Development of a Computer Program to Assess Gas Compressor Performance

by

Ahmad Nadiy Bin Mohd Ghazali

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

JANUARY 2009

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Development of a Computer Program to Assess Gas Compressor Performance

by

Ahmad Nadiy B Mohd Ghazali

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Ir. Idris Ibrahim)

Idris bin Ibrahim, P.Eng. MIEM
Senior Lecturer
Mechanical Engineering Department
Universiti Teknologi PETRONAS

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2009

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

(AHMAD NADIY B MOHD GHAZALI)

ABSTRACT

This report discusses the preliminary research done and basic understanding of the chosen topic, which is Development of a Computer Program to Assess Gas Compressor Performance. The author has compiled all the materials related to the topic and utilizes them as the main source to start the project. The main objective of the project is to develop a computer program for the usage of evaluating the performance of gas compressor specifically centrifugal compressor performance. There are two (2) phases in the development of the computer program. The first phase is the development of the basic spreadsheet which has a very limited function but still able to perform the calculations to assess gas compressor performance. The second phase is the critical improvement of the program which more user-friendly and has modern-look. This project enhanced the assessment of gas compressor performance by eliminating the usage of manual calculations on a basic spreadsheet to evaluate the gas compressor performance. By using this computer program, gas compressor operators will be able to perform calculations by giving inputs to this program and get specific outputs in order for them to use for assessment. The outputs of this program which are in a graph plots can be assessed to evaluate the performance of the gas compressor. Recommendations were given to improve the design and features of the computer program for any future works.

ACKNOWLEDGEMENT

This thesis is submitted in fulfillment of the requirements for the degree in Mechanical Engineering at the University Technology PETRONAS, Malaysia. The research presented has been carried out at the University Technology PETRONAS in the period from July 2008 to June 2009.

I would like to use this opportunity to thank my supervisor at University Technology PETRONAS, Ir. Haji Idris Ibrahim for the guidance, help and critique during this work.

I would also like to thank the PETRONAS Bintulu Fertilizer, Sarawak specifically En. Mohd Izhar Mohd Ghazali for providing me with the necessary data and information that contributes to the development of this project. I am grateful his cooperation in order to make this project a success.

Not forgetting my previous plant supervisors, En. Nurhisyam and En. Restoto from PETRONAS Carigali Sdn Bhd (PCSB), KLCC which had given me guidance in understanding the necessary knowledge and information that allow me to carry out this project.

Finally, I would like to thank my colleague, En. Muamar Gadafi for his supports throughout the completion of this work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Gas compressors are widely used in mechanical related industries in compressing the air / gas to increase the pressure of the Gas. Applications of compressed gas vary from consumer products, such as the home refrigerator, to large complex petrochemical plant installations. Mainly, there are two types of Compressor; Dynamic Compressor and Positive-Displacement Compressor. A widely used gas compressor is the centrifugal compressor, one of the dynamic compressors which exhibit a contrary behaviour to the positive displacement-type compressors. For example, in a reciprocating compressor (positive-displacement compressor) a quantity of gas is drawn into the cylinder and trapped by the action of the valves and motion of a piston. As the piston moves in the cylinder, compression is achieved by direct volume reduction. By comparison, centrifugal compressor achieve compression by applying inertial forces to the gas (acceleration, deceleration, turning) by means of rotating impellers at high speed (Figure 1.1), that continuously impact and perform work on the gas during operation.

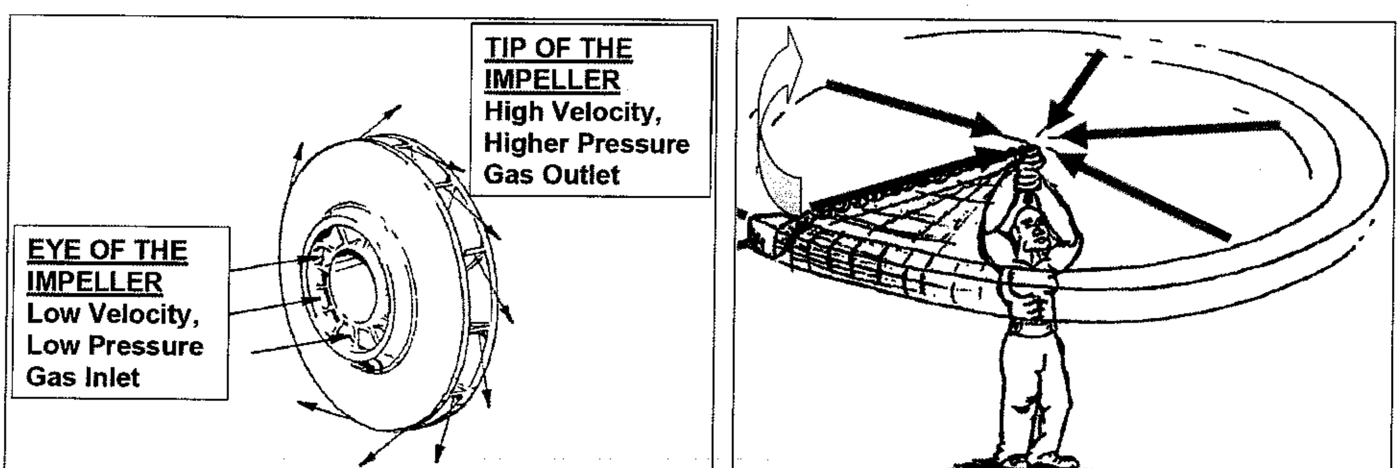


Figure.1.1 : Basic principles of centrifugal compressor. (Dresser Rand, 2008)

Next, the impellers rotation is utilized with a rotor shaft compresses the gas where the high speed gas will enter a diffuser passage (Figure 1.2) which will enter the low flow path which increase significantly the gas pressure (Figure 1.3). Stationary components form a flow path for the gas to flow from suction to discharge. Pressurized gas is contained inside a casing during operation.

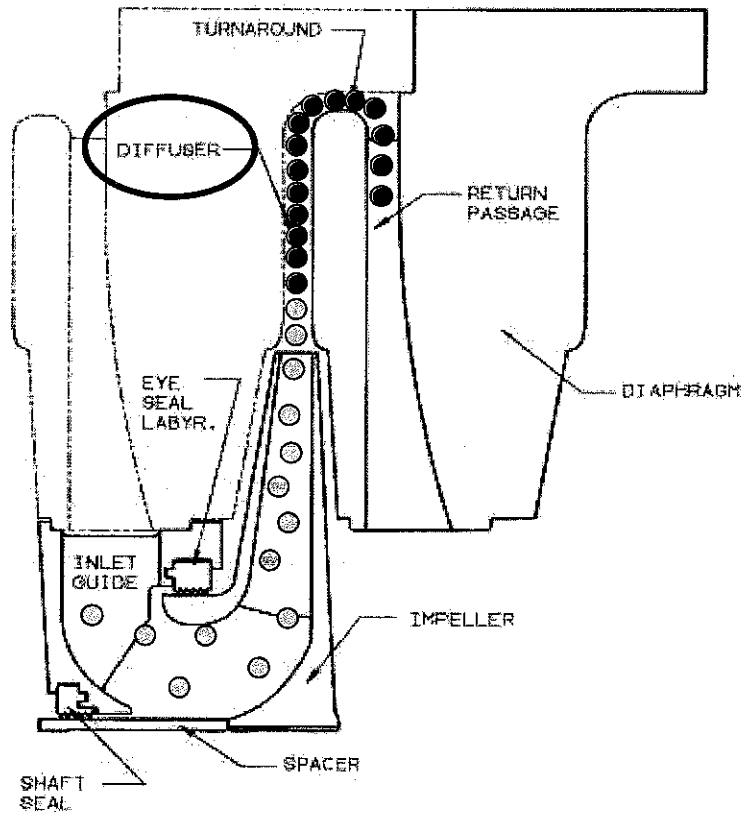


Figure 1.2 : Compression of high velocity gas through the diffuser. (Dresser Rand, 2008)

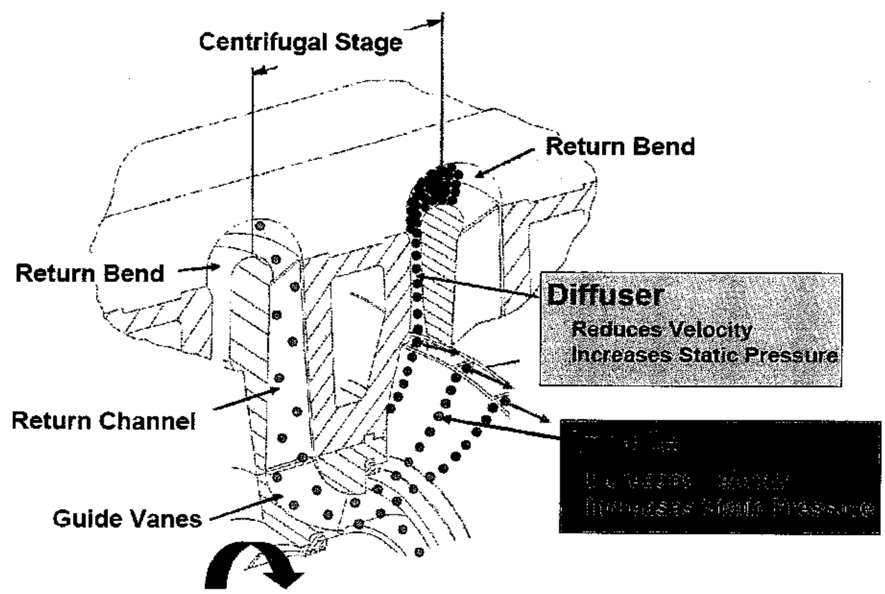


Figure 1.3 : Stage of Compression. (Dresser Rand, 2008)

Every centrifugal compressor is designed to operate at a preferred optimum speed point relative to the impeller design. Impellers are designed to raise the gas pressure within limits that ensure the gas will flow at a desired production rate from the suction [inlet] of the compressor to the discharge of the compressor. This operating point is graphically defined (Figure 1.4) along an operating curve and is referred to as "Design Point" operation which sometimes are called as the Best Efficiency Point.

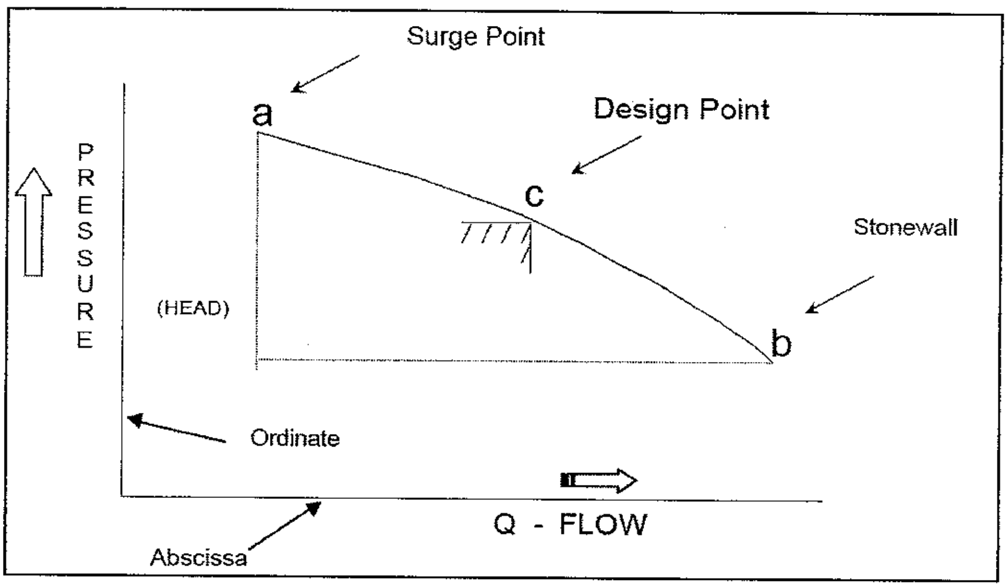


Figure 1.4 : Compressor performance curve (Dresser Rand, 2008).

Although in reality, it is rarely for the centrifugal compressors to run consistently on the design point parameters, it should be run at the nearest point to the design point parameter. Therefore, a consistent check up or test on the centrifugal compressor performance should always be observed. Such test is called Compressor Performance Test. The main reasons for conducting such test are to confirm aerodynamic performance of the compressor and the guaranteed operating conditions are met. The overall picture of the Centrifugal Compressor Assessment is shown in Figure 1.5 in the next page.

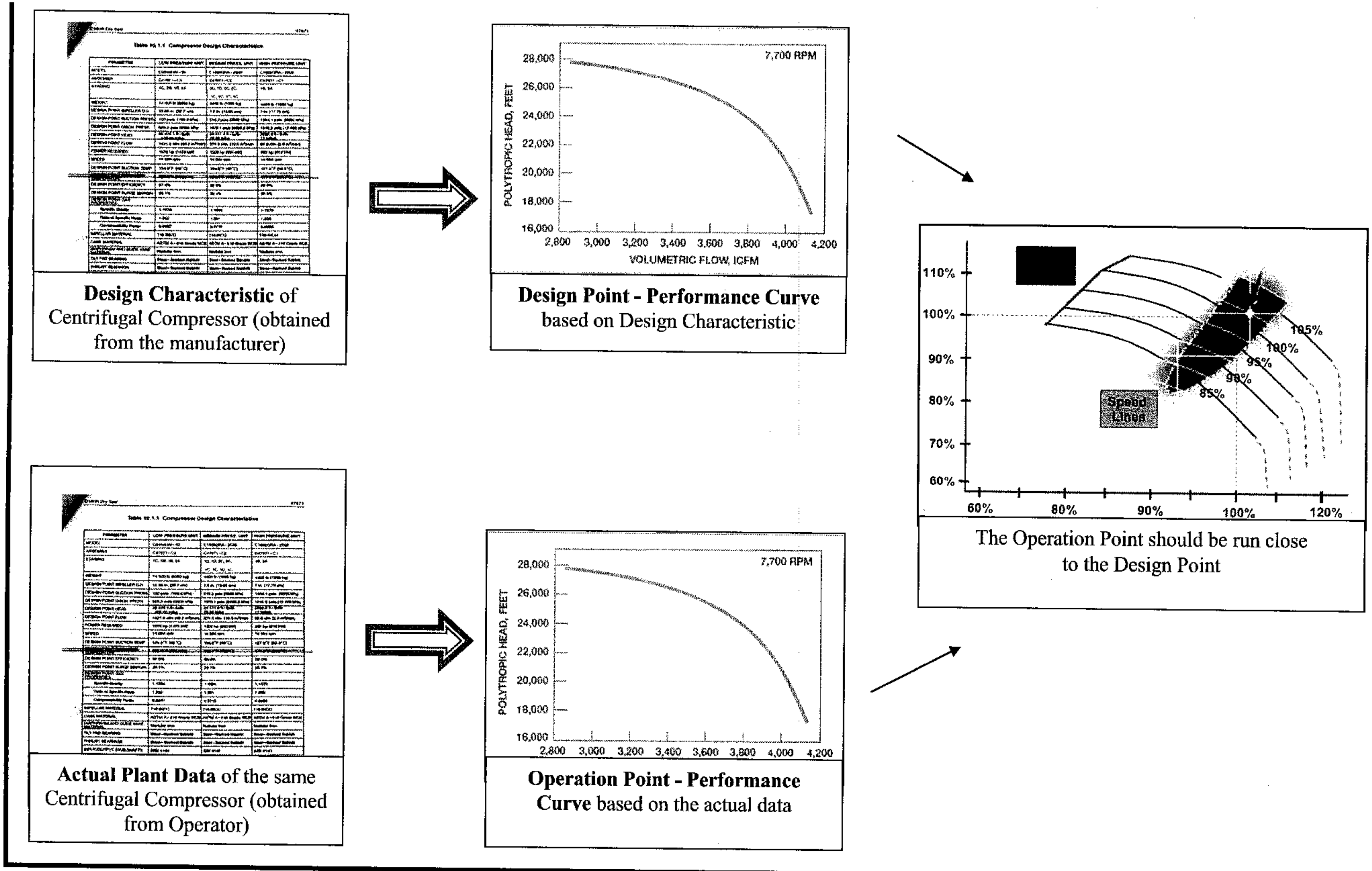


Figure 1.5 : Overall picture of centrifugal compressor performance assessment. (Dresser Rand, 2006)

.2 PROBLEM STATEMENT

Gas Compressor performance assessment is crucial in ensuring the Gas Compressor is working at the best efficiency point (BEP) or Desired Point. The Gas Compressor performance is assessed by evaluating the thermodynamics efficiency as well as the head produced. The assessment is conducted using computer program which normally is proprietary to the owner of the program making it inaccessible to any other parties and thus not available in the market. Therefore, this project is commenced to develop a Generic Gas Compressor performance assessment program that can be used for any model of the Gas Compressor.

.3 OBJECTIVES

The main objectives of this project are:

- Design the performance assessment program
- Evaluate Gas Compressor performance
- Validate the assessment result with the actual data.

.4 SCOPE OF STUDY

The work to be carried out can be summarized as follows:

- Develop mathematical model to allow thermodynamic analysis of the Centrifugal Compressor system
- Validate the mathematical model by using an actual set of plant data obtained from any Gas Compressor vendor
- Apply the mathematical models into the computer program
- Develop a user-friendly computer program to assess centrifugal compressor performance based on the mathematical models.

CHAPTER 2
LITERATURE REVIEW

1.5 LITERATURE REVIEW

After a certain time period of operation, the Gas Compressor performance will drop and need to be improved. The user must try to obtain the same compressor performance as designed by the compressors' vendor since it is the point where the Gas compressor will work at the best efficiency point or desired point. The operation of a centrifugal compressor units means keeping the performance within the operating limits for which machines were specified in order to avoid any inefficiency in the plant and to obtain the highest economic profit. The Gas Compressor performance is assessed generally by evaluating the thermodynamics efficiency as well as the head produced. The parameters that should be taken into consideration when running a thermodynamic test of the centrifugal compressors are:

- Polytrophic Head
- Inlet Flow Rate
- Compressor Efficiency

In Appendix III, the author has compiled several mathematical models from other authors whose works are related to this project. After making a critical literature review, the author has decided to use the following as the reference of this project:

1.5.1 Polytrophic Head

The Polytrophic Head is an expression used for dynamic compressors to denote the foot-pounds of work required per pound of gas. It can be defined as the energy accumulated in the fluid of the system and expressed in feet *(ft)*.

Article refer to Scott Golden, Scott A. Fulton & Daryl W. Hanson (2002), the compressor curve flow term is always based on the inlet conditions; consequently inlet gas density, ρ influences volumetric flow, v. Flow rate, v is shown on the X-axis and head, H on the Y-axis. For a fixed impeller speed (RPM), the curve shows that for a known inlet flow rate v, a fixed head, H is developed. Centrifugal compressor inlet flow rate, v increases as the head, H decreases. Gas plant operating pressure and gas composition determine the value of head, H.

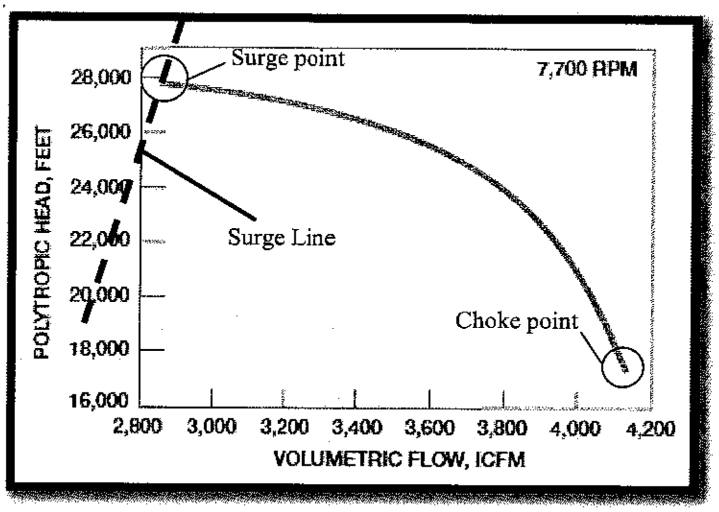


Figure 2.1 : Compressor performance curve. (Scott Golden, Scott A. Fulton and Daryl W. Hanson, 2002)

Increasing suction pressure, P_S, decreasing gas plant operating pressure, P_D and/or decreasing process system pressure drop, P_{drop} will increase inlet flow rate, v as long as the compressor is not operating at choke flow. A compressor curve as can be seen in Figure 2.1 starts at the surge point and ends at stonewall, or choke flow. The surge point is the head at which inlet flow is at its minimum. At this point, the compressor suffers from flow reversal, which is a very unstable operation that is accompanied by vibration and possible damage. Surge begins when the operating point of the compressor crosses the surge line. Surge line is the stability limit of the compressor performance map [7].

On the other end of the curve is the choke (or stonewall) point. At the choke point, the inlet flow through the compressor cannot increase no matter what operating changes are made. Therefore, the range of compressor performance is defined between these two flow head limitations. Normally, the curve is flat near the surge point and becomes steeper as flow is increased. Thus, small head, H changes near the surge point causes a large increase in compressor flow rate capacity, v. As compressor operation moves toward stonewall, decreasing head, H has less influence on inlet flow rate because the curve slope increases. As the stonewall point is approached, changes in head, H will have negligible effect on inlet flow rate [3].

Equation 1 shows the polytrophic head term. (Appendix III-E)

$$H_{poly}[ft] = \frac{1,545}{MW} Z_{avg} T_s \times \left(\frac{k}{k-1}\right) \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right] \qquad \textbf{... (1)}$$

Where ;

Z_{avg} is the average compressibility factor between the suction and discharge section, $Z_{avg} = \dfrac{Z_s + Z_d}{2}$;

T_s is the gas suction temperature (R);

P_s is the gas suction pressure ($psia$);

P_d is the gas discharge pressure ($psia$);

k is the ratio of specific heat $k = \left(C_P / C_V \right)$

MW is the gas molecular weight

The value of the constant 1545 in the Equation 1 represents the universal gas constant, R which:

$$R = \frac{1545\ [ft.lb/{}^\circ R]}{MW\ [lb/mol]} = [ft.lb/lb.mol.{}^\circ R]$$

The compressibility, Z_s value is determine at the suction condition with respect to the suction pressure, P_s and suction temperature, T_s. While for the Z_d the value is determine at the discharge condition.

The value of Z at each suction and discharge can be determined from the following equation:

$$Pv = ZRT$$

where P is the absolute pressure in Pascal, Pa.

v is the specific volume in m^3/kg.

R is the Universal Gas Constant in $J/kg.K$

T is the absolute temperature in Kelvin, K

Specific Heat Ratio, k is the ratio of the specific heat at constant pressure, c_p to the specific heat at constant volume, c_v. These two values can be obtained from the thermodynamic table (refer Appendix VI).

Reducing polytrophic head, H will increase compressor capacity, v by moving the operating point to the right (Figure 2.2). A higher gas molecular weight, MW raising suction pressure, P_S or lowering discharge pressure, P_D are few process changes that move the operating point to right of the performance curve (Figure 2.2). However, the gas temperature, T changes have little influence on head, H.

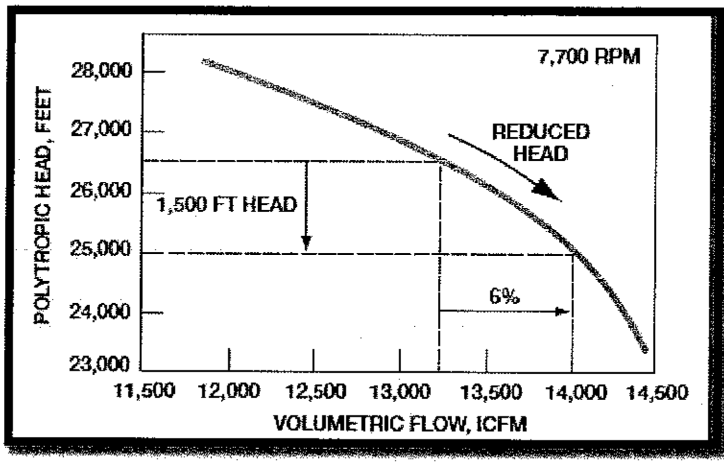


Figure 2.2 : Any process changes will moves the operating point on the curve. (Scott Golden, Scott A. Fulton and Daryl W. Hanson, 2002)

Volumetric Inlet Flowrate

The Compressor performance curve is also developed based on the volumetric flowrate capacity of the suction conditions. The volumetric flowrate capacity is located at the x-axis of the compressor performance map. Typically, the unit of ACFM (actual cubic feet per minute) is used to represents the volumetric flowrate capacity. However, some compressor operators & manufacturers use ICFM (inlet cubic feet per minute). But ICFM is not a standard gas flow metering units since wet gas is a compressible fluid, and thus changes in a compressor suction conditions that increase the gas density will reduce the wet gas volumetric flow rate and free up compressor capacity. Hence, for a better result, the author has decided to use the unit of ACFM to represent the flowrate capacity.

The equation for volumetric flowrate capacity is:

$$\text{ACFM} = \frac{14.73 \times Q \times ZT_s}{520 \times Ps \times 0.00144} \qquad \textbf{... (2)}$$

Where Z is the Compressibility Factor at the inlet

T_s is the Suction Temperature in (°R)

P_s is the Suction Pressure in (psia)

Q is the unit flow in MMcfd

1.5.2 Compressor Efficiency, η_{isen}

Compressor efficiency can be measured using suction and discharge gas temperatures. However, the gas temperature measurement necessary for accurate compressor efficiency measurement requires "laboratory" type temperature measurement accuracy that is not practical for field measurement. The equation for Compressor efficiency using gas temperatures is:

$$\eta_{isen}[\%] = \left[\frac{T_s + 460}{T_d - T_s}\right] \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right] \qquad \text{... (3)}$$

where T_s is the suction temperature Fahrenheit, $^\circ F$

T_d is the discharge temperature in Fahrenheit, $^\circ F$

the value 460 is to convert the Temperature into the unit of Rankine, R.

Commonly, the efficiency of a compressor ranged from a minimum of 60% to a maximum of 80 %. Lower than this value shows the operator that maintenance is required.

CHAPTER 3
METHODOLOGY

.1 METHODOLOGY AND PROJECT WORK

3.1.1

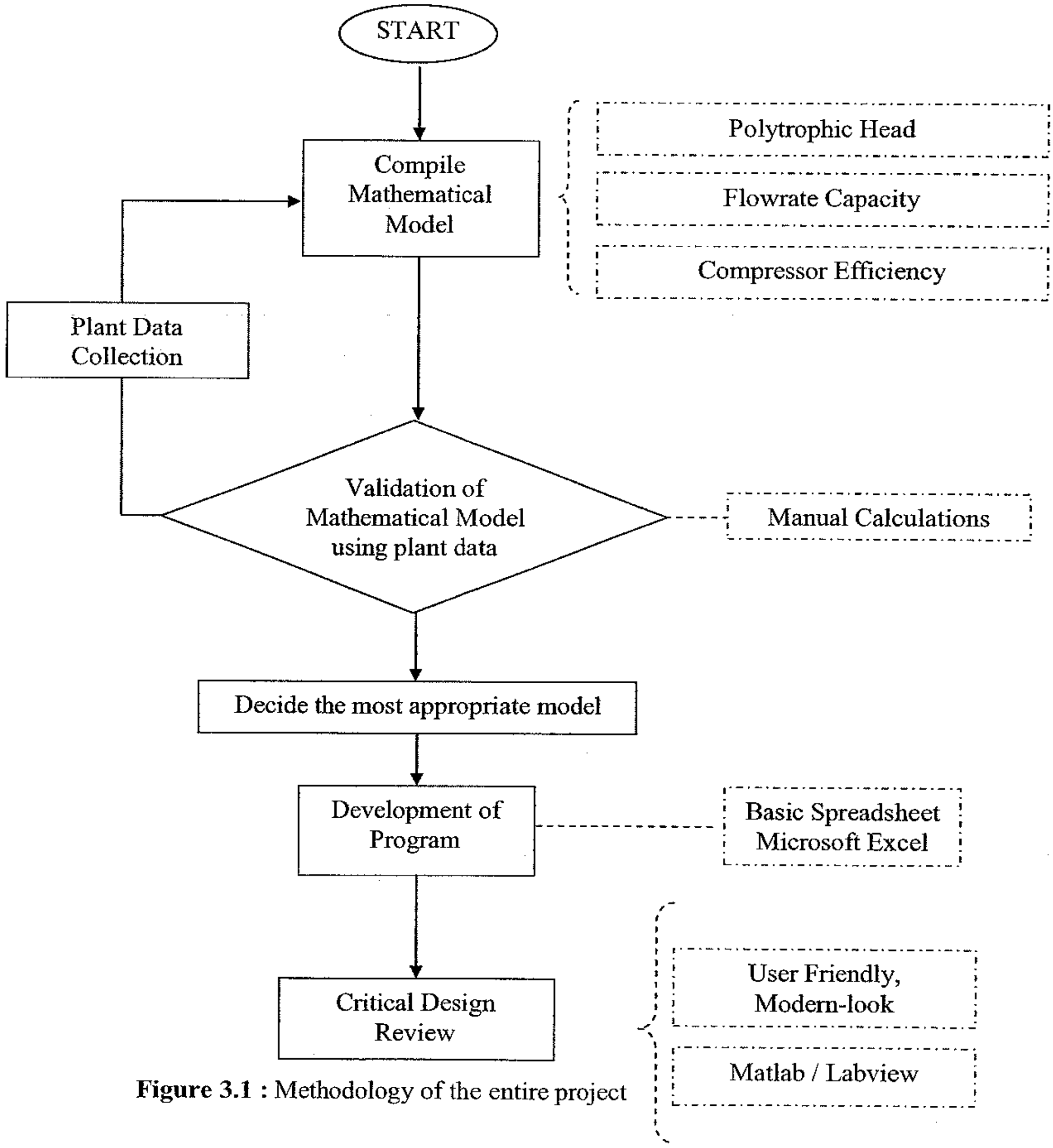


Figure 3.1 : Methodology of the entire project

3.1.2 Compilation of Mathematical Model:

In this part, the author would compile several mathematical models which are related to a thermodynamic of a compressor system; i.e. Polytrophic head, Volumetric Flowrate and also the Compressor Efficiency. These mathematical models are taken from any previous author's paper-work, training manual, lecture notes and etc which are related to the centrifugal systems. Each mathematical model is similar from one author to another, but there are slight different in term of the results output.

The author will then compare all the compiled mathematical models to choose one which is the most suitable mathematical model for this project. The criteria of the most suitable mathematical model are based on the compromise between accurate result and simplicity.

After the author has chosen a particular mathematical model for the project, the next step would be using the mathematical model in a program to evaluate the output of the centrifugal gas compressor. In order to build this program, the author would be using either MatLab software or Labview software. However, before the author uses the said software, the author would first develop the basic spreadsheet by using Microsoft Excel.

3.1.3 Collection of Plant Data:

In order to evaluate these mathematical models (Appendix III), the author will use a same data acquired from the plant as the input (refer Appendix V). The said plant data must at least consist of:-

- Inlet Pressure
- Inlet Temperature
- Flowrate capacity
- Gas compositions, thus the Gas Molecular Weight

The data can be obtained from any plant/factory that operates centrifugal compressor. The author however can obtain the set of data from PETRONAS Fertilizer, Bintulu in Sarawak; the place where he has had gone through his industrial internship. Example of plant data can be seen in **Appendix IV.**

However, the example of plant data showed in Appendix IV is a Design Characteristics of a particular Centrifugal Compressor. Thus, it is not an actual data of the centrifugal compressor. The user will have to use this data as the Design Point / Recommended Point / Best Efficiency Point for the Centrifugal Compressor. And next, the user should have another list of actual data for the same centrifugal compressor from the operator. He should then compared the current performance of the centrifugal compressor (evaluated from the actual data) with the design point (refer. Appendix IV). The illustration of the centrifugal compressor performance assessment can be seen above in Figure 1.5.

However, the author will use these set of data obtained to demonstrate the performance assessment of the centrifugal gas compressor. Using the same flowrate from the Design Data, the operator has come out with the Actual Operating Data. The compilation of these data can be seen in Table 4.2 and Table 4.3.

3.1.4 Development of Computer Program

The last stage of this project would be the development of computer program to assess centrifugal compressor performance. The computer program would be able to plot the centrifugal compressor performance map after the user has entered input to it.

As a start, the author would use Microsoft Excel to construct a basic spreadsheet in order for him to have a rough idea on the computer program but still meets the main objective. At this level, the user would have to enter the particular properties of the gas being compressed in the centrifugal compressor in order to obtain a particular output. The properties of the gas are:

- Gas Compositions (Molecular Weight or Percentage)
- Inlet Pressure & Temperature

Next, the user would need to vary the flowrate capacity and as well as discharge pressure. Each vary would determine one specific point for the compressor performance map (Appendix IV). Basically, the detailed processes in the development of the basic spreadsheet are:

i. Construct a column for input to be entered
ii. Set any unknown parameters using assumptions
iii. Evaluate polytrophic head and Flowrate Capacity for the first point of the Compressor Performance Map
iv. Evaluate polytrophic head and Flowrate Capacity for the second – final point
v. Plot the graph
vi. Repeat the process for other data in order to make comparison

However, the author does not intend to use basic spreadsheet as the main tool to assess the centrifugal compressor performance assessment since they are few set-backs using it. They are:

- the instructions may be unclear for a first time user,
- the user has to manually plot the performance curve by selecting the correct data,
- the user has to save each performance curve construct – thus he can then compare the current compressor performance with the one recommended by the manufacturer

Therefore, after developing the basic spreadsheet, the author would then start to use more advanced software such as **Matlab** or **LabView** to develop the computer program that able to assess the centrifugal compressor performance. In the end, the computer program will be a user-friendly, easy to conduct, and modern-look.

CHAPTER 4
RESULTS

4.1 THE PLANT DATA

For demonstration purposes, the author will utilize the developed program to evaluate the performance of the centrifugal compressor based on the obtained plant data. For this purposes, the author will use the basic spreadsheet program developed in order to have a quick grasp of evaluation on the main concept of the program. The obtained plant data for both design point and actual operating point can be seen in Appendix VII. For the ease of reference, Appendix VII has been compressed into the table below:

Table 4.1 : List of gas properties for both obtained design data and operating plant data.

Properties	Unit	Value
Atm Pressure	barg	1.01
Suction Pressure, P_s	barg	3.43
Suction Temperature, T_s	°C	20.00
Specific Volume, v (from table)	kJ/kg	0.3083
Specific Heat at Constant Volume, c_v (from table)	kJ/kg	1.66
Specific Heat at Constant Pressure, c_p (from table)	kJ/kg	2.25
Gas Molecular Weight, MW	g/mol	17.03
Specific Heat Ratio, k	-	1.36
(k-1)/k	-	0.26
Universal Gas Constant, R	ft-lb / (lbmol · °R)	90.72
Specific Gas Constant, R	J/kg.K	488.20
Compressibility Factor, Z	-	0.96

Table 4.2 : List of design data discharge properties.

#	Flow Rate q (ft^3/min)	Discharge Temperature T_d (°C)	Discharge Pressure P_d (barg)	Pressure Ratio P_r
1	3450	100	4.73	1.29
2	3800	110	4.72	1.29
3	4200	120	4.69	1.28
4	4600	130	4.63	1.27
5	5000	140	4.55	1.25
6	5400	150	4.44	1.23
7	5800	160	4.28	1.19
8	6100	170	4.13	1.16
9	3690	100	4.95	1.34
10	3800	110	4.94	1.34
11	4200	120	4.93	1.34
12	4600	130	4.88	1.33
13	5000	140	4.82	1.31
14	5400	150	4.72	1.29
15	5800	160	4.61	1.26
16	6200	170	4.43	1.23
17	6490	180	4.24	1.18
18	3950	100	5.18	1.39
19	4200	110	5.16	1.39
20	4600	120	5.13	1.38
21	5000	130	5.07	1.37
22	5400	140	5.01	1.36
23	5800	150	4.91	1.33
24	6200	160	4.78	1.30
25	6600	170	4.58	1.26
26	6920	180	4.37	1.21
27	4200	100	5.44	1.45
28	4600	110	5.40	1.44
29	5000	120	5.36	1.43
30	5400	130	5.28	1.42
31	5800	140	5.21	1.40
32	6200	150	5.11	1.38
33	6600	160	4.96	1.34
34	7000	170	4.77	1.30
35	7400	180	4.54	1.25

Continue . . .

Continued . . .

#	Flow Rate q (ft^3/min)	Discharge Temperature T_d (°C)	Discharge Pressure P_d (*barg*)	Pressure Ratio P_r
36	4480	100	5.74	1.52
37	4600	110	5.73	1.52
38	5000	120	5.69	1.51
39	5400	130	5.63	1.50
40	5800	140	5.55	1.48
41	6200	150	5.45	1.45
42	6600	160	5.32	1.43
43	7000	170	5.18	1.39
44	7400	180	4.98	1.35
45	7840	190	4.66	1.28
46	4700	100	6.04	1.59
47	5000	110	6.02	1.58
48	5400	120	5.98	1.57
49	5800	130	5.91	1.56
50	6200	140	5.82	1.54
51	6600	150	5.70	1.51
52	7000	160	5.57	1.48
53	7400	170	5.41	1.45
54	7800	180	5.17	1.39
55	8240	190	4.83	1.32
56	4980	100	6.37	1.66
57	5400	110	6.34	1.66
58	5800	120	6.29	1.64
59	6200	130	6.22	1.63
60	6600	140	6.11	1.60
61	7000	150	5.98	1.57
62	7400	160	5.85	1.54
63	7800	170	5.65	1.50
64	8200	180	5.35	1.43
65	8680	190	4.99	1.35
66	5200	100	6.72	1.74
67	5800	110	6.67	1.73
68	6200	120	6.62	1.72
69	6600	130	6.52	1.69
70	7000	140	6.41	1.67
71	7400	150	6.29	1.64
72	7800	160	6.13	1.61
73	8200	170	5.90	1.56
74	8600	180	5.61	1.49
75	9110	190	5.16	1.39

Table 4.3 : List of operating plant data discharge properties.

#	Flow Rate q (ft^3/min)	Discharge Temperature T_d (°C)	Discharge Pressure P_d (*barg*)	Pressure Ratio P_r
1	3450	100	4.74	1.30
2	3800	110	4.74	1.29
3	4200	120	4.71	1.29
4	4600	130	4.65	1.28
5	5000	140	4.56	1.25
6	5400	150	4.46	1.23
7	5800	160	4.28	1.19
8	6100	170	4.15	1.16
9	3690	100	4.96	1.35
10	3800	110	4.96	1.34
11	4200	120	4.93	1.34
12	4600	130	4.89	1.33
13	5000	140	4.83	1.32
14	5400	150	4.74	1.29
15	5800	160	4.64	1.27
16	6200	170	4.46	1.23
17	6490	180	4.25	1.18
18	3950	100	5.22	1.40
19	4200	110	5.18	1.39
20	4600	120	5.17	1.39
21	5000	130	5.10	1.38
22	5400	140	5.02	1.36
23	5800	150	4.93	1.34
24	6200	160	4.79	1.31
25	6600	170	4.59	1.26
26	6920	180	4.38	1.21
27	4200	100	5.45	1.45
28	4600	110	5.41	1.45
29	5000	120	5.35	1.43
30	5400	130	5.30	1.42
31	5800	140	5.22	1.40
32	6200	150	5.12	1.38
33	6600	160	4.99	1.35
34	7000	170	4.81	1.31
35	7400	180	4.56	1.25

Continue…

Continued…

#	Flow Rate q (ft^3/min)	Discharge Temperature T_d (°C)	Discharge Pressure P_d (*barg*)	Pressure Ratio P_r
36	4480	100	5.77	1.53
37	4600	110	5.73	1.52
38	5000	120	5.69	1.51
39	5400	130	5.67	1.50
40	5800	140	5.55	1.48
41	6200	150	5.45	1.45
42	6600	160	5.32	1.42
43	7000	170	5.18	1.39
44	7400	180	4.98	1.35
45	7840	190	4.67	1.28
46	4700	100	6.06	1.59
47	5000	110	6.02	1.58
48	5400	120	5.96	1.57
49	5800	130	5.91	1.56
50	6200	140	5.81	1.53
51	6600	150	5.70	1.51
52	7000	160	5.57	1.48
53	7400	170	5.41	1.45
54	7800	180	5.16	1.39
55	8240	190	4.82	1.31
56	4980	100	6.37	1.66
57	5400	110	6.34	1.66
58	5800	120	6.29	1.64
59	6200	130	6.15	1.61
60	6600	140	6.04	1.59
61	7000	150	5.90	1.56
62	7400	160	5.77	1.53
63	7800	170	5.57	1.48
64	8200	180	5.34	1.43
65	8680	190	4.85	1.32
66	5200	100	6.73	1.74
67	5800	110	6.69	1.73
68	6200	120	6.64	1.72
69	6600	130	6.52	1.69
70	7000	140	6.39	1.67
71	7400	150	6.29	1.64
72	7800	160	6.13	1.61
73	8200	170	5.74	1.52
74	8600	180	5.41	1.45
75	9110	190	4.85	1.32

4.2 THE PERFORMANCE CURVE

By using the data from Table 4.2 & Table 4.3, two separate Performance Curves of Polytrophic Head at the Y-axis versus Flowrate at the X-axis are plotted. These two curves are then compared to evaluate the performance of the compressor. Refer to the figures (Figure 4.1 & Figure 4.2) below to see the differences: The behavior of each figure is discussed on the next section.

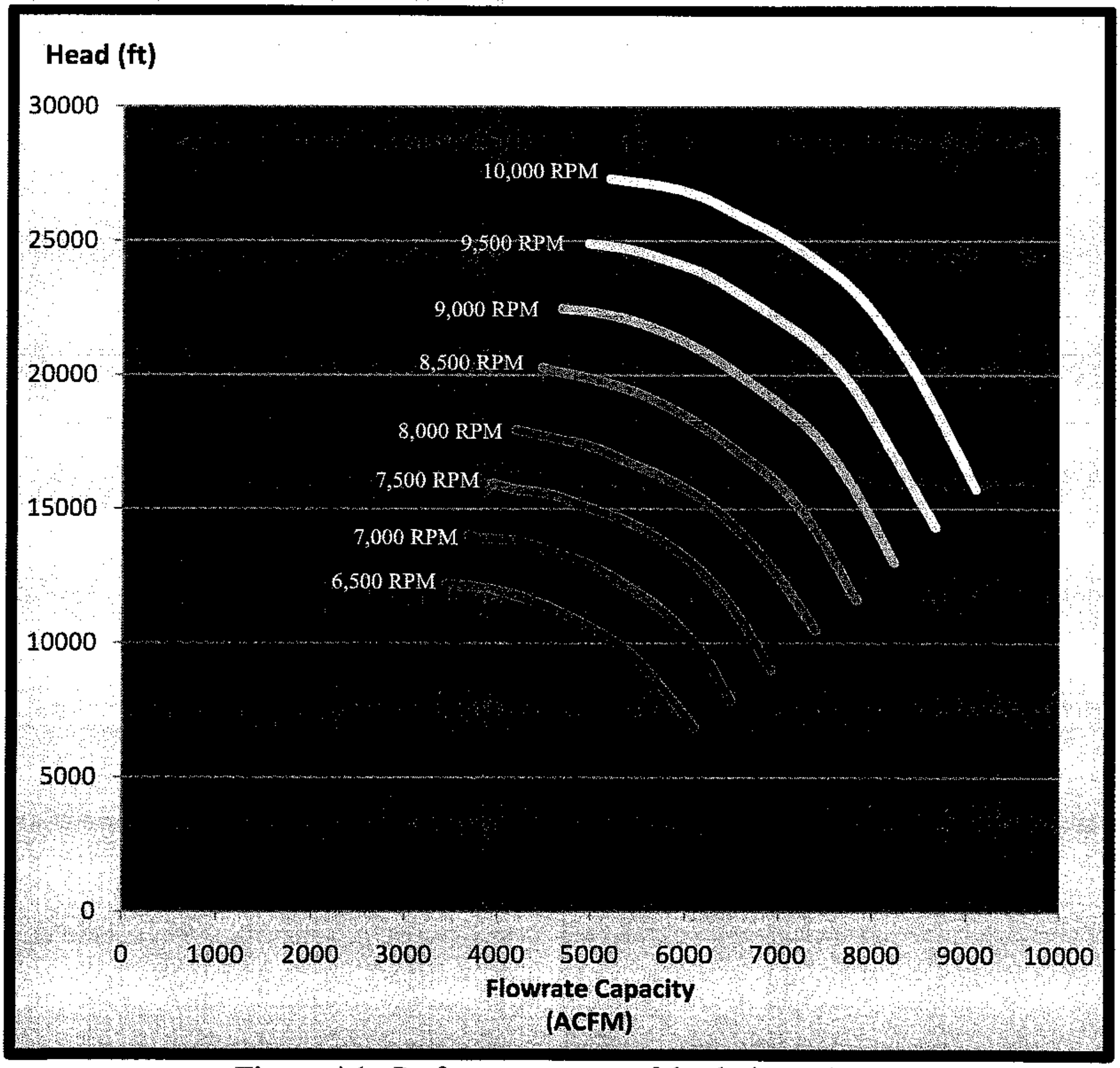


Figure 4.1 : Performance curve of the design point

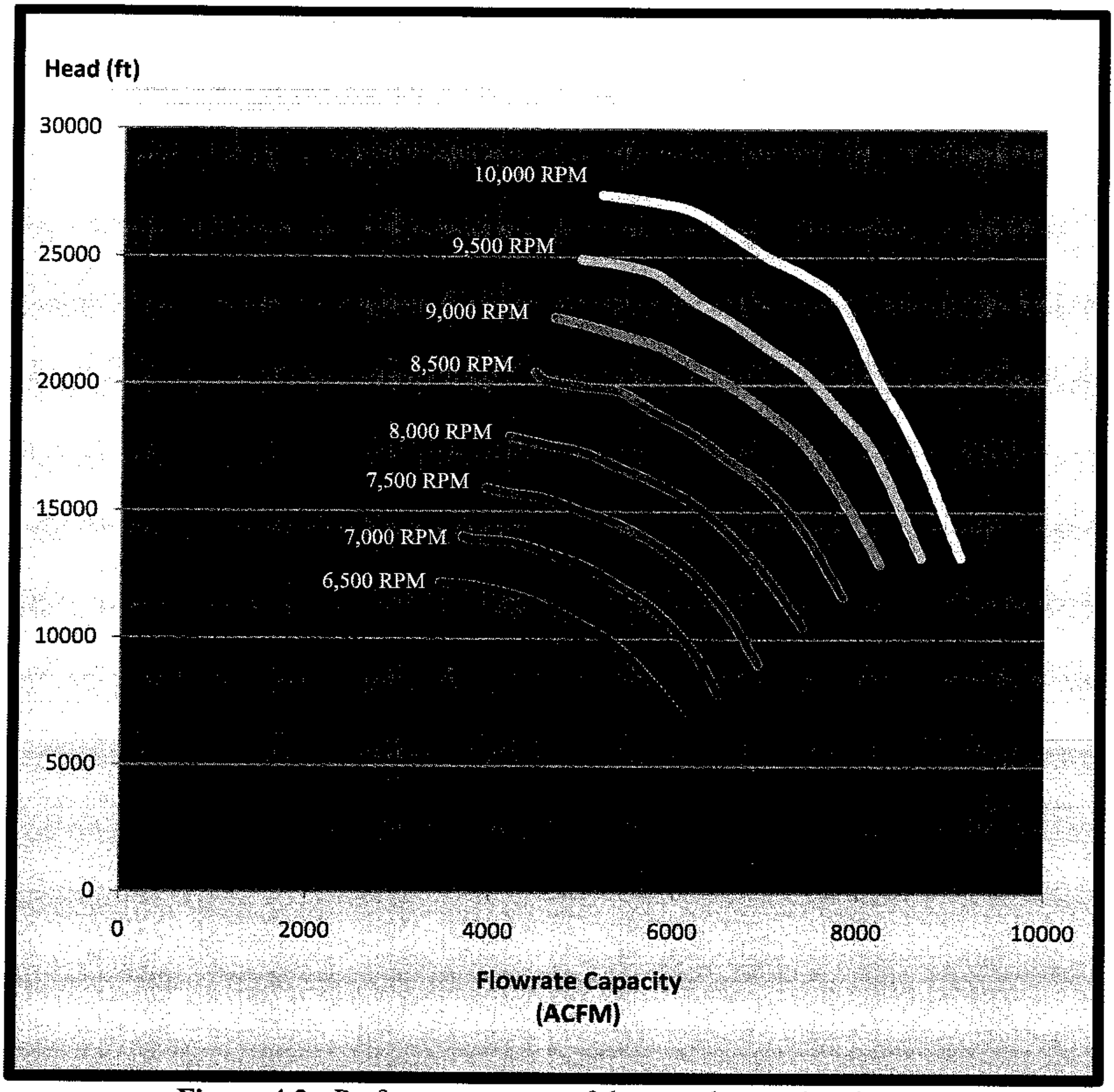


Figure 4.2 : Performance curve of the actual operation data.

4.3 COMPRESSOR EFFICIENCY VS FLOWRATE

Additionally, a graph of Compressor Efficiency versus Flowrate for each curve is plotted. These graphs are shown in figure below (Figure 4.3 & Figure 4.4). This graphs show the efficiency of the compressor at any particular flowrate capacity. The behavior of each curve is discussed in the next chapter.

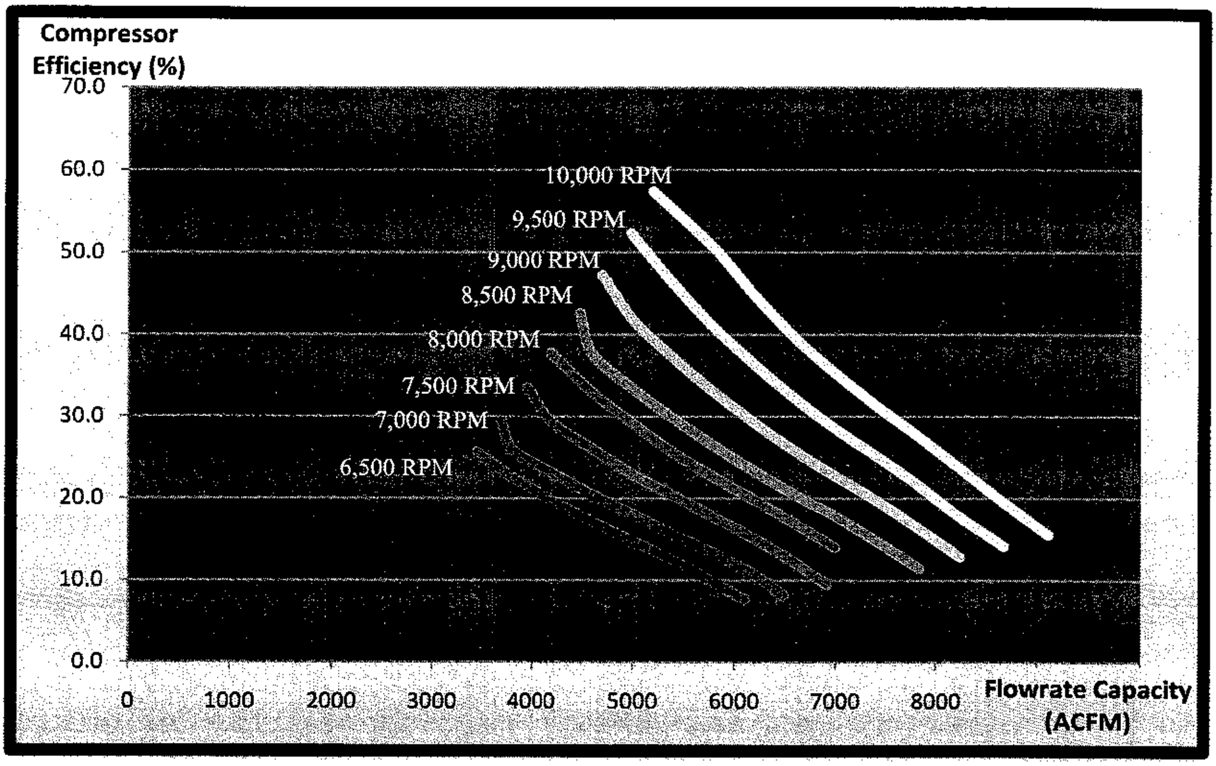


Figure 4.3 : Compressore efficiency vs flowrate (design point).

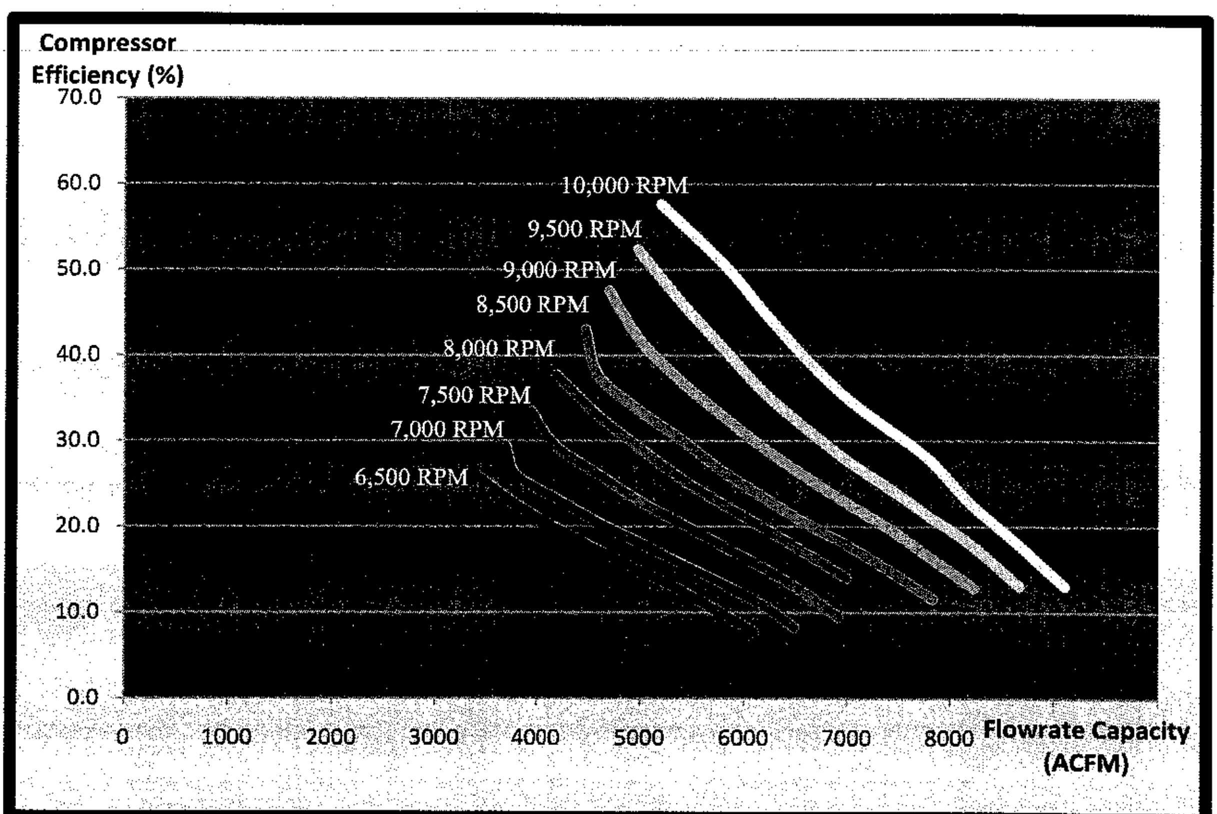


Figure 4.4 : Compressor efficiency vs flowrate (actual operating point)

CHAPTER 5

DATA EVALUATION & DISCUSSION

5.1 DATA EVALUATION

5.1.1 The Performance Curve

The two performance curves in the previous chapter represent the data obtained from the PETRONAS Fertilizer Bintulu, Sarawak as compiled in Appendix VII. The two data; Design Point and Actual Operating Point are taken from the same centrifugal compressor. By using the same values of the flowrate from the Design Point, the operator had obtained the actual polytrophic head values for the centrifugal compressor. These values are called Actual Operating Data. These two data; Design Data and Actual Operation Data the performance curves are plotted as in Figure 4.1 and Figure 4.2.

There are number of curves in each of the figure, which represents the speed of the compressor was running. The lowest curve represents the lowest speed which was running around 6500 RPM and the highest curve represents the highest compressor speed which was around 10,000 RPM. The lowest curves for both figures (Figure 4.1 and Figure 4.2) have only 8 points and these numbers of points increase as the compressor speed increase. For instance, the second, third and fourth (from bottom) curves for each data have 9 points in each curve, and the rest have 10 points. The first point in each curve is called the surge point (the point where surge will occur), while the last point is called the choke point. The line that connects all the surge point is called the surge line; while the line connecting the choke point is called the choke line.

Overall, the two performance curves are showing a similar behavior, data ranged but a very slight different for the top curves. Apparently, we can see a same characteristic / behavior of the curves which are; a slope-down curve as shown in figure below:

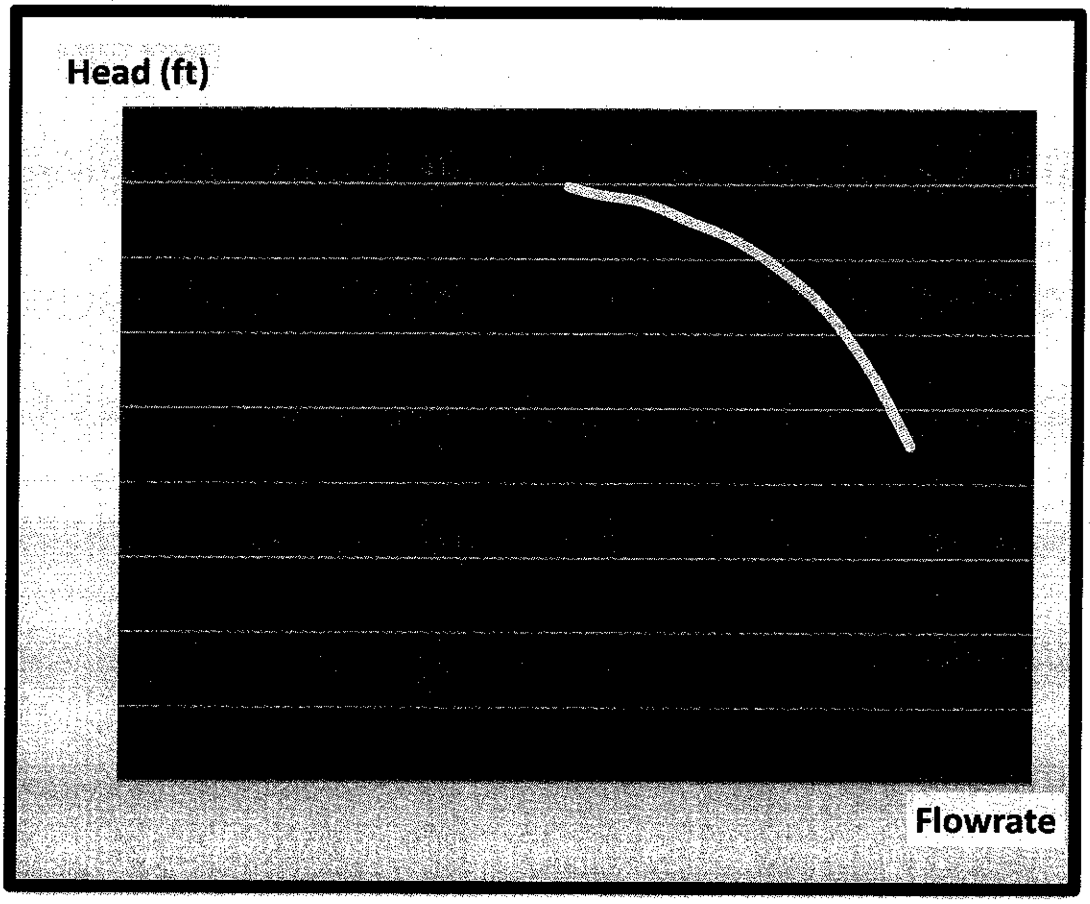


Figure 4.5 : The two performance curves from Figure 4.1 and Figure 4.2 show the same behavior; a slope-out curve

Although these two performance curves are showing the same behavior, there are little differences for the top curves behavior. To see them clearly, the author has superimposed both of the performance curves together as can be seen in the figure on the next page (Figure 4.6).

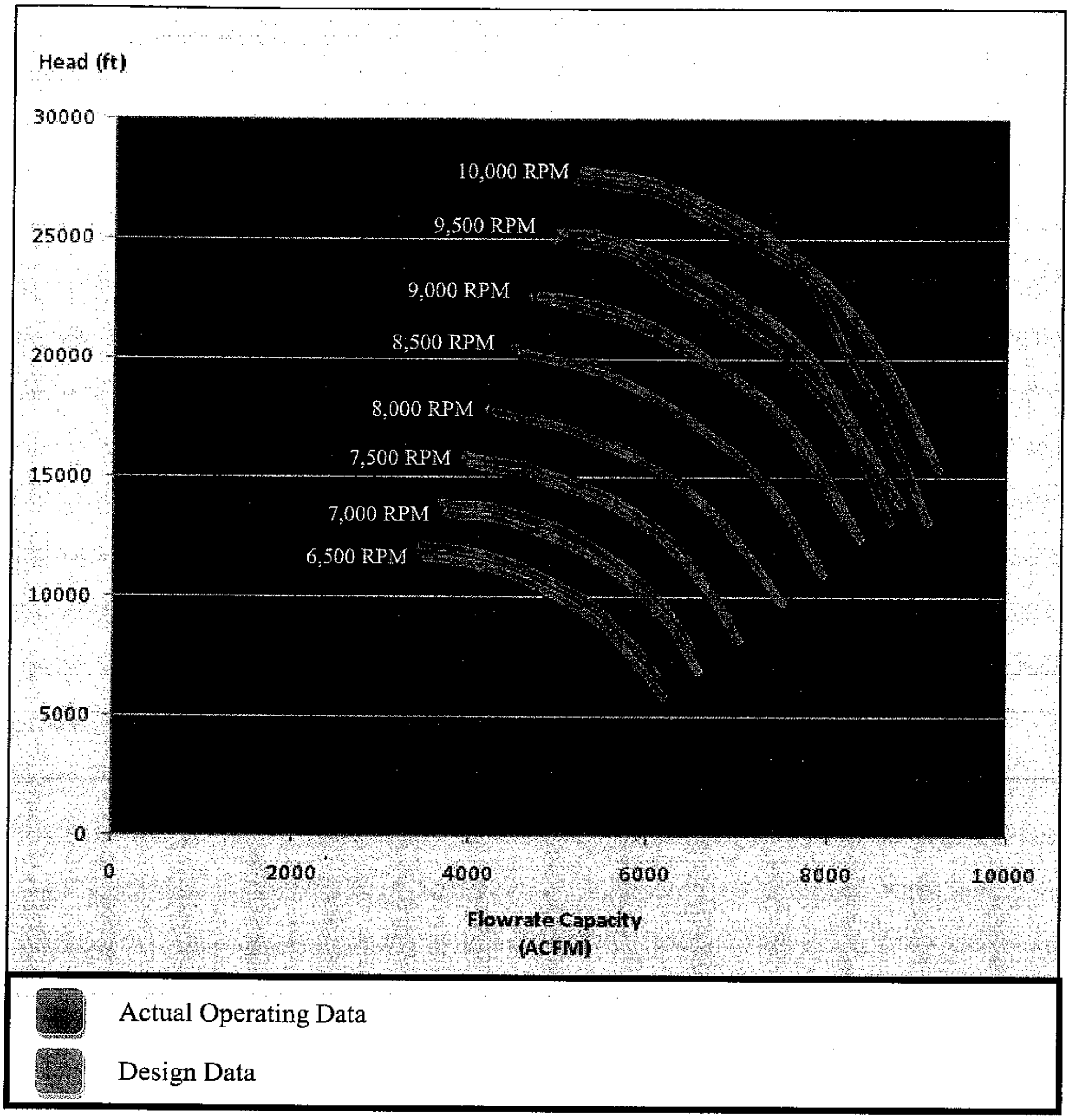


Figure 4.6 : Comparison of the two performance curves from Figure 4.1 and Figure 4.2. Green curves are the Design Data while curves in Orange are the Actual Operating Data

As shown in Figure 4.6, there are slight differences between the green curves (design data) and the orange curves (actual operating data). These differences are not much noticeable for the middle curves where the speed of the centrifugal compressor is around 8000 RPM or operating nearby the 100% of the compressor speed. The differences are much clearer for the top curves and the bottom curves.

There are few variables and conditions that lead to such differences of these two (2) data types. These differences are not desirable and considered as drop of performance. The reasons that lead to the performance drop are may due to mechanical failure such as fouling inside the compressor, leakage of the system, high friction between the devices and etc.

Thus, if the operators intend to run the compressor at the high compressor speed, some modifications should be made in order to obtain a high efficiency. They are required either to increase the compressor speed at the same flowrate, or increase the discharge pressure to obtain a higher Polytrophic Head and eliminate any mechanical failures and etc.

5.1.2 Compressor Efficiency versus Flowrate

The other two graphs in the previous chapter represent the centrifugal compressor efficiency for the Design Point and Actual Operating. From the Design Point Flowrate values, the operators are able to obtain the readings for the Actual Operating Point. The Compressor Efficiency basically is derived from the Temperature Readings and Pressure Ratio of the centrifugal compressor as can be seen in Equation 3 in page 12.

There are number of curves in each of the figure, which represents the speed of the compressor. The lowest curve represents the lowest speed which is running around 6500 RPM and the highest curve represents the highest compressor speed which is around 10,000 RPM. The lowest curves for both figures (Figure 4.1 and 4.2) have only 8 points and these numbers of points increase as the compressor speed increase. i.e. The second, third and fourth (from bottom) curves for each data have 9 points in each curve, and the rest have 10 points.

Taken as a whole, the two graphs are showing a similar behavior and data ranged. Apparently, we can see a same characteristic / behavior of the curves which are; a slope-down curve as shown in figure below:

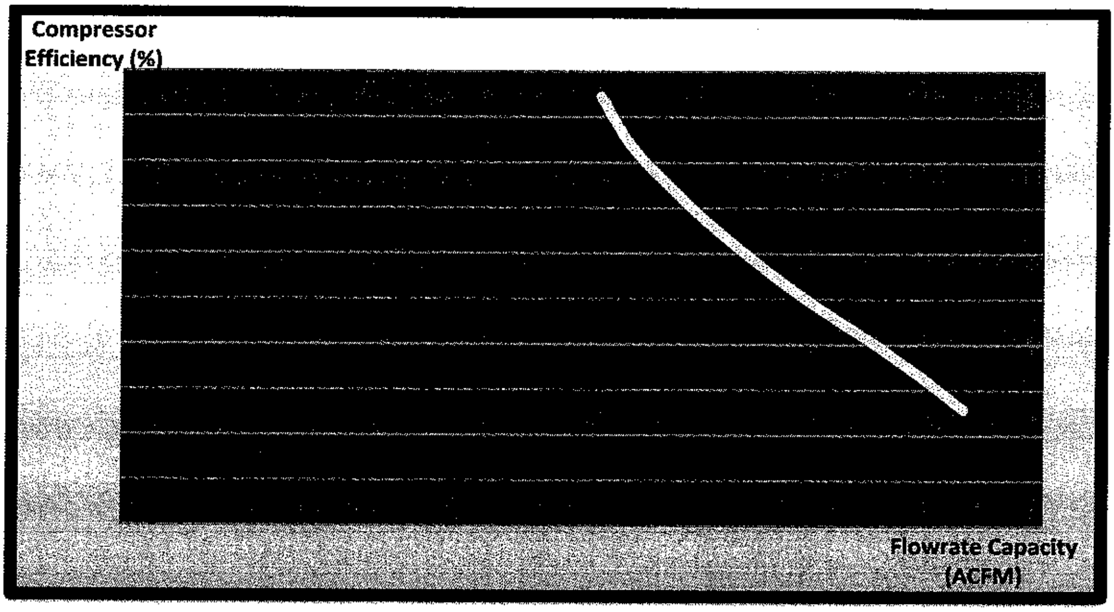


Figure 4.7 : Graphs from Figure 4.3 & 4.4 are showing the similar behavior curve which is a non-linear slope-in curve.

From those two (2) figures as well, we can conclude that as the flowrate increases the compressor efficiency of the compressor drops. Another thing that can be seen here is that as the compressor speed increases the compressor efficiency increases for the same value of the flowrate.

CONCLUSION

By using the program designed by the author, it provides the basic necessary evaluation of centrifugal compressor by showing the operator at which point or condition does the problem occurs. The operator then can check for any failure that brings to the differences of the performance curves evaluated from the program. The differences of the performance curves are often referred as performance drop of the centrifugal compressor. Next, the operator can perform any action to remedy the performance drop and assure the centrifugal compressor is operating at the highest efficiency which is closely related to the fuel consumption of the centrifugal compressor driver. Therefore, consistent check-up of the centrifugal compressor should always be made in order to maintain a high-efficiency of the centrifugal compressor performance. This is to avoid the increase of fuel-consumption and thus affecting the profits made. Two data types are required to make a performance check. The Design Point where usually obtained from the compressor manufacturer and the Actual Operating Data where is obtained from the operator of the centrifugal compressor. These two (2) types of data are then compared to each other to see any bid dissimilarities between them. Any dissimilarity in the Performance Curve of the Actual Operating Data to the Performance Curve of the Design Data shows that the centrifugal gas compressor is not running at the desired point at the particular compressor speed and flowrate capacity. The operator is then able to make any modification or changes to the centrifugal compressor which will relocate the point of dissimilarities of the curve to the desired point as in the Design Data's performance curve. The said spreadsheet program can be used by any company with the permission and approval of the university.

RECOMMENDATIONS

In order to improve the program, several things should be made. The LabView software has the capability to run a real-time assessment of any device. By connecting the program from a computer to the centrifugal gas compressor, the operator will be able to run the assessment continuously for a quick detection of performance drop. This will surely enhanced the assessment mode of the centrifugal gas compressor. The user can as well perform real-time thermodynamic analysis on the compressor by using this software.

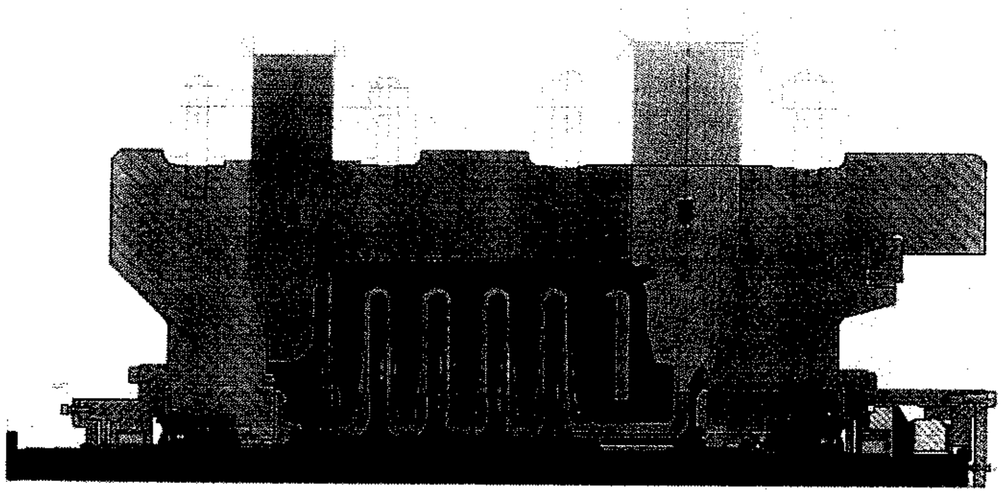
This program however, requires the operators to have Microsoft Excel installed into their computer in order to run it. Thus, the other improvement that can be made is using Microsoft Visual Basic to create a similar program. This is because Microsoft Visual Basic can create a standalone / independent program without any Microsoft products installed on the user's computer. Thus it can be run by any computer which is used to perform the assessment.

REFERENCES

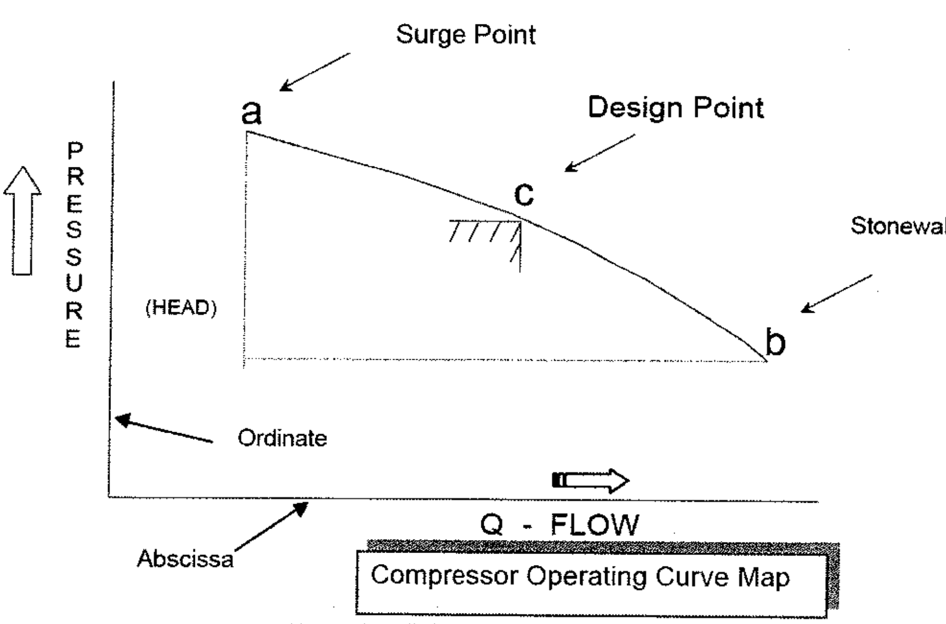
1. Brown, Royce N, 1997, "Compressor Selection and Sizing," Butterworth-Heinemen, the United States of America.
2. Scott Golden, Scott A. Fulton and Daryl W. Hanson, 2002, "Petroleum Technology Quarterly", *Process Consulting Services Inc., Houston, Texas.*
3. Scott Golden, Scott A. Fulton and Daryl W. Hanson, 2002, "Understanding Centrifugal Compressor Performance in a Connected Process System" Petroleum Technology Quarterly, *Process Consulting Services Inc., Houston, Texas.*
4. Rolls Royce, Technical Training, 2008, www.**rolls-royce**.com .
5. Rick Brown & Kevin Rahman, Pasific Gas and Electric Corporation, Turbine / Compressor Performance Monitoring Software and Flow Capacity.
6. Dresser Rand: Compressor Training, 2008, www.dresser-rand.com, info@dresser-rand.com.
7. Syuieb Ali, Centrifugal Compressor, Basic and Understanding, 2006, PETRONAS Carigali Sdn Bhd (PCSB)
8. Ing. Jiří Oldřich, CSc, 2004, Variable Composition Gas Centrifugal Compressor Antisurge Protection, Klečákova Praha, Czech Republic

APPENDICES

I. Anatomy of Centrifugal Compressor (Rolls Royce Training, 2008)



II. Operating at Design Point (Dresser Rand Training, 2008)



III. Critical Literature Review

No	*Author & Title of Paper*	*Scope of Mathematical Model*	*Approach*	*Discussion*
A	Syuieb Ali, Centrifugal Compressor, Basic and Understanding, 2006, PETRONAS Carigali Sdn Bhd (PCSB)	Polytrophic Head, Isentropic Head	$H_{poly}[{ft.lb_f}/{lb_m}] = 53.3Z_{avg}\left(\frac{T_s}{SG}\right)\left(\frac{k \times n_p}{k-1}\right)\left\|\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{kn_p}} - 1\right\|$ $H_{isen}[{ft.lb_f}/{lb_m}] = 53.3Z_{avg}\left(\frac{T_s}{SG}\right)\left(\frac{k}{k-1}\right)\left\|\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right\|$ Where Z_{avg} is average compressibility factor = $(Z_s + Z_d)/2$ T_s is the Suction Temperature (°R) P_d is the Discharge Pressure (*psia*) SG is the specific gravity of the gas = $\frac{\rho_{gas}}{\rho_{H_2O}}$ k is the ratio of the specific heat = $\frac{c_p}{c_v}$	Required a lot of information gathering, Moderate calculations difficulty, Accurate result evaluation

No	*Author & Title of Paper*	*Scope*	*Approach*	*Discussion*
B	Rolls Royce Technical Training	Polytrophic Head	$$H = ZRT_s \times \frac{\left[\left(\frac{P_d}{P_s}\right)^{\frac{(k-1)}{k}} - 1\right]}{\frac{k-1}{k} \times MW}$$ Where Z is the Compressibility Factor R is the Universal Gas Constant T_s is the Suction Temperature (°R) P_d is the Discharge Pressure in (*psia*) MW is the gas mole weight k is the ratio of the specific heat = $\frac{c_p}{c_v}$	Less data required, Basic calculations Difficulty, Acceptable result of calculations

No	Author & Title of Paper	Scope	Approach	Discussion
C	Dresser Rand: Compressor Training, www.dresser-rand.com, info@dresser-rand.com.	Polytrophic Head, Polytrophic Efficiency	Head $[{}^{ft.lb_f}/_{lb_m}]$, $H = ZRT_s \times \left(\frac{\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k-\eta}} - 1}{\left(\frac{k-1}{k-\eta}\right)} \right)$ Polytropic Efficiency, $\eta_p = \left(\frac{k-1}{k}\right) \times \left(\frac{\log {}^{P_d}/_{P_s}}{\log {}^{T_d}/_{T_s}}\right)$ Where; Z is the Compressibility Factor R is the Universal Gas Constant = $\frac{1545\ ft.lbf/lbmol.^{\circ}R}{MW}$ T_s is the Suction Temperature (°R) k is the ratio of the specific heat = $\frac{c_p}{c_v}$ η is the polytrophic index	Less data required, Basic calculations Difficulty, Few conversions needed, Strong result of calculations

No	*Author & Title of Paper*	*Scope*	*Approach*	*Discussion*
D	Rick Brown & Kevin Rahman, Pacific Gas and Electric Corporation, Turbine / Compressor Performance Monitoring Software and Flow Capacity	Isentropic Head, Volumetric flowrate, Compressor Efficiency	$H_{isen}[{ft.lb_f}/{lb_m}] = ZRT_s \times \frac{\left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right]}{\frac{k-1}{k}}$ $ACFM = \frac{14.73 \times Q \times ZT_s}{520 \times Ps \times 0.00144}$ $\eta = \left[\frac{T_s + 460}{T_d - T_s}\right] \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right]$ Where; Z is the Compressibility Factor, $Z = \frac{Pv}{RT}$ T_s is the Suction Temperature in (°R) P_d is the Discharge Pressure in (*psia*) Q is the unit flow in MMcfd $R = 91.3 = \frac{1545\ ft.lbf/lbmol.^\circ R}{S.G. \times 28.97}$	Less data required, Basic calculations Difficulty, Acceptable result of calculations

No	*Author & Title of Paper*	*Scope*	*Approach*	*Discussion*
E	Scott Golden, Scott A. Fulton & Daryl W. Hanson; Understanding Centrifugal Compressor Performance in a Connected Process System; Process Consulting Services Inc., Houston, Texas, U.S.A	Polytrophic Head	$H_{poly}[ft] = \frac{1,545}{MW} Z_{avg} T_s \times \left(\frac{k}{k-1}\right) \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right]$ Where Z_{avg} is average compressibility factor = $(Z_s + Z_d)/2$ T_s is the Suction Temperature (°R) P_d is the Discharge Pressure (*psia*) k is the ratio of the specific heat = $\frac{c_p}{c_v}$ MW is the molecular weight k is the ratio of the specific heat = $\frac{c_p}{c_v}$	Less data required, Basic calculations Difficulty, Acceptable result of calculations

IV. A. Example of Data-sheet

	Technical Specification COMPRESSOR "THERMODYNAMIC DATA"	UAN: 01-0793 TON / CODE: 02-K001 Page: 11

X No	DESIGNATION	DIM	DIM				
X1	Operating point	—	—	NORMAL (LEANEST)			
2	Process stage	—	—	1	2	3	4
3	Casing arrangement	—	—	LP	LP	HP	HP
4		—	—				
X5	Medium	—	—	AIR			
6	Volume flow at 1.013 bar / 273 K DRY		Nm³/h	38567	—	—	37.218.4
7	Inlet volume flow ☐ dry ☒ wet		m³/h	45930	21980	7760	4446
8	Inlet mass flow ☐ dry ☒ wet	kg/h		51020	—	50300	48540
X9	Outlet mass flow ☒ dry ☐ wet	Kmol/h					1.660.27
X10	Inlet pressure abs.		bar	0.9955	2.14	5.75	10.32
X11	Outlet pressure, after COMPRESSOR abs.		bar	2.27	5.88	10.45	35.3
X12	Inlet temperature		°C	55	42	47	55
13	Outlet temperature, after COMPRESSOR		°C	139	122	110	254
14	Pressure ratio p/p	—	—	2.28	2.75	1.82	3.42
15	Pressure losses (COOLER, PIPING, SEPARATOR)		bar	0.13	0.13	0.13	
16	Blow-off vol. flow at 1.013 bar / 273 K		Nm³/h				
X17	REL. HUMIDITY (SUCTION)		%	40.1			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
23	Extraction flow ☒ dry		m³/h	—	—	159	—
24	Extraction pressure (10-12 bar) abs.		bar	—	—	10.3	—
25	Extraction temperature		°C	—	—	55	—
X26	EXTRACTION FLOW & DRY		kmol/h			60.2	
X27	EXTRACTION FLOW & DRY		Nm³/h			1349	
28							
[illegible]	Overall specific work ☐ ☒ ☐		kJ/kg	3.70 X 10⁵			
[illegible]	Overall efficiency ☐ ☒ ☐		%	60.5 (INTERNAL EFF. WITHOUT M.L.)			
[illegible]	Spec. work per stage ☐ ☐ ☒		kJ/kg	85.790	112.500	61.020	149.480
[illegible]	Efficiency per stage ☐ ☐ ☒		%	79	77	74	72
[illegible]	Total efficiency at coupling		%	59.2 (ISOTHERM EFF. WITH M.L.)			
[illegible]	Speed		min⁻¹	7960		10397	
[illegible]	Speed range		min⁻¹				
[illegible]	Speed range		%	80 ÷ 105			
[illegible]	Surge limit at p/p const. 2)		%	APPROX. 65			
[illegible]							
[illegible]	Total power consumption 3)		kW	7570			
[illegible]	Power consumption per STAGE		kW	1543	2080	1145	2802
[illegible]	Mechanical losses		kW	97			
[illegible]	Gear losses (IF APPLICABLE)		kW	80			
[illegible]							
[illegible]	Power recommended for driver		kW				
[illegible]							
[illegible]	Rotation of compressor viewed from TURBINE	☒ cw (clockwise)		☐ ccw (counterclockwise)			
[illegible]	Remarks						

IV) B. Example of Data sheet

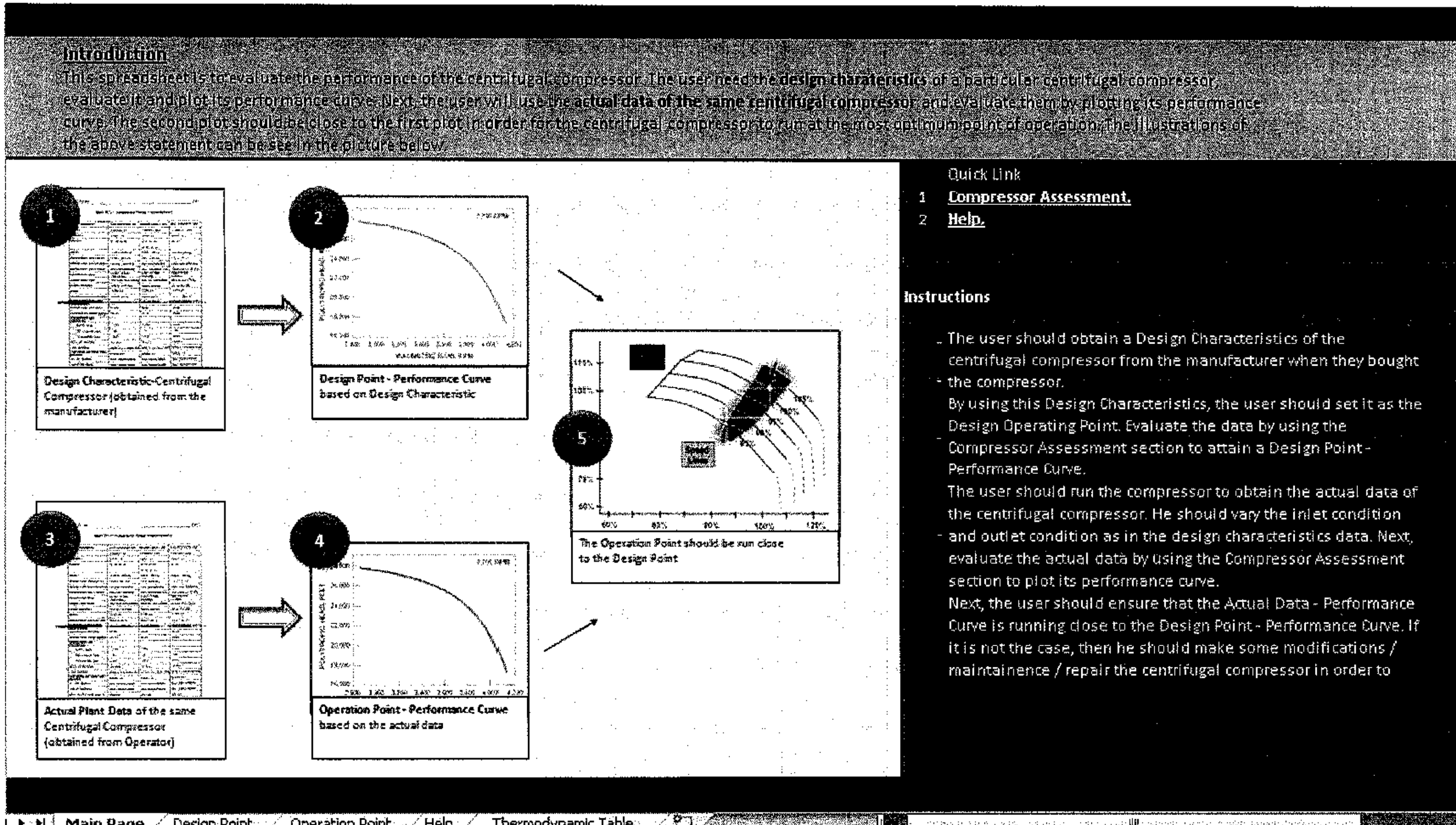
Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

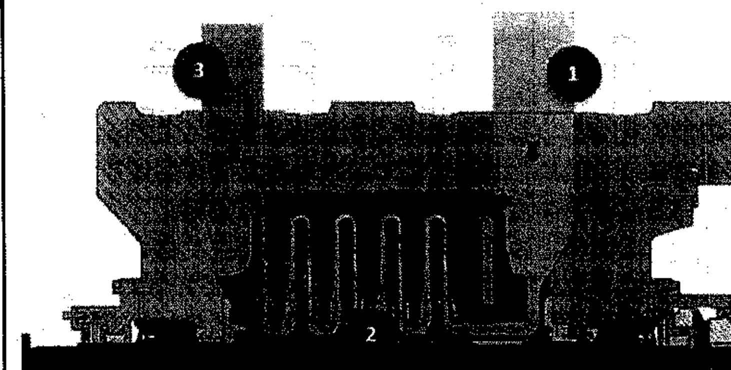
X	No	DESIGNATION	DIM	DIM		
			–	–		
			–	–		HP
	3	Casing arrangement	–	–	HORIZONTAL	
			–	–	SEE PROCESS ARRANGEMENT PAGE 14a	
X	5	Medium	–	–	NH_3	
	6	Volume flow at 1.013 bar / 273 K DRY		m^3/h	42760	50130
	7	Inlet volume flow ☒ dry ☐ wet		m^3/h	12270	6507
		Inlet mass flow ☒ dry ☐ wet				
		Outlet mass flow ☒ dry ☐ wet		kg/h	32 500	38 400
		Inlet pressure abs.		bar	3.43	8.0
		Outlet pressure, after COMPR. abs.		bar	8.25	18.1
X	12	Inlet temperature,		°C	0	22
	13	Outlet temperature, after COMPR.		°C	81	100
	14	Pressure ratio p/p	–	–	2.41	2.26
X	15	Pressure losses		bar	0.25	
	16	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h		
	17					
	18					
	19					
	20	Intermediate inlet flow		m^3/h		
	21	Intermediate inlet pressure abs.		bar		
	22	Intermediate inlet temperature		°C		
	23	Extraction flow ☐ dry		m^3/h		
	24	Extraction pressure abs.		bar		
	25	Extraction temperature		°C		
	26					
	27					
	28					
	29	Overall specific work ☐ Y_S ☒ Y_T ☐ Y_{pol} 1)		kJ/kg	211.6	
	30	Overall efficiency ☐ η_S ☒ η_T ☐ η_{pol} 1)		%	66	
	31	Spec. work per stage ☐ Y_S ☐ Y_T ☒ Y_{pol} 1)		kJ/kg	129.200	125.600
	32	Efficiency per stage ☐ η_S ☐ η_T ☒ η_{pol} 1)		%	75	74
	33	Total efficiency at coupling		%	74	
	34	Speed		min^{-1}	10800	
	35	Speed range		min^{-1}	8445 - 11823	
				%	75	
				%	63	
	39	Total power consumption 3)		kW	3350	
	40	Power consumption per STAGE		kW	1552	1798
	41	Mechanical losses		kW	88	
	42	Gear losses		kW		
	43					
	44			kW		

V. A. Gas Compressor Performance Assessment Program – Main Section



B. Gas Compressor Performance Assessment Program – Help Section

Symbol	Unit	Descriptions
P_s	barg	Suction Pressure in bar (gauge)
	bara	Suction Pressure in bar (absolute)
	psig	Suction Pressure in psi (gauge)
	Pa	Suction Pressure in Pascal
T_s	°C	Suction Temperature in Celcius
	°F	Suction Temperature in Fahrenheit
	K	Suction Temperature in Kelvin
v (from table)	m³/kg	Specific Volume
c_v (from table)	kJ/kg.K	Specific Heat at constant volume
c_p (from table)	kJ/kg.K	Specific Heat at constant pressure
MW	g/mol	Molecular weight
k	-	Specific Heat ratio
(k-1)/k	-	-
R	ft-lb / (lbmol · °R)	Universal Gas Constant in English Unit
$\overline{R}$	J/kg.K	Universal Gas Constant Metric Unit
MW	g/mol	Molecular weight
q (ft^3/min)	ft³/min	
T_d (°C)	°C	Suction Temperature in Celcius
T_d (°F)	°F	Suction Temperature in Fahrenheit
P_d (barg)	barg	Suction Pressure in bar (gauge)



1. Suction Nozzle
2. Compresion Process
3. Discharge Nozzle

$$H_{poly}[ft] = \frac{1{,}545}{MW} Z_{avg} T_s \times \left(\frac{k}{k-1}\right) \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right]$$

Back to Main Page.

Compressor Assessment.

$$\eta_{isen}[\%] = \left[\frac{T_s + 460}{T_d - T_s}\right] \times \left[\left(\frac{P_d}{P_s}\right)^{\frac{k-1}{k}} - 1\right]$$

Main Page | Design Point | Operation Point | **Help** | Thermodynamic Table

C. Gas Compressor Performance Assessment Program - Assessment Section

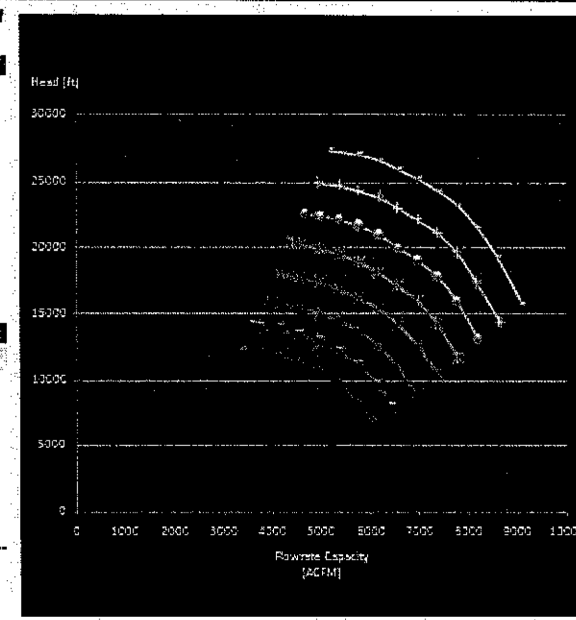
i. Data Input Section

This section will calculate the Polytrophic Head vs the Flow rate. The graph on the right-hand side shows the performance curve of the input data. Boxes in white are the inputs required.

Gas Properties

Atm Pressure (*barg*)	1.01	υ (from table)	0.3083
P_s(*barg*)	3.43	c_v (from table	1.66
P_s(*bara*)	4.4	c_p (from table	2.25
P_s(*psig*)	49.75	MW	17.03
P_s(*Pa*)	444325	k	1.36
T_s(°C)	20.00	(k-1)/k	0.26
T_s(°F)	68.00	R	90.72
T_s(K)	293.15	$\bar{R}$	488.20
		Z	0.96

Performance Curve



Calculations

Point	q (ft³/min)	T_d(°C)	T_d(°F)	P_d(*barg*)	P_d(*psig*)	H_{poly}(ft)	P_r	η_{comp}(%)
1	3450	100.0	212.0	4.7	68.7	**12198**	1.3	25.6
2	3800	110.0	230.0	4.7	68.5	**12097**	1.3	22.6
3	4200	120.0	248.0	4.7	68.0	**11795**	1.3	19.8
4	4600	130.0	266.0	4.6	67.1	**11291**	1.3	17.3
5	5000	140.0	284.0	4.5	66.0	**10585**	1.3	14.8
6	5400	150.0	302.0	4.4	64.5	**9677**	1.2	12.5
7	5800	160.0	320.0	4.3	62.0	**8165**	1.2	9.8
8	6100	170.0	338.0	4.1	59.9	**6854**	1.2	7.7
9	3690	100.0	212.0	4.9	71.8	**14013**	1.3	29.4
10	3800	110.0	230.0	4.9	71.6	**13913**	1.3	26.0
11	4200	120.0	248.0	4.9	71.4	**13812**	1.3	23.2
12	4600	130.0	266.0	4.9	70.7	**13408**	1.3	20.5
13	5000	140.0	284.0	4.8	69.9	**12904**	1.3	18.1
14	5400	150.0	302.0	4.7	68.5	**12097**	1.3	15.6
15	5800	160.0	320.0	4.6	66.8	**11089**	1.3	13.3
16	6200	170.0	338.0	4.4	64.3	**9576**	1.2	10.7
17	6490	180.0	356.0	4.2	61.5	**7862**	1.2	8.3
18	3950	100.0	212.0	5.2	75.2	**15930**	1.4	33.5
19	4200	110.0	230.0	5.2	74.8	**15728**	1.4	29.4
20	4600	120.0	248.0	5.1	74.5	**15526**	1.4	26.1

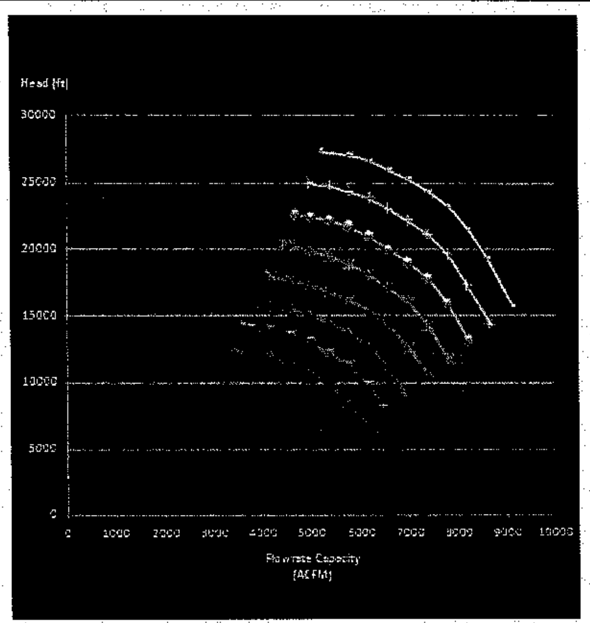
Main Page | **Design Point** | Operation Point | Help | Thermodynamic Table

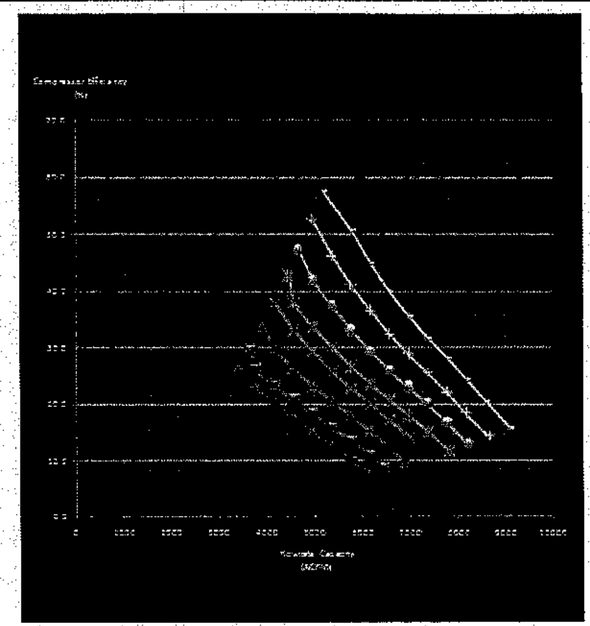
ii. Performance Curves Plotter

shows the performance curve of

mance Curve

P_r	η_{Isen} (%)
1.3	25.6
1.3	22.6
1.3	19.8
1.3	17.3
1.3	14.8
1.2	12.5
1.2	9.8
1.2	7.7
1.3	29.4
1.3	26.0
1.3	23.2
1.3	20.5
1.3	18.1
1.3	15.6
1.3	13.3
1.2	10.7
1.2	8.3
1.4	33.5
1.4	29.4
1.4	26.1





Main Page | Design Point | Operation Point | Help | Thermodynamic Table

VI. a. Properties of various common gases:

THERMODYNAMICS

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, M kg/kmol	Gas constant, R kJ/kg · K*	Critical-point properties: Temperature, K	Critical-point properties: Pressure, MPa	Critical-point properties: Volume, m^3/kmol
Air	—	28.97	0.2870	132.5	3.77	0.0883
Ammonia	NH_3	17.03	0.4882	405.5	11.28	0.0724
Argon	Ar	39.948	0.2081	151	4.86	0.0749
Benzene	C_6H_6	78.115	0.1064	562	4.92	0.2603
Bromine	Br_2	159.808	0.0520	584	10.34	0.1355
n-Butane	C_4H_{10}	58.124	0.1430	425.2	3.80	0.2547
Carbon dioxide	CO_2	44.01	0.1889	304.2	7.39	0.0943
Carbon monoxide	CO	28.011	0.2968	133	3.50	0.0930
Carbon tetrachloride	CCl_4	153.82	0.05405	556.4	4.56	0.2759
Chlorine	Cl_2	70.906	0.1173	417	7.71	0.1242
Chloroform	$CHCl_3$	119.38	0.06964	536.6	5.47	0.2403
Dichlorodifluoromethane (R-12)	CCl_2F_2	120.91	0.06876	384.7	4.01	0.2179
Dichlorofluoromethane (R-21)	$CHCl_2F$	102.92	0.08078	451.7	5.17	0.1973
Ethane	C_2H_6	30.070	0.2765	305.5	4.48	0.1480
Ethyl alcohol	C_2H_5OH	46.07	0.1805	516	6.38	0.1673
Ethylene	C_2H_4	28.054	0.2964	282.4	5.12	0.1242
Helium	He	4.003	2.0769	5.3	0.23	0.0578
n-Hexane	C_6H_{14}	86.179	0.09647	507.9	3.03	0.3677
Hydrogen (normal)	H_2	2.016	4.1240	33.3	1.30	0.0649
Krypton	Kr	83.80	0.09921	209.4	5.50	0.0924
Methane	CH_4	16.043	0.5182	191.1	4.64	0.0993
Methyl alcohol	CH_3OH	32.042	0.2595	513.2	7.95	0.1180
Methyl chloride	CH_3Cl	50.488	0.1647	416.3	6.68	0.1430
Neon	Ne	20.183	0.4119	44.5	2.73	[illegible]
Nitrogen	N_2	28.013	0.2968	126.2	3.39	0.0899
Nitrous oxide	N_2O	44.013	0.1889	309.7	7.27	[illegible]
Oxygen	O_2	31.999	0.2598	154.8	5.08	[illegible]
Propane	C_3H_8	44.097	0.1885	370	4.26	[illegible]
Propylene	C_3H_6	42.081	0.1976	365	4.62	[illegible]
Sulfur dioxide	SO_2	64.063	0.1298	430.7	7.88	[illegible]
Tetrafluoroethane (R-134a)	CF_3CH_2F	102.03	0.08149	374.3	4.067	[illegible]
Trichlorofluoromethane (R-11)	CCl_3F	137.37	0.06052	471.2	4.38	[illegible]
Water	H_2O	18.015	0.4615	647.3	22.09	[illegible]
Xenon	Xe	131.30	0.06332	289.8	5.88	[illegible]

*The unit kJ/kg · K is equivalent to kPa · m^3/kg · K. The gas constant is calculated from $R = R_u/M$, where R_u = 8.314 kJ/kmol · K and M is the [illegible]

Source: K. A. Kobe and R. E. Lynn, Jr., *Chemical Review* 52 (1953), pp. 117–236; and ASHRAE, *Handbook of Fundamentals* (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1993), pp. 16.4 and 36.1.

a. Properties of various common gases:

TABLE A-2

Ideal-gas specific heats of various common gases

(a) At 300 K

Gas	Formula	Gas constant, R kJ/kg · K	C_p kJ/kg · K	C_v kJ/kg · K	k
Air	—	0.2870	1.005	0.718	1.400
Argon	Ar	0.2081	0.5203	0.3122	1.667
Butane	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Carbon dioxide	CO_2	0.1889	0.846	0.657	1.289
Carbon monoxide	CO	0.2968	1.040	0.744	1.400
Ethane	C_2H_6	0.2765	1.7662	1.4897	1.186
Ethylene	C_2H_4	0.2964	1.5482	1.2518	1.237
Helium	He	2.0769	5.1926	3.1156	1.667
Hydrogen	H_2	4.1240	14.307	10.183	1.405
Methane	CH_4	0.5182	2.2537	1.7354	1.299
Neon	Ne	0.4119	1.0299	0.6179	1.667
Nitrogen	N_2	0.2968	1.039	0.743	1.400
Octane	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxygen	O_2	0.2598	0.918	0.658	1.395
Propane	C_3H_8	0.1885	1.6794	1.4909	1.126
Steam	H_2O	0.4615	1.8723	1.4108	1.327

TABLE A-2

Ideal-gas specific heats of various common gases (*Continued*)

(b) At various temperatures

Temperature, K	C_p kJ/kg · K	C_v kJ/kg · K	k	C_p kJ/kg · K	C_v kJ/kg · K	k	C_p kJ/kg · K	C_v kJ/kg · K	k
	Air			*Carbon dioxide, CO_2*			*Carbon monoxide, CO*		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335
	Hydrogen, H_2			*Nitrogen, N_2*			*Oxygen, O_2*		
250	14.051	9.927	1.416	1.039	0.742	1.400	0.913	0.653	1.398
300	14.307	10.183	1.405	1.039	0.743	1.400	0.918	0.658	1.395
350	14.427	10.302	1.400	1.041	0.744	1.399	0.928	0.668	1.389
400	14.476	10.352	1.398	1.044	0.747	1.397	0.941	0.681	1.382
450	14.501	10.377	1.398	1.049	0.752	1.395	0.956	0.696	1.373
500	14.513	10.389	1.397	1.056	0.759	1.391	0.972	0.712	1.365
550	14.530	10.405	1.396	1.065	0.768	1.387	0.988	0.728	[illegible]
600	14.546	10.422	1.395	1.075	0.778	1.382	1.003	0.743	1.353
650	14.571	10.447	1.395	1.086	0.789	1.376	1.017	0.758	[illegible]
700	14.604	10.480	1.394	1.098	0.801	1.371	1.031	0.771	[illegible]
750	14.645	10.521	1.392	1.110	0.813	1.365	1.043	0.783	[illegible]
800	14.695	10.570	1.390	1.121	0.825	1.360	1.054	0.794	[illegible]
900	14.822	10.698	1.385	1.145	0.849	1.349	1.074	0.814	[illegible]
1000	14.983	10.859	1.380	1.167	0.870	1.341	1.090	0.830	[illegible]

Source: Kenneth Wark, *Thermodynamics,* 4th ed. (New York: McGraw-Hill, 1983), p. 783, Table A-4M. Originally published in *Tables of Thermal Properties of Gases,* NBS Circular 564, 1955.

VII. The Plant Data Obtained from PETRONAS Fertilizer, Bintulu

a. Design Point Data

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

UAN

TON / CODE

Page

X No	DESIGNATION	DIM	DIM				
X 1	Operating point	—	—				
X 2	Process stage	—	—				
X 3	Casing arrangement	—	—	1	2	3	4
4		—	—	LP	LP	LP	LP
X 5	Medium	—	—	NH3			
X 6	Volume flow at 1.013 bar / 273 K, DRY		Nm³/h	39547	—	—	39218 →
X 7	Inlet volume flow ☐ dry ☒ wet		m³/h	5867	6436	7735	7875
X 8	Inlet mass flow ☐ dry ☒ wet	kg/h					
X 9	Outlet mass flow ☒ dry ☐ wet	kmol/h					
X 10	Inlet pressure abs.		bar	4.4920	4.443	4.443	4.443
X 11	Outlet pressure, after COMPRESSOR abs.		bar	5.743	5.799	5.763	5.443
X 12	Inlet temperature		°C	20	20	76	76
X 13	Outlet temperature, after COMPRESSOR		°C	160	160	132	132
X 14	Pressure ratio p/p	—	—				
X 15	Pressure losses (INLET PIPING SEPARATOR)		bar	0.13	0.13	0.13	
16	Blow-off vol. flow at 1.013 bar / 273 K		Nm³/h				
X 17	REL. HUMIDITY (SUCTION)		%	88.7			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
X 23	Extraction flow ☒ dry		m³/h	—	—	159	—
X 24	Extraction pressure (10–12 bar abs.)		bar	—	—	10.3	—
X 25	Extraction temperature		°C	—	—	35	—
X 26	EXTRACTION FLOW ☒ DRY		kmol/h			60.2	—
X 27	EXTRACTION FLOW ☒ DRY		kg/h			1349	
28							
X 29	Overall specific work		kJ/kg	3.20 x 10²			
X 30	Overall efficiency		%	60.5 (INTERNAL EFF. WITHOUT M.L.)			
X 31	Spec. work per stage		kJ/kg	25,790	112,500	61,020	149,400
X 32	Efficiency per stage		%	79	77	74	72
X 33	Total efficiency at coupling		%	57.2 (ISOTHERM EFF. WITH M.L.)			
X 34	Speed		min⁻¹	7260		10,497	
X 35	Speed range		min⁻¹				
X 36	Speed range		%				
X 37	Surge limit at p/p const. 2)		%	80 – 105			
38			%	APPROX. 65			
X 39	Total power consumption 3)		kW	3270			
X 40	Power consumption per STAGE		kW	1543	2200	1145	7467
X 41	Mechanical losses		kW	27			
X 42	Gear losses (IF APPLICABLE)		kW	30			
43							
X 44	Power recommended for driver		kW				
45							
X 46	Rotation of compressor viewed from DRIVE END			☒ cw (clockwise)		☐ ccw (counterclockwise)	
47	Remarks						
48	1) ☒ A. isentropic compression						
49	☐ A. isothermal compression						
50	☐ polytropic compression						
51	2) related to guarantee point						
52	3) incl. all losses						
53	4) AT COMPRESSOR DISCHARGE)			AFTER CHECK VALVE ESTIMATED ΔP = 0.15 bar			
54	5) AT COMPRESSOR INLET (1.013 bar – 0.03 bar ΔP FOR AIR FILTER			BETWEEN COMP & CHECK VALVE			
55	6) DOWNSTREAM NOZZLES SILENCER AND SUCTION PIPING)						

Rev. | Date | Name | Check | Description — Rev. | Date | Name | Check | Description

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

No.	DESIGNATION	DIM	DIM				
1	Operating point	–	–				
2	Process stage	–	–	5	6	7	8
3	Gas no. arrangement	–	–	[illegible]	[illegible]	[illegible]	[illegible]
4		–	–				
5	Medium	–	–				
6	Volume flow at 1.013 bar / 273 K dry		Nm³/h	40427	—	—	32 072 [illegible]
7	Inlet volume flow ☐ dry ☒ wet		m³/h	[illegible]	[illegible]	[illegible]	[illegible]
8	Inlet mass flow ☐ dry ☐ wet	[illegible]	—				
9	Outlet mass flow ☒ dry ☐ wet	[illegible]	—				
10	Inlet pressure abs.		bar	4.44	4.44	4.44	4.44
11	Outlet pressure, after [illegible] abs.		bar	5.36	5.45	5.27	[illegible]
12	Inlet temperature		°C	20	20	20	20
13	Outlet temperature, after [illegible]		°C	120	[illegible]	[illegible]	[illegible]
14	Pressure ratio	–	–				
15	Pressure losses [illegible]		bar	0.15	—	—	—
16	Blowoff vol. flow at 1.013 bar / 273 K		m³/h				
17	[illegible]		%	[illegible]			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
23	Extraction flow		m³/h	—	—	[illegible]	—
24	Extraction pressure abs.		bar	—	—	[illegible]	—
25	Extraction temperature		°C	—	—	[illegible]	—
26	[illegible] DRY		[illegible]			[illegible]	
27	[illegible] FLOW DRY		[illegible]			[illegible]	
28							
29	Overall specific work		kJ/kg	8.77 X 10⁴			
30	Overall efficiency		%	80.4 (INTERNAL EFF. WITHOUT M.L.)			
31	Spec. work per stage		kJ/kg	[illegible]	[illegible]	[illegible]	[illegible]
32	Efficiency per stage		%	77	77	75	[illegible]
33	Total efficiency at coupling		%	[illegible] (ISOTHERMAL EFF. WITH M.L.)			
34	Speed		min⁻¹	7180		10575	
35	Speed range		min⁻¹	[illegible] – [illegible]		[illegible] – [illegible]	
36	Speed range		%	85 – 105			
37	Surge limit at [illegible]		%	APPROX. 65			
38							
39	Total power consumption		kW	[illegible]			
40	Power consumption per STAGE		kW	[illegible]	[illegible]	[illegible]	[illegible]
41	Mechanical losses		kW	27			
42	Gear losses		kW	[illegible]			
43							
44	Power requirement for driver		kW				
45							
46	Rotation of compressor viewed from [illegible]			☒ cw (clockwise)		☐ ccw (counterclockwise)	
47	Remarks:						
48	1) ☒ = centrifugal compressor						
49	☐ = [illegible] compressor						
50	[illegible]						
51	2) related to guarantee point						
52	3) incl. all losses						
53	[illegible] COMPRESSOR DISCHARGE						
54	[illegible] COMPRESSOR INLET						
55	[illegible] INTER COOLER						

Rev. | Date | Name | Check | Designation | Rev. | Date | Name | Check | Designation

[illegible]

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

No	DESIGNATION	DIM	DIM				
1	Operating point	—	—		[illegible]	[illegible]	
2	Process stage	—	—				
3	Casing arrangement	—	—	[illegible]	[illegible]	[illegible]	[illegible]
4		—	—				
5	Medium	—	—				
6	Volume flow at 1.013 bar / 273 K dry		Nm³/h	40427	—	—	[illegible]
7	Inlet volume flow □ dry ☒ wet		m³/h	[illegible]	7254	10538	[illegible]
8	Inlet mass flow □ dry ☒ wet	[illegible]	—				
9	Outlet mass flow ☒ dry □ wet	[illegible]	—				
10	Inlet pressure abs.		bar	4.44	4.44	4.44	4.44
11	Outlet pressure, after COMPRESSOR abs.		bar	4.22	5.61	5.18	5.62
12	Inlet temperature		°C	20	20	20	20
13	Outlet temperature, after COMPRESSOR		°C	140	150	[illegible]	110
14	Pressure ratio	—	—				
15	Pressure losses [illegible]		bar	0.15	—	—	—
16	Blowoff vol. flow at 1.013 bar / 273 K		[illegible]				
17	REL. HUMIDITY [illegible]		%	[illegible]			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
23	Extraction flow ☒ dry		m³/h	—	—	120	—
24	Extraction pressure [illegible] abs.		bar	—	—	12.41	—
25	Extraction temperature		°C	—	—	52	—
26	EXTRACTION FLOW [illegible]		[illegible]			[illegible]	
27	EXTRACTION FLOW [illegible]		[illegible]			26.2	
28			[illegible]		—	1349	
29	Overall specific work [illegible]		kJ/kg		9.27 x 10⁴		
30	Overall efficiency [illegible]		%	80.4 (INTERNAL EFF. WITHOUT M.L.)			
31	Spec. work per stage [illegible]		kJ/kg	44.320	113.000	51.440	150.400
32	Efficiency per stage [illegible]		%	77	77	75	72
33	Total efficiency at coupling		%	59.1 (ISOTHERMAL EFF. WITH M.L.)			
34	Speed		min⁻¹	7140		15510	
35	Speed range		min⁻¹	5724 – 7512		3250 – 11424	
36	Speed range		%	85 – 105			
37	Surge limit at g.p. [illegible] 2)		%	APPROX. 65			
38							
39	Total power consumption 3)		kW		7995		
40	Power consumption per STAGE		kW	1624	2143	1204	2970
41	Mechanical losses		kW		29		
42	Gear losses		kW		24		
43							
44	Power recommended for driver		kW				
45							
46	Rotation of compressor viewed from DRIVE END			☒ cw (clockwise)		□ ccw counterclockwise	

Remarks:

1) ηs = isentropic compression; ηT = isothermal compression; ηP = polytropic compression

2) related to guarantee point

3) incl. all losses

4) 2nd COMPRESSOR [illegible]

5) 4th COMPRESSOR [illegible]

6) DOWNSTREAM AFTER COOLER

[illegible]

Rev.	Date	Name	Check.	Description	Rev.	Date	Name	Check.	Description

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

UAN
TDN / CODE
Page:

X No	DESIGNATION	DIM	DIM				
X 1	Operating point	—	—				
X 2	Process stage	—	—	27	28	29	30
X 3	Casing arrangement	—	—	LP	LP	LP	LP
4		—	—				
X 5	Medium	—	—		AMB		
X 6	Volume flow at 1.013 bar / 273 K DRY		Nm³/h	29567	—	—	57 212
X 7	Inlet volume flow ☐ dry ☐ wet		m³/h	7193	7275	3495	974
X 8	Inlet mass flow ☐ dry ☒ wet	kg/h	—				
X 9	Outlet mass flow ☒ dry ☐ wet	kmol/h	—				
X 10	Inlet pressure abs.		bar	4.443	4.443	4.443	4.443
X 11	Outlet pressure, after COMPRESSOR abs.		bar	6.45	5.41	6.37	6.29
X 12	Inlet temperature		°C	20	20	26	26
X 13	Outlet temperature, after COMPRESSOR		°C	160	116	122	135
X 14	Pressure ratio	—	—				
X 15	Pressure losses [illegible]		bar	0.13	0.13	0.13	
16	Blow-off vol. flow at 1.013 bar / 273 K		Nm³/h				
X 17	REL. HUMIDITY [illegible]		%	[illegible]			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
X 23	Extraction flow ☒ dry		m³/h	—	—	157	—
X 24	Extraction pressure (10 ÷ 13 bar abs.)		bar	—	—	10.3	—
X 25	Extraction temperature		°C	—	—	55	—
X 26	EXTRACTION FLOW % DRY		[illegible]			40.2	
X 27	EXTRACTION FLOW % DRY		Nm³/h		—	1349	
28							
X 29	Overall specific work ☐ Ys ☒ Yт ☐ Ypol		kJ/kg		3.20 x 10³		
X 30	Overall efficiency ☐ ηs ☒ ηт ☐ ηpol		%	40.5 (INTERNAL EFF. WITHOUT M.L.)			
X 31	Spec. work per stage ☐ Ys ☐ Yт ☒ Ypol		kJ/kg	85.790	117.500	61.020	149.400
X 32	Efficiency per stage ☐ ηs ☐ ηт ☒ ηpol		%	79	77	74	73
X 33	Total efficiency at coupling		%	59.2 (ISOTHERM EFF. WITH M.L.)			
X 34	Speed		min⁻¹	7260		10397	
X 35	Speed range		min⁻¹				
X 36	Speed range		%		80 ÷ 105		
X 37	Surge limit at p/p const. 2)		%		APPROX. 65		
38							
X 39	Total power consumption 3)		kW		7070		
X 40	Power consumption per STAGE		kW	1543	2390	1145	2407
X 41	Mechanical losses		kW		27		
X 42	Gear losses (IF APPLICABLE)		kW		80		
43							
X 44	Power recommended for driver		kW				
45							

46 Rotation of compressor viewed from [illegible] ☒ cw (clockwise) ☐ ccw (counterclockwise)

47 Remarks

48 1) Y ≙ isentropic compression

49 T ≙ isothermal compression

50 pol ≙ polytropic compression

51 2) related to guarantee point

52 3) incl. all losses — AFTER CHECK VALVE ESTIMATED ΔP = 0.15 bar

53 4) AT COMPRESSOR DISCHARGE BETWEEN COMP. & CHECK VALVE

54 5) AT COMPRESSOR INLET [illegible] FOR AIR FILTER

55 5) DOWNSTREAM [illegible] SILENCER AND SUCTION PIPING

Rev. | Date | Name | Check | Description | Rev. | Date | Name | Check | Description

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

UAN

VON / CODE

Page

X	No	DESIGNATION	DIM	DIM				
X	1	Operating point	—	—				
X	2	Process stage	—	—	46	47	48	49
X	3	Casing arrangement	—	—	LP	LP	LP	LP
	4		—	—				
X	5	Medium	—	—		NH3		
X	6	Volume flow at 1.013 bar / 273 K DRY		Nm³/h	29567	—	—	55319
X	7	Inlet volume flow ☐ dry ☒ wet		m³/h	7985	5495	9174	9454
X	8	Inlet mass flow ☐ dry ☒ wet	kg/h	—				
X	9	Outlet mass flow ☒ dry ☐ wet	kmol/h	—				
X	10	Inlet pressure abs.		bar	4.443	4.445	4.445	4.443
X	11	Outlet pressure, after COMPRESSOR abs.		bar	7.05	7.044	4.99	4.92
X	12	Inlet temperature		°C				
X	13	Outlet temperature, after COMPRESSOR		°C	160	170	120	130
X	14	Pressure ratio p/p	—	—				
X	15	Pressure losses (INLET PIPING, SEPARATOR)		bar	0.13	0.13	0.13	
	16	Blow-off vol. flow at 1.013 bar / 273 K		Nm³/h				
X	17	REL. HUMIDITY (SUCTION)		%	40.4			
	18							
	19							
	20	Intermediate inlet flow		m³/h				
	21	Intermediate inlet pressure abs.		bar				
	22	Intermediate inlet temperature		°C				
X	23	Extraction flow ☒ dry		m³/h	—	—	159	—
X	24	Extraction pressure (TO HZ abs.)		bar	—	—	12.3	—
X	25	Extraction temperature		°C	—	—	35	—
X	26	EXTRACTION FLOW ☒ DRY		kmol/h			60.2	
X	27	EXTRACTION FLOW ☒ DRY		Nm³/h			1349	
	28							
X	29	Overall specific work ☐ Ys ☒ Yt ☐ Ypol 1)		kJ/kg	3.20 x 10²			
X	30	Overall efficiency ☐ ηs ☒ ηt ☐ ηpol 1)		%	40.5 (INTERNAL EFF. WITHOUT M.L.)			
X	31	Spec. work per stage ☐ Ys ☐ Yt ☒ Ypol 1)		kJ/kg	25.790	112.500	61.020	149.400
X	32	Efficiency per stage ☐ ηs ☐ ηt ☒ ηpol 1)		%	79	77	74	72
X	33	Total efficiency at coupling		%	52.2 (ISOTHERM EFF. WITH M.L.)			
X	34	Speed		min⁻¹	7060		10397	
X	35	Speed range		min⁻¹				
X	36	Speed range		%	85 ÷ 105			
X	37	Surge limit at p/p const. 2)		%	APPROX. 65			
	38							
X	39	Total power consumption 3)		kW	7570			
X	40	Power consumption per STAGE		kW	1543	2340	1145	2407
X	41	Mechanical losses		kW	57			
X	42	Gear losses (IF APPLICABLE)		kW	80			
	43							
X	44	Power recommended for driver		kW				
	45							

46 Rotation of compressor viewed from DRIVE END ☐ cw (clockwise) ☐ ccw (counterclockwise)

47 Remarks:

48 1) ☐ s: isentropic compression

49 ☐ t: isothermal compression

50 ☐ pol: polytropic compression

51 2) related to guarantee point

52 3) incl. all losses ★ AFTER CHECK VALVE. ESTIMATED ΔP=0.15 bar

53 4) AT COMPRESSOR DISCHARGE) BETWEEN COMP. & CHECK VALVE

54 5) AT COMPRESSOR INLET (1.013 abs. – 0.012 bar FOR AIR FILTER

55 5) DOWNSTREAM INTERCOOLER SILENCER AND SUCTION PIPING)

0 16SEP87 PM

Rev.	Date	Name	Checked	Description	Rev.	Date	Name	Checked	Description

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

No.	DESIGNATION	DIM	DIM				
X 11	Operating point	–	–				
X 12	Process stage	–	–	[illegible]	[illegible]	[illegible]	[illegible]
X 13	Casing arrangement	–	–	[illegible]	[illegible]	[illegible]	[illegible]
14		–	–				
X 15	Medium	–	–				
X 16	Volume flow at 1.013 bar / 273 K [illegible]		[illegible]	40400	—	—	[illegible]
X 17	Inlet volume flow ☐ dry ☐ wet		m^3/h	11285	13112	[illegible]	[illegible]
X 18	Inlet mass flow ☐ dry ☐ wet	[illegible]	—				
X 19	Outlet mass flow ☐ dry ☐ wet	[illegible]	—				
X 20	Inlet pressure abs.		bar	4.44	4.44	4.44	4.44
X 21	Outlet pressure, after [illegible] abs.		bar	1.42	1.30	1.16	5.35
X 22	Inlet temperature		°C	20	20	20	20
X 23	Outlet temperature, after [illegible]		°C	140	150	60	210
X 24	Pressure ratio e/a	–	–				
X 25	Pressure losses [illegible]		bar	0.15	—	—	—
26	Blowoff vol. flow at 1.013 bar / 273 K		m^3/h				
X 27	[illegible]		%	[illegible]			
28							
29							
30	Intermediate inlet flow		m^3/h				
31	Intermediate inlet pressure abs.		bar				
32	Intermediate inlet temperature		°C				
X 33	Extraction flow ☐ dry		m^3/h	—	—	[illegible]	—
X 34	Extraction pressure [illegible] abs.		bar	—	—	10.41	—
X 35	Extraction temperature		°C	—	—	35	—
X 36	EXTRACTION FLOW [illegible]		[illegible]			40.3	
X 37	EXTRACTION FLOW [illegible]		[illegible]			1341	
38							
X 39	Overall specific work [illegible]		[illegible]	3.27 x 10⁴			
X 40	Overall efficiency [illegible]		%	60.4 (INTERNAL EFF. WITHOUT M.L.)			
X 41	Spec. work per stage [illegible]		[illegible]	46.320	113.000	[illegible]	150.300
X 42	Efficiency per stage [illegible]		%	77	77	75	74
X 43	Total efficiency at coupling		%	58.1 (ISOTHERMAL EFF. WITH M.L.)			
X 44	Speed		min^{-1}	9140		10515	
X 45	Speed range		min^{-1}	6224 – 9612		5430 – 11444	
X 46	Speed range		%	85 – 105			
X 47	Surge limit at n = const. 3)		%	APPROX. 65			
48							
X 49	Total power consumption 2)		kW	7993			
X 50	Power consumption per STAGE		kW	1524	3183	1492	2970
X 51	Mechanical losses		kW	23			
X 52	Gear losses		kW	38			
53							
X 54	Power recommended for driver		kW				
55							
X 56	Rotation of compressor viewed from [illegible]			☐ cw (clockwise)		☐ ccw (counterclockwise)	

Remarks

1) 5 = isentropic compression

T = isothermal compression

P = polytropic compression

2) related to guarantee point

3) including losses

1) AT COMPRESSOR DISCHARGE

2) AT COMPRESSOR INLET

3) [illegible]

Rev. | Date | Name (Check) | Description | Rev. | Date | Name (Check) | Description

b. Actual Operating Data

Technical Specification
COMPRESSOR
"THERMODYNAMIC DATA"

UAN

TCN / CODE

Page:

No	DESIGNATION	DIM	DIM				
X 11	Operating point	–	–	NORMAL (HIGHEST)			
X 12	Process stage	–	–	1	2	3	4
X 13	Casing arrangement	–	–	LP	LP		
14		–	–				
X 15	Medium	–	–				
16	Volume flow at 1.013 bar / 273 K		m^3/h	33937	—	—	33522
17	Inlet volume flow ☐ dry ☒ wet		m^3/h	7765	7775	8405	9174
X 18	Inlet mass flow ☒ dry ☐ wet	kmol/h					
X 19	Outlet mass flow ☐ dry ☐ wet	kmol/h					
20	Inlet pressure abs.		bar	4.445	4.445	4.445	4.445
21	Outlet pressure, after [illegible] abs.		bar	5.75	5.75	5.75	5.66
22	Inlet temperature		°C	20	20	26	26
23	Outlet temperature, after [illegible]		°C	160	116	125	130
24	Pressure ratio p_2/p_1	–	–				
25	Pressure losses [illegible]		bar	0.14	—	—	—
26	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h				
X 27	[illegible]		%	22.1			
28							
29							
30	Intermediate inlet flow		m^3/h				
31	Intermediate inlet pressure abs.		bar				
32	Intermediate inlet temperature		°C				
33	Extraction flow ☒ dry		m^3/h	—	—	156	—
34	Extraction pressure [illegible] abs.		bar	—	—	10.81	—
35	Extraction temperature		°C	—	—	35	—
X 36	EXTRACTION FLOW [illegible]		kmol/h			46.2	
X 37	EXTRACTION [illegible]		[illegible]			1349	
38							
39	Overall specific work		kJ/kg	3.20 x 10³			
40	Overall efficiency		%	60.5 (INTERNAL EFF WITHOUT [illegible])			
41	Spec. work per stage		kJ/kg	85.790	117.550	61.070	149.400
42	Efficiency per stage		%	79	77	74	72
43	Total efficiency at coupling		%	54.2 (ISOTHERMAL EFF WITH [illegible])			
44	Speed		min^{-1}	7070		10412	
45	Speed range		min^{-1}	4724 – 7413		7439 – 11664	
X 46	Speed range		%	67 – 105			
47	Surge limit at p/p const. 1)		%	APPROX. 65			
48							
49	Total power consumption 3)		kW	7645			
X 50	Power consumption per stage		kW	1559	2101	1156	2820
51	Mechanical losses		kW	27			
52	Gear losses		kW	80			
53							
54	Power recommended for driver		kW				
55							

Rotation of compressor viewed from [illegible] ☒ cw (clockwise) ☐ ccw (counterclockwise)

Remarks:

1) [illegible] % isentropic compression
[illegible] % isothermal compression
[illegible] % polytropic compression
2) related to guarantee point
3) incl. all losses
4) AT COMPRESSOR DISCHARGE
5) AT COMPRESSOR INLET
6) [illegible]

Rev. | Date | Name | Checked | Description

2282947

UHDE	Technical Specification COMPRESSOR "THERMODYNAMIC DATA"	UAN TON / CODE Page:

X	No	DESIGNATION	DIM	DIM				
X	1	Operating point	–	–				
X	2	Process stage	–	–	52 – 55			
X	3	Casing arrangement	–	–	HORIZONTAL			
X	4		–	–	SEE PROCESS ARRANGEMENT PAGE 4			
X	5	Medium	–	–	NH_3			
X	6	Volume flow at 1.013 bar / 273 K DRY		m^3/h				
X	7	Inlet volume flow ☒ dry ☐ wet		m^3/h	11893	12572	13252	13777
X	8	Inlet mass flow ☒ dry ☐ wet		kg/h				
		Outlet mass flow ☒ dry ☐ wet		kg/h				
		Inlet pressure abs.		bar	4.443	4.443	4.443	4.443
		Outlet pressure, after COMPR. abs.		bar	6.58	6.42	6.17	5.83
X	12	Inlet temperature		°C	20	20	20	20
X	13	Outlet temperature, after COMPR.		°C	160	170	180	190
X	14	Pressure ratio p/p	–	–				
X	15	Pressure losses		bar	0.25			
	16	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h				
	17							
	18							
	19							
	20	Intermediate inlet flow		m^3/h				
	21	Intermediate inlet pressure abs.		bar				
	22	Intermediate inlet temperature		°C				
	23	Extraction flow ☐ dry		m^3/h				
	24	Extraction pressure abs.		bar				
	25	Extraction temperature		°C				
	26							
	27							
	28							
X	29	Overall specific work ☐ Y_S ☒ Y_T ☐ Y_{pol} 1)		kJ/kg	211.6			
X	30	Overall efficiency ☐ η_S ☒ η_T ☐ η_{pol} 1)		%	66			
X	31	Spec. work per stage ☐ Y_S ☐ Y_T ☒ Y_{pol} 1)		kJ/kg	129.200		125.600	
X	32	Efficiency per stage ☐ η_S ☐ η_T ☒ η_{pol} 1)		%	75		74	
X	33	Total efficiency at coupling		%	74			
X	34	Speed		min^{-1}	10800			
X	35	Speed range		min^{-1}	8445 – 11823			
X	36	Speed range		%	75 – 105			
X	37	Surge limit at p/p const. 2)		%	63			
	38							
X	39	Total power consumption 3)		kW	3350			
X	40	Power consumption per STAGE		kW	1552		1798	
X	41	Mechanical losses		kW	88			
	42	Gear losses		kW				
	43							
	44	Power recommended for driver		kW				
	45							
X	46	Rotation of compressor viewed from TURBINE ☒ cw (clockwise) ☐ ccw (counterclockwise)						
	47	Remarks:						
	48	1) S = isentropic compression						
	49	T = isothermal compression						
	50	pol = polytropic compression						
	51	2) related to guarantee point						
	52	3) incl. all losses						
X	53	~~*) PRESSURE MAY VARY ACC. TO DESIGN OF COMPRESSOR~~						
	54	~~HOWEVER VENDOR MUST INFORM UHDE ABOUT ANY VARIATIONS~~						
	55							

6

UP 1006 - 01 Part 1/10 E 9 80 - 02

Rev.	Date	Name	Check.	Description	Rev.	Date	Name	Check.	Description
1	24.11.82	[illegible]		№ 4					
0	[illegible] 82	[illegible]							

c.

[logo]	Technical Specification COMPRESSOR "THERMODYNAMIC DATA"	UAN …ON / CODE Page: [illegible]

X	No	DESIGNATION	DIM	DIM				
X	1	Operating point	–	–				
X	2	Process stage	–	–	62 – 65			
X	3	Casing arrangement	–	–	HORIZONTAL			
X	4		–	–	SEE PROCESS ARRANGEMENT PAGE 4/4			
X	5	Medium	–	–	NH_3			
X	6	Volume flow at 1.013 bar / 273 K DRY		m^3/h				
X	7	Inlet volume flow ☒ dry ☐ wet		m^3/h	12572	13252	13731	14271
X	8	Inlet mass flow ☒ dry ☐ wet		kg/h				
		Outlet mass flow ☒ dry ☐ wet		kg/h				
		Inlet pressure abs.		bar	4.443	4.443	4.443	4.443
		Outlet pressure, after COMPR. abs.		bar	6.75	6.58	6.35	5.86
X	12	Inlet temperature		°C	20	20	20	20
X	13	Outlet temperature, after COMPR.		°C	160	170	180	190
X	14	Pressure ratio p/p	–	–				
X	15	Pressure losses		bar	0.25			
	16	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h				
	17							
	18							
	19							
	20	Intermediate inlet flow		m^3/h				
	21	Intermediate inlet pressure abs.		bar				
	22	Intermediate inlet temperature		°C				
	23	Extraction flow ☐ dry		m^3/h				
	24	Extraction pressure abs.		bar				
	25	Extraction temperature		°C				
	26							
	27							
	28							
X	29	Overall specific work ☐ Y_S ☒ Y_T ☐ Y_{pol} 1)		kJ/kg	211.6			
X	30	Overall efficiency ☐ η_S ☒ η_T ☐ η_{pol} 1)		%	66			
X	31	Spec. work per stage ☐ Y_S ☐ Y_T ☒ Y_{pol} 1)		kJ/kg	129.200		125.600	
X	32	Efficiency per stage ☐ η_S ☐ η_T ☒ η_{pol} 1)		%	75		74	
X	33	Total efficiency at coupling		%	74			
X	34	Speed		min^{-1}	10800			
X	35	Speed range		min^{-1}	8445 – 11823			
X	36	Speed range		%	75 – 105			
X	37	Surge limit at p/p const. 2)		%	63			
	38							
X	39	Total power consumption 3)		kW	3350			
X	40	Power consumption per STAGE		kW	1552		1798	
X	41	Mechanical losses		kW	88			
	42	Gear losses		kW				
	43							
	44	Power recommended for driver		kW				
	45							
X	46	Rotation of compressor viewed from TURBINE			☒ cw (clockwise)		☐ ccw (counterclockwise)	
	47	Remarks:						
	48	1) S ≙ isentropic compression						
	49	T ≙ isothermal compression						
	50	pol ≙ polytropic compression						
	51	2) related to guarantee point						
	52	3) incl. all losses						
X	53	~~*) PRESSURE MAY VARY ACC. TO DESIGN OF COMPRESSOR~~						
	54	~~HOWEVER VENDOR MUST INFORM UHDE ABOUT PRESS. VARIATION~~						
	55							

Rev.	Date	Name	Check.	Description	Rev.	Date	Name	Check.	Description
A	24.11.82	Fm		Nº 4					
0	[illegible]	Ma							

6

UF 1006 - 01 Part 1/10 E 9 80 - 02

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

UAN

TCN / [illegible]

Page

No.	DESIGNATION	DIM	DIM				
1	Operating point	–	–				
2	Process stage	–	–	[illegible]	[illegible]	[illegible]	[illegible]
3	Casing arrangement	–	–	LP	LP	LP	LP
4		–	–				
5	Medium	–	–				
6	Volume flow at 1.013 bar / 273 K		m^3/h	22937	—	—	22522.7
7	Inlet volume flow □ dry ☒ wet		m^3/h	5711	7125	7275	3495
8	Inlet mass flow ☒ dry □ wet	kmol/h					
9	Outlet mass flow ☒ dry □ wet	kmol/h					
10	Inlet pressure abs.		bar	4.445	4.445	4.445	4.445
11	Outlet pressure, after compressor abs.		bar	6.22	6.10	6.06	6.11
12	Inlet temperature		°C	20	20	26	26
13	Outlet temperature, after compressor		°C	110	[illegible]	[illegible]	132
14	Pressure ratio	–	–				
15	Pressure losses [illegible]		bar	0.14	—	—	—
16	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h				
17	Air humidity [illegible]		%	[illegible]			
18							
19							
20	Intermediate inlet flow		m^3/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
23	Extraction flow ☒ dry		m^3/h	—	—	106	—
24	Extraction pressure [illegible] abs.		bar	—	—	10.31	—
25	Extraction temperature		°C	—	—	55	—
26	EXTRACTION FLOW, DRY		kmol/h			56.2	
27	EXTRACTION FLOW, DRY		Nm^3/h			1349	
28							
29	Overall specific work		kJ/kg	3.20 × 10[illegible]			
30	Overall efficiency		%	70.5 (INTERNAL EFF WITHOUT M.L.)			
31	Spec. work per stage		kJ/kg	45,770	112,580	61,020	149,400
32	Efficiency per stage		%	79	77	74	7?
33	Total efficiency at coupling		%	58.2 (ISOTHERMAL EFF WITH M.L.)			
34	Speed		min^{-1}	7071		10412	
35	Speed range		min^{-1}	5724 – 7113		8430 – 11064	
36	Speed range		%	80 – 105			
37	Surge limit at des. cond. 2)		%	APPROX. 75			
38							
39	Total power consumption 3)		kW	7645			
40	Power consumption per stage		kW	1552	2101	1150	2830
41	Mechanical losses		kW	29			
42	Gear losses		kW	80			
43							
44	Power recommended for driver		kW				
45							

Rotation of compressor viewed from [illegible] ☒ cw (clockwise) □ ccw (counterclockwise)

Remarks:

1) [illegible] isentropic compression

isothermal compression

polytropic compression

2) related to guarantee point

3) incl. all losses

4) AT COMPRESSOR DISCHARGE

5) AT COMPRESSOR INLET

6) [illegible]

Rev. | Date | Name | Check. | Designation | Rev. | Date | Name | Check. | Designation

Technical Specification

COMPRESSOR

"THERMODYNAMIC DATA"

No.	Designation	Dim	Dim				
1	Operating point	—	—				
2	Process stage	—	—	[illegible]	27	[illegible]	[illegible]
3	Casing arrangement	—	—	LP	LP	LP	LP
4		—	—				
5	Medium	—	—				
6	Volume flow at 1.013 bar / 273 K		Nm³/h	29937	—	—	22522 *
7	Inlet volume flow ☐ dry ☒ wet		m³/h	7613	7225	3405	2172
8	Inlet mass flow ☒ dry ☐ wet	kmol/h	—				
9	Outlet mass flow ☒ dry ☐ wet	kmol/h	—				
10	Inlet pressure abs.		bar	4.445	4.445	4.445	4.445
11	Outlet pressure, after [illegible] abs.		bar	6.73	6.34	6.76	6.58
12	Inlet temperature		°C	20	20	26	26
13	Outlet temperature, after [illegible]		°C	100	115	125	130
14	Pressure ratio p/p	—	—				
15	Pressure losses [illegible]		bar	0.14	—	—	—
16	Blowoff vol. flow at 1.013 bar / 273 K		Nm³/h				
17	[illegible]		%	[illegible]			
18							
19							
20	Intermediate inlet flow		m³/h				
21	Intermediate inlet pressure abs.		bar				
22	Intermediate inlet temperature		°C				
23	Extraction flow		m³/h	—	—	155	—
24	Extraction pressure abs.		bar	—	—	10.81	—
25	Extraction temperature		°C	—	—	35	—
26	EXTRACTION [illegible]		[illegible]			40.3	
27	EXTRACTION [illegible]		[illegible]			1849	
28							
29	Overall specific work		kJ/kg	3.20 x 10[illegible]			
30	Overall efficiency		%	60.5 (INTERNAL EFF WITHOUT M.L.)			
31	Spec. work per stage		kJ/kg	85,790	112,500	61,020	108,200
32	Efficiency per stage		%	79	77	74	72
33	Total efficiency at coupling		%	59.2 (ISOTHERMAL EFF WITH M.L.)			
34	Speed		min⁻¹	7870		10412	
35	Speed range		min⁻¹	5724 – 7413		7439 – 11064	
36	Speed range		%	80 – 105			
37	Surge limit at o/p const. 2)		%	APPROX. 65			
38							
39	Total power consumption 3)		kW	7645			
40	Power consumption per stage		kW	1552	2101	1150	2290
41	Mechanical losses		kW	27			
42	Gear losses		kW	70			
43							
44	Power recommended for driver		kW				
45							

Rotation of compressor viewed from [illegible] ☒ cw (clockwise) ☐ ccw (counterclockwise)

Remarks:

1) S.E. isentropic compression
T.E. isothermal compression
Pol. E. polytropic compression

2) related to guarantee point

3) incl. all losses

4) AT COMPRESSOR DISCHARGE

5) AT COMPRESSOR INLET

6) [illegible]

Rev. | Date | Name | Check. | Description

282947

Uhde	Technical Specification COMPRESSOR "THERMODYNAMIC DATA"	UAN CON / CODE Page: 12

X	No	DESIGNATION	DIM	DIM				
X	1	Operating point	—	—				
X	2	Process stage	—	—	72 – 75			
	3	Casing arrangement	—	—	HORIZONTAL			
X	4		—	—	SEE PROCESS ARRANGEMENT PAGE 14 a			
X	5	Medium	—	—	NH_3			
	6	Volume flow at 1.013 bar / 273 K DRY		m^3/h				
	7	Inlet volume flow ☒ dry ☐ wet		m^3/h	13252	13931	14611	15477
X	8	Inlet mass flow ☒ dry ☐ wet		kg/h				
		Outlet mass flow ☒ dry ☐ wet		kg/h				
		Inlet pressure abs.		bar	4.443	4.443	4.443	4.443
		Outlet pressure, after COMPR. abs.		bar	7.14	6.75	6.44	5.86
X	12	Inlet temperature		°C	20	20	20	20
	13	Outlet temperature, after COMPR.		°C	160	170	180	190
	14	Pressure ratio p/p	—	—				
X	15	Pressure losses		bar	0.25			
	16	Blow-off vol. flow at 1.013 bar / 273 K		m^3/h				
	17							
	18							
	19							
	20	Intermediate inlet flow		m^3/h				
	21	Intermediate inlet pressure abs.		bar				
	22	Intermediate inlet temperature		°C				
	23	Extraction flow ☐ dry		m^3/h				
	24	Extraction pressure abs.		bar				
	25	Extraction temperature		°C				
	26							
	27							
	28							
	29	Overall specific work ☐ Y_S ☒ Y_T ☐ Y_{pol} 1)		kJ/kg	211.6			
	30	Overall efficiency ☐ η_S ☒ η_T ☐ η_{pol} 1)		%	66			
	31	Spec. work per stage ☐ Y_S ☐ Y_T ☒ Y_{pol} 1)		kJ/kg	129.200			125.600
	32	Efficiency per stage ☐ η_S ☐ η_T ☒ η_{pol} 1)		%	75			74
	33	Total efficiency at coupling		%	74			
	34	Speed		min^{-1}	10800			
	35	Speed range		min^{-1}	8445 – 11823			
X	36	Speed range		%	75 – 105			
	37	Surge limit at p/p const. 2)		%	63			
	38							
	39	Total power consumption 3)		kW	3350			
	40	Power consumption per STAGE		kW	1552			1798
	41	Mechanical losses		kW	88			
	42	Gear losses		kW				
	43							
	44	Power recommended for driver		kW				
	45							
	46	Rotation of compressor viewed from TURBINE			☒ cw (clockwise)		☐ ccw (counterclockwise)	
	47	Remarks:						
	48	1) S ≙ isentropic compression						
	49	T ≙ isothermal compression						
	50	pol ≙ polytropic compression						
	51	2) related to guarantee point						
	52	3) incl. all losses						
X	53	~~*) PRESSURE MAY VARY ACC. TO DESIGN OF COMPRESSOR~~						
	54	~~HOWEVER VENDOR MUST INFORM UHDE ABOUT THE VARIATION~~						
	55							

Rev.	Date	Name	Check.	Description	Rev.	Date	Name	Check.	Description
1	24.11.82	[illegible]		№ 4					
0	[illegible] 77	[illegible]							

6

UF 1006 - 01 Part 1/10 E 7 80 - 02