1	0.46472	219.42	14.011	31.544
1.1	0.28797	1	0.50159	218.43	15.191	34.698
1.2	0.28797	1	0.52144	217.51	16.371	37.852
1.3	0.28796	0.98575	0.55631	217	17.551	40.924
1.4	0.28784	0.93	0.59277	217.16	18.73	43.684
1.5	0.28754	0.8774	0.63065	217.83	19.909	46.16
1.6	0.28703	0.82798	0.66979	218.88	21.085	48.376
1.7	0.28619	0.78143	0.71003	220.2	22.259	50.356
1.8	0.2852	0.7381	0.75119	221.71	23.428	52.125
1.9	0.28394	0.69762	0.79312	223.36	24.594	53.706
2	0.28241	0.65981	0.83569	225.09	25.753	55.117
2.1	0.28059	0.62448	0.87873	226.87	26.905	56.377
2.2	0.27849	0.59148	0.92213	228.66	28.05	57.503
2.3	0.27597	0.56043	0.96573	230.46	29.185	58.507
2.4	0.27327	0.53151	1.0094	232.23	30.31	59.406
2.5	0.27027	0.50436	1.0532	233.97	31.424	60.209
2.6	0.26695	0.47882	1.0968	235.67	32.525	60.928
2.7	0.26333	0.45476	1.1401	237.33	33.612	61.572
2.8	0.25939	0.43203	1.1832	238.93	34.685	62.149
2.9	0.25515	0.41053	1.2259	240.47	35.741	62.665
3	0.2506	0.39013	1.2681	241.96	36.78	63.128
3.1	0.24575	0.37075	1.3097	243.38	37.799	63.544
3.2	0.24061	0.35229	1.3507	244.75	38.799	63.916
3.3	0.23508	0.33455	1.391	246.05	39.778	64.251
3.4	0.22943	0.31778	1.4304	247.3	40.734	64.551
3.5	0.22348	0.30167	1.469	248.49	41.667	64.821
3.6	0.21722	0.28616	1.5067	249.62	42.576	65.064
3.7	0.21073	0.27125	1.5434	250.69	43.458	65.282
3.8	0.20398	0.25688	1.5791	251.71	44.314	65.479
3.9	0.19699	0.24296	1.6136	252.68	45.142	65.656
4	0.18958	0.22931	1.647	253.59	45.94	65.815
4.1	0.18223	0.21638	1.6791	254.45	46.708	65.958
4.2	0.17463	0.20378	1.71	255.26	47.445	66.087
4.3	0.1668	0.19149	1.7396	256.02	48.15	66.203
4.4	0.15876	0.17948	1.7679	256.73	48.822	66.308
4.5	0.15014	0.16733	1.7946	257.39	49.459	66.402
4.6	0.14194	0.15609	1.82	258.01	50.062	66.486
4.7	0.28797	1	2.1387	240.49	65.649	84.661
4.8	0.28797	1	2.4329	230.74	81.236	102.85
4.9	0.28797	1	2.8239	225.77	96.822	121.03

5	0.28797	1	3.1546	222.81	112.41	139.11
5.1	0.28797	1	3.4922	221.38	128	157.28
5.2	0.28797	1	3.6884	219.93	143.58	175.25
5.3	0.28797	1	3.9611	219.68	159.17	193.42
5.4	0.28797	1	4.2185	219.76	174.76	211.8
5.5	0.28797	1	4.691	221.82	190.34	229.97
5.6	0.28797	1	5.0251	223.09	205.93	248.03
5.7	0.28797	1	5.3664	224.59	221.52	265.91
5.8	0.28797	1	5.7101	226.17	237.1	284.08
5.9	0.28797	1	5.796	226.03	252.69	302.44
6	0.28797	1	6.4006	229.48	268.28	320.39
6.1	0.28796	0.99466	6.4584	229.33	283.86	338.5
6.2	0.28796	0.98678	7.0951	232.9	299.45	355.92
6.3	0.28773	0.90644	7.4706	235.02	315.03	369.14
6.4	0.28742	0.86428	7.8665	237.3	330.59	380.36
6.5	0.28697	0.82335	7.9234	237.77	346.12	389.31
6.6	0.28689	0.81771	8.4685	240.81	361.66	398.51
6.7	0.28589	0.76682	9.0327	243.87	377.14	405.67
6.8	0.28467	0.71954	9.9549	248.43	392.57	411.19
6.9	0.28202	0.65152	10.42	250.78	407.86	415.22
7	0.28037	0.62081	10.886	252.81	423.08	423.52
7.1	0.27853	0.59211	11.167	254.29	438.2	425.93
7.2	0.27731	0.57567	12.032	257.92	453.26	428.07
7.3	0.27297	0.52854	12.896	261.3	468.11	429.87
7.4	0.26798	0.48631	13.761	264.47	482.7	431.05
7.5	0.26218	0.4478	14.62	267.42	497.01	432.17
7.6	0.25557	0.41255	14.621	267.7	510.98	433.74
7.7	0.25556	0.41253	15.337	270.02	524.95	435.66
7.8	0.24938	0.38505	16.07	272.27	538.61	437.31
7.9	0.24235	0.35834	16.811	274.43	551.91	439.1
8	0.2344	0.33244	17.555	276.48	564.8	441.04
8.1	0.22574	0.30763	18.296	278.42	577.24	443.13
8.2	0.21614	0.28359	19.028	280.24	589.18	445.35
8.3	0.20567	0.26037	19.744	281.94	600.58	447.69
8.4	0.1943	0.23786	20.439	283.52	611.37	450.11
8.5	0.18192	0.21586	21.101	284.94	621.5	453.15

Table A.4.3. Series of three sources at 2, 10 and 24.8 MPa

Time	Ma in	Ma out	P (Mpa)	T(K)	Moles	E loss (kJ)
0.1	0.28797	1	0.13724	267.72	3.3911	3.1544
0.2	0.28797	1	0.17324	250.72	4.5711	6.3088
0.3	0.28797	1	0.20934	240.8	5.7511	9.4631
0.4	0.28797	1	0.24553	234.35	6.9311	12.618
0.5	0.28797	1	0.28182	229.85	8.1111	15.772
0.6	0.28797	1	0.31821	226.57	9.2911	18.926
0.7	0.28797	1	0.35469	224.08	10.471	22.081
0.8	0.28797	1	0.39127	222.16	11.651	25.235
0.9	0.28797	1	0.42794	220.64	12.831	28.389
1	0.28797	1	0.46472	219.42	14.011	31.544
1.1	0.28797	1	0.50159	218.43	15.191	34.698
1.2	0.28797	1	0.52144	217.51	16.371	37.852
1.3	0.28796	0.98575	0.55631	217	17.551	40.924
1.4	0.28784	0.93	0.59277	217.16	18.73	43.684
1.5	0.28754	0.8774	0.63065	217.83	19.909	46.16
1.6	0.28703	0.82798	0.66979	218.88	21.085	48.376
1.7	0.28619	0.78143	0.71003	220.2	22.259	50.356
1.8	0.2852	0.7381	0.75119	221.71	23.428	52.125
1.9	0.28394	0.69762	0.79312	223.36	24.594	53.706
2	0.28241	0.65981	0.83569	225.09	25.753	55.117
2.1	0.28059	0.62448	0.87873	226.87	26.905	56.377
2.2	0.27849	0.59148	0.92213	228.66	28.05	57.503
2.3	0.27597	0.56043	0.96573	230.46	29.185	58.507
2.4	0.27327	0.53151	1.0094	232.23	30.31	59.406
2.5	0.27027	0.50436	1.0532	233.97	31.424	60.209
2.6	0.26695	0.47882	1.0968	235.67	32.525	60.928
2.7	0.26333	0.45476	1.1401	237.33	33.612	61.572
2.8	0.25939	0.43203	1.1832	238.93	34.685	62.149
2.9	0.25515	0.41053	1.2259	240.47	35.741	62.665
3	0.2506	0.39013	1.2681	241.96	36.78	63.128
3.1	0.24575	0.37075	1.3097	243.38	37.799	63.544
3.2	0.24061	0.35229	1.3507	244.75	38.799	63.916
3.3	0.23508	0.33455	1.391	246.05	39.778	64.251
3.4	0.22943	0.31778	1.4304	247.3	40.734	64.551
3.5	0.22348	0.30167	1.469	248.49	41.667	64.821
3.6	0.21722	0.28616	1.5067	249.62	42.576	65.064
3.7	0.21073	0.27125	1.5434	250.69	43.458	65.282
3.8	0.20398	0.25688	1.5791	251.71	44.314	65.479
3.9	0.19699	0.24296	1.6136	252.68	45.142	65.656
4	0.18958	0.22931	1.647	253.59	45.94	65.815
4.1	0.18223	0.21638	1.6791	254.45	46.708	65.958

4.2	0.17463	0.20378	1.71	255.26	47.445	66.087
4.3	0.1668	0.19149	1.7396	256.02	48.15	66.203
4.4	0.15876	0.17948	1.7679	256.73	48.822	66.308
4.5	0.15014	0.16733	1.7946	257.39	49.459	66.402
4.6	0.14194	0.15609	1.82	258.01	50.062	66.486
4.7	0.28797	1	1.979	252.49	56.367	78.958
4.8	0.28797	1	2.1352	248.31	62.671	91.432
4.9	0.28797	1	2.2884	245.11	68.976	103.91
5	0.28797	1	2.4386	242.63	75.281	116.38
5.1	0.28797	1	2.5857	240.7	81.585	128.86
5.2	0.28796	0.99299	2.7311	239.26	87.89	141.15
5.3	0.28789	0.94556	2.8815	238.63	94.193	152.17
5.4	0.28769	0.90051	3.1432	239.24	100.49	162.11
5.5	0.28706	0.83048	3.3272	239.98	106.78	170.33
5.6	0.28629	0.78638	3.5166	241.06	113.05	177.56
5.7	0.28538	0.74504	3.7109	242.39	119.3	183.91
5.8	0.28424	0.70617	3.9094	243.9	125.53	189.5
5.9	0.28285	0.66964	4.1124	245.58	131.74	194.22
6	0.28118	0.63514	4.3184	247.34	137.91	198.34
6.1	0.27924	0.60276	4.5266	249.14	144.04	201.93
6.2	0.27705	0.57233	4.7365	250.96	150.13	205.09
6.3	0.27445	0.54349	4.9475	252.78	156.16	207.86
6.4	0.27168	0.51653	5.159	254.58	162.14	210.31
6.5	0.26861	0.49111	5.3705	256.35	168.06	212.5
6.6	0.26525	0.4671	5.5816	258.08	173.9	214.47
6.7	0.26159	0.44437	5.7918	259.76	179.68	216.26
6.8	0.25764	0.42282	6.0006	261.39	185.37	217.89
6.9	0.25339	0.40235	6.2076	262.97	190.98	219.41
7	0.24884	0.38287	6.4125	264.49	196.49	220.84
7.1	0.24401	0.36429	6.6149	265.95	201.91	222.19
7.2	0.23874	0.34633	6.8143	267.36	207.21	223.48
7.3	0.23342	0.32945	7.0104	268.7	212.41	224.74
7.4	0.22779	0.31321	7.203	269.99	217.48	225.96
7.5	0.22185	0.29753	7.3917	271.21	222.43	227.16
7.6	0.21566	0.28246	7.5762	272.38	227.25	228.34
7.7	0.2092	0.26791	7.754	273.45	231.94	229.85
7.8	0.20255	0.25395	7.9272	274.46	236.48	231.33
7.9	0.19569	0.2405	8.0953	275.42	240.87	232.8
8	0.18841	0.22721	8.258	276.33	245.11	234.24
8.1	0.18116	0.21458	8.4152	277.19	249.19	235.66
8.2	0.17366	0.20224	8.5667	278.01	253.11	237.05
8.3	0.16593	0.19016	8.712	278.77	256.86	238.41
8.4	0.15797	0.17834	8.8511	279.49	260.43	239.74
8.5	0.14944	0.16636	8.9832	280.16	263.82	241.02
8.6	0.14129	0.15522	9.1086	280.79	267.02	242.26
8.7	0.28448	0.71354	9.5668	280.98	282.44	247.63

8.8	0.28323	0.67889	10.038	281.48	297.79	251.98
8.9	0.28174	0.64589	10.523	282.19	313.08	255.49
9	0.27998	0.61434	11.02	283.09	328.27	258.3
9.1	0.27796	0.58421	11.112	282.59	343.36	260.31
9.2	0.27755	0.57881	11.704	283.98	358.44	262.51
9.3	0.27466	0.54571	12.324	285.49	373.37	264.26
9.4	0.27138	0.51385	12.967	287.07	388.13	265.75
9.5	0.26754	0.48307	13.63	288.69	402.71	267.07
9.6	0.26312	0.45348	14.304	290.27	417.06	268.84
9.7	0.25811	0.42526	14.99	291.85	431.16	270.54
9.8	0.25246	0.39819	15.684	293.4	444.97	272.24
9.9	0.24614	0.37223	16.382	294.92	458.47	273.99
10	0.23898	0.34715	17.078	296.38	471.59	275.82
10.1	0.23139	0.32343	17.771	297.78	484.33	277.76
10.2	0.22306	0.30059	18.454	299.11	496.63	279.81
10.3	0.21397	0.27855	19.124	300.37	508.46	281.96
10.4	0.20421	0.25733	19.777	301.55	519.78	284.2
10.5	0.19349	0.23653	20.407	302.66	530.52	286.49
10.6	0.18251	0.21687	21.012	303.68	540.68	288.82

Table A.4.4. Series of four sources at 2, 10, 17 and 24.8 MPa

Time	Ma in	Ma out	P (Mpa)	T(K)	Moles	E loss (kJ)
0.1	0.28797	1	0.13724	267.72	3.3911	3.1544
0.2	0.28797	1	0.17324	250.72	4.5711	6.3088
0.3	0.28797	1	0.20934	240.8	5.7511	9.4631
0.4	0.28797	1	0.24553	234.35	6.9311	12.618
0.5	0.28797	1	0.28182	229.85	8.1111	15.772
0.6	0.28797	1	0.31821	226.57	9.2911	18.926
0.7	0.28797	1	0.35469	224.08	10.471	22.081
0.8	0.28797	1	0.39127	222.16	11.651	25.235
0.9	0.28797	1	0.42794	220.64	12.831	28.389
1	0.28797	1	0.46472	219.42	14.011	31.544
1.1	0.28797	1	0.50159	218.43	15.191	34.698
1.2	0.28797	1	0.52144	217.51	16.371	37.852
1.3	0.28796	0.98576	0.55631	217	17.551	40.924
1.4	0.28784	0.93	0.59277	217.16	18.73	43.684
1.5	0.28754	0.8774	0.63065	217.83	19.909	46.16
1.6	0.28703	0.82798	0.66979	218.88	21.085	48.376
1.7	0.28619	0.78143	0.71003	220.2	22.259	50.356
1.8	0.2852	0.7381	0.75119	221.71	23.428	52.125
1.9	0.28395	0.69771	0.79312	223.36	24.594	53.706
2	0.28241	0.65989	0.83568	225.09	25.753	55.117
2.1	0.28059	0.62455	0.87873	226.87	26.905	56.378
2.2	0.27849	0.59154	0.92212	228.66	28.05	57.504
2.3	0.27597	0.56043	0.96573	230.46	29.185	58.509
2.4	0.27327	0.53151	1.0094	232.23	30.31	59.407
2.5	0.27027	0.50436	1.0532	233.97	31.424	60.211
2.6	0.26695	0.47883	1.0967	235.67	32.525	60.93
2.7	0.26333	0.45476	1.1401	237.33	33.612	61.573
2.8	0.25939	0.43204	1.1832	238.93	34.685	62.15
2.9	0.25515	0.41053	1.2259	240.47	35.741	62.666
3	0.2506	0.39014	1.2681	241.95	36.78	63.13
3.1	0.24575	0.37075	1.3097	243.38	37.8	63.545
3.2	0.24061	0.35229	1.3507	244.75	38.8	63.918
3.3	0.23508	0.33455	1.391	246.05	39.778	64.252
3.4	0.22943	0.31778	1.4304	247.3	40.735	64.552
3.5	0.22348	0.30167	1.469	248.49	41.668	64.823
3.6	0.21722	0.28616	1.5067	249.62	42.576	65.065
3.7	0.21073	0.27126	1.5434	250.69	43.458	65.284
3.8	0.20395	0.25682	1.5791	251.71	44.314	65.48
3.9	0.19699	0.24296	1.6136	252.68	45.142	65.657
4	0.18958	0.22931	1.647	253.59	45.94	65.816
4.1	0.18226	0.21644	1.6791	254.45	46.708	65.959

4.2	0.17468	0.20387	1.71	255.26	47.445	66.089
4.3	0.1668	0.19149	1.7396	256.02	48.151	66.205
4.4	0.15876	0.17948	1.7679	256.73	48.823	66.31
4.5	0.15014	0.16733	1.7946	257.39	49.459	66.403
4.6	0.14194	0.15609	1.82	258.01	50.062	66.488
4.7	0.28797	1	1.979	252.49	56.367	78.96
4.8	0.28797	1	2.1352	248.31	62.672	91.433
4.9	0.28797	1	2.2884	245.11	68.976	103.91
5	0.28797	1	2.4386	242.63	75.281	116.38
5.1	0.28797	1	2.5857	240.7	81.586	128.86
5.2	0.28796	0.99298	2.7311	239.26	87.89	141.15
5.3	0.28789	0.94566	2.8815	238.62	94.194	152.17
5.4	0.2877	0.9006	3.1432	239.24	100.49	162.12
5.5	0.28706	0.83048	3.3272	239.98	106.78	170.34
5.6	0.28629	0.78648	3.5166	241.06	113.05	177.57
5.7	0.28538	0.74514	3.7109	242.39	119.3	183.92
5.8	0.28424	0.70625	3.9093	243.9	125.54	189.51
5.9	0.28285	0.66972	4.1124	245.58	131.74	194.23
6	0.28119	0.63521	4.3183	247.33	137.91	198.35
6.1	0.27925	0.60277	4.5266	249.14	144.04	201.95
6.2	0.27705	0.57233	4.7365	250.96	150.13	205.1
6.3	0.27445	0.5435	4.9474	252.77	156.16	207.88
6.4	0.27168	0.51654	5.1589	254.57	162.14	210.33
6.5	0.26861	0.49112	5.3704	256.34	168.06	212.52
6.6	0.26525	0.46711	5.5815	258.07	173.91	214.49
6.7	0.26159	0.44438	5.7917	259.76	179.68	216.27
6.8	0.25764	0.42283	6.0005	261.39	185.37	217.91
6.9	0.25339	0.40236	6.2076	262.97	190.98	219.43
7	0.24884	0.38287	6.4125	264.49	196.49	220.86
7.1	0.24401	0.36429	6.6148	265.95	201.91	222.21
7.2	0.23874	0.34634	6.8142	267.35	207.21	223.5
7.3	0.23342	0.32945	7.0104	268.7	212.41	224.75
7.4	0.22779	0.31321	7.203	269.98	217.48	225.97
7.5	0.22185	0.29754	7.3917	271.21	222.43	227.17
7.6	0.21566	0.28247	7.5761	272.38	227.25	228.36
7.7	0.20916	0.26783	7.754	273.44	231.94	229.86
7.8	0.20255	0.25395	7.9271	274.46	236.48	231.35
7.9	0.1957	0.2405	8.0952	275.42	240.87	232.81
8	0.18842	0.22722	8.2579	276.33	245.11	234.25
8.1	0.1812	0.21464	8.4152	277.19	249.19	235.67
8.2	0.17372	0.20232	8.5667	278	253.11	237.07
8.3	0.16593	0.19016	8.712	278.77	256.86	238.43
8.4	0.15797	0.17834	8.8511	279.49	260.43	239.75
8.5	0.14944	0.16636	8.9832	280.16	263.82	241.04
8.6	0.14129	0.15522	9.1086	280.79	267.03	242.28
8.7	0.26546	0.46846	9.468	281.99	277.15	243.78

8.8	0.26181	0.44565	9.828	283.2	287.15	245.18
8.9	0.25784	0.42388	10.188	284.4	297	246.53
9	0.25355	0.40308	10.548	285.58	306.71	247.86
9.1	0.24891	0.38316	10.598	286.74	316.25	234.7
9.2	0.24824	0.38043	10.988	287.95	325.76	236.5
9.3	0.24276	0.35978	11.38	289.15	335.08	238.33
9.4	0.23667	0.33958	11.772	290.33	344.18	240.22
9.5	0.23029	0.32025	12.163	291.47	353.05	242.17
9.6	0.22339	0.30144	12.552	292.58	361.67	244.2
9.7	0.21594	0.28312	12.935	293.65	370.02	246.29
9.8	0.20801	0.26534	13.312	294.68	378.08	248.45
9.9	0.19955	0.24796	13.681	295.66	385.82	250.66
10	0.19045	0.23091	14.039	296.59	393.23	252.9
10.1	0.18121	0.21466	14.385	297.47	400.29	255.17
10.2	0.17135	0.19855	14.717	298.29	406.98	257.44
10.3	0.16103	0.18282	15.034	299.06	413.28	259.68
10.4	0.14988	0.16697	15.333	299.77	419.15	261.87
10.5	0.24941	0.38517	15.993	300.93	432.81	263.62
10.6	0.24312	0.36108	16.657	302.08	446.15	265.45
10.7	0.23608	0.33769	17.321	303.21	459.13	267.39
10.8	0.22857	0.31537	17.981	304.32	471.72	269.44
10.9	0.22033	0.29373	18.634	305.39	483.88	271.61
11	0.21144	0.27283	19.275	306.41	495.57	273.87
11.1	0.20188	0.25259	19.9	307.38	506.77	276.22
11.2	0.19142	0.23269	20.506	308.29	517.4	278.61
11.3	0.18068	0.21377	21.088	309.15	527.47	281.04

APPENDIX V

ENERGY REQUIREMENT VERSUS RECEIVER' S INITIAL GAS CONTENT

Table A.5. Energy Requirement with respect to different initial gas content in the vehicle tank

% Tank Max Pressure	Initial Tank Pressure (MPa)	Time (s)	Total moles transferred (moles)	Gas from source 1 (moles)	Gas from source 2 (moles)	Gas from source 3 (moles)	Total Energy Requirement (J)	Average Molar Energy Requirement (J/mole)
0.50%	0.101	10.6	546.05	47.85	213.59	284.62	1.184E+07	2.17E+04
0.05	1.05	8.2	519.77	18.78	216.94	284.05	1.148E+07	2.21E+04
0.1	2.1	5.9	492.56		206.82	285.74	1.104E+07	2.24E+04
0.15	3.15	5.5	462.27		179.02	283.25	1.041E+07	2.25E+04
0.2	4.2	5.0	432.49		147.84	284.65	9.799E+06	2.27E+04
0.25	5.25	4.6	407.14		122.36	284.78	9.275E+06	2.28E+04
0.3	6.3	4.2	383.44		98.47	284.97	8.787E+06	2.29E+04
0.35	7.35	3.8	361.00		75.86	285.14	8.323E+06	2.31E+04
0.4	8.4	3.4	339.64		54.45	285.19	7.882E+06	2.32E+04
0.45	9.45	2.4	320.86		37.28	283.58	7.489E+06	2.33E+04
0.5	10.5	2.2	301.26			301.26	7.138E+06	2.37E+04
0.55	11.55	2.1	282.22			282.22	6.687E+06	2.37E+04
0.6	12.6	1.9	254.27			254.27	6.025E+06	2.37E+04
0.65	13.65	1.8	236.27			236.27	5.598E+06	2.37E+04
0.7	14.7	1.6	209.15			209.15	4.956E+06	2.37E+04
0.75	15.75	1.5	191.96			191.96	4.548E+06	2.37E+04

APPENDIX VI

ECONOMIC ANALYSIS

Table A.6. 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	100,000 Liter equivalent
Daily Compression operating cost	0.025 USD/ Liter equivalent x 100,000 Liter equivalent / day = 2,500 USD/ day = 9,500 RM/ day
Annual compression cost	9,500 RM/ day x 365 days/ year = 3,47 millions RM/ year
Annual cost saving by reduction of energy requirement	3,47 millions RM/ year x 17.5% = ***607,000 RM/ year***