

PREDICTING PERFORMANCE

Massimiliano Di Febo and Pasquale Paganini, IPC, Italy, outline how to predict centrifugal compressor performance in an off-design condition.

The downstream oil and gas industry is approaching its first century. Today, the refining and gas processing industry has gigantic dimensions and a high degree of technological sophistication, and rotating machinery technology plays an important role. In fact, plant process conditions may be severe. Rotating machinery for compression applications can often have a critical role in determining the overall robustness of a plant. Today, centrifugal compressors are present in almost all plant processes and the centrifugal compressor market covers downstream process applications with a wide range of sizes.

Understanding how the machine runs and operates is essential. Detecting early indicators of malfunctioning and identifying the cause and possible

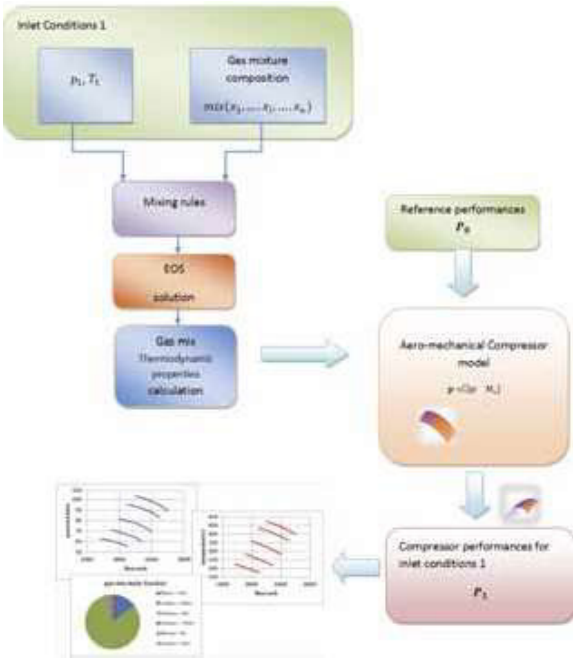


Figure 1. How Cmap software works.

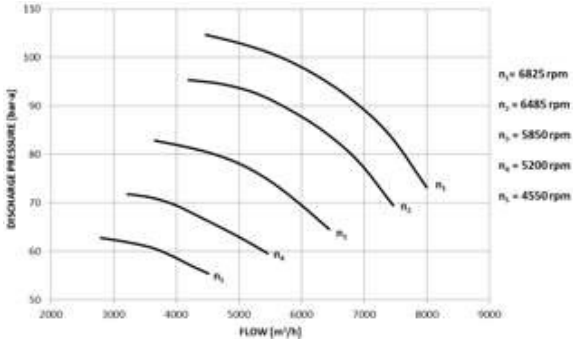


Figure 2. Design map compressor 1: discharge pressure vs inlet flow.

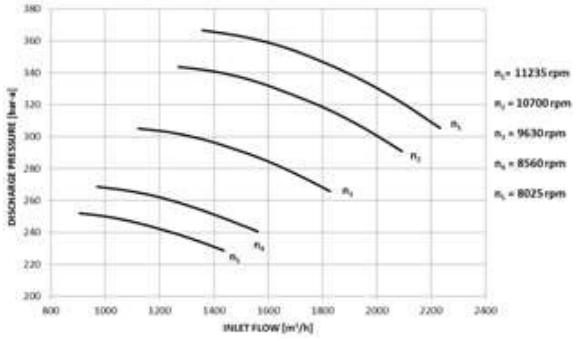


Figure 3. Design map compressor 2: discharge pressure vs inlet flow.

remedies in a timely manner provides a valuable contribution to the plant's proficiency, allowing for the minimisation of overall operational costs.

This trend is generally known as predictive maintenance, and is present across all relevant industries and applied to several kinds of machinery. For most common centrifugal machines, the predictive techniques commonly implemented are connected to the vibrational and structural dynamic aspects of the machine rotor operational conditions. This approach can be applied in the design stage where original equipment manufacturers (OEMs) provide insight into rotor dynamics, but it often assumes a more practical and empirical form on the operation floor where the machine's vibrational parameters are measured and compared to acceptable limits and used for alarm triggering. Predictive strategies, based on performance analysis, are increasing their presence as a tool for diagnostics and evaluation of machine health status during operation.

For example, using a machine model for comparing the measured performance of centrifugal pumps to the design performance is relatively easy and straightforward. For centrifugal compressors, the same process is more complex because of the dependency on compressor performance from the gas mix composition and operative inlet conditions (inlet pressure and inlet temperature). Therefore, an approach based on performance assessment requires a more complex machine model that should embed and couple several calculation capabilities from aeromechanics to thermodynamic.

In fact, one of the main difficulties of centrifugal compressor performance analysis arises from the need to have the compressor performance map adjusted to actual inlet conditions and ready and available. Usually, expected performances are outlined in graphs of discharge pressures, discharge temperatures, polytropic heads, efficiencies, and absorbed power related to the design inlet gas conditions. In general, it may be that inlet conditions in the field are different from the specification conditions defined in the machine's data sheets. A somewhat diffused practice is trying to reduce the complexity of the problem considering the compressor head as invariant with inlet gas conditions, and applying simplified machine formulas. While this method holds for very low pressure ranges and constant gas mixes, it introduces considerable errors as soon as the pressure goes up and the gas mix variability is introduced into the problem.

In order to assess compressor performance in these situations it is necessary to proceed to adjust the design performance to operative conditions, taking the complexity of the problem into account and then comparing it to measured values. This is basically the approach set out by the American Society of Mechanical Engineers (ASME) Performance

Table 1. Inlet design gas conditions of compressor 1	
Pressure	40.2 bar a
Temperature	50°C
Gas mixture	(Mw 19.24 g/mol)
Methane	80.51%
Nitrogen	1.46%
Ethane	14.69%
Propane	3.19%
I-butane	0.07%
N-butane	0.08%

Table 2. Inlet design gas conditions of compressor 2	
Pressure	150 bar a
Temperature	37°C
Gas mixture	(Mw 19.1 g/mol)
Methane	87%
Nitrogen	1.2%
Ethane	3.5%
Propane	0.8%
I-butane	0.5%
N-butane	0.5%
Carbon dioxide	4.5%
I-pentane	0.1%
N-pentane	0.1%
N-octane	0.1%
Hydrogen sulfide	1.7%

Table 3. Inlet off-design conditions of compressor 1	
Pressure	43 bar a
Temperature	47 °C
Gas mixture	(Mw 19.64 g/mol)
Methane	78%
Nitrogen	0.5%
Ethane	17.9%
Propane	3.5%
I-butane	0.03%
N-butane	0.07%

Test Code on Compressors and Exhausters (PTC10) standard.

The main purpose of this article is to present a general method and calculation tool for predicting the field performance of a centrifugal compressor in an off-design condition. All numerical evaluations executed with Cmap software (Figure 1) have been developed using the most recent thermodynamic theories and machine aeromechanical models and in accordance to the ASME PTC10 standard. Cmap software has been used in re-injection plants in the Middle East, Houston (US), and North Africa to predict the performance when the gas mixture changed and to verify the performance during the shop test.

Method description

What follows is a simple explanation of the calculation process used to evaluate the compressor performances. For centrifugal compressors, performances are strictly linked to the inlet gas conditions. This consideration is valid both to the design and off-design performance.

The starting point is the availability of a centrifugal compressor performance curve, the relevant gas mix composition and thermodynamic conditions (pressure and temperature). Having this input data available, the software will perform all complex calculations in a fully automated way and will produce the expected compressor performances for inlet off-design conditions different from design/reference ones. The calculation algorithms used are able to predict both machine behaviour and thermodynamic real gas properties in off-design conditions.

From a fluid dynamic point of view, a strict similarity of flow at each performance point is necessary. For this reason, the non-dimensional parameters head coefficient, flow coefficient and Mach number must be conserved primarily (some additional conditions are requested on the machine Reynolds number and volume ratio).

The proposed method requires the following input:

- Reference/design compressor maps: in general, these maps provided by the machine's OEM provide a reliable indication of the machine capability and are considered as a starting point. If the input data is affected by error, the error shall be propagated in the outputs generated by this method. OEMs usually supply two different machine maps related to different moments of the compressor manufacturing process. 'Expected' maps are usually issued in the commercial/design stage, as tested maps are issued at the end of the manufacturing process when the compressor is shop or field tested. In general, both maps may be used as input for the method although 'as tested' maps may be considered preferable.
- Reference input conditions: reference/design maps are linked to specific inlet conditions such as inlet pressure, inlet temperature and gas mix composition. This data set shall be stated in order to proceed to off-design calculations.
- Off-design input conditions: these are the conditions at the compressor inlet (pressure, temperature and gas mix composition) in which the new performance should be obtained. Off-design conditions may be some alternative inlet conditions to be considered in the compressor design stage, or may be the actual inlet conditions at specific times during compressor operation.

Starting from the aforementioned inputs, the method proceeds to calculate the compressor

performances in off-design inlet conditions. Performance obtained as output from the described method shall be referenced in this article as off-design conditions, i.e. design performance adjusted to off-design operative conditions. When reference is made to off-design performance in off-design operative condition during operational time, these performances are also indicated as 'actual' performance. The calculation of off-design performance requires the capability to extract the invariant information that describe the compressor behaviour and use that information to rebuild the performance in new conditions. These calculations are intimately coupled with a thermodynamic of gas compression and of real gas mixtures, so that a variation in each component of the gas mixture is potentially able to manifest its effects, as well as change the inlet pressure and temperature. The connection among these different modelling areas allows the method to provide an accurate prediction of the compressor's performance. The method does not require information about the internal parts of the machine and, in this sense, should not be considered as a design tool but as an analysis tool that begins work after the machine design stage.

Table 4. Inlet off-design gas conditions of compressor 2

Pressure	154 bar a
Temperature	30°C
Gas mixture	(Mw 20.1 g/mol)
Methane	83.7%
Nitrogen	1.1%
Ethane	4.7%
Propane	2.8%
I-butane	0.4%
N-butane	0.4%
Carbon dioxide	4%
I-pentane	0.5%
N-pentane	0.2%
N-octane	0.3%
Hydrogen sulfide	1.9%

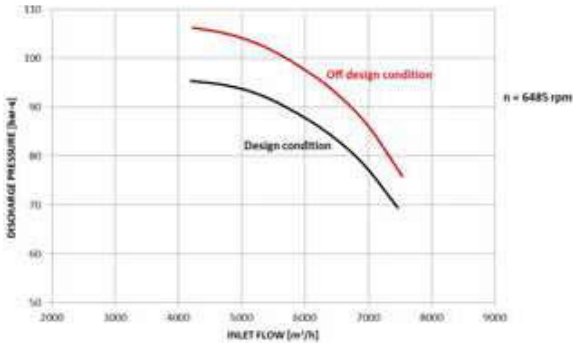


Figure 4. Comparison of discharge pressure between design and off-design condition (compressor 1).

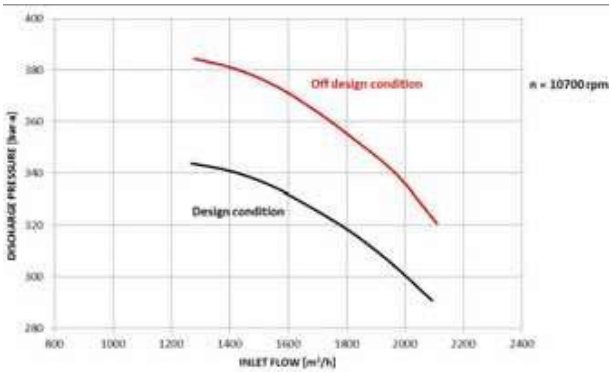


Figure 5. Comparison of discharge pressure between design and off-design condition (compressor 2).

Case study

Prediction of performance in off-design conditions

What follows describes how the presented method is applied using the Cmap software tool with two case studies. Compressors were running under off-design inlet conditions. The analysis developed with Cmap obtained the performances and compared them to the measured field values. In these case studies, the compressor performance maps, in design condition, were available for both machines. Figures 2 and 3 show the design maps (discharge pressure vs inlet flow) for compressor 1 and compressor 2 and relative design inlet conditions. The inlet design gas conditions of compressor 1 are in Table 1, while the conditions of compressor 2 are in Table 2.

Working from Figures 2 and 3, the expected performance curves in the off-design conditions have been calculated. The off-design inlet condition for compressor 1 and compressor 2 are in Tables 3 and 4. Figure 4 compares the performance curves (discharge pressure vs inlet flow) in design and off-design condition.

The Cmap software calculates the actual flow, the values of expected pressure, temperature, head and efficiency in the actual (off-design) conditions and compares them to the measured ones. With reference to the field values, Table 5 compares the pressures, temperatures – as read from transducers – to the software's predicted values.

Reading from Table 5, compressor 1's maximum error calculated is less than 1% and is approximately 9% for compressor 2. The analysis indicates that compressor 1 was running an operative performance aligned with design expectations. Compressor 2's performance, however, was not aligned with design expectations. For a compressor analyst, this comparison provides an important quantitative indication of the machine's health status and should drive the analysis towards an understanding of the possible causes.

Table 5. Comparing pressure and temperature

Compressor 1			
Properties	**Field value**	**Cmap prediction**	**Percentage error**
Discharge pressure (bar a)	98	97.6	+0.4%
Discharge temperature (°C)	122	123	-0.8%
Compressor 2			
Discharge pressure (bar a)	240.5	263.7	-8.8%
Discharge temperature (°C)	99	102	-2.9%



Figure 6. A screenshot of the Cmap 2.0 software.

The analysis obtained an evaluation of the efficiency deviation (difference between the actual compressor efficiency and the expected efficiency in the actual operative conditions). Time trends of the calculation results provided a useful analytical basis for compressor maintenance decisions. The method has been profitably used to predict compressor performance and support machinery maintenance activity planning.

Cmap conducts compressor performance predictions with different equations of state (EOS), depending on the gas mix considered in the calculation. For a hydrocarbon gas mixture, Lee-Kesler or Peng Robinson (PR) EOS can be used. For Freon R134a (CH_2FCF_3), the modified Benedict-Webb-Rubin (MBWR) EOS can determine the thermodynamic properties of the operating fluid.

Conclusion

Experiences with real compressors demonstrated that the performance predicted by the software was aligned with OEM predictions and field measurement for machines in good condition. It also showed that, in most cases, the deviation of a parameter, such as efficiency, indicates a problem.

The proposed method can be fully automated and offers benefits, especially for machines working in high and very high pressure ranges and under rapidly time varying process conditions.

The software's automated application makes it possible to provide continuous monitoring of machine performance and, therefore, exert automated surveillance and diagnostics. Furthermore, protection from surge for the compressor can be automatically and continuously updated to actual inlet conditions, overcoming the limitation of actual systems.

The methods proposed and described in this article can:

- Predict the performances of a centrifugal compressor in an off-design condition. The prediction of compressor performances is accurate even at high pressures, where the commonly used ideal gas theory introduces considerable errors.
- Predict the modification of surge points in actual operative conditions, with different inlet pressures and temperatures, different operative gas and implement advanced protection from surge.
- Have useful indications on the health of the compressor (diagnostics) based on the capability to analyse the performances and efficiency of the machine in a simple and immediate way.
- Support the decisions and planning of predictive maintenance activities.