PREDICTION OF CENTRIFUGAL COMPRESSOR PERFORMANCE IN OFF-DESIGN CONDITION

BY MASSIMILIANO DI FEBO AND PASQUALE PAGANINI

ABOUT THE AUTHORS

Massimiliano Di Febo is operation manager for IPC S.r.l. He holds a master's degree in mechanical engineering and is a registered professional engineer. He has more than 10 years' professional experience in centrifugal pump testing GE Nuovo Pignone specifications, applications, installations, diagnostic, and maintenance. He also has experience with machinery vibration diagnosis and rotating machinery field performances.

Pasquale Paganini is technical manager for IPC S.r.l. He holds a master's degree in mechanical engineering and is specialized in thermodynamic and energetic systems. He is a registered professional engineer with more than 10 years' experience. Email: pasquale.paganini@ipc-eng.com

INTRODUCTION

Centrifugal compressors are a vital component within process plants, are used widely in upstream and middle stream plants, and accomplish critical missions for the overall production goals in almost all cases. Compressors are important assets because of their impact on capital investment, critical impact on output loss caused by possible machine temporary unavailability, and related maintenance and repair costs.

In this perspective it is evident that understanding how the machine runs and works properly assumes a primary role. The capability to detect early indicators of eventual malfunctioning and identify and understand their causes and possible remedies gives valuable contributions to the plant's proficiency, minimizing overall operational costs due to the mentioned causes. This is known as predictive maintenance.

Today, a predictive approach is present across all the involved industries and applied over several kinds of machinery. For many and 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, being phenomenological, can be applied in the design stage where insight is given by original equipment manufacturers (OEMs) to rotor dynamics but often it assumes a more practical and empirical form on the operation floor, where the machine vibrational parameters are measured and compared to acceptable limits and used merely for alarm triggering. Predictive strategies based on the analysis of performance are increasing their presence as a tool for diagnostic and evaluation of the machine's health status during operational time. For centrifugal pumps, for instance, the use of the machine's model for comparing measured performance to design ones is relatively easy and straightforward. For centrifugal compressors, the same process is more complex because of the dependency of compressor performance from the gas mix composition and operative inlet conditions (inlet pressure and inlet temperature). For centrifugal compressors, therefore, an approach based on performance assessment requires a more complex machine model that should embed and couple several calculation capabilities from aeromechanics to thermodynamics.

One of the main difficulties of analyzing centrifugal compressors' operative performances arises from the need to have ready and available the compressor performance map adjusted to actual inlet conditions. Usually expected performances are described in terms of graphs of discharge pressures, discharge temperatures, polytropic heads, efficiencies, and absorbed power, related to the design inlet gas conditions. In general, it may happen that inlet conditions in the field are different from specification conditions defined in the machine's data sheets. A somewhat diffused practice consists in 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 pressures go up and the gas mix variability is introduced into the problem.

In these situations, to assess compressor performance, it is then necessary to proceed to adjust the design performance to operative conditions, taking into account all the complexity of the problem and then comparing that to measured values. This approach also is indicated in ASME PTC 10.[1]

The main purpose of this paper is to present a general method and calculation tool for prediction of centrifugal compressor field performances in off-design condition.[A]

[A]All numerical evaluations executed with Cmap software reported in this paper have been developed using the most recent thermodynamic theories and machine aeromechanical models and according to ASME PTC 10.

Item	Gas Name	Symbol
1	Acetylene	C_2H_2
2	Ammonia	NH_3
3	Argon	Ar
4	Benzene	C_6H_6
5	Iso-Butane	C_4H_{10}
6	n-Butane	C_4H_{10}
7	Iso-Butylene	C_4H_8
8	Carbon Dioxide	CO_2
9	Carbon Monoxide	CO
10	Chlorine	Cl_2
11	n-Decane	$C_{10}H_{22}$
12	Ethane	C_2H_6
13	Ethyl Acohol	C_2H_5OH
14	Ethylene	C_2H_4
15	Helium	He
16	n-Heptane	C_7H_{16}
17	n-Hexane	C_6H_{14}
18	Hydrogen	H_2
19	Hydrogen Chloride	HCL
20	Hydrogen Sulfide	H_2S
21	Methane	CH_4
22	Methyl Alcohol	CH_3OH
23	Nitrogen	N_2
24	n-Nonane	C_9H_{20}
25	Iso-Pentane	C_5H_{12}
26	n-Pentane	C_5H_{12}
27	n-Octane	C_8H_{18}
28	Oxygen	O_2
29	Propane	C_3H_8
30	Propylene	C_3H_6
31	Sulfur Dioxide	SO_2
32	Water Vapor	H_20
33	1-Butene	C_4H_8
34	2-Butene	C_4H_8
35	1.3 Butadiene	C_4H_6
36	Ethyl Chloride	C_2H_5Cl
37	Methyl Chloride	CH_3Cl
38	Pentylene	C_5H_{10}
39	Propadiene (Allene)	C_3H_4
40	Methyl Acetylene (Propyne)	C_3H_4
41	Toluene	C_7H_8
42	Freon R134a	CH_2FCF_3

Table 1. Gas Components

METHOD

Consider that, for a centrifugal compressor, performances are linked strictly to the inlet gas conditions. This consideration is valid to the design and off-design performance.

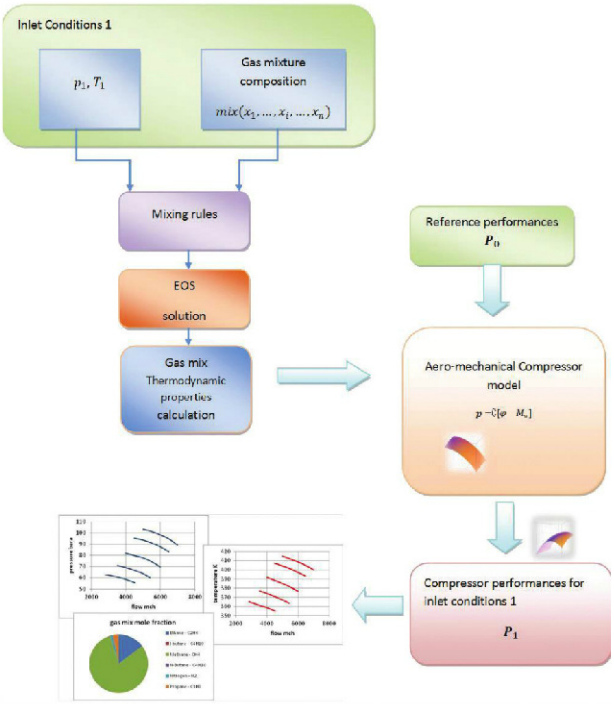


Figure 1. How Cmap Works

This 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 and produce the expected compressor performances for inlet pressures, inlet temperatures, and gas mix compositions different for design/reference ones.

Algorithms can predict both machine behavior and thermodynamic real gas properties in off-design conditions. Table 1 lists the gases that can be configured.

From a fluid dynamic point of view, a strict similarity of flow at each performance point is necessary. For this reason, the non-dimensional parameter head coefficient, flow coefficient, and Mach number must be conserved primarily.

The proposed method needs, then, the following inputs:

Reference/Design Compressor Maps: These maps generally are provided by the machine's OEM, give a reliable indication of the machine's capability, and are considered here as the starting point. These input data should be affected by error, and these errors 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, because 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, though "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 set of data is used 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 condition in some specific time during compressor operation.

Starting from the above-described inputs, the method proceeds to calculate the compressor performances in off-design inlet conditions. Performance

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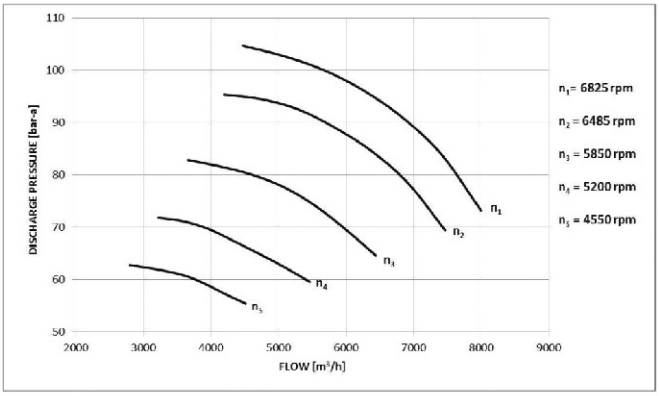


Figure 2. Design Map Of Compressor 1

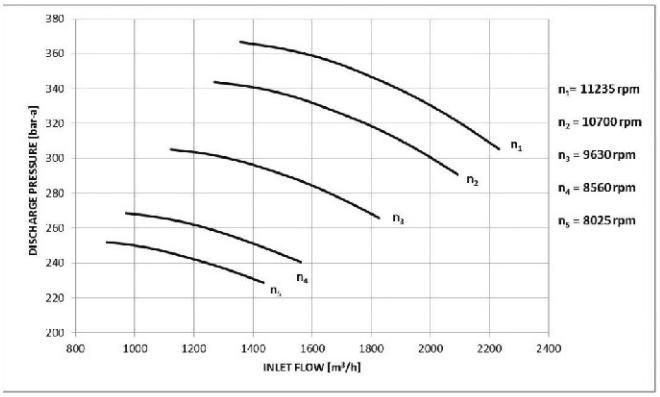


Figure 3. Design Map Of Compressor 2

• Pressure:	40.2 bara (583.1 psi)
•Temperature:	50°C (122°F)
• Gas Mixture (Molecular Weight [MW] 19.24 g/mole):	
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 Condition: Compressor 1

• Pressure:	150 bara (725 psi)
• Temperature:	37°C (98.6°F)
• Gas Mixture (MW 19.1 g/mole):	
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 Design Gas Condition: Compressor 2

• Pressure:	43 bara (623 psi)
• Temperature :	47°C (117°F)
• Gas Mixture (MW 19.64 g/mole):	
Methane	78%
Nitrogen	0.5%
Ethane	17.9%
Propane	3.5%
I-Butane	0.03%
N-Butane	0.07%

Table 4. Inlet Off-Design Condition: Compressor 1

• Pressure:	
• Temperature:	
• Gas Mixture (MW 20.1 g/mole):	
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%

Table 5. Inlet Off-Design Gas Condition: Compressor 2

obtained as output from the described method shall be referenced in the following paragraphs as "off-design conditions," i.e., design performance adjusted to off-design operative conditions. When reference is made to off-design performance in the off-design operative condition during operational time, these performances shall be indicated also as "actual" performance. Calculation of off-design performance requires the capability to extract the invariant information that describe the compressor behavior and use this information to rebuild the performance in new conditions. These calculations are intimately coupled with thermodynamics of gas compression and thermodynamics 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 a change of the inlet pressure and temperature. The connection among these different modeling areas allows the method to provide an accurate prediction of the compressor performance. The method does not require information about the internal parts of the machine, and should be not considered as a design tool but more correctly as an analysis tool that starts its job just after the completion of the machine design stage.

CASE STUDY: PREDICTION OF PERFORMANCE IN OFF-DESIGN CONDITIONS

Two real cases will be presented. The compressors under study were running under off-design inlet conditions. The analysis developed with Cmap allowed the performances in these off-design conditions to be obtained and a comparison to the measured field values.

In these case studies the compressor performances map in the 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.

Starting from Figures 2 and 3, the expected performance curves in the off-design conditions have been calculated.

Figures 4 and 5 compare the performance curves (discharge pressure vs. inlet flow) in design and off-design conditions.

The software Cmap calculated, at the actual flow, the values of expected pressure, temperature, head, and efficiency in the actual (off-design) condi-

Compressor 1

Properties	Field Value	Cmap Predict Value	% Error
Discharge Pressure (bar a)	98	97.6	0.4
Discharge Temperature (°C)	122	123	–0.8

Compressor 2

Properties	Field Value	Cmap Predict Value	% Error
Discharge Pressure (bar a)	240.5	263.7	–8.8
Discharge Temperature (°C)	99	102	–2.9

Table 6. Values Predicted By Cmap Software

tions and then compared that to the measured ones.

As field values for reference, Table 6 compares the pressures and temperatures as read from transducers to the value predicted by Cmap software.

The same comparison has been executed for head and polytropic efficiency. In Table 6, note how the maximum error calculated is less than 1% for Compressor 1 and the error calculated is about 9% for Compressor 2.

The analysis indicates then that Compressor 1 was running with operative performance aligned with design expectations. Compressor 2, however, was running with performance not aligned with design expectation. This comparison gives the compressor analyst an important quantitative indication on the machine health status and should drive the analysis toward an understanding of possible causes that may justify the observed difference.

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

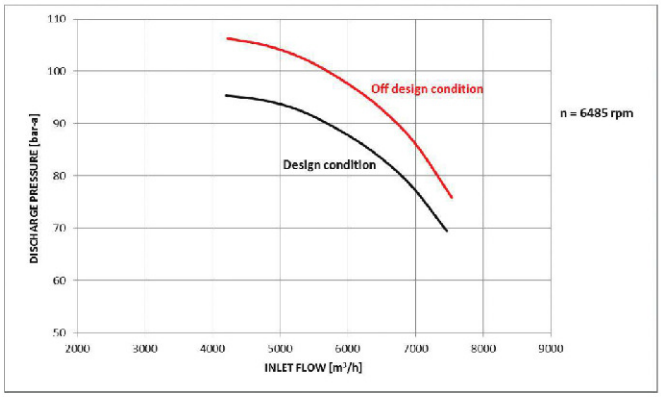


Figure 4. Comparison Of Discharge Pressure Between Design And Off-Design Condition (Compressor 1)

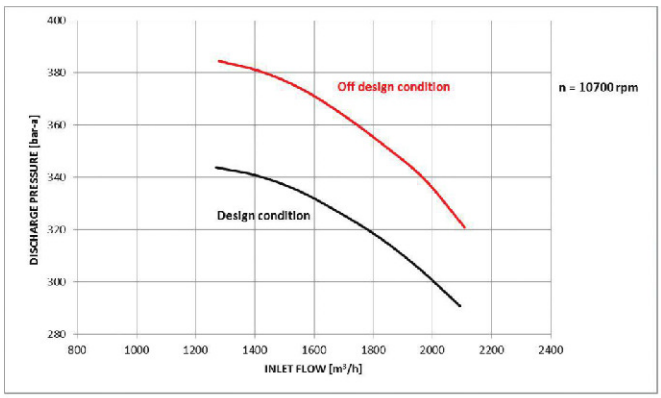


Figure 5. Comparison Of Discharge Pressure Between Design And Off-Design Condition (Compressor 2)

Cmap allows compressor performance prediction using different equations of state depending on gas mix considered in the calculation. For hydrocarbon gas mixture, Lee-Kesler or PR EOS can be used. For Freon R134a, the MBWR EOS shall be selected to determine the thermodynamic properties of the operating fluid.

CONCLUSIONS

Experience with real machinery showed that compressor performance prediction obtained with Cmap software are in very good alignment with OEM predictions and field measurement for machines in good condition. Experience also showed that, in most cases, the deviation of some parameters, such as efficiency, indicates potential problems on the machine.

The proposed method may be used in full automation and could provide benefits, especially for those machines that work in high- and very high-pressure ranges and under rapidly time varying process conditions.

Automated application of Cmap provides a continuous monitoring of the machine performance, therefore exerting automated surveillance and diagnostics. Also, the compressor protection from surge can be updated automatically and continuously to actual inlet conditions, overcoming limitations of actual systems.

Methods proposed and described in this paper allow the following:

- Prediction of centrifugal compressor performance in an off-design condition. The prediction of compressor performances is accurate even at high pressures, where the ideal gas theory commonly used introduces considerable errors.
- Prediction of the modification of surge points in actual operative conditions, with different inlet pressure and temperatures, different operative gas, and implementation of advanced protection from surge.
- Indications on the health of the compressor (diagnostics) based on the capability to analyze the performance and efficiency of the machine.
- Predictive maintenance and activities to support decisions and planning. GCM

REFERENCE

[1] ASME PTC 10-1997 (R2014), "Performance Test Code on Compressors and Exhausters" (New York, NY: American Society of Mechanical Engineers, 1997).