# A Study on Centrifugal Compressor Performance and Developing Compressor Performance Analysis Software

by

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Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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May 2011

# 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 references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Anis Farhana Binti Abdul Halim

# ABSTRACT

This report basically discusses the research and the work done on the project entitles A Study on Centrifugal Compressor Performance and Developing Compressor Performance Analysis Software. The objective of this project is to study centrifugal compressor behavior and analyze factors that affect the performance of compressor. Compressors have a limited operational range that operator will take into seriously. If exceeded will cause damage to the compressor. Moreover, centrifugal compressors are costly processing equipment and also consume a lot of energy. Thus, it is crucial to monitor and controlled compressor performance. Polytropic head are plotted to trend real time performance monitoring for centrifugal compressors as it consider changes in gas characteristics during compression. By using Microsoft Excel 2008, the author can automatically get the outputs by inserting all the data into a calculation sheet after put in required formulas as a function in Excel. From the compressor performance map one can analyze the behavior of compressor in real time operation. By trending necessary variables against time, operator can do a planning on troubleshoot and also composition analysis. All the theory can be validate by analyzing the results. The author also manage to construct an interface to determine compressibility factor, Z and polytropic head using Visual Basic Application.

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## LIST OF ABBREVIATION

| | |
|---|---|
| VBA | Visual Basic Application |
| GUI | Graphic User Interface |

## LIST OF NOMENCLATURES

| | | |
|---|---|---|
| $C_p$ | Heat capacity at constant pressure | [J/(mol.K)] |
| g | Gravitational acceleration | [$m/s^2$] |
| h | Enthalpy | [kJ/kg] |
| $H_p$ | Polytropic head | [ft.lb/lb] |
| $H_s$ | Isentropic Head | [ft.lb/lb] |
| MW | Molecular weight | [kg/kmol] |
| N | Rotational speed | [rpm] |
| P | Pressure | [psi] |
| Q | Volumetric flow | [ACFM] |
| R | Gas constant | [J/mol.K] |
| T | Temperature | [degree C] |
| W | Work | [J] |
| Z | Compressibility factor | [-] |
| $\eta_p$ | Polytropic efficiency | [-] |
| $\eta_s$ | Isentropic efficiency | [-] |

### Subscript

| | |
|---|---|
| 1 | Suction |
| 2 | Discharge |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND OF STUDY

Centrifugal compressor is critical equipment in oil and gas industry, which applied in gas injection, gas lifting, gas pipeline compression and many more. Compressor achieves compression by applying inertial forces to the gas using rotating blade impellers, continuously impacting and performing work on the gas during operation.

Inability to maintain flow within the design parameters and pressure characteristics for a particular compressor can and probably would result in turbulent gas flow patterns, back flow and development of an operating condition know as "surge" inside the compressor. This condition is very detrimental or destructive to the working parts of a centrifugal gas compressor.

Compressors have a limited operational range that operator will look into seriously. If exceeded, it will cause damage to the compressor. Moreover, centrifugal compressors are costly processing equipment and also consume a lot of energy. Thus, it is crucial to monitor and controlled compressor performance.

## 1.2 Problem Statement

i. Compressor performance has a significant impact on overall plant performance. Compressor performance need to be monitored in order to avoid operation shutdown that will lead to lost of money.
ii. Surge is a fluctuation of flow and pressure and it causes overheating and damages; it may be violent enough to damage a compressor in a few cycles. Surging gives cyclic flow, back-flow, high vibrations, pressure shocks and rapid temperature increase.
iii. There is no current performance monitoring software that able to calculate polytropic head for each operating point during real time operation.

## 1.3 Objective

i. To study compressor behavior and analyze factors that affect the performance of compressor.
ii. To be able to describe surge phenomena in the compressor while provide validation of the existing theory of surge occurrence through data analysis.
iii. To study the importance of performance monitoring and develop a compressor performance analysis software.

## 1.4 Scope of Study

In order to complete this project, several scope of study had to achieve. The major scopes are follows:

### *1.4.1 Understanding Centrifugal Compressor Operation*

- Research on how a centrifugal compressor works
- Research on surge mechanism
- Research on basic thermodynamic law and equation in describing centrifugal compressor performance and operation.

### *1.4.2 Constructing Mathematical Model of Centrifugal Compressor*

- Investigate related equation to used to construct the model
- Acquire data needed for performance analysis
- Training on how to use Visual Basic Application to provide GUI in determining performance parameters.

The scope of study is to understand operation and characteristic of centrifugal compressor applied for oil and gas industry. First of all is to seek all the relevant information that related to compressor operation. To understand about compressor we need to know basic concept of compressor process and also compressor performance. The next scope is to explore about surge mechanism, how it happen and the parameter that drive it. This study will go further by construct a mathematical model of compressor. It is important to have mathematical model of compressor as it describes the phenomena of interest in the actual system with sufficient accuracy. The author then acquires compressor data from a plant, which operate centrifugal compressor. The data used as input for the mathematical model to find the polytropic head of the compressor. Plot all the results on a compressor performance map. From the map, one can see the behavior of the compressor as the parameters change. Using Visual Basic Application, the author then provides a GUI for a better interface in determining the compressor performance parameters.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Centrifugal Compressor

Centrifugal compressor is a dynamic machine. Centrifugal compressors achieve compression by applying inertial forces to the gas (acceleration, deceleration, turning) by means of rotating blades that continuously impact and perform work on the gas during operation. Below are the applications of centrifugal compressor in oil and gas industry:

| Upstream Sector | Gas Transmission |
|---|---|
| • Gas Injection<br>• Gas Lift<br>• Gas Boosting / Export | • Gas Pipeline Compression<br>• Gas Storage / Withdrawal Compression |

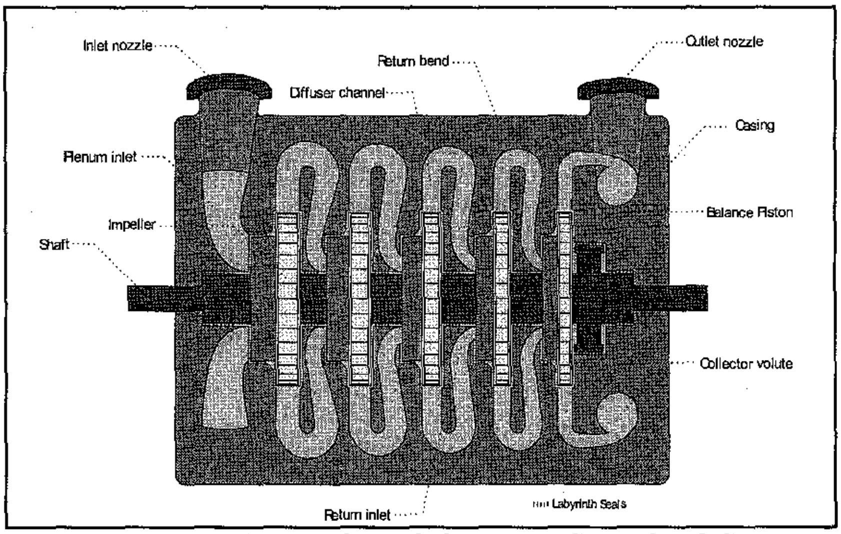
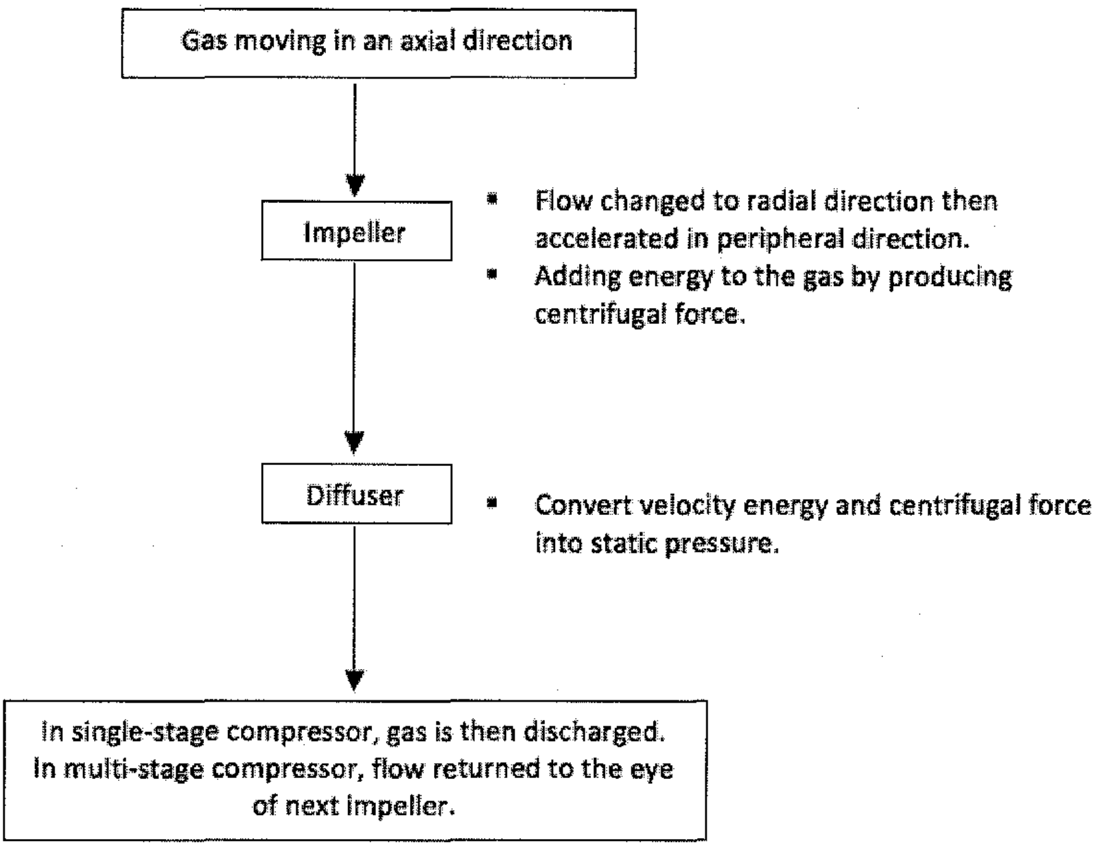


*Figure 1: Cross sectional view of a with five stage Centrifugal Compressor* [1]

Each compression stage consists of an impeller, a diffuser channel, a return bend and a return inlet. Following the gas through the compressor it enters through the inlet nozzle and is distributed around the shaft in the plenum inlet. The gas is then led into the impellers where it is accelerated up to high velocities. In the diffuser channel the gas is decelerated whereby the kinetic energy is converted to potential energy. The return bend and the return inlet lead the gas on the next stage in the compressor. After the last impeller stage the gas collected in the collector volute and via the outlet nozzle it is sent for further processing.

Below is the mechanism of gas flow in centrifugal compressor:



Gas moving in an axial direction

Impeller

- Flow changed to radial direction then accelerated in peripheral direction.
- Adding energy to the gas by producing centrifugal force.

Diffuser

- Convert velocity energy and centrifugal force into static pressure.

In single-stage compressor, gas is then discharged.
In multi-stage compressor, flow returned to the eye of next impeller.

The mechanism starts once the gas enters the impellers at the eye, moving in an axial direction. The flow is then changed to a radial direction and accelerated in a peripheral direction as it moves through the impeller from the eye to the tip. Gas then exits into some type of diffuser (flow decelerator). In a single-stage compressor the gas is then discharged to the process. In a multi-stage compressor the flow must be returned to the eye of the next impeller. About two- thirds of the pressure rise occurs in the impeller with the remaining increase taking place in the diffusion (velocity reduction) process. Flow passages are open throughout the compressor.

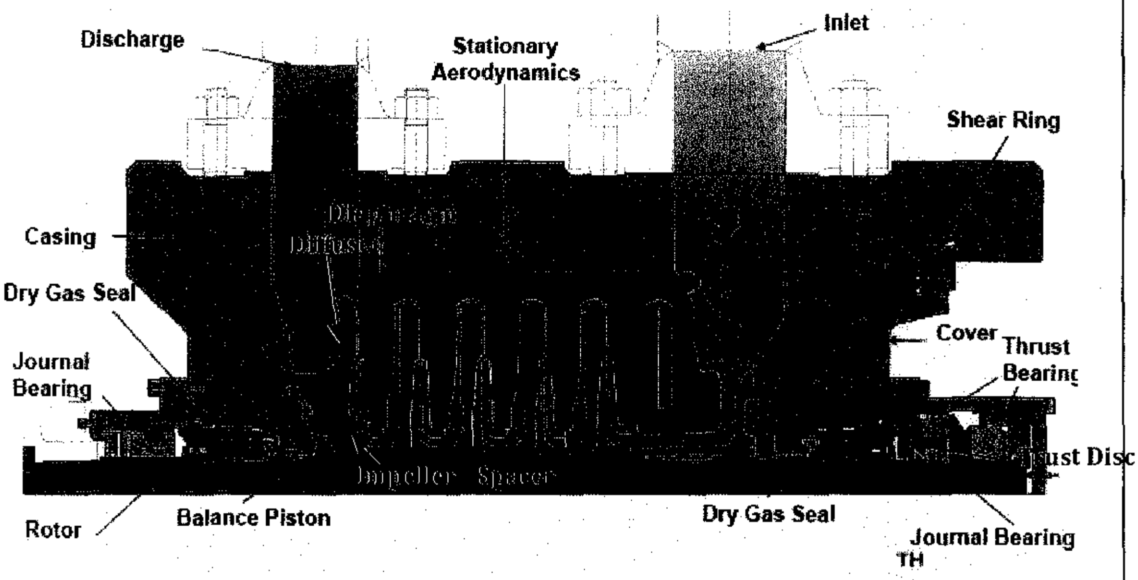


*Figure 2 : Anatomy of centrifugal compressor* [2]

The mechanism starts once the gas enters the impellers at the eye, moving in an axial direction. The flow is then changed to a radial direction and accelerated in a peripheral direction as it moves through the impeller from the eye to the tip. Gas then exits into some type of diffuser (flow decelerator). In a single-stage compressor the gas is then discharged to the process. In a multi-stage compressor the flow must be returned to the eye of the next impeller. About two- thirds of the pressure rise occurs in the impeller with the remaining increase taking place in the diffusion (velocity reduction) process. Flow passages are open throughout the compressor.

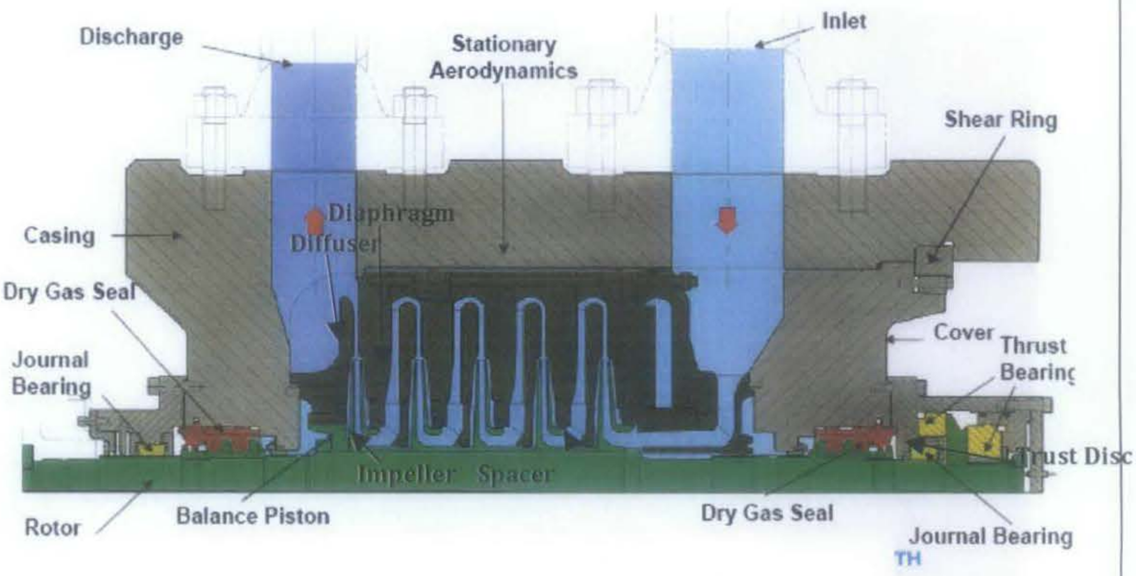


*Figure 2 : Anatomy of centrifugal compressor* [2]

Below are the components of centrifugal compressor and its functions:

*Table 1: Components of centrifugal compressor*

| **Components** | **Function** |
|---|---|
| ***Impellers*** | Impart energy to the gas by means of centrifugal force |
| ***Shaft*** | Rotating element on which the rotating parts are mounted |
| ***Balance piston*** | To prevent contact under normal operating conditions |
| ***Thrust disc*** | Transmit rotor thrust to thrust bearing |
| ***Inlet guide vanes*** | Reduce turbulence in the gas stream and to direct the flow |
| ***Diaphragm*** | Dividing wall between individual impellers of a multi-stage compressor. |
| ***Diffuser*** | Stationary passage surrounding an impeller in which velocity imparted to the gas by the impeller is converted into static pressure. |
| ***Internal seals*** | Used between rotating and stationary parts to separate and minimize gas leakage between areas of unequal pressure. |
| ***Shaft seals*** | To isolate the gas stream from the atmosphere and from the journal bearings. |
| ***Journal bearing*** | To support the rotor load (steady state and dynamic), provide stiffness and damping, and to control rotor position. |
| ***Thrust bearing*** | To prevent axial motion of the rotating shaft, thereby maintaining the axial position of the rotor assembly within the compressor. |

## 2.2 Surge Mechanism

There is a minimum capacity for each compressor, at every speed, below which the operation becomes unstable. This instability is accompanied by a characteristic noise known as surge. Surging occurs when the pressure at the outlet of the compressor is higher than that produced by the compressor, this causes the flow to reverse momentarily. The gas volume at discharge is higher than the compressor can achieve cause the tendency of flow from higher to the lower pressure. However, the reduction of flow causes the discharge pressure to drop, and the flow returns. The resulting violent oscillation of gas pressure can cause severe and costly damage to the compressor in a few seconds. Surge occurs at low flow rate and high compression ratio.

$$\boxed{\textbf{Compression ratio} = \frac{\text{Discharge Pressure (Absolute)}}{\text{Suction Pressure (Absolute)}}}$$

The compressor loses the ability to maintain the peak head when surge occurs and the entire system becomes unstable. Under normal conditions, the compressor operates to the right of the surge line. However, as fluctuations in flow rate occur, or under startup / emergency shutdown, the operating point will move towards the surge line because flow is reduced. If conditions are such that the operating point approaches the surge line, the impeller and diffuser begin to operate in stall and flow recirculation occurs. The flow separation will eventually cause a decrease in the discharge pressure and flow from suction to discharge will resume.

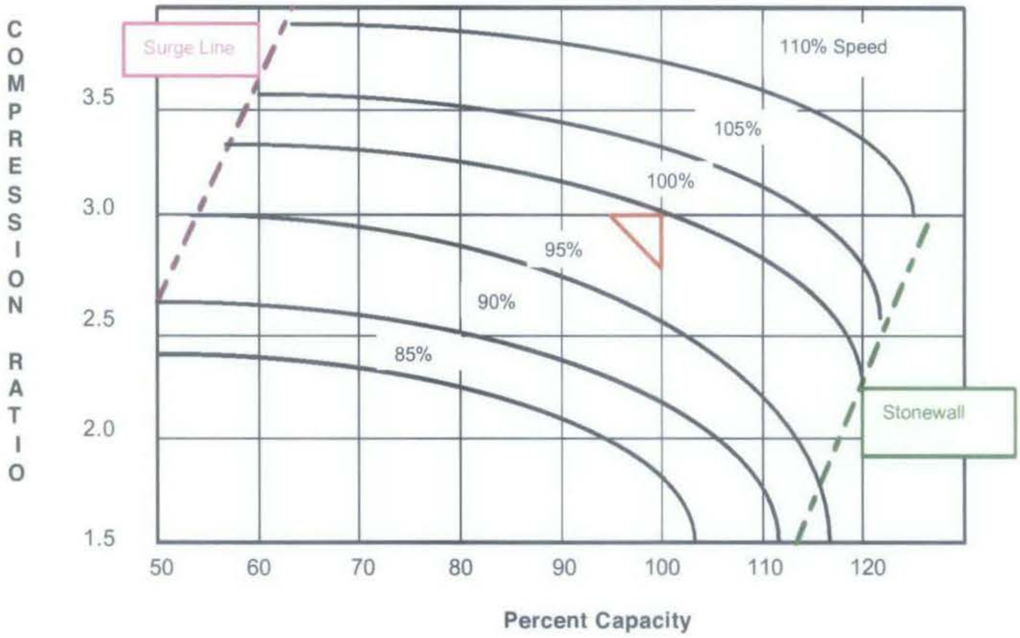


*Figure 3: Above is Compressor Operating Map. The operating range of a centrifugal compressor is restricted by a condition called surge, and a condition called stonewall. The surge limitation is most critical of the two operating conditions. Operating point must not reach surge line and stonewall.* [2]

Surge is a powerful disturbance that can disrupt or trip a process. It can damage equipment, and in catastrophic incidents, may result in the complete destruction of the compressor rotor. The surge cycle will repeat itself unless control systems are installed or operational changes are made to bring the compressor out of the surge cycle. The surge cycle may result in a small or large flow reversal period depending on the discharge gas volume and the pressure ratio.

## 2.3 Centrifugal Compressor Parameters

The following parameters used to describe the performance of a centrifugal compressor. There are measurements (operating conditions) required to calculate these parameters that will be discussed later.

Performance Parameters (behavior)

1. Flow coefficient

   If an orifice meter is used as flow-measuring device, the mass flow rate equation is

   $$W_s = CE\frac{\pi}{4}d^2 \cdot \sqrt{2\Delta p \rho_s}$$

   The actual suction volumetric flow given by

   $$Q_s = \frac{W_s}{\rho_s}$$

   The flow coefficient used for similarity comparisons is

   $$\varphi = \frac{Q_s}{\frac{\pi}{4}{D_{tip}}^2 U_{tip}} = \frac{Q_s}{\frac{\pi^2}{4}{D_{tip}}^3 \omega}$$

2. Head coefficient

   Head coefficient can be used to describe the pressure ratio across a compressor from suction to discharge.

   Isentropic head

   $$H^* = h_d^* - h_s = h(p_d, s_s) - h(p_s, T_s)$$

   Actual head

   $$H = h_d - h_s = h(p_d, T_d) - h(p_s, T_s)$$

which $h_d$* is the enthalpy associated with the discharge pressure at suction entropy, $s_s$ ,because the entropy change is zero. Isentropic enthalpy can also estimate by assuming ideal gas behavior by

$$h_d^* \approx c_p{}^* \cdot T_d^* = c_{p_s} \cdot T_s \cdot \left( \frac{P_d}{P_s} \right)^{\frac{k-1}{k}}$$

and the isentropic exponent k defined as

$$k = \frac{\ln \frac{P_d}{P_s}}{\ln \frac{v_s}{v_d^*}}$$

Polytropic head

$$H^P = \left[ \frac{n^P}{n^P - 1} \right] \cdot \left[ \left( \frac{P_d}{P_S} \right)^{\frac{n^P - 1}{n^P}} - 1 \right] \cdot f \cdot P_S v_S$$

which the polytropic exponent $n^P$ defined as

$$n^P = \frac{\ln \frac{P_d}{P_s}}{\ln \frac{v_S}{v_d}}$$

the Schultz Polytropic Head Correction Factor, f is defined as

$$f = \frac{h_d^* - h_s}{\left[ \frac{k}{k-1} \right] \cdot \left[ P_d v_d^* - P_s v_s \right]}$$

Isentropic head coefficient

$$\psi^* = \frac{H^*}{\frac{U^2}{2}} = \frac{2H^*}{(\pi D_{tip} \omega)^2}$$

Actual head coefficient

$$\psi = \frac{H}{\frac{U^2}{2}} = \frac{2H}{(\pi D_{tip} \omega)^2}$$

Polytropic head coefficient

$$\psi^P = \frac{H^P}{\frac{U^2}{2}} = \frac{2H^P}{(\pi D_{tip} N)^2}$$

3. Compressor efficiency

Isentropic efficiency

$$\eta^* = \frac{H^*}{H} = \frac{\psi^*}{\psi}$$

Polytropic efficiency

$$\eta^P = \frac{H^P}{H} = \frac{\left[\frac{n^P}{(n^P-1)}\right] \cdot \left[\left(\frac{P_d}{P_s}\right)^{\frac{n^P-1}{n^P}} - 1\right] \cdot f \cdot P_s v_s}{h_d - h_s}$$

## 2.4 Operating Conditions

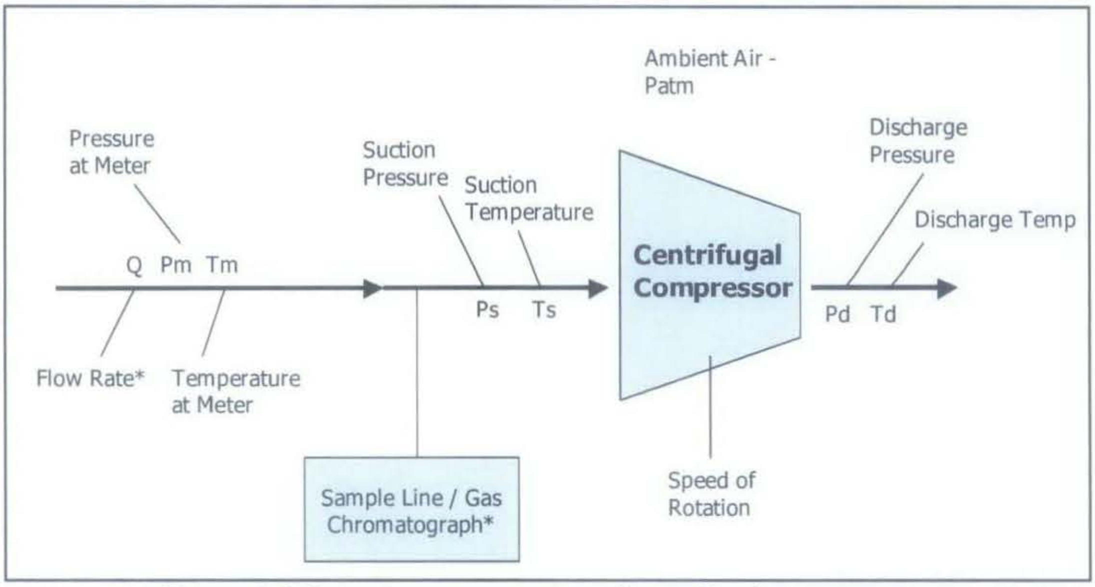


*Figure 4: Schematic representation of centrifugal compressor*

1. Pressures

   Centrifugal compressors have a suction and discharge that is unobstructed to flow gas from a lower pressure to a higher pressure. The pressure ratio across the compressor is equal to the discharge pressure divided by the suction pressure. As the ratio increase, it will increased corresponding head and power required to perform the work. Increasing compressor suction pressure and reducing discharge pressure will increase compressor capacity. Discharge pressure should be minimized without affecting gas plant performance.

2. Temperatures

   If the suction temperature is reduced, the head will be less because this variable is in numerator. By reducing suction temperature will also reduce the actual inlet volume flow along with the power required. That is why some compressor employs a chiller at the inlet. Discharge temperature is a function of the compressor efficiency. The lower the compressor efficiency, more losses that will occur that will cause discharge temperature to increase.

3. Mass or standard flows

   The performance curve flow rate is based on suction conditions. Changes in compressor suction conditions that increase gas density will reduce gas volumetric flow rate and raise compressor capacity.

4. Gas composition

   The gas composition is comprised of all the individual gas constituents that are being compressed. Individual gas constituents that determine the gas molecular weight. As the molecular weight increases, the corresponding head decreases. From performance map, if required head for a given operating point is less, then the compressor can be operated at lower speed.

### 2.5 Thermodynamics of Gas Compression

General description of the thermodynamics of gas compression applies to any type of compressor. Working principles of gas compressors can be described using the first and second law of thermodynamics together with basic laws of physics.

For a compressor receiving gas at certain suction pressure and temperature, and delivering it at certain output pressure, the isentropic head represents the energy input required by a reversible, adiabatic (isentropic) compression. The actual compressor will require a higher amount of energy input than needed for the ideal compression.

The first law which describing the conservation of energy becomes:

$$\left(h_2 + \frac{w_2^2}{2} + gz_2\right)\dot{m} - \left(h_1 + \frac{w_1^2}{2} + gz_1\right)\dot{m}$$
$$= q_{12} + W_{t,12} \qquad (1)$$

with q=0 for adiabatic processes and gz=0 as we assume it negligible. Enthalpy and velocity can be combined into total enthalpy by

$$h_t = h + \frac{w^2}{2} \qquad (2)$$

$W_{t,12}$ is the amount of work that affect the change in enthalpy in the gas and related to required power, P by

$$P = \dot{m}W_{t,12} \qquad (3)$$

Power and enthalpy difference are related by

$$P = \dot{m}\left(h_{t,2} - h_{t,1}\right) \qquad (4)$$

For a perfect gas, with constant heat capacity, the relationship between enthalpy, pressures and temperatures is

$$\Delta h = c_p (T_2 - T_1) \tag{5}$$

For an isentropic compression, the discharge temperature is determined by the pressure ratio

$$T_2 = T_1 \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} + T_1 \tag{6}$$

For an isentropic compression of a perfect gas, isentropic head, temperatures and pressures can be relate by

$$\Delta h_s = c_p T_1 \left[ \left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right] \tag{7}$$

We can calculate the actual head (relates to amount of power need for the compression) and isentropic head for the compression by

$$\Delta h = h(p_2, T_2) - h(p_1, T_1) \tag{8}$$

$$\Delta h = h(p_2, s_1) - h(p_1, T_1) \tag{9}$$

$$s_1 = s(p_1, T_1) \tag{10}$$

The performance quality of compressor can be defined by comparing actual head with the ideal head (isentropic compression). This defines the isentropic efficiency

$$\eta_s = \frac{\Delta h_s}{\Delta h} \tag{11}$$

Second law of thermodynamic tells that

$$\dot{m}(s_2 - s_1) = \int_1^2 \frac{dq}{T} + s_{irr} \tag{12}$$

For adiabatic flows, there are no heat q enters or leaves, change in entropy describes losses generated in the compression process which come from friction of gas with solid surfaces and the mixing of gas of different energy levels. Therefore, an adiabatic, reversible compression process does not change the entropy of he system (isentropic). Equation for actual head implicitly includes the entropy rise Δs

$$\Delta h = h(p_2, T_2) - h(p_1, T_1) = h(p_2, s_1 + \Delta s) - h(p_1, s_1) \qquad (13)$$

The absorbed gas power $P_g$ (power transferred into the gas) defined as

$$P_g = \dot{m} \cdot \Delta h \qquad (14)$$

while the mechanical power P required to drive the compressor is the gas absorbed power increased by all mechanical losses defined by a mechanical efficiency $\eta_m$

$$P = \frac{1}{\eta_m} \dot{m} \cdot \Delta h = \frac{\dot{m} \cdot \Delta h_s}{\eta_m \eta_s} \qquad (15)$$

## 2.6 Real Gas Behavior and Equation of State

For ideal gas at very low pressure can be described by

$$\frac{p}{\rho} = RT \qquad (16)$$

For high pressures natural gas compression, the compressibility factor Z is introduced in the equation

$$\frac{p}{\rho} = ZRT \qquad (17)$$

The compressibility factor is a function of pressure, temperature and gas composition.

The most frequently used equations of state for gas compression applications are Redlich-Kwong, Soave-Redlich-Kwong, Benedict-Webb-Rubin, Benedict-Webb-Rubin-

Starling and Lee-Kessler-Ploecker. The most effective equation from computational point of view is the Redlich Kwong equation of state. This is because the solution is found directly rather than through an iteration.

### 2.7 Redlich-Kwong Equation

The Redlich-Kwong equation is given by

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)\sqrt{T}} \tag{18}$$

P = pressure in atm V = molar volume in liters/g-mol T = temperature in K R = gas constant (R = 0.08206 (atm·liter/g-mol·K)) Tc = critical temperature in K Pc = critical pressure in atm

where

$$a = 0.42747\left(\frac{R^2 T_c^{\frac{5}{2}}}{P_c}\right) \tag{19}$$

$$b = 0.08664\left(\frac{RT_c}{P_c}\right) \tag{20}$$

To determine compressibility factor

$$z = \frac{PV}{RT} \tag{21}$$

After consider algebra, equation 18 can be written in terms of the compressibility factor as cubic equation

$$f(z)) = z^3 - z^2 - qz - r = 0 \tag{22}$$

where

$$r = A^2 B \tag{23}$$

$$q = B^2 + B - A^2 \tag{24}$$

$$A^2 = 0.42747\left(\frac{P_R}{T_R^{5/2}}\right) \tag{25}$$

$$B = 0.08664\left(\frac{P_R}{T_R}\right) \tag{26}$$

as a function reduced pressure $P_r = P/P_c$ ,at various cases of reduced temperature $T_r = T/T_c$ .

Equation 22 can be solved analytically for three roots. Some of these roots are complex.

Considering only the real roots, the sequence of calculations involves the steps

$$C = \left(\frac{f}{3}\right)^3 + \left(\frac{g}{2}\right)^2 \tag{27}$$

where

$$f = \frac{-3q-1}{3} \tag{28}$$

$$g = \frac{-27r-9q-2}{27} \tag{29}$$

If C>0 there is one real solution for z given by

$$z = D + E + 1/3 \tag{30}$$

where

$$D = (-g/2 + \sqrt{C})^{1/3} \tag{31}$$

$$E = (-g/2 - \sqrt{C})^{1/3} \tag{32}$$

If C<0, there are three solutions

$$z_k = 2\sqrt{\frac{-f}{3}}\cos\left[\left(\frac{\phi}{3}\right) + \frac{2\pi(k-1)}{3}\right] + \frac{1}{3} \quad k = 1, 2, 3 \tag{33}$$

where

$$\phi = a\cos\sqrt{\frac{g^2/4}{(-f^3)/27}} \tag{34}$$

In the supercritical region when $T_r \geq 10$, two of these solutions are negative, so the maximal $z_k$ is selected as the true compressibility factor.

### 2.8 Polytropic Head

Compare to other thermodynamic processes, a polytropic process consider changes in gas characteristics during compression. Polytropic compression process is typical of dynamic type compressor. In real time performance monitoring system, head is use for trending instead of using the efficiency. In this project, we will only deal with polytropic head as the scope of this project cover only centrifugal compressor.

# CHAPTER 3

# METHODOLOGY

## 3.1 Process Workflow

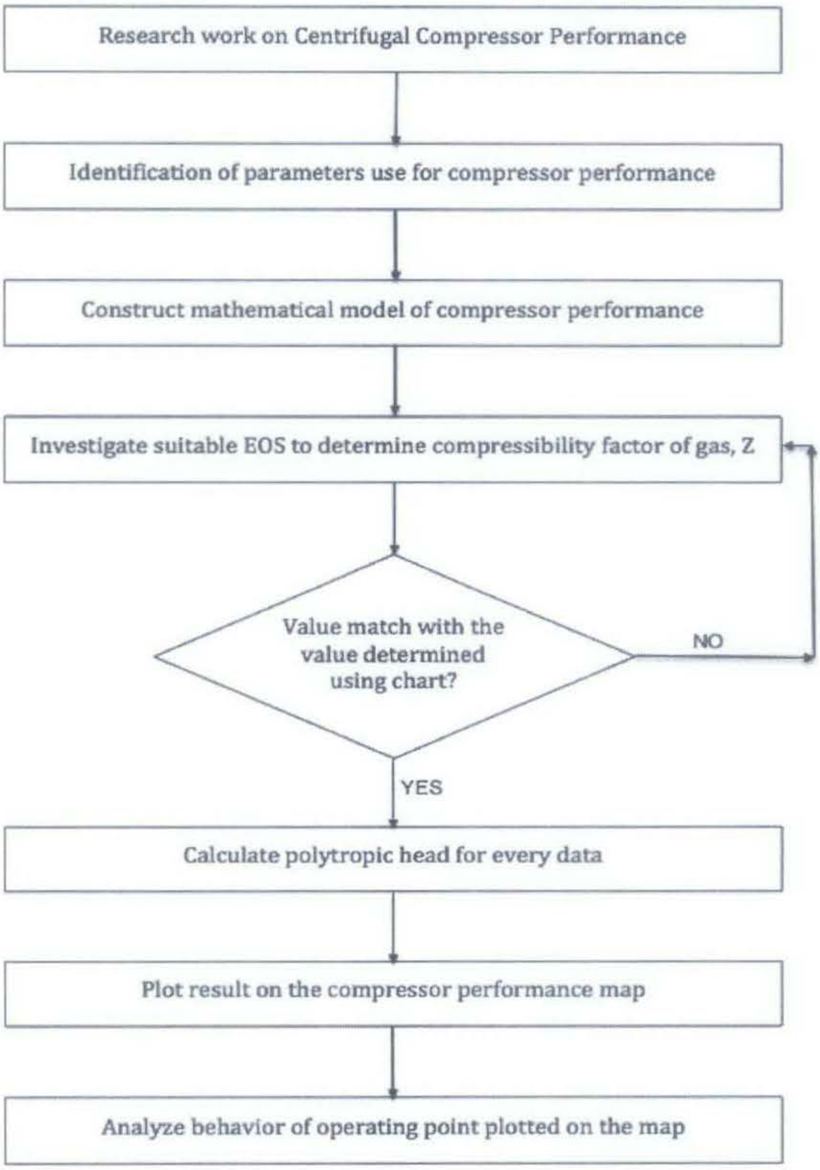


*Figure 5: Process workflow*

## 3.2 Work Scope

### *3.2.1 Data Gathering and Research*

Researches have been done first in order to understand basic principle of centrifugal compressor and also to investigate thermodynamic equations necessary in constructing mathematical model of centrifugal compressor. For performance analysis and simulation purposes, data is acquired from respective plant. The data acquired represent real operating conditions of a centrifugal compressor. Operator A operating centrifugal compressor driven by gas turbine as gas compressor that are used in natural gas pipeline transportation which is installed on an offshore platform.

### *3.2.2 Constructing Mathematical Model of Centrifugal Compressor*

Using related thermodynamic equations and assumptions, the author start to construct a mathematical model using Microsoft Excel 2008. Using necessary data acquired earlier as the inputs to the model, the author manage to simulate and trending the output for centrifugal compressor performance monitoring.

### *3.2.3 Developing GUI for Calculating Performance Parameters*

Using Visual Basic Application, the author develops an interface that can be used to determine compressibility factor, Z and polytropic head instantly by inserting necessary inputs.

## 3.3 Tool and Equipment Required

### *3.3.1 Microsoft Excel 2008*

As stated before, the author makes a full use of Microsoft Excel to calculate performance parameters by inserting mathematical equations into the cells. By using Microsoft Excel, calculations for all the data can instantly determined via a dragging tool. All simulations also can be done using this software.

### *3.3.2 Visual Basic Application (VBA) 2008*

Using this software, we can develop GUI that will provide an interactive interface that will link with the excel workbook.

## 3.4 Construction of Mathematical Model of Centrifugal Compressor

### *3.4.1 Data Acquired*

Below is hourly data acquired from a plant running centrifugal compressor on April 2010 for duration of 30 days.

*Table 2: Part of the data acquired from a plant*

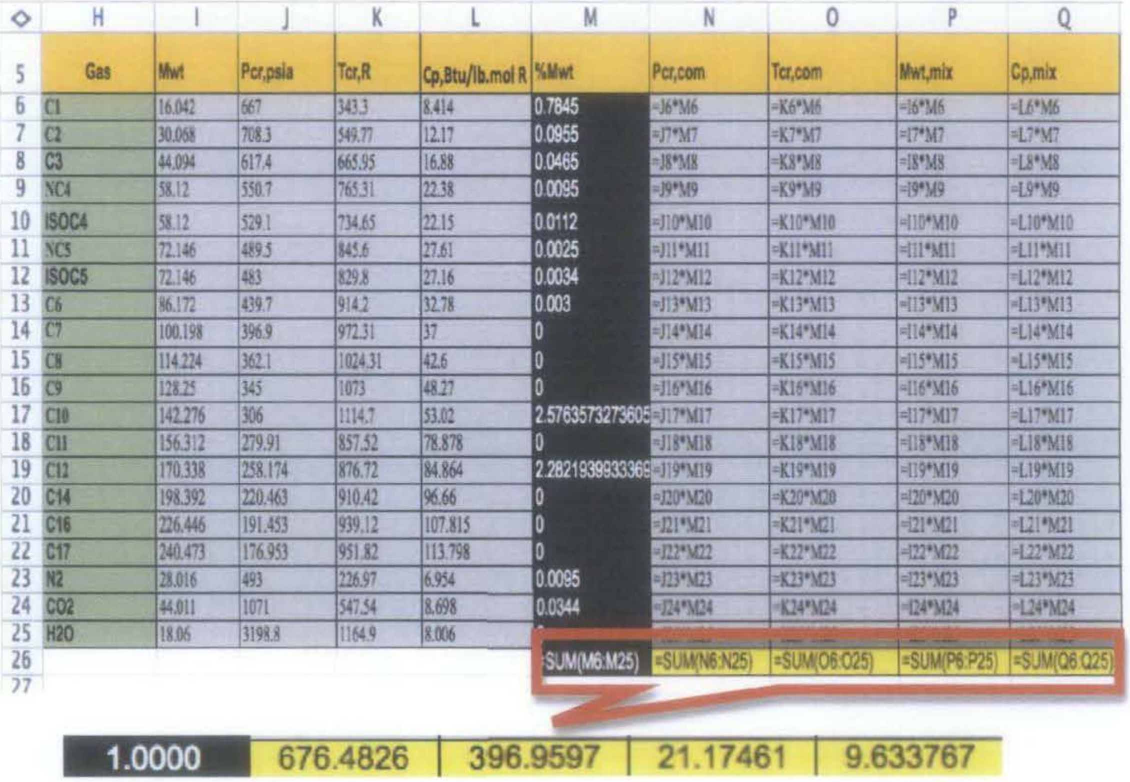
| April 2010 | Date | 01/04/2010 | | | | | |
|---|---|---|---|---|---|---|---|
| Description | Time | 0000 Hr | 0100 Hr | 0200 Hr | 0300 Hr | 0400 Hr | 0500 Hr |
| T1 | SUCTION TEMPERATURE | 32 | 32 | 32 | 32 | 32 | 32 |
| T2 | DISCHARGE TEMPERATURE | 140 | 140 | 141 | 141 | 140 | 140 |
| P1 | SUCTION PRESSURE | 1665 | 1661.25 | 1674.3 | 1636.87 | 1644.37 | 1646.25 |
| P2 | DISCHARGE PRESSURE | 5887.5 | 5906.25 | 5878.12 | 5853.12 | 5875 | 5912.5 |
| Q | VOLUME FLOW AT CONDITIONS (ACMH) | 10591.7 | 10483.2 | 10825.4 | 10782.4 | 10725.9 | 10814.4 |

*Table 3: Gas composition of working fluid of the compressor*

| Composition | %mw |
|---|---|
| C1 | 0.7845 |
| C2 | 0.0955 |
| C3 | 0.0465 |
| IC4 | 0.0112 |
| NC4 | 0.0095 |
| IC5 | 0.0034 |
| NC5 | 0.0025 |
| C6* | 0.0030 |
| C7* | 0.0000 |
| C8* | 0.0000 |
| C9* | 0.0000 |
| C10* | 0.0000 |
| C12* | 0.0000 |
| N2 | 0.0095 |
| CO2 | 0.0344 |
| H2O | 0.0000 |
| | |
| Total | 1.00 |

### *3.4.2 Gas Composition Calculation*

Using a set data of gas composition, the author key in the entire input which is the percentage of composition for each type of gas into black row as shown below. By using function in excel, the total critical pressure and temperature, molecular weight and specific heat coefficient are automatically calculated and shown in the yellow cells.



| ◇ | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Gas | Mwt | Pcr,psia | Tcr,R | Cp,Btu/lb.mol R | %Mwt | Pcr,com | Tcr,com | Mwt,mix | Cp,mix |
| 6 | C1 | 16.042 | 667 | 343.3 | 8.414 | 0.7845 | =J6*M6 | =K6*M6 | =I6*M6 | =L6*M6 |
| 7 | C2 | 30.068 | 708.3 | 549.77 | 12.17 | 0.0955 | =J7*M7 | =K7*M7 | =I7*M7 | =L7*M7 |
| 8 | C3 | 44.094 | 617.4 | 665.95 | 16.88 | 0.0465 | =J8*M8 | =K8*M8 | =I8*M8 | =L8*M8 |
| 9 | NC4 | 58.12 | 550.7 | 765.31 | 22.38 | 0.0095 | =J9*M9 | =K9*M9 | =I9*M9 | =L9*M9 |
| 10 | ISOC4 | 58.12 | 529.1 | 734.65 | 22.15 | 0.0112 | =J10*M10 | =K10*M10 | =I10*M10 | =L10*M10 |
| 11 | NC5 | 72.146 | 489.5 | 845.6 | 27.61 | 0.0025 | =J11*M11 | =K11*M11 | =I11*M11 | =L11*M11 |
| 12 | ISOC5 | 72.146 | 483 | 829.8 | 27.16 | 0.0034 | =J12*M12 | =K12*M12 | =I12*M12 | =L12*M12 |
| 13 | C6 | 86.172 | 439.7 | 914.2 | 32.78 | 0.003 | =J13*M13 | =K13*M13 | =I13*M13 | =L13*M13 |
| 14 | C7 | 100.198 | 396.9 | 972.31 | 37 | 0 | =J14*M14 | =K14*M14 | =I14*M14 | =L14*M14 |
| 15 | C8 | 114.224 | 362.1 | 1024.31 | 42.6 | 0 | =J15*M15 | =K15*M15 | =I15*M15 | =L15*M15 |
| 16 | C9 | 128.25 | 345 | 1073 | 48.27 | 0 | =J16*M16 | =K16*M16 | =I16*M16 | =L16*M16 |
| 17 | C10 | 142.276 | 306 | 1114.7 | 53.02 | 2.5763573273605 | =J17*M17 | =K17*M17 | =I17*M17 | =L17*M17 |
| 18 | C11 | 156.312 | 279.91 | 857.52 | 78.878 | 0 | =J18*M18 | =K18*M18 | =I18*M18 | =L18*M18 |
| 19 | C12 | 170.338 | 258.174 | 876.72 | 84.864 | 2.2821939933369 | =J19*M19 | =K19*M19 | =I19*M19 | =L19*M19 |
| 20 | C14 | 198.392 | 220.463 | 910.42 | 96.66 | 0 | =J20*M20 | =K20*M20 | =I20*M20 | =L20*M20 |
| 21 | C16 | 226.446 | 191.453 | 939.12 | 107.815 | 0 | =J21*M21 | =K21*M21 | =I21*M21 | =L21*M21 |
| 22 | C17 | 240.473 | 176.953 | 951.82 | 113.798 | 0 | =J22*M22 | =K22*M22 | =I22*M22 | =L22*M22 |
| 23 | N2 | 28.016 | 493 | 226.97 | 6.954 | 0.0095 | =J23*M23 | =K23*M23 | =I23*M23 | =L23*M23 |
| 24 | CO2 | 44.011 | 1071 | 547.54 | 8.698 | 0.0344 | =J24*M24 | =K24*M24 | =I24*M24 | =L24*M24 |
| 25 | H2O | 18.06 | 3198.8 | 1164.9 | 8.006 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 26 |  |  |  |  |  | SUM(M6:M25) | =SUM(N6:N25) | =SUM(O6:O25) | =SUM(P6:P25) | =SUM(Q6:Q25) |
| 27 |  |  |  |  |  |  |  |  |  |  |

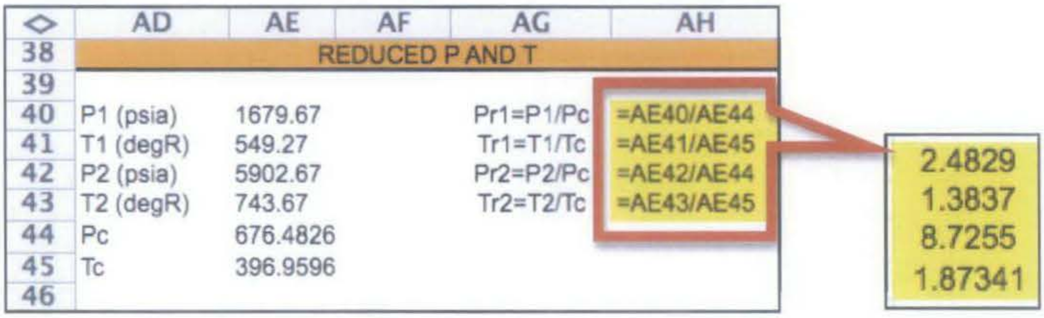
| 1.0000 | 676.4826 | 396.9597 | 21.17461 | 9.633767 |
|---|---|---|---|---|

*Figure 6: Gas composition calculation*

### *3.4.3 Compressibility Factor, Z Calculation*

Compressibility factor, Z can be determined using compressibility factor chart provided by manufacturer. Using reduced pressure Pr and reduced temperature, Z factor can manually obtain from the chart.

For the first data, reduced pressure and temperature are calculated as shown below:



| ◇ | AD | AE | AF | AG | AH |
|---|---|---|---|---|---|
| 38 | REDUCED P AND T | | | | |
| 39 | | | | | |
| 40 | P1 (psia) | 1679.67 | | Pr1=P1/Pc | =AE40/AE44 |
| 41 | T1 (degR) | 549.27 | | Tr1=T1/Tc | =AE41/AE45 |
| 42 | P2 (psia) | 5902.67 | | Pr2=P2/Pc | =AE42/AE44 |
| 43 | T2 (degR) | 743.67 | | Tr2=T2/Tc | =AE43/AE45 |
| 44 | Pc | 676.4826 | | | |
| 45 | Tc | 396.9596 | | | |
| 46 | | | | | |

2.4829
1.3837
8.7255
1.87341

*Figure 7: Reduced P and T calculator*

By plotting Pr and Tr in the chart below, the value of Z during suction is 0.74 :

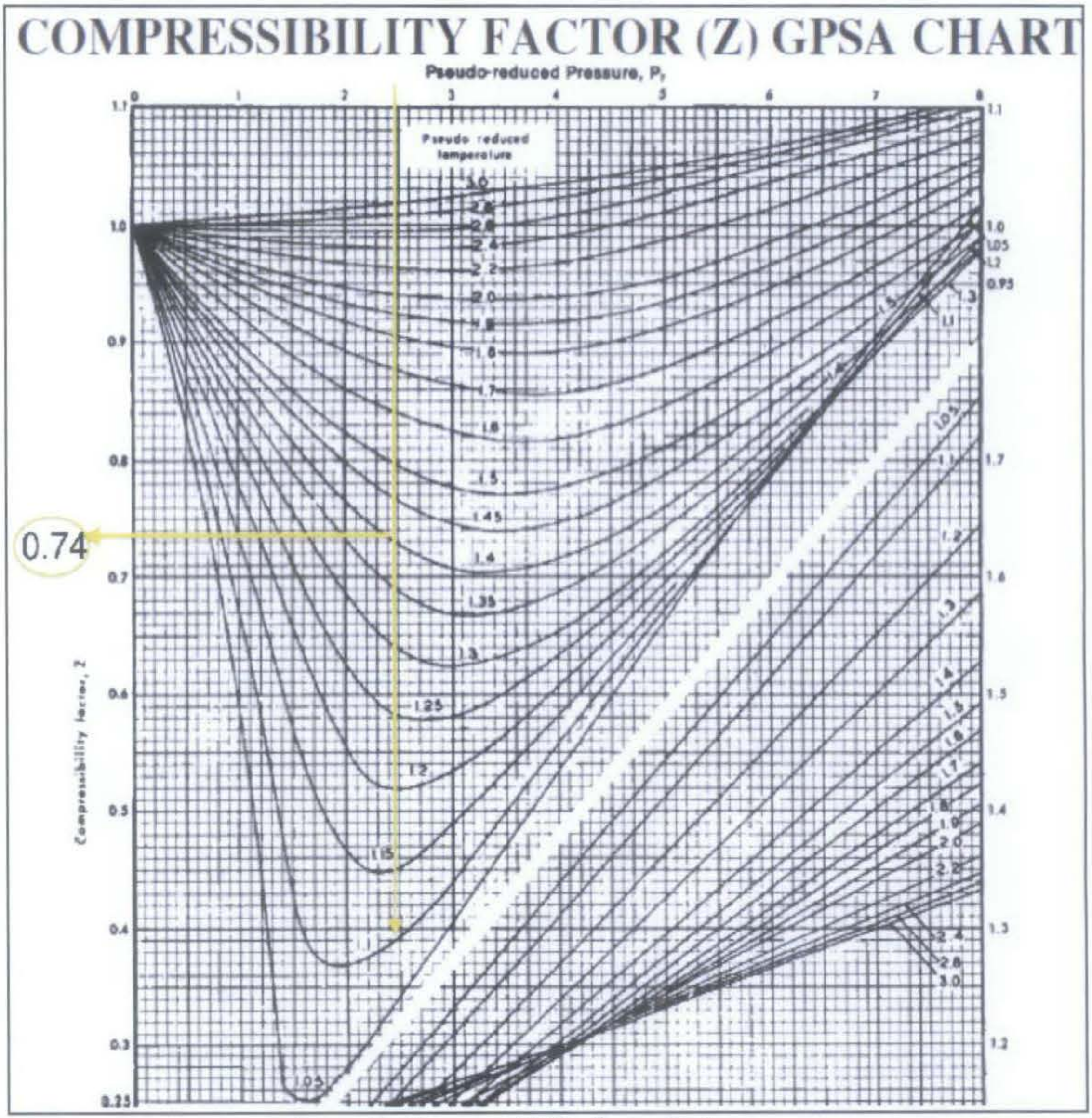
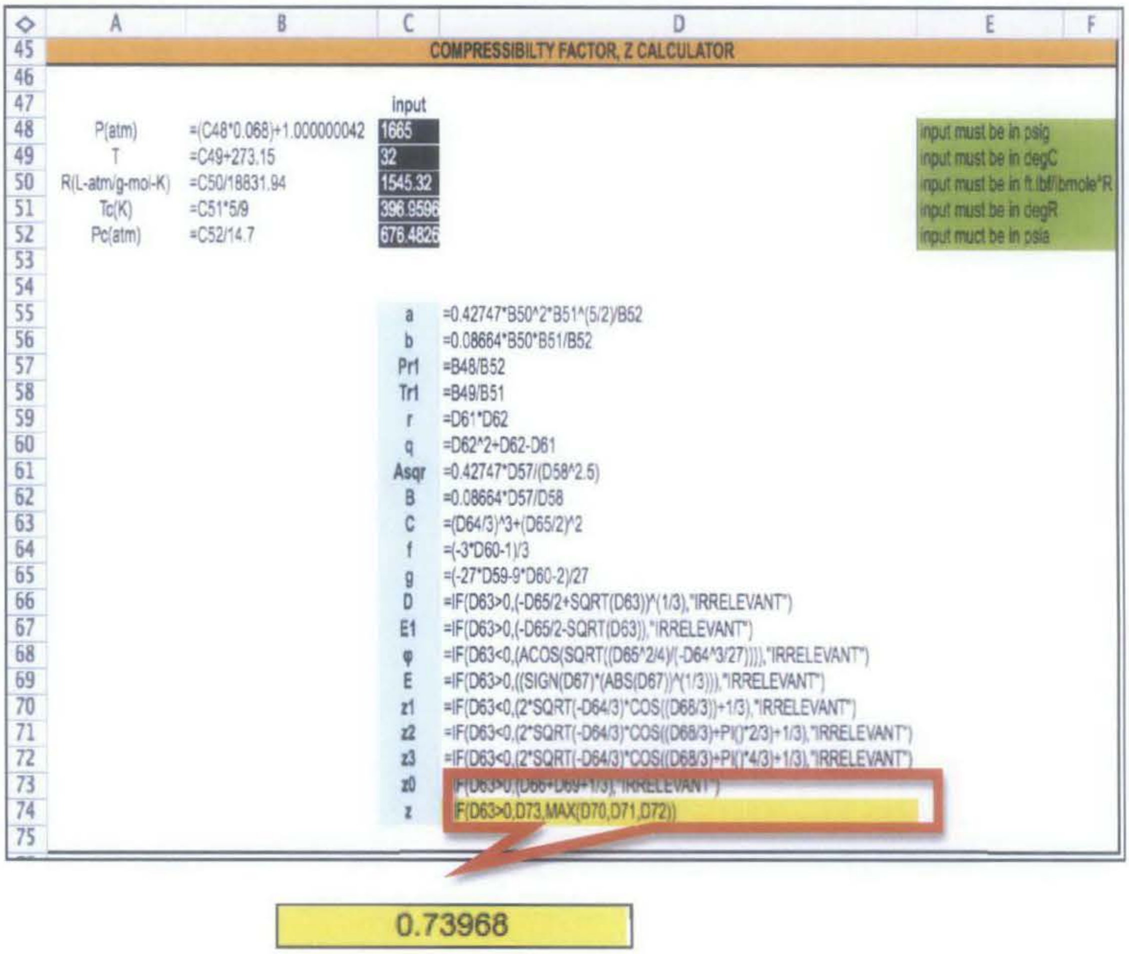


*Figure 8: Compressibility factor Z chart*

For the ease of obtaining Z factor for bunch of data, the author has find another way using Redlich-Kwong Equation.

Using variables calculated before, we can calculate compressibility factor Z using Redlich-Kwong equation of state.



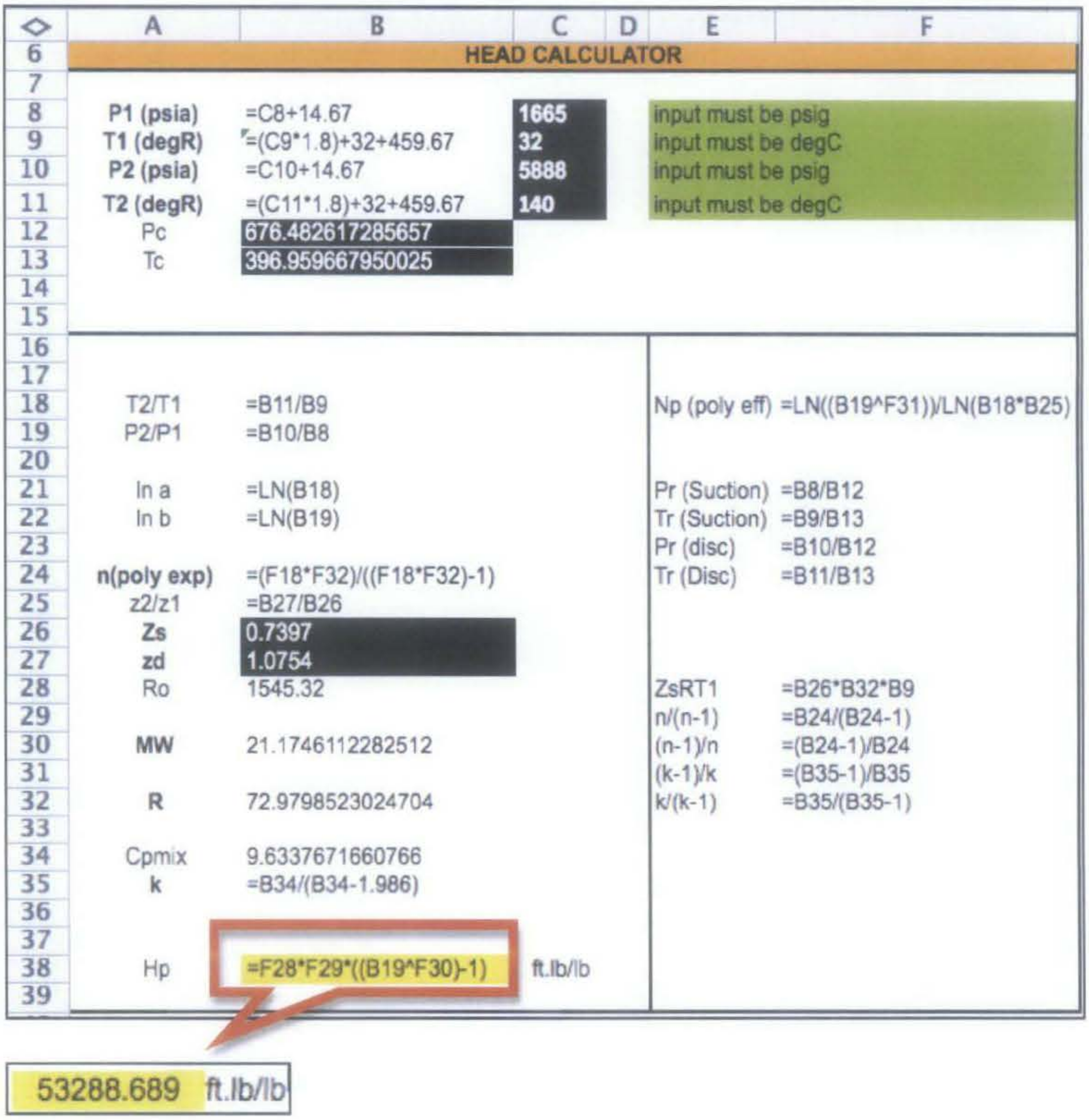
| ◇ | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 45 | | | | COMPRESSIBILTY FACTOR, Z CALCULATOR | | |
| 46 | | | | | | |
| 47 | | | input | | | |
| 48 | P(atm) | =(C48*0.068)+1.000000042 | 1665 | | input must be in psig | |
| 49 | T | =C49+273.15 | 32 | | input must be in degC | |
| 50 | R(L-atm/g-mol-K) | =C50/18831.94 | 1545.32 | | input must be in ft.lbf/lbmole*R | |
| 51 | Tc(K) | =C51*5/9 | 396.9596 | | input must be in degR | |
| 52 | Pc(atm) | =C52/14.7 | 676.4826 | | input muct be in psia | |
| 53 | | | | | | |
| 54 | | | | | | |
| 55 | | | a | =0.42747*B50^2*B51^(5/2)/B52 | | |
| 56 | | | b | =0.08664*B50*B51/B52 | | |
| 57 | | | Pr1 | =B48/B52 | | |
| 58 | | | Tr1 | =B49/B51 | | |
| 59 | | | r | =D61*D62 | | |
| 60 | | | q | =D62^2+D62-D61 | | |
| 61 | | | Asqr | =0.42747*D57/(D58^2.5) | | |
| 62 | | | B | =0.08664*D57/D58 | | |
| 63 | | | C | =(D64/3)^3+(D65/2)^2 | | |
| 64 | | | f | =(-3*D60-1)/3 | | |
| 65 | | | g | =(-27*D59-9*D60-2)/27 | | |
| 66 | | | D | =IF(D63>0,(-D65/2+SQRT(D63))^(1/3),"IRRELEVANT") | | |
| 67 | | | E1 | =IF(D63>0,(-D65/2-SQRT(D63)),"IRRELEVANT") | | |
| 68 | | | φ | =IF(D63<0,(ACOS(SQRT((D65^2/4)/(-D64^3/27)))),"IRRELEVANT") | | |
| 69 | | | E | =IF(D63>0,((SIGN(D67)*(ABS(D67))^(1/3))),"IRRELEVANT") | | |
| 70 | | | z1 | =IF(D63<0,(2*SQRT(-D64/3)*COS((D68/3))+1/3),"IRRELEVANT") | | |
| 71 | | | z2 | =IF(D63<0,(2*SQRT(-D64/3)*COS((D68/3)+PI()*2/3)+1/3),"IRRELEVANT") | | |
| 72 | | | z3 | =IF(D63<0,(2*SQRT(-D64/3)*COS((D68/3)+PI()*4/3)+1/3),"IRRELEVANT") | | |
| 73 | | | z0 | F(D63>0,(D66+D69+1/3),"IRRELEVANT") | | |
| 74 | | | z | F(D63>0,D73,MAX(D70,D71,D72)) | | |
| 75 | | | | | | |

0.73968

*Figure 9: Compressibility factor Z calculator*

### *3.4.4 Polytropic Head Calculation*

After compressibility factors, Z are calculated for both suction and discharge condition, pressure and temperature are inserted as inputs for head calculation. We need to make sure all the inputs are converted into units that applicable for respective formulas. The output, which is the head then calculated and shown in the yellow cell bellow.



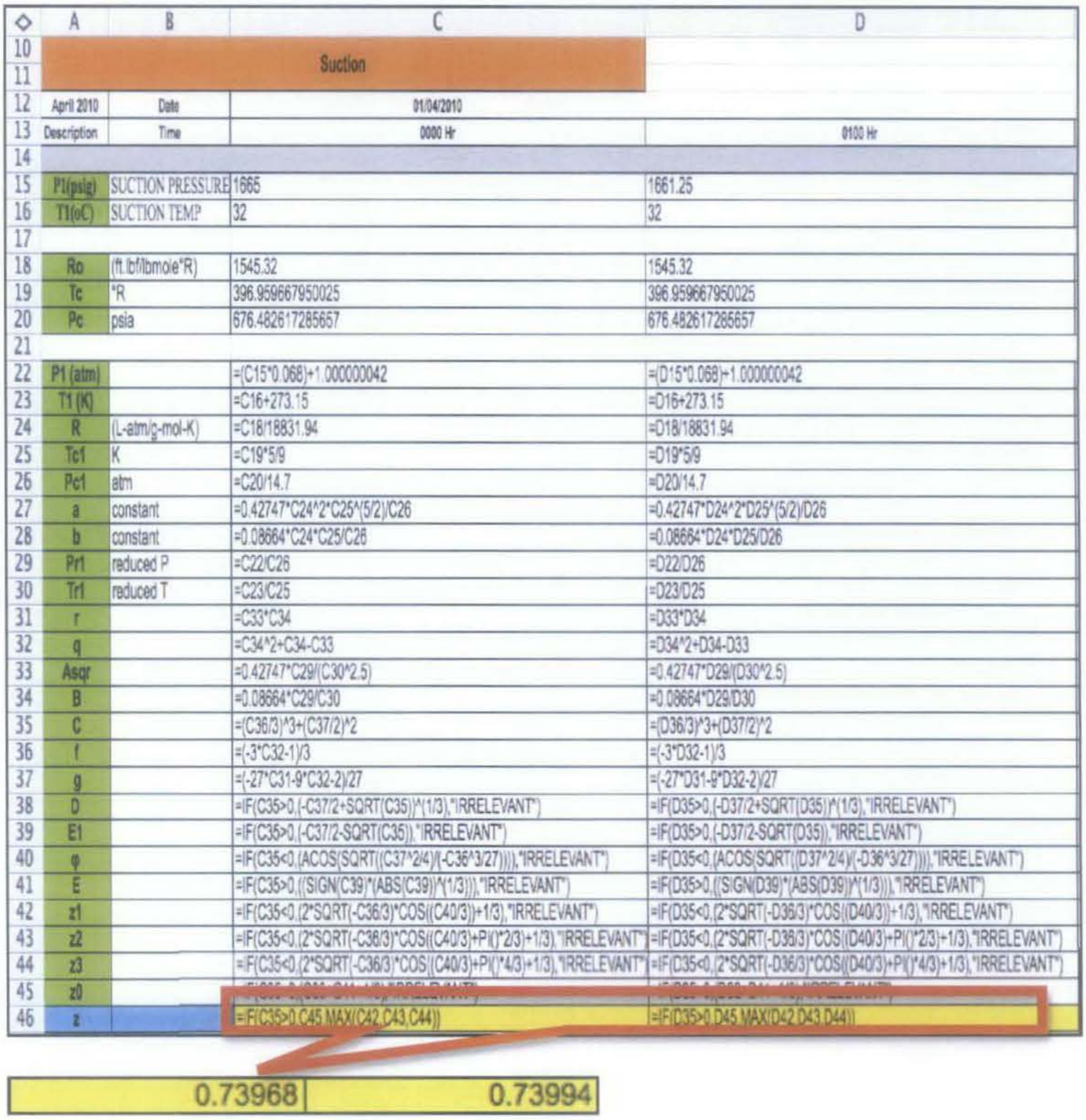
| ◇ | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 6 | **HEAD CALCULATOR** | | | | | |
| 7 | | | | | | |
| 8 | **P1 (psia)** | =C8+14.67 | **1665** | | input must be psig | |
| 9 | **T1 (degR)** | =(C9*1.8)+32+459.67 | **32** | | input must be degC | |
| 10 | **P2 (psia)** | =C10+14.67 | **5888** | | input must be psig | |
| 11 | **T2 (degR)** | =(C11*1.8)+32+459.67 | **140** | | input must be degC | |
| 12 | Pc | 676.482617285657 | | | | |
| 13 | Tc | 396.959667950025 | | | | |
| 14 | | | | | | |
| 15 | | | | | | |
| 16 | | | | | | |
| 17 | | | | | | |
| 18 | T2/T1 | =B11/B9 | | | Np (poly eff) | =LN((B19^F31))/LN(B18*B25) |
| 19 | P2/P1 | =B10/B8 | | | | |
| 20 | | | | | | |
| 21 | ln a | =LN(B18) | | | Pr (Suction) | =B8/B12 |
| 22 | ln b | =LN(B19) | | | Tr (Suction) | =B9/B13 |
| 23 | | | | | Pr (disc) | =B10/B12 |
| 24 | **n(poly exp)** | =(F18*F32)/((F18*F32)-1) | | | Tr (Disc) | =B11/B13 |
| 25 | z2/z1 | =B27/B26 | | | | |
| 26 | **Zs** | 0.7397 | | | | |
| 27 | **zd** | 1.0754 | | | | |
| 28 | Ro | 1545.32 | | | ZsRT1 | =B26*B32*B9 |
| 29 | | | | | n/(n-1) | =B24/(B24-1) |
| 30 | **MW** | 21.1746112282512 | | | (n-1)/n | =(B24-1)/B24 |
| 31 | | | | | (k-1)/k | =(B35-1)/B35 |
| 32 | **R** | 72.9798523024704 | | | k/(k-1) | =B35/(B35-1) |
| 33 | | | | | | |
| 34 | Cpmix | 9.6337671660766 | | | | |
| 35 | **k** | =B34/(B34-1.986) | | | | |
| 36 | | | | | | |
| 37 | | | | | | |
| 38 | Hp | =F28*F29*((B19^F30)-1) | ft.lb/lb | | | |
| 39 | | | | | | |

53288.689 ft.lb/lb

*Figure 10: Head calculator*

### *3.4.5 Calculation for One Month Data (hourly)*

As we got a huge amount of data (hourly in a complete one month) which is about 720 in total, it is more conventional to keep all the data in another sheet of excel where we only need to drag the formula, thus all the values required are calculated. Hence, all the formulas used are similar from the previous section. Below is part of Z factor calculation during suction:

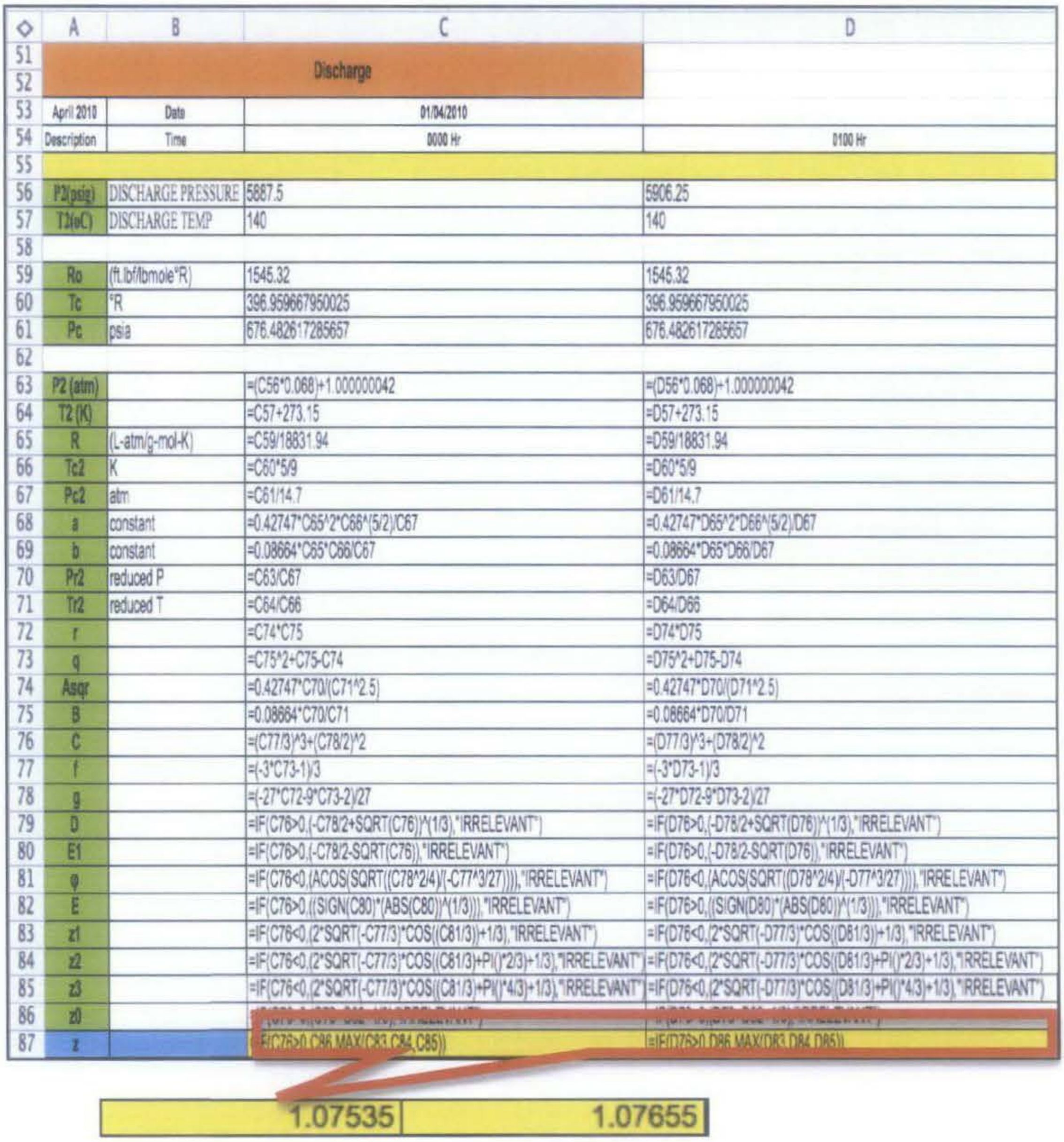


| ◇ | A | B | C | D |
|---|---|---|---|---|
| 10 | Suction | | | |
| 11 | | | | |
| 12 | April 2010 | Date | 01/04/2010 | |
| 13 | Description | Time | 0000 Hr | 0100 Hr |
| 14 | | | | |
| 15 | P1(psig) | SUCTION PRESSURE | 1665 | 1661.25 |
| 16 | T1(oC) | SUCTION TEMP | 32 | 32 |
| 17 | | | | |
| 18 | Ro | (ft.lbf/lbmole*R) | 1545.32 | 1545.32 |
| 19 | Tc | *R | 396.959667950025 | 396.959667950025 |
| 20 | Pc | psia | 676.482617285657 | 676.482617285657 |
| 21 | | | | |
| 22 | P1 (atm) | | =(C15*0.068)+1.000000042 | =(D15*0.068)+1.000000042 |
| 23 | T1 (K) | | =C16+273.15 | =D16+273.15 |
| 24 | R | (L-atm/g-mol-K) | =C18/18831.94 | =D18/18831.94 |
| 25 | Tc1 | K | =C19*5/9 | =D19*5/9 |
| 26 | Pc1 | atm | =C20/14.7 | =D20/14.7 |
| 27 | a | constant | =0.42747*C24^2*C25^(5/2)/C26 | =0.42747*D24^2*D25^(5/2)/D26 |
| 28 | b | constant | =0.08664*C24*C25/C26 | =0.08664*D24*D25/D26 |
| 29 | Pr1 | reduced P | =C22/C26 | =D22/D26 |
| 30 | Tr1 | reduced T | =C23/C25 | =D23/D25 |
| 31 | r | | =C33*C34 | =D33*D34 |
| 32 | q | | =C34^2+C34-C33 | =D34^2+D34-D33 |
| 33 | Asqr | | =0.42747*C29/(C30^2.5) | =0.42747*D29/(D30^2.5) |
| 34 | B | | =0.08664*C29/C30 | =0.08664*D29/D30 |
| 35 | C | | =(C36/3)^3+(C37/2)^2 | =(D36/3)^3+(D37/2)^2 |
| 36 | f | | =(-3*C32-1)/3 | =(-3*D32-1)/3 |
| 37 | g | | =(-27*C31-9*C32-2)/27 | =(-27*D31-9*D32-2)/27 |
| 38 | D | | =IF(C35>0,(-C37/2+SQRT(C35))^(1/3),"IRRELEVANT") | =IF(D35>0,(-D37/2+SQRT(D35))^(1/3),"IRRELEVANT") |
| 39 | E1 | | =IF(C35>0,(-C37/2-SQRT(C35)),"IRRELEVANT") | =IF(D35>0,(-D37/2-SQRT(D35)),"IRRELEVANT") |
| 40 | φ | | =IF(C35<0,(ACOS(SQRT((C37^2/4)/(-C36^3/27)))),"IRRELEVANT") | =IF(D35<0,(ACOS(SQRT((D37^2/4)/(-D36^3/27)))),"IRRELEVANT") |
| 41 | E | | =IF(C35>0,((SIGN(C39)*(ABS(C39))^(1/3))),"IRRELEVANT") | =IF(D35>0,((SIGN(D39)*(ABS(D39))^(1/3))),"IRRELEVANT") |
| 42 | z1 | | =IF(C35<0,(2*SQRT(-C36/3)*COS((C40/3))+1/3),"IRRELEVANT") | =IF(D35<0,(2*SQRT(-D36/3)*COS((D40/3))+1/3),"IRRELEVANT") |
| 43 | z2 | | =IF(C35<0,(2*SQRT(-C36/3)*COS((C40/3)+PI()*2/3)+1/3),"IRRELEVANT") | =IF(D35<0,(2*SQRT(-D36/3)*COS((D40/3)+PI()*2/3)+1/3),"IRRELEVANT") |
| 44 | z3 | | =IF(C35<0,(2*SQRT(-C36/3)*COS((C40/3)+PI()*4/3)+1/3),"IRRELEVANT") | =IF(D35<0,(2*SQRT(-D36/3)*COS((D40/3)+PI()*4/3)+1/3),"IRRELEVANT") |
| 45 | z0 | | =IF(C35>0,(C38+C41+1/3),"IRRELEVANT") | =IF(D35>0,(D38+D41+1/3),"IRRELEVANT") |
| 46 | z | | =IF(C35>0,C45,MAX(C42,C43,C44)) | =IF(D35>0,D45,MAX(D42,D43,D44)) |

| | |
|---|---|
| 0.73968 | 0.73994 |

*Figure 11: Calculation of Z factor during suction*

Below is part of Z factor calculation during discharge :

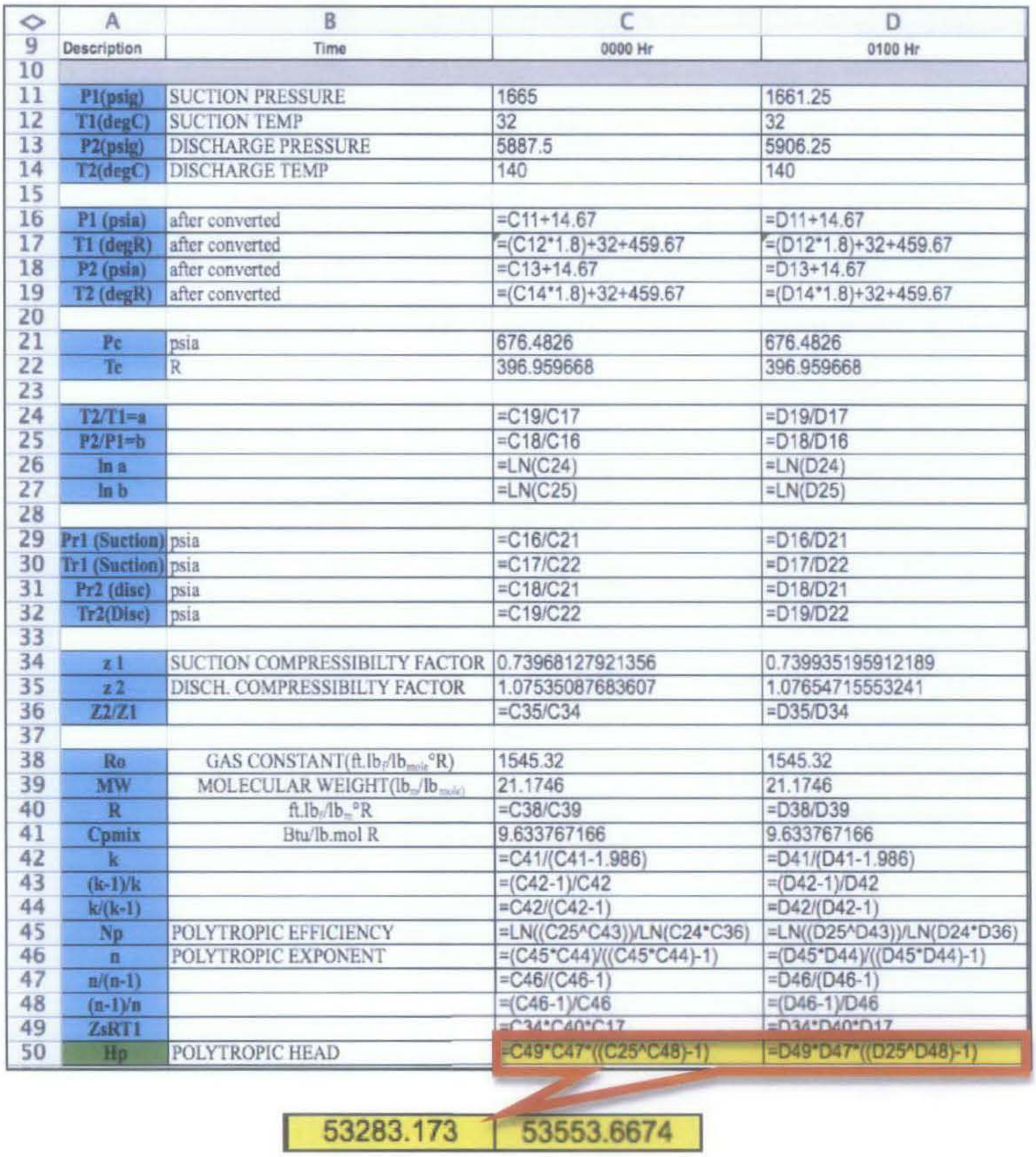


| ◇ | A | B | C | D |
|---|---|---|---|---|
| 51 |  |  | Discharge |  |
| 52 |  |  |  |  |
| 53 | April 2010 | Date | 01/04/2010 |  |
| 54 | Description | Time | 0000 Hr | 0100 Hr |
| 55 |  |  |  |  |
| 56 | P2(psig) | DISCHARGE PRESSURE | 5887.5 | 5906.25 |
| 57 | T2(oC) | DISCHARGE TEMP | 140 | 140 |
| 58 |  |  |  |  |
| 59 | Ro | (ft.lbf/lbmole°R) | 1545.32 | 1545.32 |
| 60 | Tc | °R | 396.959667950025 | 396.959667950025 |
| 61 | Pc | psia | 676.482617285657 | 676.482617285657 |
| 62 |  |  |  |  |
| 63 | P2 (atm) |  | =(C56*0.068)+1.000000042 | =(D56*0.068)+1.000000042 |
| 64 | T2 (K) |  | =C57+273.15 | =D57+273.15 |
| 65 | R | (L-atm/g-mol-K) | =C59/18831.94 | =D59/18831.94 |
| 66 | Tc2 | K | =C60*5/9 | =D60*5/9 |
| 67 | Pc2 | atm | =C61/14.7 | =D61/14.7 |
| 68 | a | constant | =0.42747*C65^2*C66^(5/2)/C67 | =0.42747*D65^2*D66^(5/2)/D67 |
| 69 | b | constant | =0.08664*C65*C66/C67 | =0.08664*D65*D66/D67 |
| 70 | Pr2 | reduced P | =C63/C67 | =D63/D67 |
| 71 | Tr2 | reduced T | =C64/C66 | =D64/D66 |
| 72 | r |  | =C74*C75 | =D74*D75 |
| 73 | q |  | =C75^2+C75-C74 | =D75^2+D75-D74 |
| 74 | Asqr |  | =0.42747*C70/(C71^2.5) | =0.42747*D70/(D71^2.5) |
| 75 | B |  | =0.08664*C70/C71 | =0.08664*D70/D71 |
| 76 | C |  | =(C77/3)^3+(C78/2)^2 | =(D77/3)^3+(D78/2)^2 |
| 77 | f |  | =(-3*C73-1)/3 | =(-3*D73-1)/3 |
| 78 | g |  | =(-27*C72-9*C73-2)/27 | =(-27*D72-9*D73-2)/27 |
| 79 | D |  | =IF(C76>0,(-C78/2+SQRT(C76))^(1/3),"IRRELEVANT") | =IF(D76>0,(-D78/2+SQRT(D76))^(1/3),"IRRELEVANT") |
| 80 | E1 |  | =IF(C76>0,(-C78/2-SQRT(C76)),"IRRELEVANT") | =IF(D76>0,(-D78/2-SQRT(D76)),"IRRELEVANT") |
| 81 | φ |  | =IF(C76<0,(ACOS(SQRT((C78^2/4)/(-C77^3/27)))),"IRRELEVANT") | =IF(D76<0,(ACOS(SQRT((D78^2/4)/(-D77^3/27)))),"IRRELEVANT") |
| 82 | E |  | =IF(C76>0,((SIGN(C80)*(ABS(C80))^(1/3))),"IRRELEVANT") | =IF(D76>0,((SIGN(D80)*(ABS(D80))^(1/3))),"IRRELEVANT") |
| 83 | z1 |  | =IF(C76<0,(2*SQRT(-C77/3)*COS((C81/3))+1/3),"IRRELEVANT") | =IF(D76<0,(2*SQRT(-D77/3)*COS((D81/3))+1/3),"IRRELEVANT") |
| 84 | z2 |  | =IF(C76<0,(2*SQRT(-C77/3)*COS((C81/3)+PI()*2/3)+1/3),"IRRELEVANT" | =IF(D76<0,(2*SQRT(-D77/3)*COS((D81/3)+PI()*2/3)+1/3),"IRRELEVANT") |
| 85 | z3 |  | =IF(C76<0,(2*SQRT(-C77/3)*COS((C81/3)+PI()*4/3)+1/3),"IRRELEVANT" | =IF(D76<0,(2*SQRT(-D77/3)*COS((D81/3)+PI()*4/3)+1/3),"IRRELEVANT") |
| 86 | z0 |  | [illegible] | [illegible] |
| 87 | z |  | F(C76>0,C86,MAX(C83,C84,C85)) | =IF(D76>0,D86,MAX(D83,D84,D85)) |

| 1.07535 | 1.07655 |
|---|---|

*Figure 12: Calculation of Z during discharge*

Using compressibility factor calculated before both for suction and discharge condition, head for each data is determined. Below is part of polytropic head calculation:



| ◇ | A | B | C | D |
|---|---|---|---|---|
| 9 | Description | Time | 0000 Hr | 0100 Hr |
| 10 | | | | |
| 11 | P1(psig) | SUCTION PRESSURE | 1665 | 1661.25 |
| 12 | T1(degC) | SUCTION TEMP | 32 | 32 |
| 13 | P2(psig) | DISCHARGE PRESSURE | 5887.5 | 5906.25 |
| 14 | T2(degC) | DISCHARGE TEMP | 140 | 140 |
| 15 | | | | |
| 16 | P1 (psia) | after converted | =C11+14.67 | =D11+14.67 |
| 17 | T1 (degR) | after converted | =(C12*1.8)+32+459.67 | =(D12*1.8)+32+459.67 |
| 18 | P2 (psia) | after converted | =C13+14.67 | =D13+14.67 |
| 19 | T2 (degR) | after converted | =(C14*1.8)+32+459.67 | =(D14*1.8)+32+459.67 |
| 20 | | | | |
| 21 | Pc | psia | 676.4826 | 676.4826 |
| 22 | Tc | R | 396.959668 | 396.959668 |
| 23 | | | | |
| 24 | T2/T1=a | | =C19/C17 | =D19/D17 |
| 25 | P2/P1=b | | =C18/C16 | =D18/D16 |
| 26 | ln a | | =LN(C24) | =LN(D24) |
| 27 | ln b | | =LN(C25) | =LN(D25) |
| 28 | | | | |
| 29 | Pr1 (Suction) | psia | =C16/C21 | =D16/D21 |
| 30 | Tr1 (Suction) | psia | =C17/C22 | =D17/D22 |
| 31 | Pr2 (disc) | psia | =C18/C21 | =D18/D21 |
| 32 | Tr2(Disc) | psia | =C19/C22 | =D19/D22 |
| 33 | | | | |
| 34 | z 1 | SUCTION COMPRESSIBILTY FACTOR | 0.73968127921356 | 0.739935195912189 |
| 35 | z 2 | DISCH. COMPRESSIBILTY FACTOR | 1.07535087683607 | 1.07654715553241 |
| 36 | Z2/Z1 | | =C35/C34 | =D35/D34 |
| 37 | | | | |
| 38 | Ro | GAS CONSTANT(ft.lb$_f$/lb$_{mole}$.°R) | 1545.32 | 1545.32 |
| 39 | MW | MOLECULAR WEIGHT(lb$_m$/lb$_{mole}$) | 21.1746 | 21.1746 |
| 40 | R | ft.lb$_f$/lb$_m$.°R | =C38/C39 | =D38/D39 |
| 41 | Cpmix | Btu/lb.mol R | 9.633767166 | 9.633767166 |
| 42 | k | | =C41/(C41-1.986) | =D41/(D41-1.986) |
| 43 | (k-1)/k | | =(C42-1)/C42 | =(D42-1)/D42 |
| 44 | k/(k-1) | | =C42/(C42-1) | =D42/(D42-1) |
| 45 | Np | POLYTROPIC EFFICIENCY | =LN((C25^C43))/LN(C24*C36) | =LN((D25^D43))/LN(D24*D36) |
| 46 | n | POLYTROPIC EXPONENT | =(C45*C44)/((C45*C44)-1) | =(D45*D44)/((D45*D44)-1) |
| 47 | n/(n-1) | | =C46/(C46-1) | =D46/(D46-1) |
| 48 | (n-1)/n | | =(C46-1)/C46 | =(D46-1)/D46 |
| 49 | ZsRT1 | | =C34*C40*C17 | =D34*D40*D17 |
| 50 | Hp | POLYTROPIC HEAD | =C49*C47*((C25^C48)-1) | =D49*D47*((D25^D48)-1) |

| 53283.173 | 53553.6674 |
|---|---|

*Figure 13: Calculation of polytopic head*

## 3.5 Developing GUI Using VBA

To make the workbook in excel more interactive and user friendly, the author has utilize VBA to develop GUI, which look like a software called 'Compressor Performance Analysis Software'.

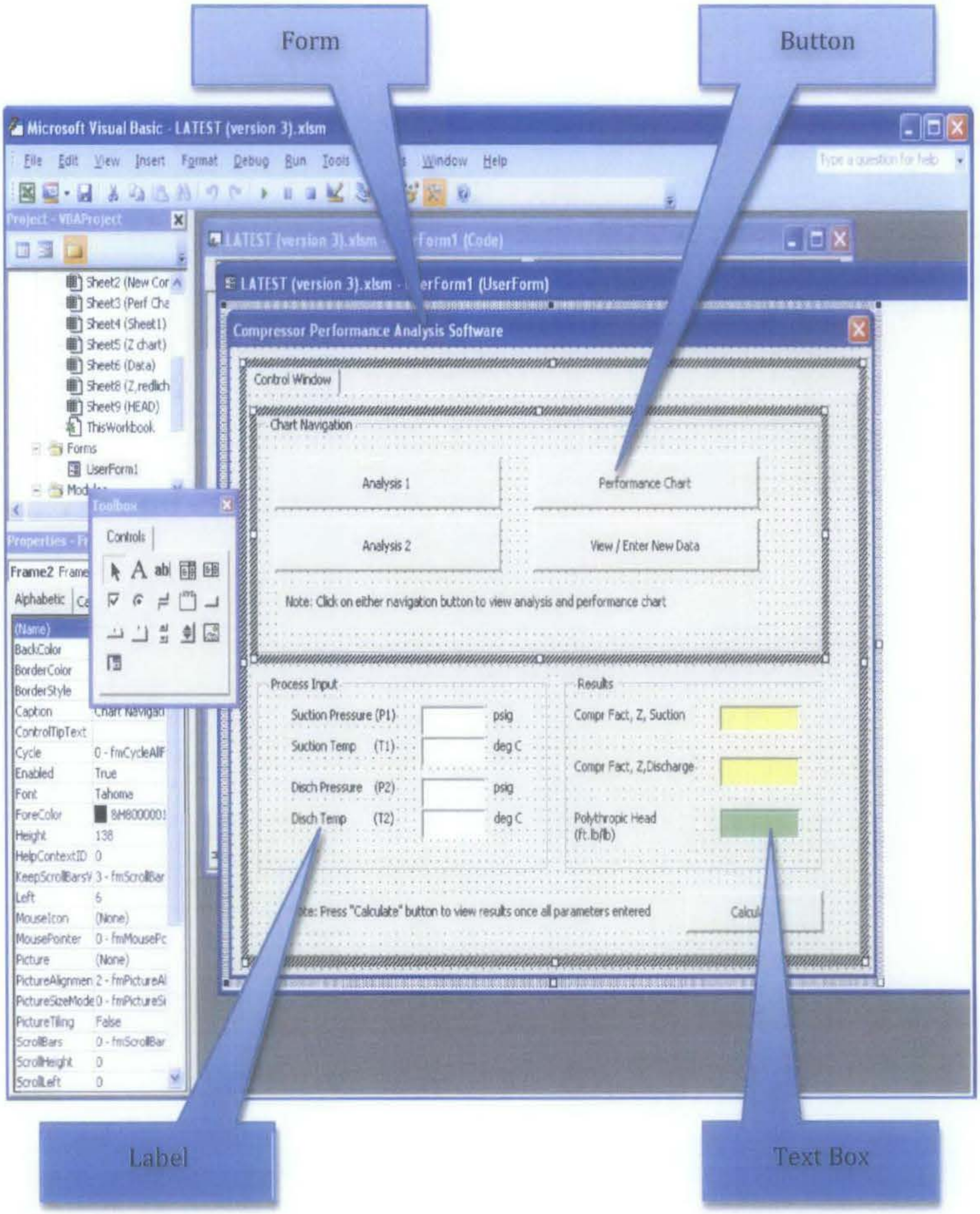
### *3.5.1 Create a Form Using VBA*

Steps taken in constructing a form that used as an interface are:

1. Create a new form in VBA.
2. Create command buttons named:
    - Analysis 1
    - Analysis 2
    - Performance Chart
    - View/Enter New Data
    - Calculate
3. Create text boxes for process inputs and also results.
4. Create labels for text boxes and name it respectively according to the function of the box.

    Process Inputs:
    - Suction Pressure
    - Suction Temperature
    - Discharge Pressure
    - Discharge Temperature

    Results:
    - Compressibility Factor, Z, Suction
    - Compressibility Factor, Z, Discharge
    - Polytropic Head



Note: Click on either navigation button to view analysis and performance chart

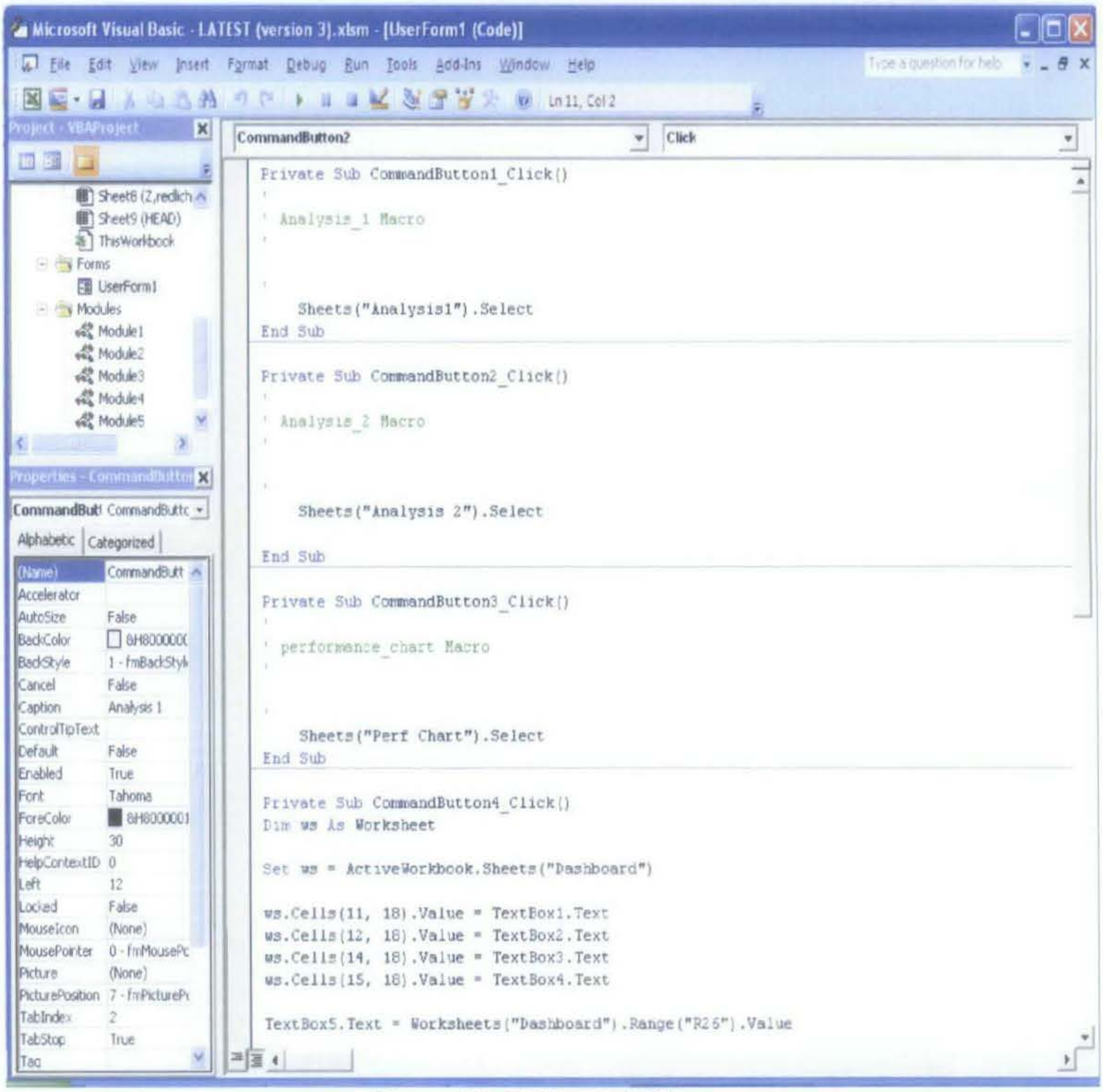
Note: Press "Calculate" button to view results once all parameters entered

| | |
|---|---|
| (Name) | |
| BackColor | |
| BorderColor | |
| BorderStyle | |
| Caption | Chart Navigati |
| ControlTipText | |
| Cycle | 0 - fmCycleAllF |
| Enabled | True |
| Font | Tahoma |
| ForeColor | &H800000 |
| Height | 138 |
| HelpContextID | 0 |
| KeepScrollBarsV | 3 - fmScrollBar |
| Left | 6 |
| MouseIcon | (None) |
| MousePointer | 0 - fmMouseP |
| Picture | (None) |
| PictureAlignmen | 2 - fmPictureAl |
| PictureSizeMode | 0 - fmPictureSi |
| PictureTiling | False |
| ScrollBars | 0 - fmScrollBar |
| ScrollHeight | 0 |
| ScrollLeft | 0 |

*Figure 14: Construction of a form using VBA*

### 3.5.2 Coding In VBA

Coding are needed in order to link developed form with excel workbookBasic coding are used to link all the buttons, text boxes in the form to either sheets or cells in the excel workbook.



| | |
|---|---|
| (Name) | CommandButt |
| Accelerator | |
| AutoSize | False |
| BackColor | ☐ &H8000000( |
| BackStyle | 1 - fmBackStyl |
| Cancel | False |
| Caption | Analysis 1 |
| ControlTipText | |
| Default | False |
| Enabled | True |
| Font | Tahoma |
| ForeColor | ■ &H80000001 |
| Height | 30 |
| HelpContextID | 0 |
| Left | 12 |
| Locked | False |
| MouseIcon | (None) |
| MousePointer | 0 - fmMousePc |
| Picture | (None) |
| PicturePosition | 7 - fmPicturePc |
| TabIndex | 2 |
| TabStop | True |
| Tag | |

```
Private Sub CommandButton1_Click()
'
' Analysis_1 Macro
'


'
    Sheets("Analysis1").Select
End Sub

Private Sub CommandButton2_Click()
'
' Analysis_2 Macro
'


'

    Sheets("Analysis 2").Select

End Sub

Private Sub CommandButton3_Click()
'
' performance_chart Macro
'


'
    Sheets("Perf Chart").Select
End Sub

Private Sub CommandButton4_Click()
Dim ws As Worksheet

Set ws = ActiveWorkbook.Sheets("Dashboard")

ws.Cells(11, 18).Value = TextBox1.Text
ws.Cells(12, 18).Value = TextBox2.Text
ws.Cells(14, 18).Value = TextBox3.Text
ws.Cells(15, 18).Value = TextBox4.Text

TextBox5.Text = Worksheets("Dashboard").Range("R26").Value
```

Figure 15: Coding in VBA

# CHAPTER 4

# RESULT AND DISCUSSION

## 4.1 Operational Integrity

Figure 16 shows the integrity of the compressor operation. By comparing points on the graphs above we can see a similar pattern. As we increase the compressor speed, this will give a rise to other variables too. When the speed is lower down to certain values this will cause other variables to drop. These theories are proved by pattern shown in the graphs above. From here we can say that the transmitters on the compressor works properly and the data produced is reliable to use for further analysis.

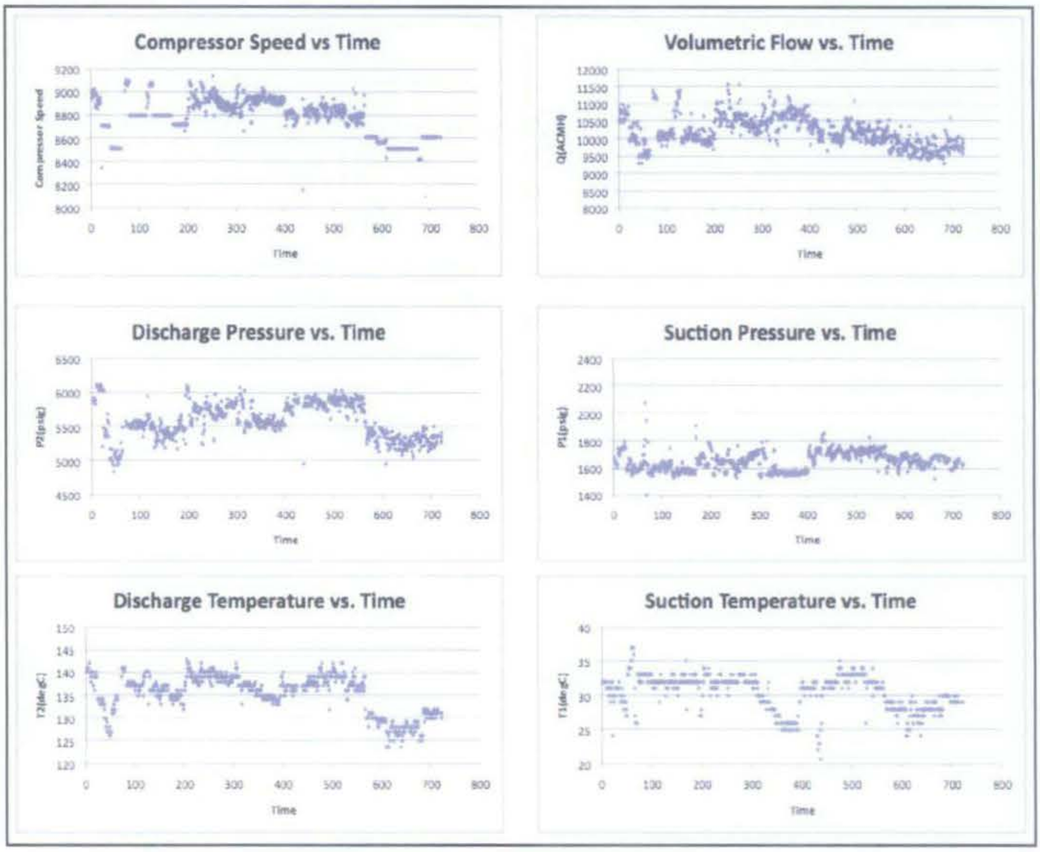


*Figure 16: Evaluation of operational integrity*

### 4.2 Trending of Results

Graph above shows that as the Z ratio increase, polytropic efficiency will decrease. From the graph we can see that there are two populations of data. This may due to the changes of load made by the operator. We can refer to speed of the compressor to see the variation of compressor load. Points plotted for polytropic efficiency is around 36% to 41%, which are quite low. This give indication that the compressor is degrade may due to deposits from the working fluid. From this graph the operator can plan when the next gas composition analysis is required.

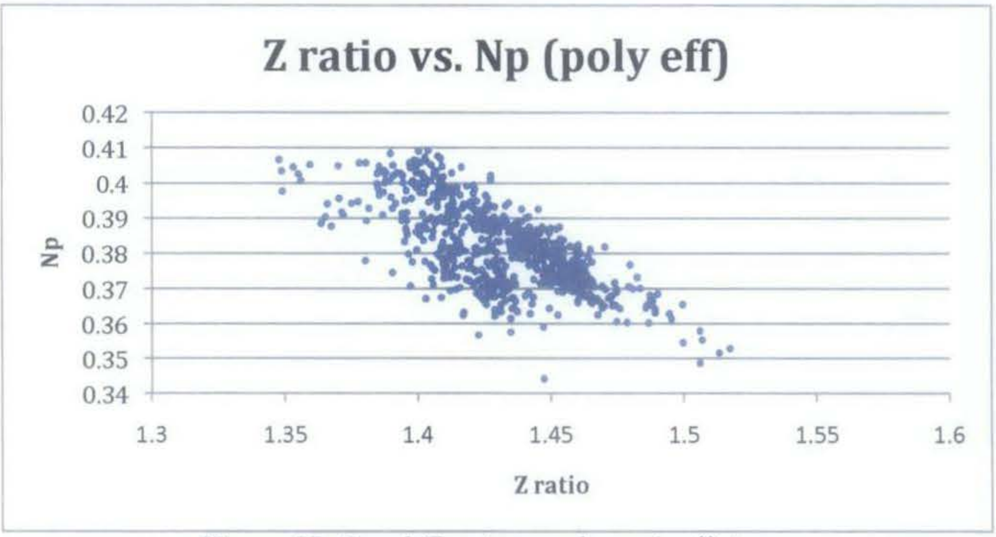


*Figure 17: Graph Z ratio vs polytropic efficiency*

From figure 18, we can see the relationship between compressibility factor, Z during suction with the polytropic head. As the compressibility factor during suction increase, polytropic head will increase.

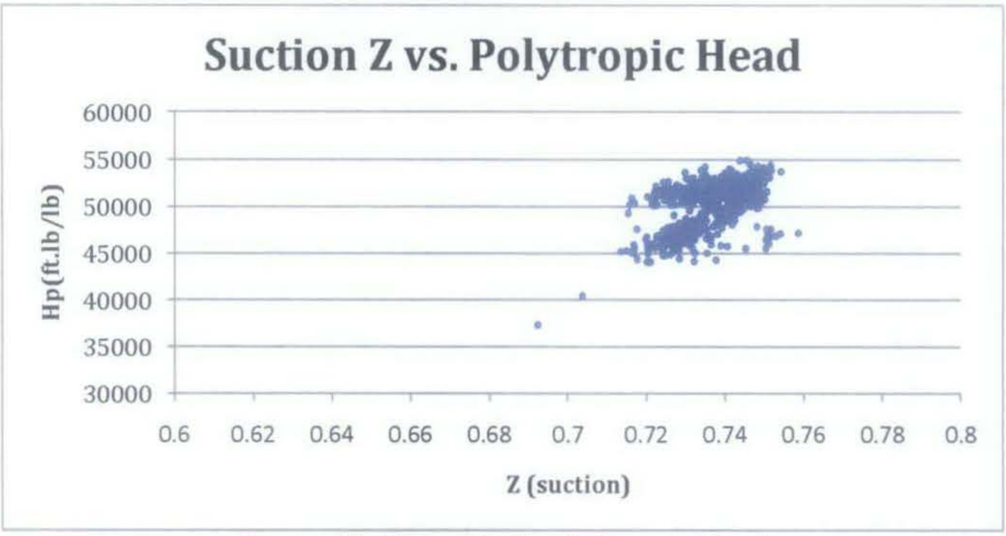


*Figure 18: Z1 (suction) vs Polytropic Head*

From figure 19, we can see vertical pattern which are operating points that regulate at almost the same temperate with different value of head. This indicates the temperature stability. Temperature will not change much in a short period, which is why we need a long term of data when we want to analyze the behavior of temperature change.

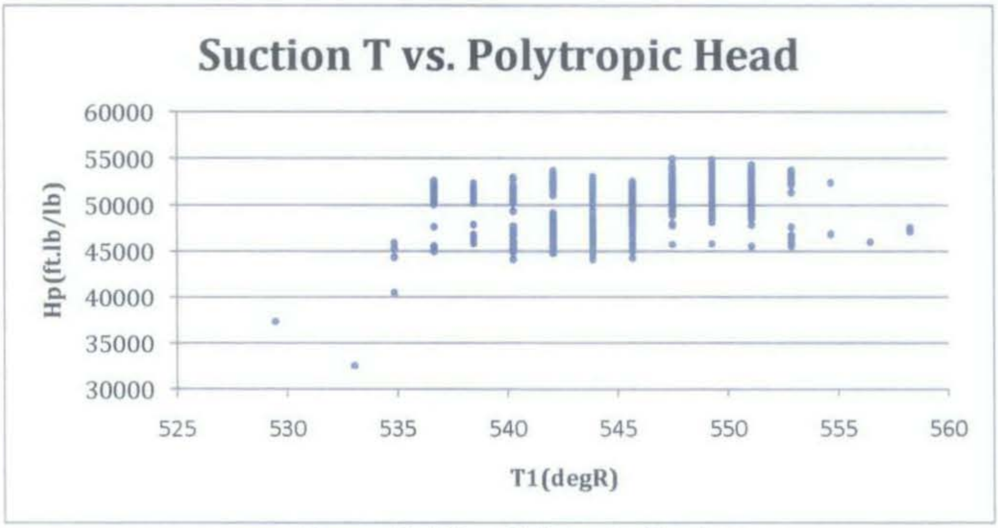


*Figure 19: T1 vs Polytropic Head*

From figure 20, above we can see two groups of data. This indicates change of load during operation.

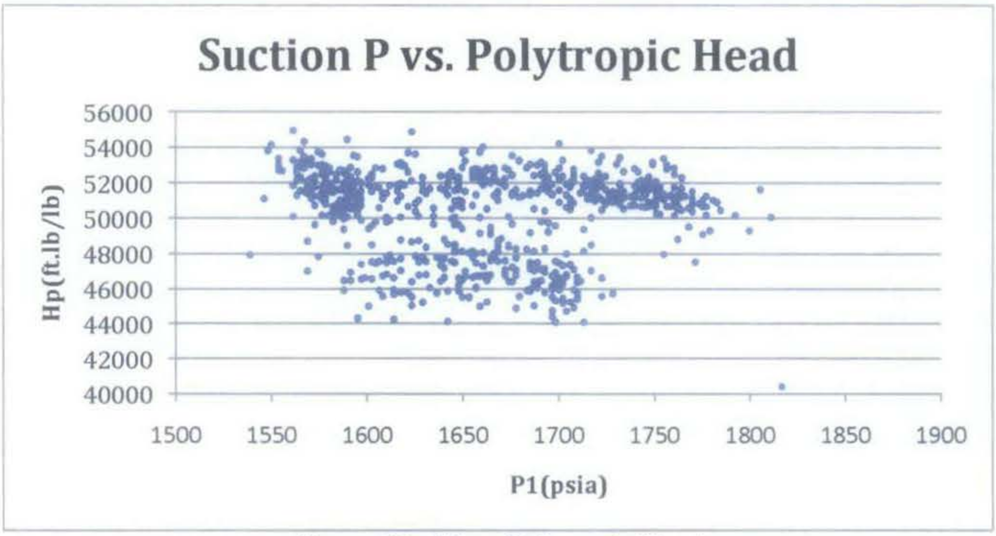


*Figure 20: P1 vs Polytropic Head*

From figure 21 we can monitor the required discharge pressure against head and also pressure stability.

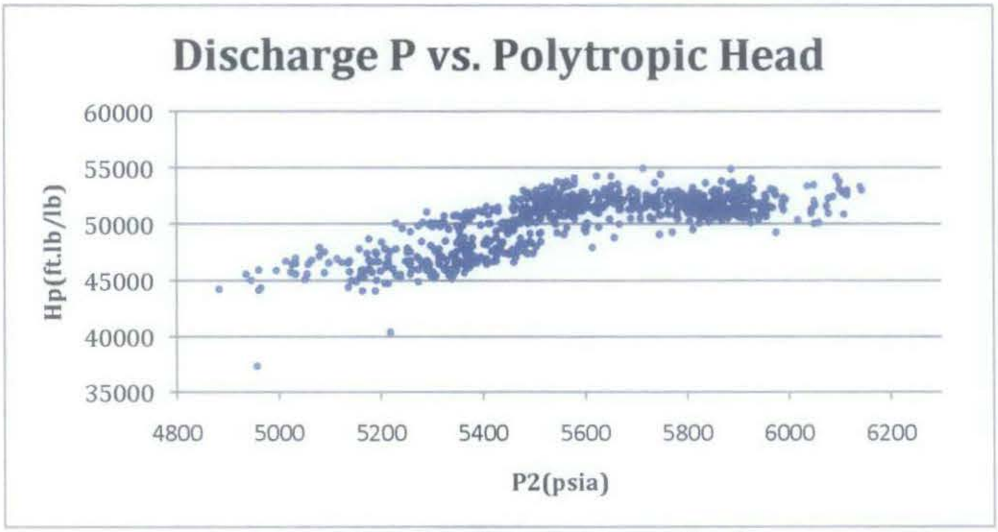


*Figure 21: P2 vs Polytropic Head*

Same as T1 (suction), T2 (discharge) also have the same behavior where the points regulate at same temperature for different head values. But compare to T1, T2 will have greater value due to temperature rise during compression process.

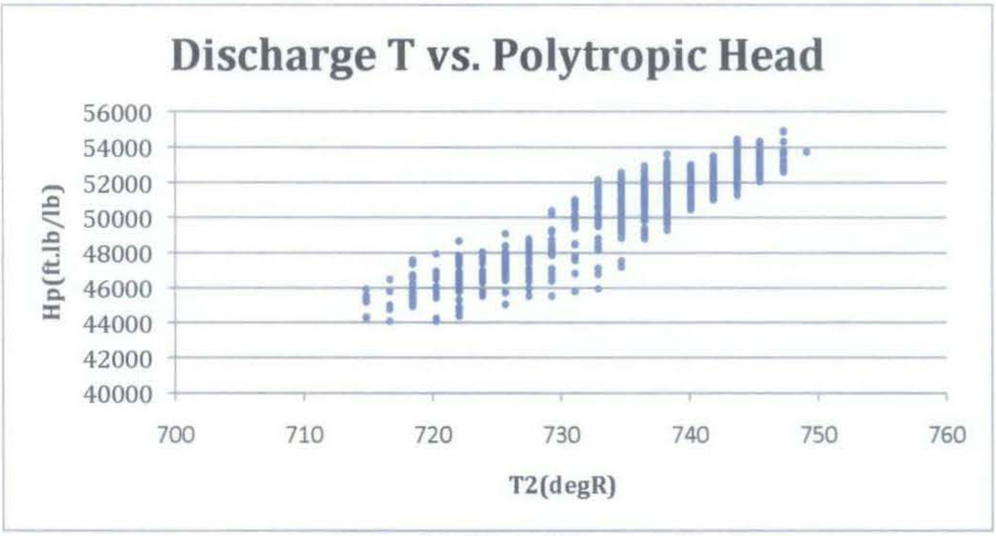


*Figure 22: T2 vs Polytropic Head*

From the graph below, operator can observe relationship of Q and head to avoid surge.

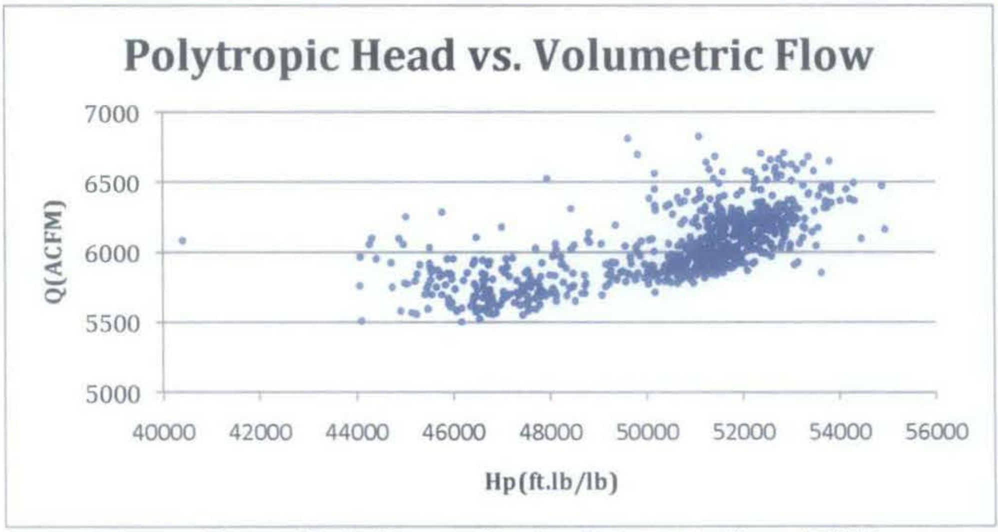


*Figure 23: Polytropic Head vs Volumetric Flow ACFM*

## 4.3 Compressor Performance Map

All the head calculated from the data are plotted on the graph above. From the graph we can see that most of operating points are regulate at one area of the graph and near to optimum or design point which represent by the red curve line at the top. All the operating points are away from the surge line which means the compressor operated at safe condition and no chance for surge to occur. If the point start to reach the surge line, the controller will immediately send a signal to the surge valve to recycle some of the discharge flow to the suction line.

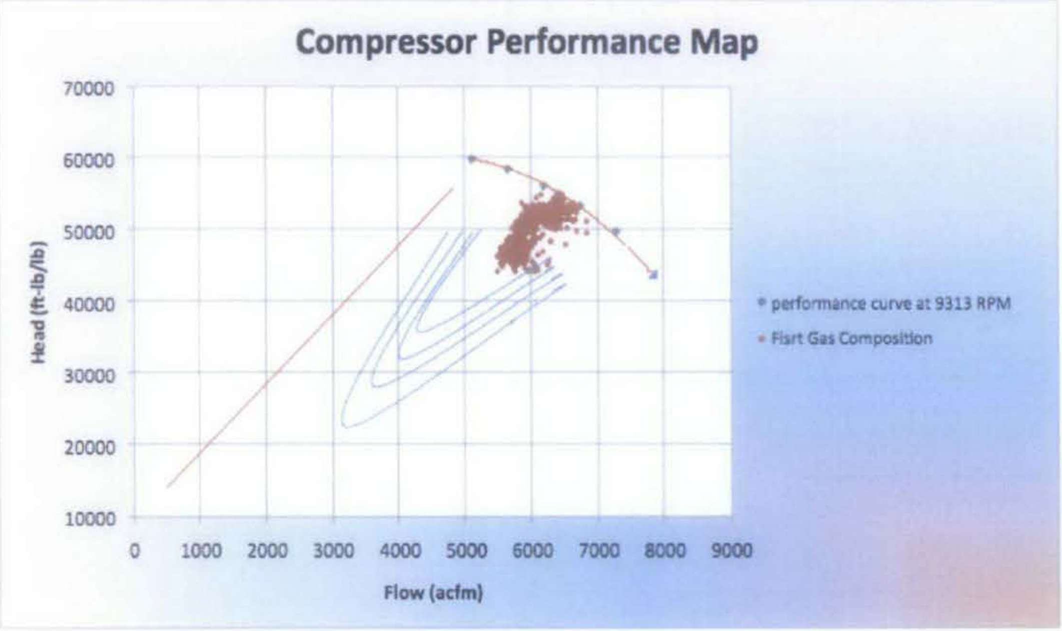
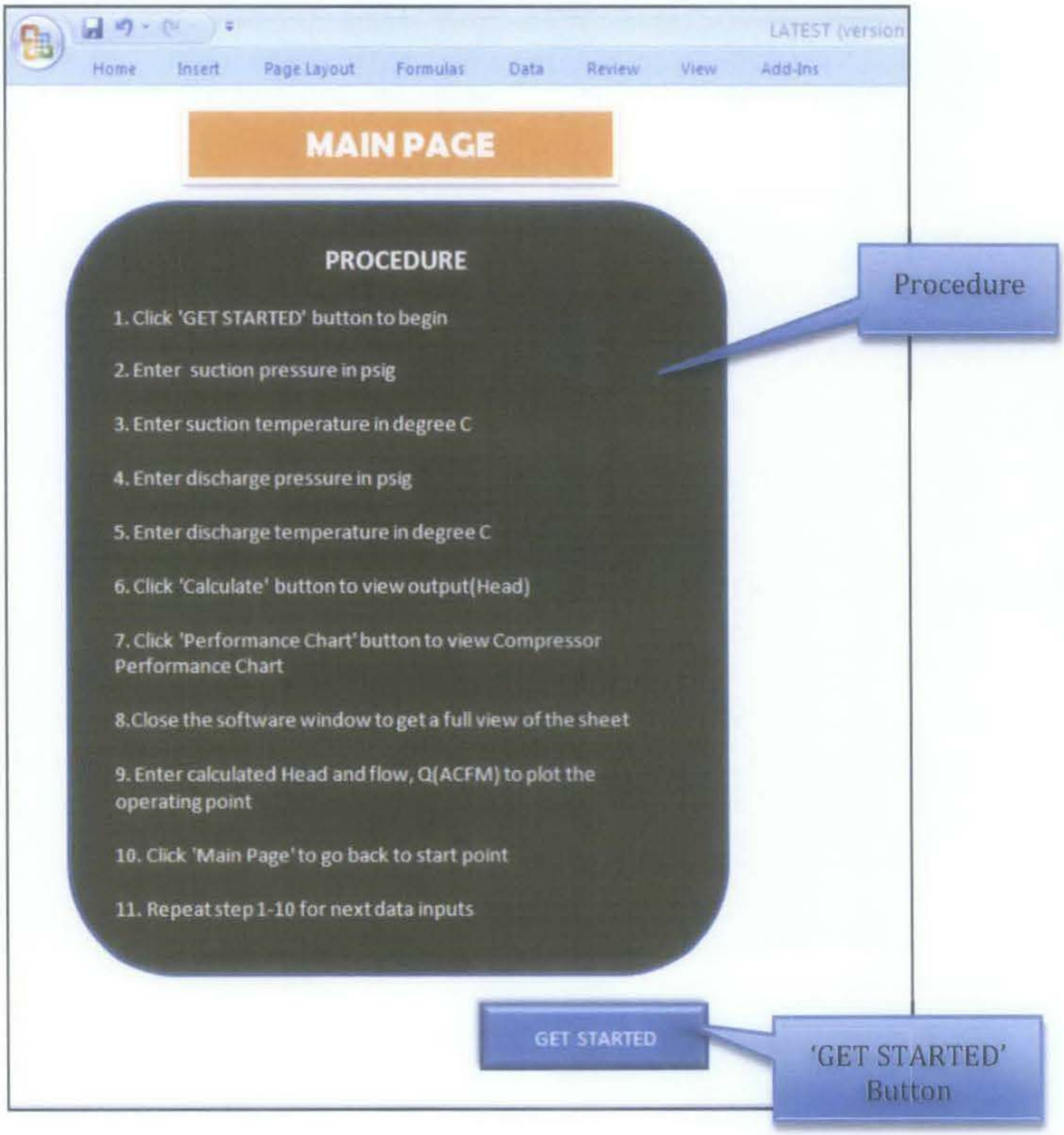


*Figure 24: Compressor performance map*

### 4.4 Compressor Performance Analysis Software

A procedure has been prepared to assist a user in using this software. A sheet named 'MAIN PAGE' locates the procedure of the process and also a button named 'GET STARTED' that link to the software window.



MAIN PAGE

PROCEDURE

1. Click 'GET STARTED' button to begin

2. Enter suction pressure in psig

3. Enter suction temperature in degree C

4. Enter discharge pressure in psig

5. Enter discharge temperature in degree C

6. Click 'Calculate' button to view output(Head)

7. Click 'Performance Chart' button to view Compressor Performance Chart

8. Close the software window to get a full view of the sheet

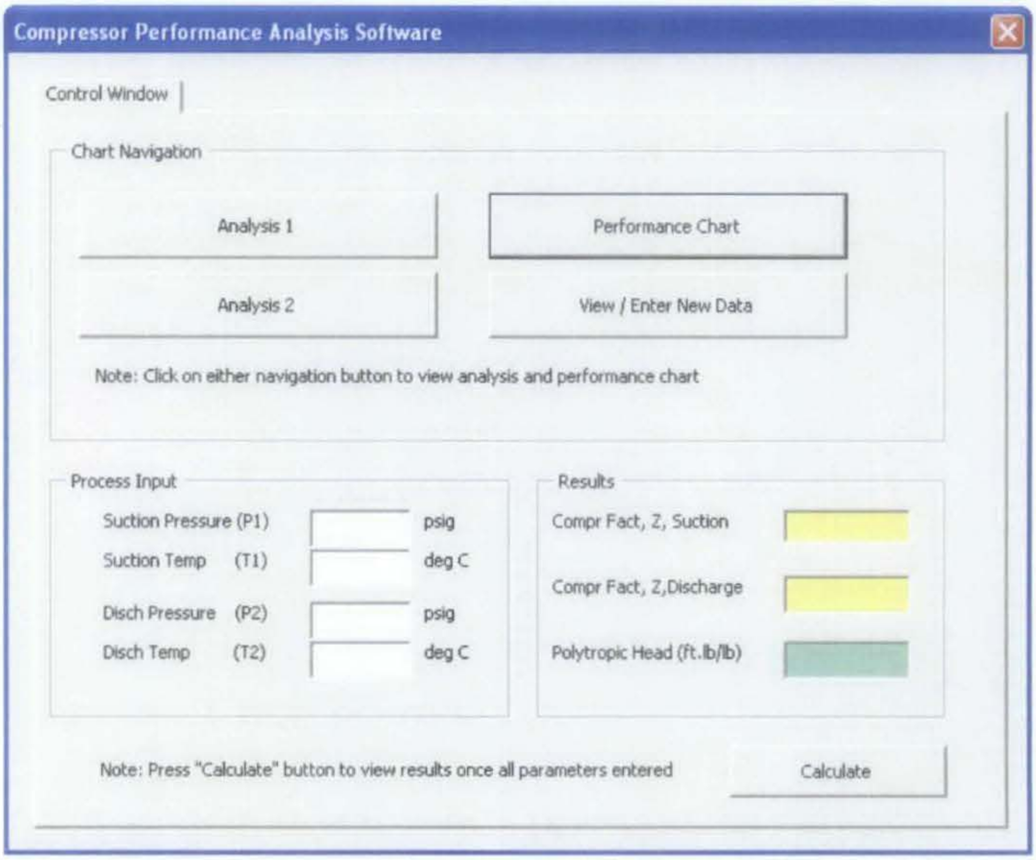
9. Enter calculated Head and flow, Q(ACFM) to plot the operating point

10. Click 'Main Page' to go back to start point

11. Repeat step 1-10 for next data inputs

*Figure 25: Procedure of using the software*

Click the 'GET STARTED' button and the software window will appears as below:

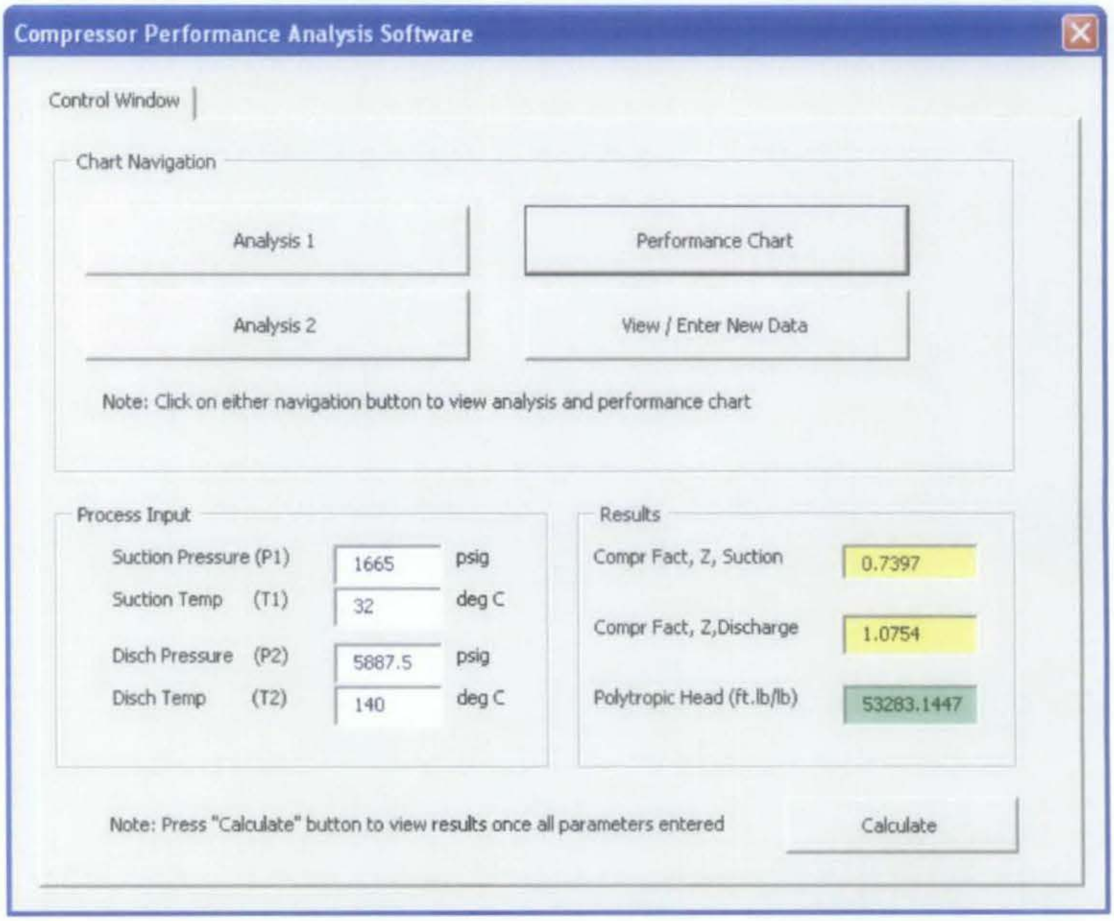


Note: Click on either navigation button to view analysis and performance chart

Note: Press "Calculate" button to view results once all parameters entered

*Figure 26: Compressor Performance Analysis Software window*

As stated in the procedure, enter all necessary inputs into the white boxes. Then, user need to click 'Calculate' button in order for the software to calculate respective outputs. Less than a second, the results will show in the coloured boxes.



Note: Click on either navigation button to view analysis and performance chart

Suction Pressure (P1) 1665 psig
Suction Temp (T1) 32 deg C
Disch Pressure (P2) 5887.5 psig
Disch Temp (T2) 140 deg C

Compr Fact, Z, Suction 0.7397
Compr Fact, Z,Discharge 1.0754
Polytropic Head (ft.lb/lb) 53283.1447

Note: Press "Calculate" button to view results once all parameters entered

*Figure 27: Results using the first set of data*

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

By monitoring the performance of the compressor, operator can achieve many outcomes. The most important purpose is to make sure the compressor is running within the design limit. By doing this, compressor can be guard from any destructive damage or mechanical failure. The operator also manages to control the load and flow of the compressor in order to prevent surge. Besides that, operator can plan when they should do composition analysis and troubleshooting due to unusual behavior from the trending. This may increase the efficiency of the compressor itself. 'Compressor Performance Analysis' software provides an interactive and user-friendly interface for a user to calculate and analyze performance parameters. By having this software, operator will be able to determine polytropic head of operating point during real time operation.

## 5.2 Recommendation

Analyze the effect of gas composition on the centrifugal compressor performance.

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[2] Rolls-Royce Customer Training Center, 2003, *Centrifugal Compressor Notes*
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Jan van Helvoirt, Bram de Jager, Maarten Steinbuch, and Jan Smeulers, 2005, *Modeling and Identification of Centrifugal Compressor Dynamics with Approximate Realizations*

R.W. Mickers DCT, 2006, *Comparative Parameter Studies of Dynamic Models for Centrifugal Compression Systems*

# APPENDICES

## Appendix A

Calculation for Compressibility Factor, Z

Data on 1st April 2010 (Hour 1):

*Suction Condition*

- P1=Ps=1665psig=1679.67psia
- T1=Ts=32 degC=549.27 degR

*Discharge Condition*

- P2=Pd=5887.5 psig=5902.17 psia
- T2=Td=140 degC=743.67 degR

*Other Variables*

- Pc=676.48 psia
- Tc=396.96 degR
- Ro=1545.32 ft.lbf/lbmole°R = 0.08205846 L-atm/g-mol-K
- MW=21.1746 lbm/lbmole

Suction Condition; reduced pressure:

$$\mathrm{Pr}_s = \frac{P_s}{Pc}$$

$$\mathrm{Pr}_s = \frac{1679.67}{676.48} = 2.48$$

Reduced temperature:

$$Tr_s = \frac{T_s}{Tc}$$

$$Tr_s = \frac{549.27}{396.96} = 1.38$$

Other variables:

$$a = 0.42747\left(\frac{R^2 T_c^{5/2}}{P_c}\right)$$

$$a = 0.42747\left(\frac{0.08205846^2 396.96^{5/2}}{676.48}\right) = 45.1749$$

$$b = 0.08664\left(\frac{RT_c}{P_c}\right)$$

$$b = 0.08664\left(\frac{0.08205846 \times 396.96}{676.48}\right) = 0.03407$$

$$A^2 = 0.42747\left(\frac{P_r}{T_r^{5/2}}\right)$$

$$A^2 = 0.42747\left(\frac{2.48}{1.38^{5/2}}\right) = 0.471$$

$$B = 0.08664\left(\frac{P_r}{T_r}\right)$$

$$B = 0.08664\left(\frac{2.48}{1.38}\right) = 0.1554$$

$$r = A^2 B$$

$$r = 0.471 \times 0.1554 = 0.07321$$

$$q = B^2 + B - A^2$$

$$f = \frac{-3q - 1}{3}$$

$$f = \frac{-3(-0.2915) - 1}{3} = -0.0418$$

$$g = \frac{-27r - 9q - 2}{27}$$

$$g = \frac{-27(0.07321) - 9(-0.2915) - 2}{27} = -0.0501$$

$$C = \left(\frac{f}{3}\right)^3 + \left(\frac{g}{2}\right)^2$$

$$C = \left(\frac{-0.0418}{3}\right)^3 + \left(\frac{-0.0501}{2}\right)^2 = 0.000625$$

Since C > 0, so:

$$z = D + E + \frac{1}{3}$$

$$z = 0.36854 + 0.03781 + \frac{1}{3} = 0.73968$$

Same calculation goes for discharge condition where at the end the results are:

$$z = 1.029$$

So compressibility factor for suction and discharge condition are:

**Zs=0.73968 Zd=1.029**

## Appendix B

### Calculation for Polytropic Head

Data on 1st April 2010 (Hour 1)

*Suction Condition*

- P1=Ps=1665psig=1679.67psia
- T1=Ts=32 degC=549.27 degR

*Discharge Condition*

- P2=Pd=5887.5 psig=5902.17 psia
- T2=Td=140 degC=743.67 degR

*Other Variables*

- Pc=676.48 psia
- Tc=396.96 degR
- Ro=1545.32 ft.lbf/lbmole°R = 0.08205846 L-atm/g-mol-K
- MW=21.1746 lbm/lbmole

Suction Condition; reduced pressure:

$$\mathrm{Pr}_s = \frac{P_s}{Pc}$$

$$\mathrm{Pr}_s = \frac{1679.67}{676.48} = 2.48$$

Reduced temperature:

$$Tr_s = \frac{T_s}{Tc}$$

$$Tr_s = \frac{549.27}{396.96} = 1.38$$

Discharge Condition; reduced pressure:

$$\Pr_d = \frac{P_d}{Pc}$$

$$\Pr_d = \frac{5902.17}{676.48} = 8.72$$

Reduced temperature:

$$Tr_d = \frac{T_d}{Tc}$$

$$Tr_d = \frac{743.67}{396.96} = 1.87$$

Gas Constant:

$$R = \frac{R_o}{MW}$$

$$R = \frac{1545.32}{21.1746} = 72.97\, ft.lbf / lbm^{o}R$$

Isentropic Exponent:

$$k = \frac{Cp_{mix}}{(Cp_{mix} - 1.986)}$$

$$k = \frac{9.633}{(9.633 - 1.986)} = 1.2596$$

Polytropic Efficiency:

$$\eta_p = \frac{\ln\left[\left(\frac{P_d}{P_s}\right)^{(k-1)/k}\right]}{\ln\left[\left(\frac{T_d}{T_s}\right)\times\left(\frac{Z_d}{Z_s}\right)\right]}$$

$$\eta_p = \frac{\ln\left[\left(\frac{5902.17}{1679.67}\right)^{(1.2596-1)/1.2596}\right]}{\ln\left[\left(\frac{743.67}{549.27}\right)\times\left(\frac{1.029}{0.73968}\right)\right]} = 0.38257$$

Polytropic Exponent:

$$n = \frac{\eta_p \times \frac{k}{(k-1)}}{\left[\eta_p \times \frac{k}{(k-1)}\right]-1}$$

$$n = \frac{0.38257 \times \frac{1.2596}{(1.2596-1)}}{\left[0.38257 \times \frac{1.2596}{(1.2596-1)}\right]-1} = 2.1685$$

Polytropic Head:

$$H_p = \frac{Z_s R T_s}{(n-1)/n} \times \left[\left(\frac{P_d}{P_s}\right)^{(n-1)/n} - 1\right]$$

$$H_p = \frac{0.73968 \times 72.9798 \times 549.27}{(2.1685-1)/2.1685} \times \left[\left(\frac{5902.17}{1679.67}\right)^{(2.1685-1)/2.1685} - 1\right] = 53283.173\text{ft.lb/lb}$$

## APPENDIX C

### Gantt Chart for first semester

| No | Details | Week | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 1 | Selection of Project Topic | ▨ | | | | | | | MID SEMESTER BREAK | | | | | | | |
| 2 | First meeting with my supervisor | | ▨ | | | | | | | | | | | | | |
| 3 | Preliminary Research work | | | | | | | | | | | | | | | |
| | a) Research about compressor operation | | | ▨ | ▨ | ▨ | ▨ | | | | | | | | | |
| | b) Research on compressor surging | | | | | ▨ | ▨ | ▨ | | | | | | | | |
| 4 | Preliminary Report preparation | | | ▨ | | | | | | | | | | | | |
| 5 | Submission of Preliminary Report | | | | ● | | | | | | | | | | | |
| 6 | Progress report preparation | | | | | | ▨ | ▨ | | | | | | | | |
| 7 | Submission of Progress Report | | | | | | | | | ● | | | | | | |
| 8 | Seminar (compulsory) | | | | | | | | | ● | | | | | | |
| 9 | Project work continues | | | | | | | | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | a) Research on performance parameters | | | | | | | | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 10 | Submission of Interim Report Final Draft | | | | | | | | | | | | | | | ● |
| 11 | Oral Presentation preparation | | | | | | | | | | | | | ▨ | ▨ | |
| 12 | Oral Presentation (during study week) | | | | | | | | | | | | | | ▨ | ▨ |

● Suggestion milestone ▨ Process

Gantt Chart for second semester

| No | Details | Week | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 1 | Identification of parameters | ▨ | | | | | | | MID SEMESTER BREAK | | | | | | | |
| 2 | Construct mathematical model | | ▨ | | | | | | | | | | | | | |
| 3 | Equation of State for Z factor | | ▨ | | | | | | | | | | | | | |
| 4 | Acquire data from plant | | | ▨ | | | | | | | | | | | | |
| 5 | Spreadsheet for overall calculation | | | | ▨ | ▨ | | | | | | | | | | |
| 6 | Result analysis | | | | | | ▨ | ▨ | | | | | | | | |
| 7 | Developing GUI for performance analysis | | | | | | ▨ | ▨ | | | | | | | | |
| 8 | Progress Report | | | | | | | | | ▨ | | | | | | |
| 9 | Poster/Pre EDX | | | | | | | | | | | | ▨ | | | |
| 10 | Dissertation and Technical Paper | | | | | | | | | | | | | | ▨ | |
| 11 | Oral Presentation | | | | | | | | | | | | | | | ▨ |
| 12 | Final Report (Hard bound) | | | | | | | | | | | | | | | ▨ |

Process ▨