OPTIMIZATION OF SINGLE STAGE CENTRIFUGAL COMPRESSOR DRIVEN BY A TURBINE WITH ANTI-SURGE

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Abstract: The response surface methodology was employed to make mathematical modeling and optimization of the temperature and pressure for centrifugal compressor. ProSimulator software was used for simulation of process parameter mainly temperature (x) and pressure (y). We considered a polynomial regression model equation between independent variable (x) and dependent variable (y). The simulation parameter revealed that the modeled values were in good agreement with simulated ones.

Keywords: centrifugal compressor, response surface methodology, optimization, analysis of variance

1. INTRODUCTION

With rising oil prices, operating companies are under pressure to ensure that their production systems operate at their maximum capacity. The performance and availability of centrifugal compressors is vital to the operation of oil and gas production facilities. Over the past 20 years, the availability of these machines has been the focus of attention and performance issues have taken a back stage. Even API 617 [1] does not require the vendor to guarantee the compressor efficiency, only the absorbed power with a +/- 4% tolerance.

Centrifugal compressors are widely used in industrial applications where a continuous flow of pressurized gas is required. They are widely used for example in combustion engine superchargers, regeneration processes and plants, the oil and gas industry, waste water treatment plants and in smaller gas turbines [2]. Determination of the parameters for model is not straightforward due to the complex geometry of actual centrifugal compression systems. The authors of [3–7] solved this by tuning one of the parameters to get good agreement between model predictions and experimental data. However, we point out that the tuning approach can still lead to different parameter values for one compression system, as becomes clear from [5–9].

In this regard the present work deals with simulation and optimization of centrifugal compressor with anti-surge is done to get the stabilized conditions for the maximization of compressor output. Centrifugal Compressor model developed by Sim Infosystems Private Limited, Chennai is used for analysis and RSM software is used for optimization of Process conditions. The present study is restricted to the variation of temperature and pressure against compressor output. Prosimulator was used to stimulate the centrifugal compressor model and

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Response surface Methodology (RSM) which is efficient statistical technique for optimization [10] of feed outlet of gas with respect to temperature and pressure.

2. EXPERIMENTAL METHODOLOGY

A typical model taken for analysis is shown in Figure 1. Required variation in temperature and pressure is made as per Table 2 in the tag BTI443 (It is a controller for Feed Temperature) and BPI441 (It is a controller for Supply Pressure).

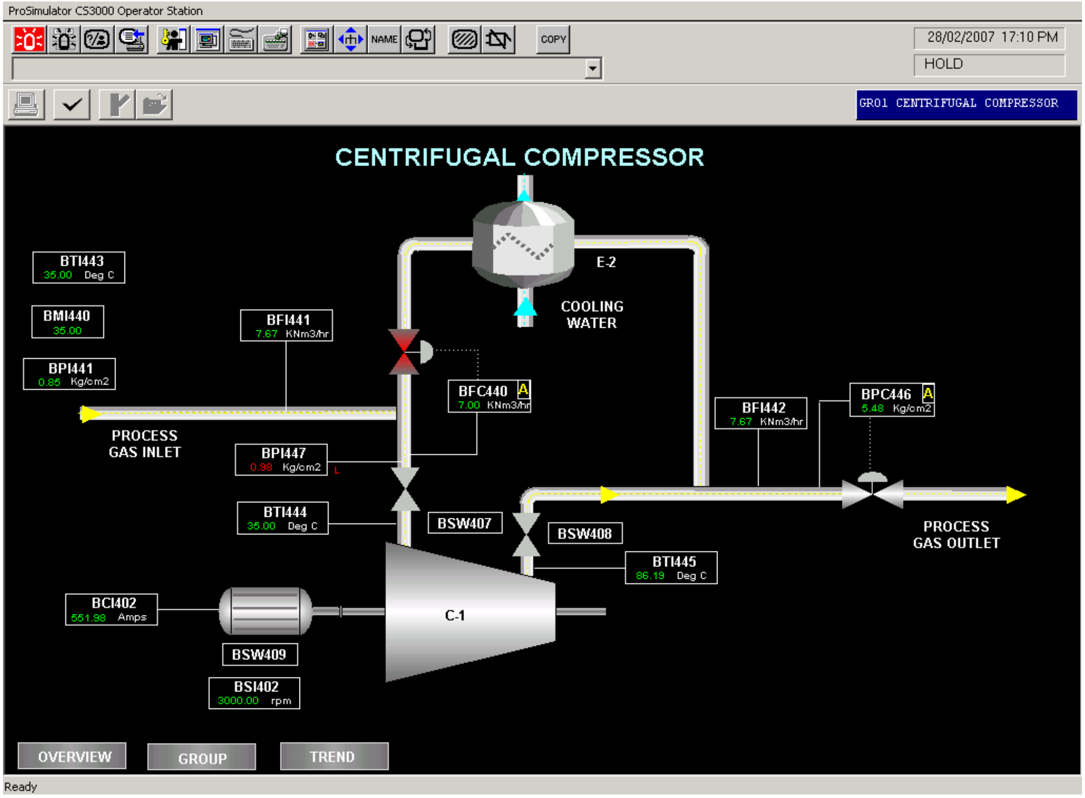

Fig. 1. Model taken for analysis.

3. EXPERIMENTAL DESIGN AND OPTIMIZATION BY RSM

Response surface methodology (RSM) is one such statistical technique, based on the fundamental principles of statistics, randomization, replication and, duplication, which simplifies the optimization by studying the mutual interactions between the variables over a range of values in a statistically valid manner. In order to study the combined effect of physical parameters such as temperature and pressure, a statistical approach namely response surface methodology has been used. The process conditions can be optimized using RSM. The central value (zero level) chosen for experimental design were: the range of temperature *(X_1)* and pressure *(X_2)* studied in this work was between 20 to 50 and 1 to 3 respectively as shown in Table 1. The low, middle, and high levels of each variable were designated as −, 0, and + respectively. -α and +α are the extreme levels in the range studied for each variable, α describe a circular design geometry, which reduce errors by locating the axial points at the lower and upper bound of the variable ranges, which gives direct , mutual, curvilinear interaction. Factorial point should range “-1” and “+1”, axial point “–1.414” and “+1.414” are intermediate levels between the central and extreme levels of each variable, and 0 is the central level in the range studied for each variable. A 2^2-factorial central composite experiment design was employed and all in duplicate, leading to 13 sets of experiments shows in Table 2, was used to optimize the out feed. Experiment plan employed for the optimization of temperature and pressure. The optimum out feed is taken as the dependent variable or response $\hat{Y}$. Regression analysis was performed on the data obtained. Second order polynomial equation is most suited for behavior of given system $Y = \beta o + \Sigma\beta i\ xi + \Sigma\beta ii\ xi2 + \Sigma\beta ij\ xi\ xj$, where, Y = predicted response, βo = offset term, βi = linear effect, βii = squared effect, and βij = interaction effect. x_i and x_j = coded value of independent variables [11-12]. MATLAB was used for optimization of regression equation to get maximum value. The second order polynomial equation was obtained using Design-Expert software. Experimental range and level of temperature and pressure based on central composite design is tabulated in Table 1 with coded and actual value of the variable at various levels.

Table 1. Experimental range and levels of temperature and pressure in Central composite design (CCD).

Parameter	**Units**	**Level**				
		-α	**-1**	**0**	**+1**	**+α**
Temperature *(X_1)*	^{o}C	13.7868	20	35	50	56.2132
Pressure *(X_2)*	kgf / cm^2	0.585786	1	2	3	3.41421

4. RESULT AND DISCUSSION

The application of response surface methodology offers, on the basis of parameter estimate, an empirical relationship between the response variable and the test variables under consideration. Multiple regression analysis of the experimental data (using Design- Expert software) gave the following second order polynomial equation in terms of out feed result shown in Table 2.

Table 2. Experimental data obtained for out feed.

Run	**Temperature $x_1(\equiv X_1)$ ^{0}C**	**Pressure $x_2(\equiv X_2)$ kgf / cm^2**	**Out feed kNm^3 / h**
1	-1 (20.0)	-1 (1.00)	5.63
2	+1 (50.00)	+1 (1.00)	5.26
3	-1 (20.00)	-1 (3.00)	9.83
4	+1 (50.00)	+1 (3.00)	9.4
5	-1.414 (13.79)	0 (2.00)	5.23
6	+1.414 (56.21)	0 (2.00)	7.39
7	0 (35.00)	-1.414 (0.59)	4.41
8	0 (35.00)	+1.414 (3.41)	10.35
9	0 (35.00)	0 (2.00)	7.67
10	0 (35.00)	0 (2.00)	7.67
11	0 (35.00)	0 (2.00)	7.67
12	0 (35.00)	0 (2.00)	7.67
13	0 (35.00)	0 (2.00)	7.67

The expression obtained in terms of coded factors is given by the equation, $Y_1 = 7.67 + 0.28x_1 + 2.09x_2 - -0.015x_1x_2 - 0.51x_1^2 + 0.026x_2^2$. Goodness of fit was examined using second order model equation with independent and dependent variables. The coefficient of determination *(R^2)* is 0.9370 which indicates that model response to total variability by 93.07% to various responses given. The closer value of coefficient of correlation *(R)* to unity, the better the fit is. Analysis of variance (ANOVA) was used for statistical testing of the model which is part of test for adequacy and significance of the model. Models reliability was tested using Fisher's statistical test *(F)*. The results of statistical testing using ANOVA are given in Table 3.

Probability with a value of less than 0.05 signifies that the model terms are significant as shown in Table 3. From Figure 2 it can be observed that a stationary point exists although it is outside the range based on the shape of the contour plot. The response surface plot shown in Figure 3 for the chosen model Y_1 illustrates the three dimensional relationship. This result indicates that two variables had mutually dependent influence on the out feed conditions. The optimal temperature and pressure were found to be 35°C and 2.06 kgf/cm^2 respectively. The maximum out feed was found to be 7.79 kNm^3/h.

Table 3. Analysis of Variance (ANOVA) Table for the effect of temperature and pressure on out feed.

Source	Sum of squares	Degrees of freedom	Mean square	F value	Probability
Model	37.53	5	7.51	18.79	0.0006
Error	2.80	7	0.40		significant

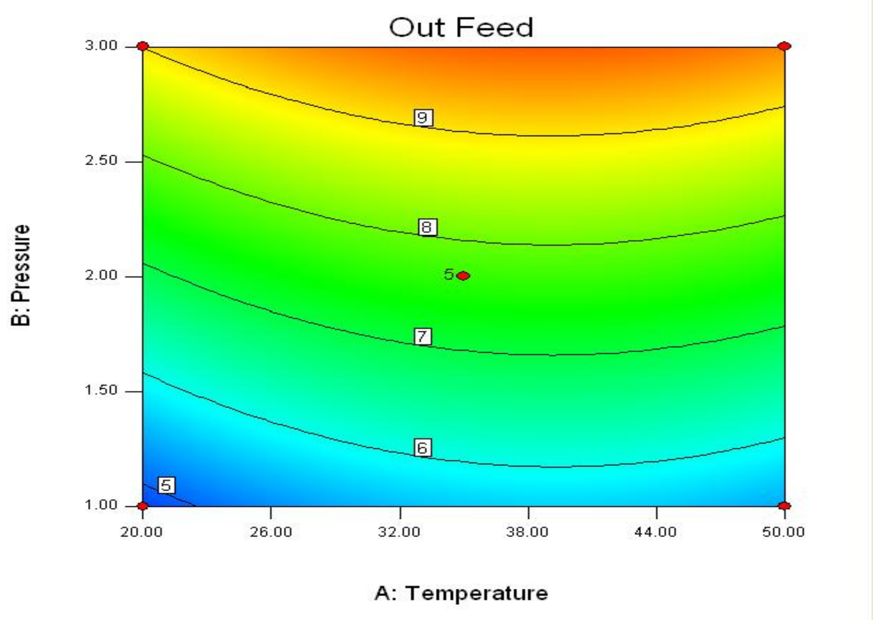

Fig. 2. Isoresponse contour plots showing the effect of temperature (°C) and pressure (kgf/cm^2) and their interactive effect on the out feed (kNm^3/h).

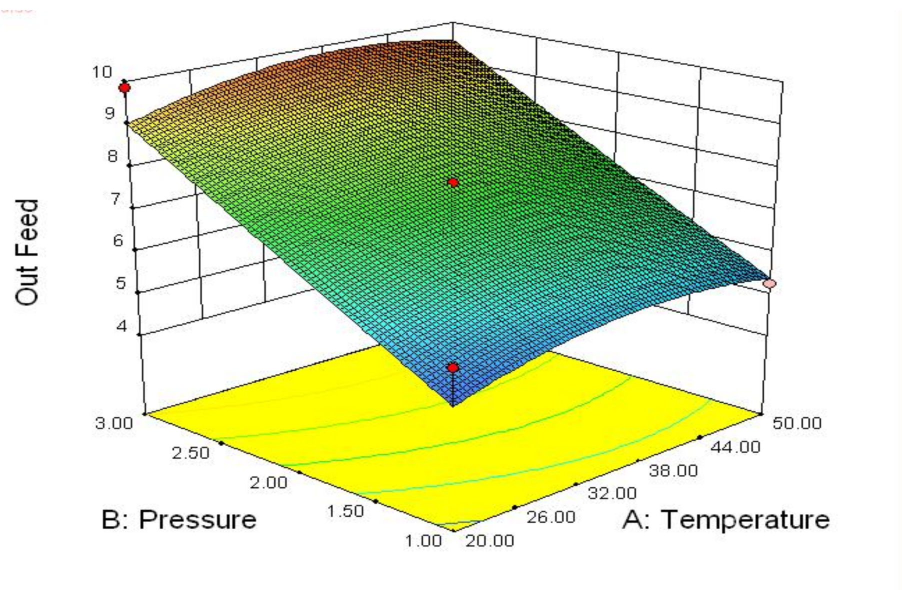

Fig. 3. Response surface plot showing the effect of temperature (°C) and pressure (kgf/cm^2) and their interactive effect on the out feed (kNm^3/h).

5. CONCLUSIONS

Compressors are designed to cover a wide range of applications. Compressors represent a significant capital investment and operating expense, and are an essential component in providing revenue streams of a plant. Mathematical models allows for evaluation of compressor performance under temperature and pressure conditions. Central composite design demonstrated that conditions leading to the optimum of out feed. The optimal conditions are temperature and pressure was found to be 35^{o}C and 2.06 kgf/cm^2 respectively. The optimal out feed was found to be 7.79 kNm^3/hr. Recent developments in the simulator technology make it possible to develop large scale simulation models. The model allows for studying the performance of a compressor under operations.

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