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COMPRESSOR PERFORMANCE ADAPTATION FOR GAS PATH ANALYSIS AND DIAGNOSTICS

SALAMAT* R.

ABSTRACT

The importance of reliable engine diagnosis cannot be over emphasized as large revenues are lost due to unplanned shut downs or unnecessary scheduled maintenances. An accurate simulation model must be set up in order to minimize the errors in performance predictions and diagnostics analysis.

The objective of the proceeding works is to have a compressor performance simulation model matching the actual site data by a novel method and a model that can be reliably used for performance predictions and diagnostics. In the adaptation process, Scaling Factors (SF) are introduced and then applied to modify the compressor maps. Linear adaptation is applied to single test point while non-linear adaptation is applied to multiple test points. Three site real base cases are available and have been analyzed and evaluated, at 99.6%, 93.0% and 90% RPM.

Predictions of compressor performance are compared with the manufacturer's fleet maps. The prediction accuracy has been improved significantly after the adaptation. Moreover, the proposed adaptation approach could be applied for most situations.

KEY WORDS

Compressor, diagnostics, performance adaptation, site data, simulation, Compressor Non-Dimensional Flow

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* PhD Researcher, Dept of Power and Propulsion, School of Engineering, Cranfield University, UK, employed at Qatar Petroleum.

INTRODUCTION

During the past several decades, tremendous effort has been made to make the engine performance simulation more efficient and accurate using thermodynamic computer software [3, 4] as the application of such software can significantly reduce operating and maintenance costs.

The objective and focus of the present paper is to have a compressor performance simulation model matching the actual site data and a model that can be reliably used for performance predictions and diagnostics.

Correct diagnostics on a compressor or gas turbine depend on accurate engine performance model. An accurate engine model may be produced by selecting a best set of design point parameters and the next step is to adapt the model to satisfy engine off design performance by creating new engine component maps. Relevant techniques have been published by Li et al [1] and others. The difference between the actual compressor map and the default compressor map may be so large that the off design performance prediction error may become unacceptable for gas path diagnostics.

To reduce the off design performance prediction errors the speed lines on the manufacturer's compressor maps need to be adapted or relocated by using observed off design performance measurements. The manufacturer supplied curves are based on certain inlet/outlet parameters which may change during operation and hence the need for adaptation. In this study the measurable parameters were inlet and outlet temperatures and pressures, compressor inlet flow rates and compressor RPM. The proceeding works describes the test and compressor data as supplied by OEM (Originally Engineered by Manufacturer) followed by setting the basic theory and method of adaptation. This section is then followed by the detailed application of the proposed adaptation theory, results and conclusions.

COMPRESSOR AND TEST DATA

Test Data

Three operating Base Cases of Site Compressor data were studied. Refer to Table 1 where the parameters at inlet and outlet of the compressor and the RPM for each base case is shown.

Compressor Manufacturer Data

The available range of predicted performance curves supplied by manufacturer were studied and the closest sets of these data to the site compressor inlet conditions were chosen to be adapted. Figure 1 and Figure 2 show the chosen performance curves as supplied by the manufacturer. The summary of rated and site performance data used for adaptation is shown in Table 2.

THEORY AND METHOD OF ADAPTATION

To obtain accurate simulation model, the following steps are applied:

(1) Start from a supplier performance map (for a fleet compressors)
(2) Adapt the map in order to match available test data
(3) Apply HYSYS to assess simulation accuracy improvement

Figure 3 shows the default map and the adapted map generated from step (1) and step (2) above. Figure 4 illustrates three curves for one of the base cases: the performance curve as supplied by the manufacturer, the corrected curve for site RPM based on supplier curve and the curve generated by HYSYS for exact performance match between site and simulated compressor. Chart 1 demonstrates the flow diagram developed for performance adaptation.

The compressor performance can be accurately modeled and predicted by HYSYS simulation programme. HYSYS is a versatile and adaptable steady state and transient state simulation programme owned by Aspentech Technology where a variety of process and rotating equipment such as compressor can be modeled. In HYSYS two modes of curves can be input for performance evaluation: Single Curve and Multiple Curves.

For single curve, the following combinations of input will allow the operation to completely solve assuming the feed composition and temperature are known:

- Inlet Pressure and Flow rate
- Inlet Pressure and Duty
- Inlet Pressure and Outlet Pressure
- Inlet Pressure and Efficiency corresponding to the Curve type (for example – if the curve is polytropic, provide a polytropic efficiency)

If multiple curves have been installed and an operating speed is specified on the Parameters page (this is a page where the Head-Flow-Efficiency values are entered), then only the curve with the corresponding speed will be used. One can specify a speed that is different than the speed values given for the curves. For example, if curves are provided for two speeds, say 7000 rpm and 8000 rpm, and a speed of 7400 rpm is specified, HYSYS will interpolate between the curves to obtain the and the component properties are calculated at that point. You must also provide an inlet pressure and one of flow rate, duty, outlet pressure or efficiency as explained above.

HYSYS can calculate the appropriate speed based on the input. In this case, one need to provide the feed composition, pressure and temperature as well as two of the following four variables:

- Flow rate
- Duty
- Efficiency
- Outlet Pressure

Once the necessary information is provided, the appropriate speed will be determined and the other two variables will then be calculated.

In the current works presented in this paper multiple curves were available from OEM for a variety of compressor inlet conditions and gas properties. These are numerically presented in Table 3 and graphically shown in Figures 1 and 2.

CASE STUDY – APPLICATION OF ADAPTATION

The Polytropic head for a compressor can be shown to be given by [5]:

$$H_p = \left(\frac{Z_{avg}}{1000}\right)\left(\frac{8314}{MW}\right) \times T_{in} \times \left(\frac{k}{k-1}\right) \times \eta_p \times \left[\left(r_p^{\left(\frac{k-1}{k}\right)\left(\frac{1}{\eta_p}\right)}\right) - 1\right] \qquad \text{..... (1)}$$

where,

H_p= Polytropic Head, kJ/kg

Z_{avg} = Gas Average Compressibility (alternatively Z_{inlet} could be used if the OEM has based his performance calculations at inlet conditions)

MW = Inlet gas molecular weight, kg/kmol

T_{in} = Compressor inlet temperature, K

η_p = Polytropic efficiency

r_p = Pressure Ratio

$k = C_p/C_v$

From equation (1), H_p varies linearly with T_{in} and Z_{avg} and it varies inversely with MW. Further, Fan laws apply well for small changes in N (the RPM of compressor) such that H_p varies nonlinearly with N^2. By comparison between k values supplied by OEM and site, the differences are diminishingly small to have any effect on H_p values in line with ASME PTC10 where variations up to +/-4% can be tolerated due to inaccuracy of measuring devices and design tolerance. Hence, it follows that for the purpose of adaptation, equation (1) could be modified as:

$$H_{p\_SiteRPM} = H_{p\_OEM} \times \left(\frac{Z_{Site}}{Z_{OEM}}\right)\left(\frac{MW_{OEM}}{MW_{Site}}\right) \times \left(\frac{T_{in,Site}}{T_{in,OEM}}\right) \times \left(\frac{N_{Site}}{N_{OEM}}\right)^2 \quad \cdots\cdot(2)$$

where subscripts “Site” denotes the parameters at site and “OEM” denotes the parameters as supplied by the compressor manufacturer.

The actual inlet volume flow is the best mean for plotting compressor performance curves as the impeller and therefore the compressor is sensitive only to actual volume throughput. The OEM supplied data were also based on actual volume throughput as shown in Figures 1 & 2.

For each of the 3 Site Base Cases, equation (2) is used to obtain the expected performance of the site compressor based on the supplier performance data. HYSYS is then innovatively applied to get the exact match between site performance data and the compressor simulation model. The corresponding polytropic head and polytropic efficiency for exact matching is extracted from HYSYS and recorded. These values are compared with the expected performance obtained earlier and the ratio gives the scaling factor required for modifying the expected performance curve obtained earlier by equation (2). This factor gives exact match for the site flow condition. The resultant performance curves thus become the real performance curves specific to the compressor under observation and these will be used for GPA and diagnostic purposes. Table 4 demonstrates a sample for exact performance matching for site Base Case 1 Using HYSYS.

RESULTS

Dependency of Expected Performance Generation on Input Data

The new default performance maps were generated using a wide range of compressor inlet condition supplied by the manufacturer. In each case it was found the generated curves described in the preceding section hardly changed; the average difference was 0.46% for the RPM of 99.6% with a variance of 0.48 and -0.8% with a variance of -0.32 for the RPM of 90%. Refer to Figure 5 to demonstrate this result.

Site Compressor Performance Curves

Figures 6 and 7 show the derived site compressor real performance curves for Polytropic Head and Polytropic Efficiency by Adaptation using HYSYS for the 3 base cases of 99.6%, 93% and 90% RPMs. Under site conditions the curves provide exact solution.

Table 5 lists a comparison of parameters between the Expected and Site Performance and the errors between values before the adaptation and site measured values. Table 6 demonstrates the comparison of parameters between Measured and Site Performance Before and After Adaptation Using HYSYS. The latter table shows how the Objective Function [1, 3] or errors are reduced to minimum possible values. To expand the application of the proposed method for any compressor inlet temperature and pressure, Table 7 is derived from HYSYS to calculate the compressor non-dimensional flow (CNDF) [2] and Figure 8 shows the Pressure Ratio versus CNDF for further diagnostic purposes.

CONCLUSIONS

- The default performance maps for performance predictions given by manufacturer are generic and may apply to a fleet of compressors within the same category, i.e., the supplied data is not specific to the site compressor
- The corrected default maps show dependence on RPM and strong independence from the variation in inlet gas conditions assumed by the manufacturer. It is deduced that the corrected default maps are not inlet case dependant and even a limited supply of manufacturer supplied performance curves will suffice the objective of default map correction
- HYSYS is innovatively applied for performance matching and it has the ability to reduce the Objective Function down to its minimum value

- The adaptation approach in this study are valid and applicable for most situations. For a given RPM, only the extremely small or extremely large flow may not be applicable since in these regions the efficiencies drops very rapidly and erratically.
- The performance curves specific to the site compressor and non-dimensional flows have been generated in this work and may be used in future diagnostics
- The advantage of proposed method of adaptation is its exact solution with minimum objective function.
- The presented works and results may be used a basis for developing the dimensionless or quasi-dimensionless parameter groups rigorously defining and predicting the engine performance

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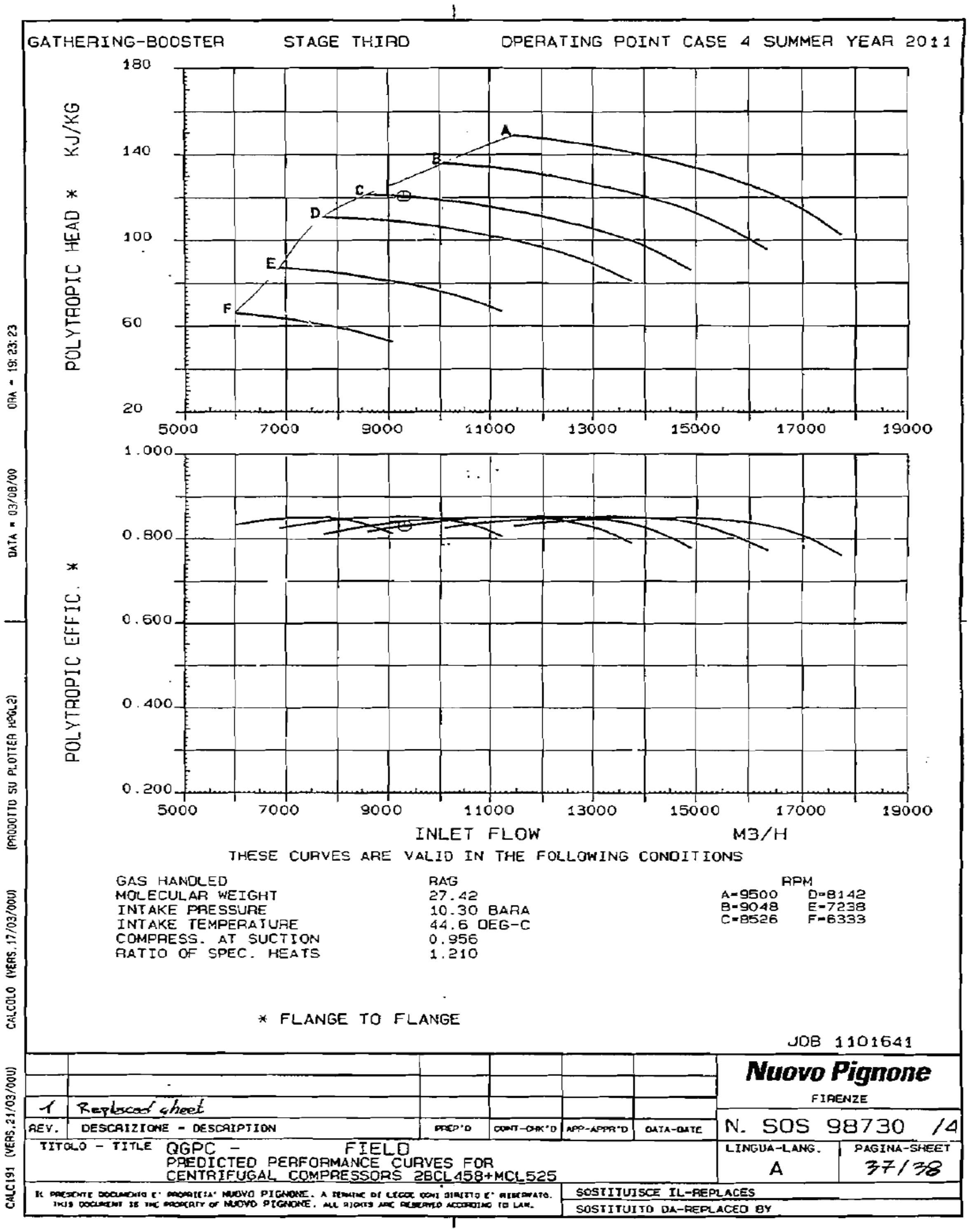

THESE CURVES ARE VALID IN THE FOLLOWING CONDITIONS

GAS HANDLED	RAG
MOLECULAR WEIGHT	27.42
INTAKE PRESSURE	10.30 BARA
INTAKE TEMPERATURE	44.6 DEG-C
COMPRESS. AT SUCTION	0.956
RATIO OF SPEC. HEATS	1.210

RPM
A=9500 D=8142
B=9048 E=7238
C=8526 F=6333

* FLANGE TO FLANGE

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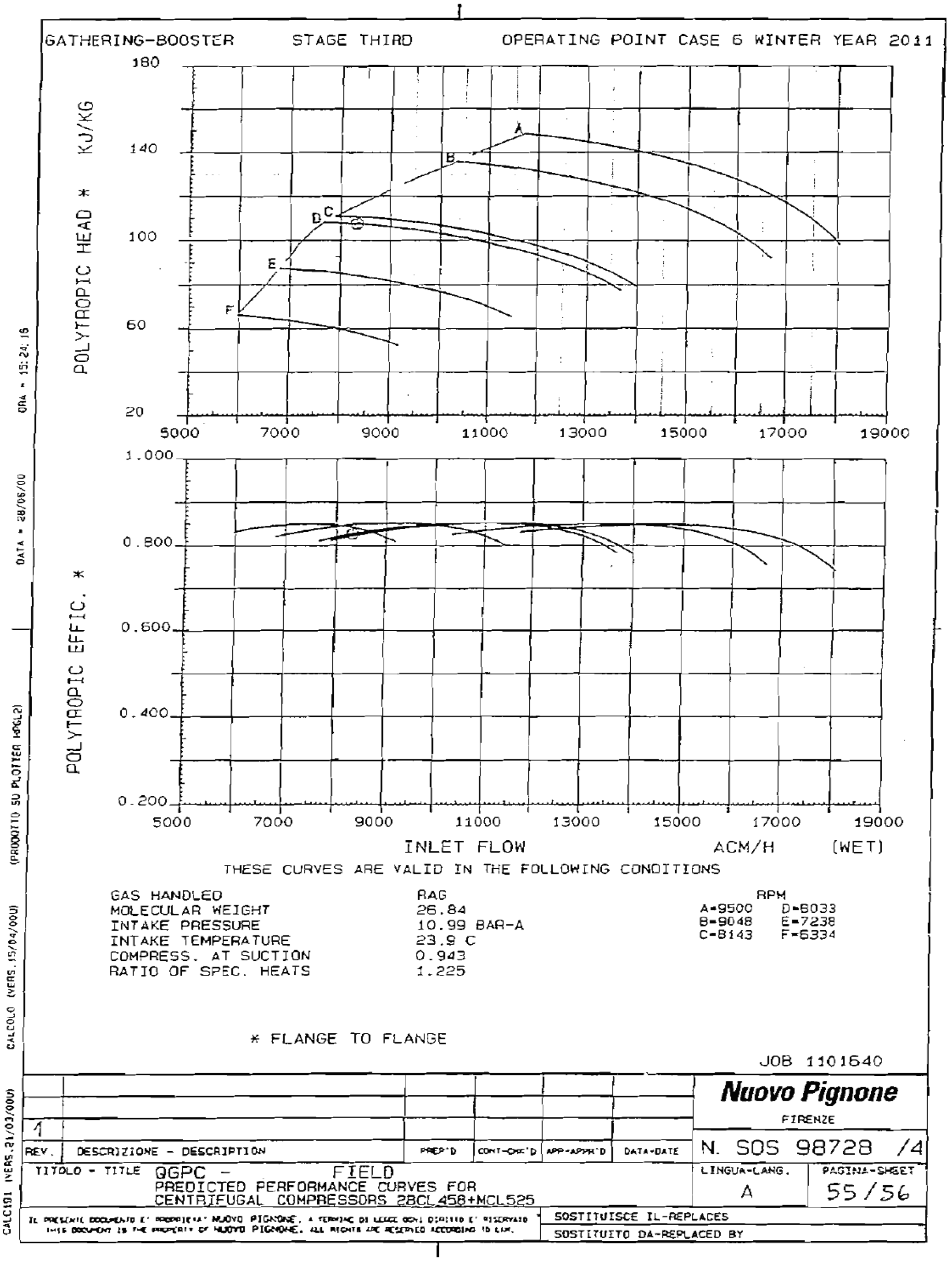
Figure 1. The adapted compressor performance curves for analysis for Base Case 1



THESE CURVES ARE VALID IN THE FOLLOWING CONDITIONS

GAS HANDLED	RAG
MOLECULAR WEIGHT	26.84
INTAKE PRESSURE	10.99 BAR-A
INTAKE TEMPERATURE	23.9 C
COMPRESS. AT SUCTION	0.943
RATIO OF SPEC. HEATS	1.225

RPM

A=9500	D=6033
B=9048	E=7238
C=8143	F=6334

* FLANGE TO FLANGE

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TITOLO - TITLE QGPC - FIELD
PREDICTED PERFORMANCE CURVES FOR
CENTRIFUGAL COMPRESSORS 28CL458+MCL525

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Figure 2. The adapted compressor performance curves for analysis for Base Case 2 and 3

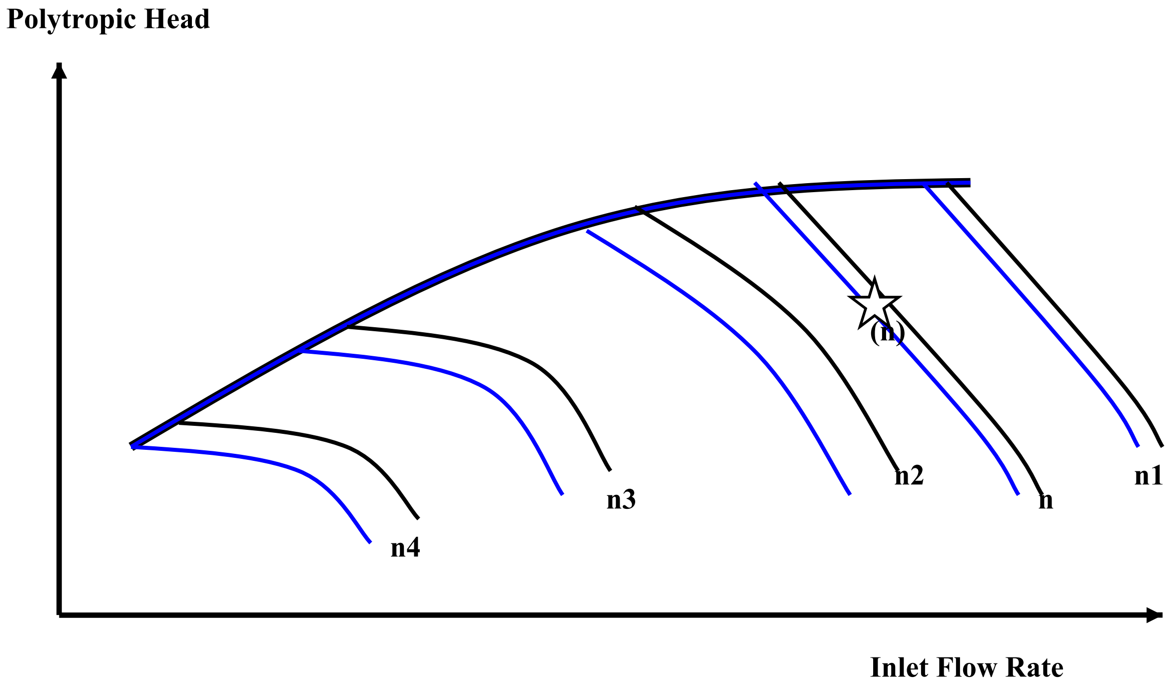

Figure 3. A general compressor performance map showing the default and the adapted curves. * denotes test point. The grey map is the default map (step 1 of theory) while the blue map is the adapted map (step 2 of theory). The adapted map is further treated by HYSYS to improve accuracy.

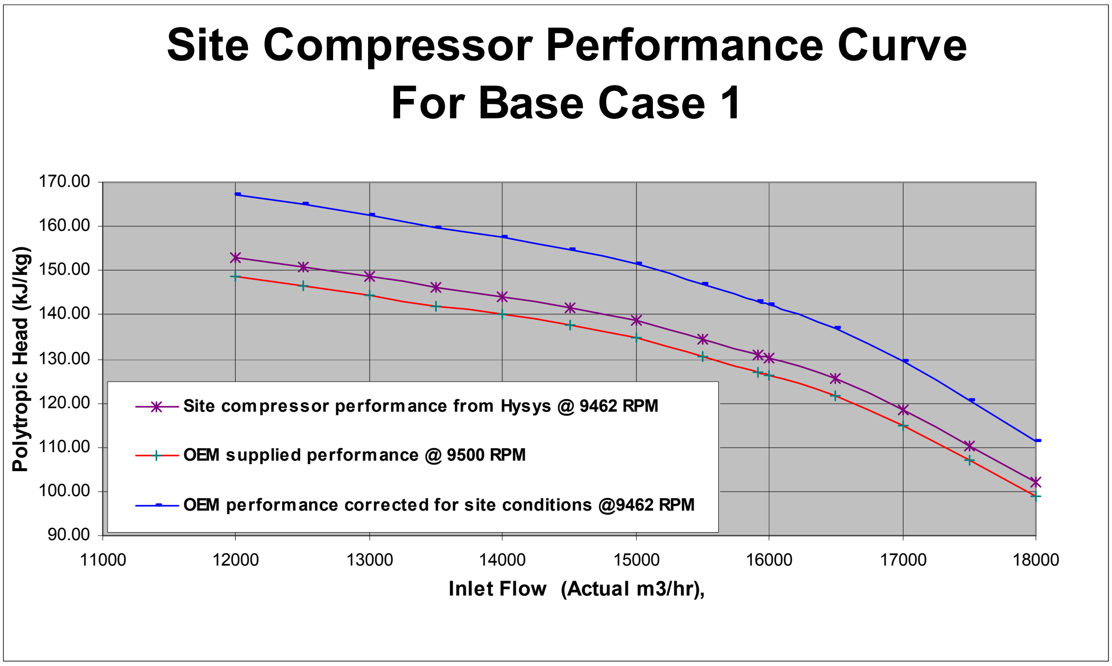

Figure 4. Superimposition of performance curve from OEM, adapted curve and the curve from HYSYS for one of the three site base cases.

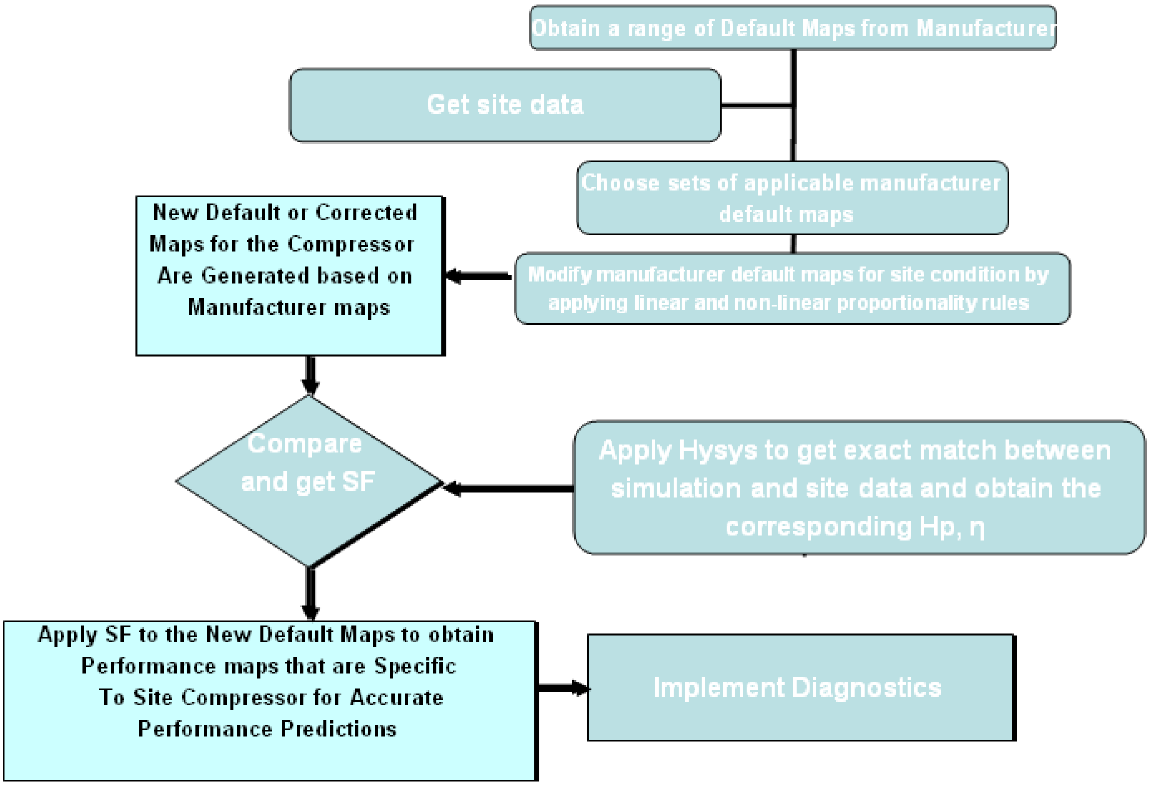

Chart 1. Flowchart for Compressor Performance Adaptation

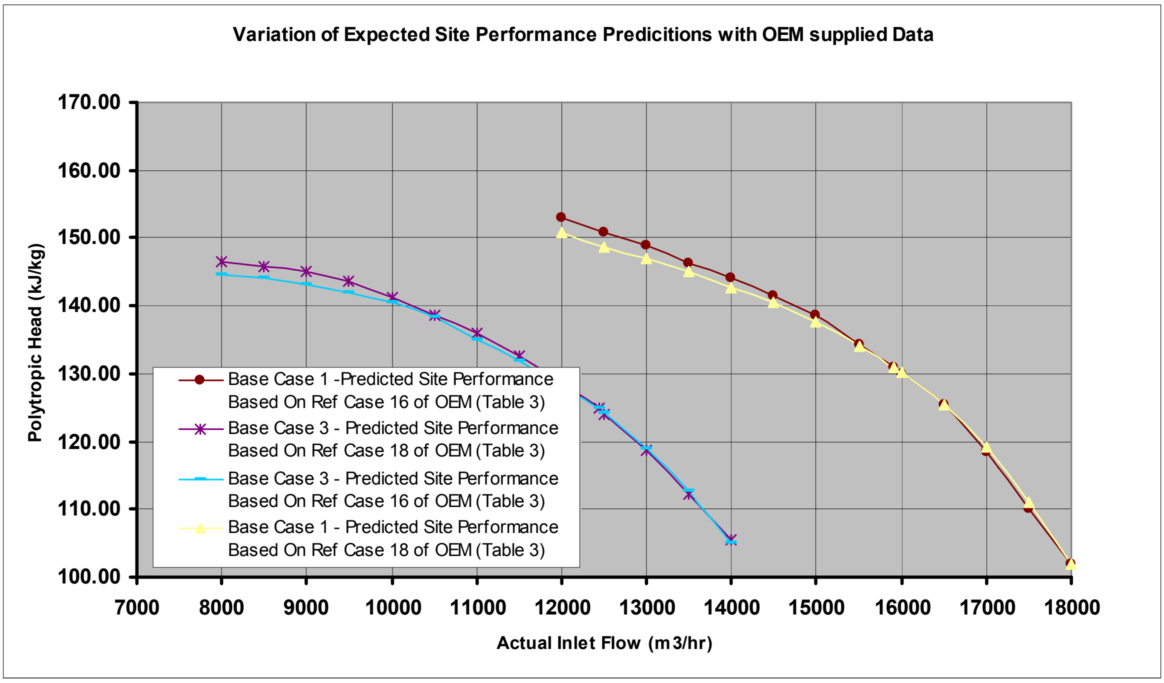

Figure 5. Dependency of expected performance calculation on input data. The overlaps show very little dependency

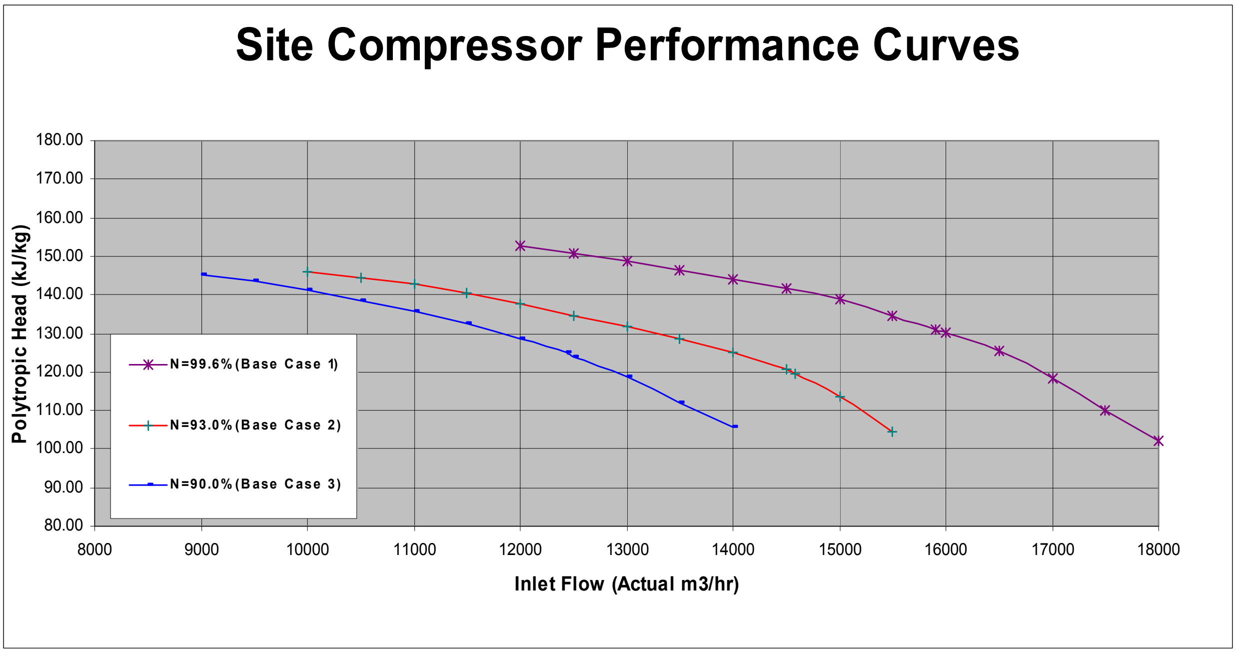

Figure 6. The generated Actual Site Compressor Performance Curves for 99.6%, 93% and 90% RPMs

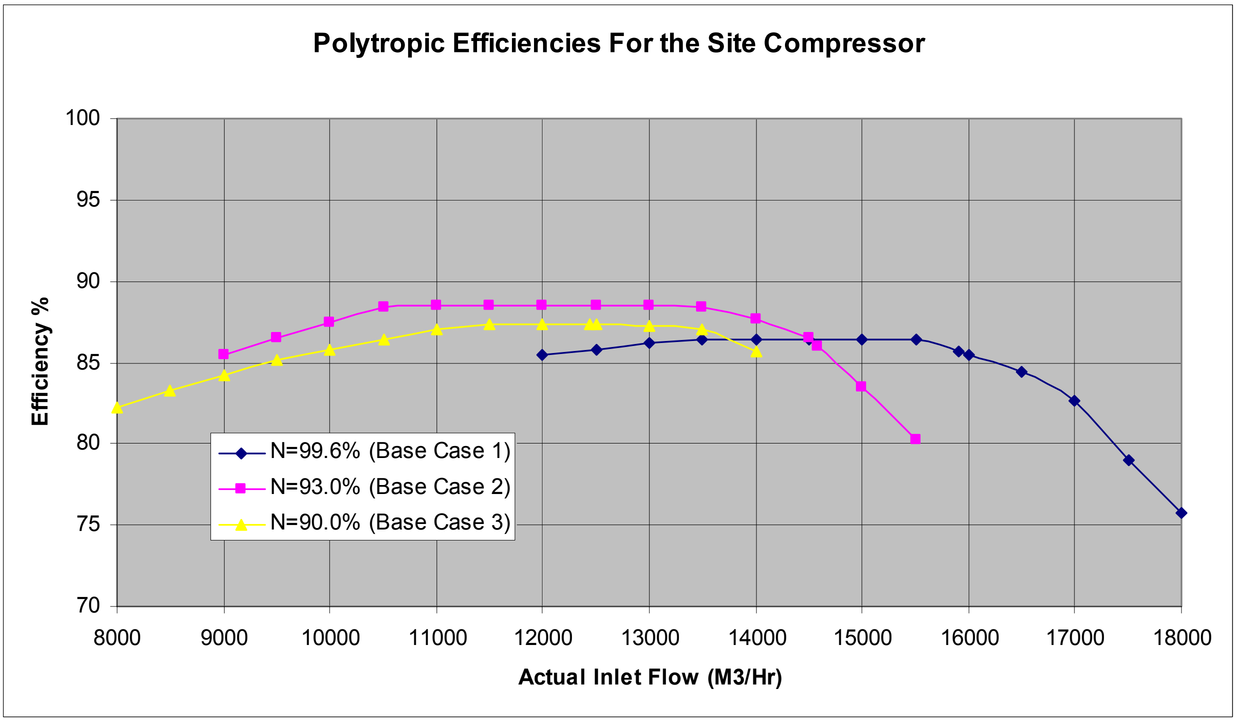

Figure 7. The generated Actual Site Compressor Polytropic Efficiencies for 99.6%, 93% and 90% RPMs.

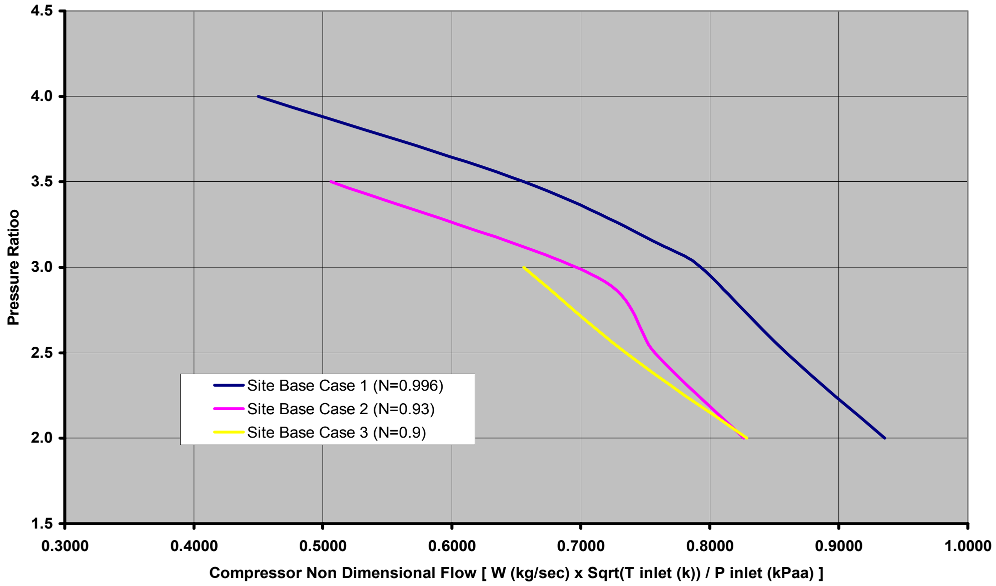

Figure 8. Pressure Ratio (PR) versus CNDF for the site compressor at various speeds

Table 1. The conditions of site compressor for the three base cases

Parameter	Base Case 1	Base Case 2	Base Case 3	Unit
Flow rate	122.58	118.3	102.7	MMScfd
	150400	145000	126000	Kg/hr
	15910	14580	12440	Actual m3/hr
Mol. Wt	24.6	24.6	24.6	Kg/kmol
Inlet Press	9.7	9.9	9.7	Bara
Inlet Temp	315.3	307.2	296.7	K°
Outlet Press	30.3	29.1	31.0	Bara
Outlet Temp	398.2	384.5	378.2	K°
Speed	99.6%	93%	90%	-

Table 2. Summary of Rated and Site Performance Data used for Adaptation

Parameter	Rated Performance Data By Manufacturer	Base Case 1	Rated Performance Data By Manufacturer	Base Case 2	Rated Performance Data By Manufacturer	Base Case 3
	Rated (OEM)	Site	Rated (OEM)	Site	Rated (OEM)	Site
Mol. Wt	27.69	24.6	24.88	24.6	26.84	24.6
Inlet T /K	316.3	315.3	303.9	307.2	297.1	296.7
Inlet P / Bara	10.86	9.7	10.06	9.9	10.99	9.7
Sp. Ht. Ratio	1.21	1.21	1.236	1.213	1.225	1.216
Suction Z	0.952	0.962	0.960	0.958	0.943	0.9544

Table 3. The Conditions At Which Predicted Performance Curves Are Available From OEM For The Site Compressor

Case Ref.	**OEM**	**Time**	**MWt**	**Intake Press**	**Intake Temp**	**Z @ Suction**	**Cp/Cv**	**SPEED RPM CURVES BY OEM**					
No.	Case No.			**Bara**	**C**			**A**	**B**	**C**	**D**	**E**	**F**
1	1	summer 04	27.24	11.31	45.3	0.953	1.213	9500	9048	8671	8142	7238	6333
2	11	summer 05	26.27	10.01	40.2	0.96	1.222	9500	9048	8824	8143	7238	6334
3	3	winter 04	25.71	10.42	17	0.949	1.239	9500	9048	8604	8142	7238	6333
4	4	summer 04	27.42	10.3	44.6	0.956	1.21	9500	9048	8526	8142	7238	6333
5	5	winter 11	24.59	9.43	6.1	0.952	1.251	9500	9048	8870	8142	7238	6333
6	6	winter 11	26.29	10.12	25.2	0.951	1.227	9500	9048	8523	8142	7238	6333
7	7	summer 04	27.57	11.06	47.4	0.953	1.209	9500	9048	8768	8142	7238	6333
8	8	summer 04	26.77	11.13	44.6	0.955	1.216	9500	9048	8671	8142	7238	6333
9	9	summer 04	27.52	11.1	46.7	0.953	1.21	9429	8980	8795	8081	7184	6285
10	10	summer 04	27.68	11.05	47.3	0.953	1.209	9492	9040	8763	8135	7232	6327
11	11	summer	26.02	9.32	40.1	0.963	1.222	9500	9188	9048	8142	7238	6333
12	11	winter	23.33	8.79	3.7	0.96	1.264	9500	9463	9048	8142	7238	6333
13	1	summer 04	28.24	11.77	45.5	0.947	1.207	9500	9048	8180	7238	6334	
14	2	winter 04	25.18	10.28	19.4	0.954	1.243	9500	9048	8677	8143	7238	6334
15	3	winter 04	26.92	11.1	20.5	0.941	1.23	9500	9048	8180	7238	6334	
16	4	summer 11	27.69	10.86	43.1	0.952	1.21	9500	9048	8224	7238	6334	
17	5	winter 11	24.88	10.06	30.7	0.96	1.236	9500	9048	8936	8143	7238	6334
18	6	winter 11	26.84	10.99	23.9	0.943	1.225	9500	9048	8143	8033	7238	6334
19	7	summer 04	28.26	11.75	45.5	0.947	1.207	9500	9048	8210	7238	6334	
20	8	summer 04	28.15	11.8	45.4	0.947	1.208	9500	9048	8208	7238	6334	
21	9	summer 04	26.92	11.79	47	0.953	1.215	9500	9048	8349	8143	7238	6334
22	10	summer 04	28.24	11.77	45.4	0.947	1.207	9500	9048	8208	7238	6334	
23	11	winter	23.48	9.4	4.1	0.957	1.264	9500	9135	9048	8143	7238	6334

Table 4. Sample Exact Performance matching - Site Base Case 1- By applying HYSYS. Scale Factor (SF=0.915) is derived through the polytropic head obtained from HYSYS for exact site match (130.9 kJ/kg) by the expected value obtained from modification of supplier data (143.1 kJ/kg). This SF is then applied to the expected performance column.

Inlet Flow	Polytropic Head @ 9500 rpm		Polytropic Head @ 9462 rpm	Polytropic Head @ 9462 rpm By HYSYS
Act M3/Hr	(Rated, NP) kJ/kg	(Corrected) kJ/kg	kJ/kg	kJ/kg
12000	148.5	168.51	167.17	152.92
12500	146.5	166.24	164.91	150.86
13000	144.5	163.97	162.66	148.80
13500	142	161.14	159.85	146.22
14000	140	158.87	157.60	144.16
14500	137.5	156.03	154.78	141.59
15000	134.7	152.85	151.63	138.71
15500	130.5	148.09	146.90	134.38
15910	127.119	144.25	143.10	130.90
16000	126.3	143.32	142.18	130.06
16500	121.8	138.21	137.11	125.42
17000	115	130.50	129.46	118.42
17500	107	121.42	120.45	110.18
18000	99	112.34	111.44	101.94

Table 5. Off-Design Performance comparison between default map and site measured values for the test compressor

No	Parameter	Base Case	Value Before Adaptation (Default Map)	Value Measured (At Site)	Error %
1	N	1	0.996		0
		2	0.93		0
		3	0.90		0
2	Pout	1	33.11	30.3	+9.3
		2	26.38	29.1	-9.3
		3	28.70	31.0	-7.4
3	Tout	1	133.5	125.0	+6.8
		2	105.6	111.3	-5.1
		3	100.5	105.0	-4.3

Table 6. The error (objective function) between measured values and the corresponding values after adaptation using HYSYS

No	Parameter	Base Case	Value Measured	Value After Adaptation	Error %
1	N	1	0.996		0
		2	0.93		0
		3	0.90		0
2	Pout, Bara	1	30.3	30.3	0.0
		2	29.1	29.1	0.0
		3	31.0	31.0	0.0
3	Tout, °K	1	398.2	398.2	0.0
		2	384.5	384.5	0.0
		3	378.2	378.2	0.0

Table 7. Compressor Non-Dimensional Flow derived from HYSYS for the site base cases

Base Case	RPM		P(Inlet)	PR	P(Outlet)	W x 10^5	W	Inlet Temp	Outlet Temp	CNDF
	%	Value	(Bara)		(Bara)	(kg/hr)	(Kg/Sec)	K	K	
1	99.6	9462	9.7	2	20.4	1.84	51.11	315.25	377.75	0.6353
	99.6	9462	9.7	2.5	25.3	1.69	46.94	315.25	388.35	0.5245
	99.6	9462	9.7	3	30.1	1.56	43.33	315.25	395.95	0.4434
	99.6	9462	9.7	3.12	31.3	1.504	41.78	315.25	398.15	0.4195
	99.6	9462	9.7	3.5	35.0	1.29	35.83	315.25	406.35	0.3403
	99.6	9462	9.7	4	39.8	0.885	24.58	315.25	419.75	0.2187
2	93.0	8835	9.9	2	20.8	1.68	46.67	307.15	368.95	0.5670
	93.0	8835	9.9	2.5	25.8	1.54	42.78	307.15	379.45	0.4672
	93.0	8835	9.9	2.94	30.1	1.45	40.28	307.15	386.45	0.4068
	93.0	8835	9.9	3.5	35.7	1.03	28.61	307.15	398.15	0.2655
3	90.0	8550	9.7	2	20.4	1.68	46.67	296.65	348.45	0.5627
	90.0	8550	9.7	2.5	25.3	1.49	41.39	296.65	362.45	0.4486
	90.0	8550	9.7	3	30.1	1.33	36.94	296.65	373.45	0.3667
	90.0	8550	9.7	3.2	32.0	1.26	35.00	296.65	378.15	0.3367
	90.0	8550	9.7	3.5	35.0	1.11	30.83	296.65	385.45	0.2840