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# Prediction of Centrifugal Compressor Performance in Off-Design Condition

## Introduction

Centrifugal compressors are a vital component within process plants and compression machines are widely used in upstream as well in mid-stream plants accomplishing critical missions toward meeting overall production goals.

Compressors are often one of the most important assets in these plants considering their capital investment costs, and the critical impact caused if temporarily unavailable along with their related maintenance and repair costs.

From this perspective it is evident how the capability to understand if the machine is running and working properly assumes a primary role. The ability to detect early indicators of potential malfunctions and understanding their causes and possible remedies gives a valuable contribution toward plant proficiency, allowing overall operational costs to be minimized.

This growing trend is generally known as predictive maintenance. Today the predictive approach is well present across all of the involved industries and applied over several types of machinery. For many of the most common centrifugal machines the predictive techniques commonly implemented are connected to the vibrational and structural dynamic aspects of the machine's rotor operational conditions. This approach, being phenomenological, can be applied in the design stage where insight is given by OEMs to rotor dynamics but often it assumes more practical and empirical form at operation floor, where basically 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 diagnostics and evaluation of machine health status during operational time. For centrifugal pumps, for instance, the use of machine model for the purpose of comparison of measured performance to design performance is relatively easy and straightforward. For the centrifugal compressor 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 an approach based on performance assessment requires a more complex machine model that should embed and couple several calculation capabilities from aeromechanics to thermodynamics.

In fact, one of the main difficulties for the analysis of 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 data sheets. A somewhat diffused practice consists of 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, in order 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 compare that to measured values. This is basically the approach also indicated on PTC10.

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 conditions. All numerical evaluations executed with Cmap software reported in this paper have been developed using the most recent thermodynamic theories and machine aero-mechanical models in accordance to the ASME PTC10 (Performance Test Code on Compressors and Exhausters) standard.

## Methodology

Here we provide a simple explanation of the calculation process used to evaluate the compressor performances. As a starting point we can consider that, for a centrifugal compressor, 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 pressures, inlet temperatures and gas mix compositions different for design / reference ones.

| Item | Gas name | Symbol |
|---|---|---|
| 1 | Acetylene | $C_2H_2$ |
| 2 | Ammonia | NH3 |
| 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 Sulphide | $H_2S$ |
| 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 | Sulphur Dioxide | $SO_2$ |
| 32 | Water Vapour | $H_20$ |
| 33 | 1-Butene | $C_4H_8$ |
| 34 | 2-Butene | $C_4H_8$ |
| 35 | 1.3 Butadiene | $C_4H_6$ |
| 36 | Ethyl chloride | $C_2H_5C_l$ |
| 37 | Methyl Chloride | $CH_3C_l$ |
| 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*

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.

The proposed method then needs the following inputs:

a) Reference/Design compressor maps: in general these maps provided by the machine OEM, give a reliable indication of the machine capability and are considered here as starting point. It is clear that in case these input data should be affected by error, these 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, while 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.

b) 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 shall be stated in order to proceed to off-design calculations.

c) 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.

With the above described 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 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 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 compressor behavior and that 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 in this sense it 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.

Calculation algorithms used are able to predict both machine behavior and thermodynamic real gas properties in off-design conditions. Below the list of gas can be configured:

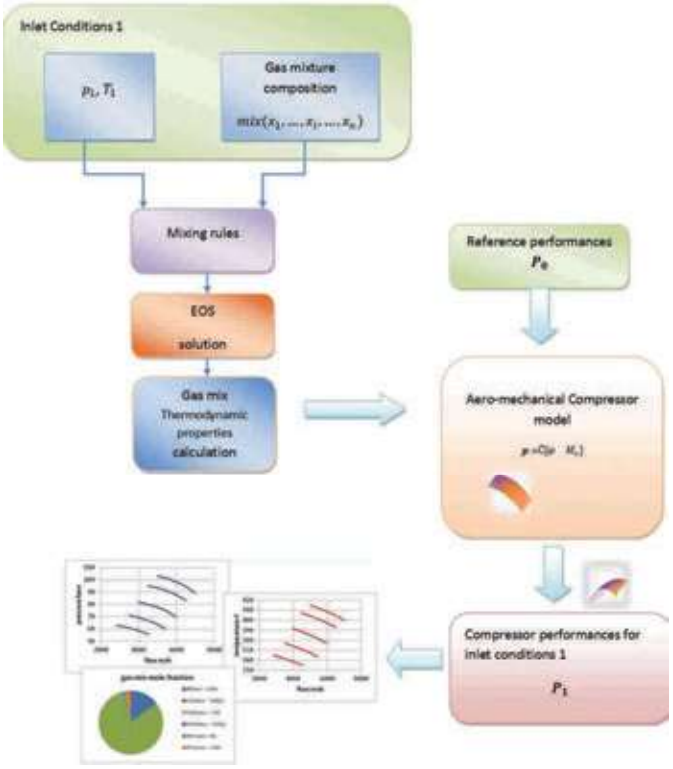



*Figure 1: How Cmap works*

Case Study: Prediction of Performance in Off-Design Conditions
This paragraph describes how the presented method is applied using the Cmap software tool.

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

In these case studies, the compressor performances map in design condition were available for both machines. The following figures and table show the design maps (discharge pressure vs inlet flow) for compressor 1 and compressor 2 and relative design inlet conditions:

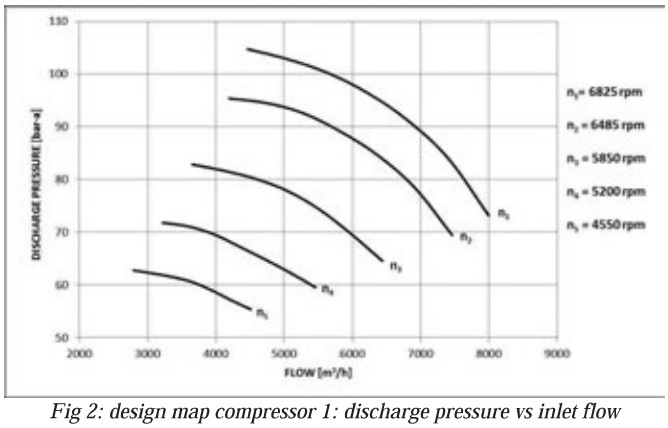



*Fig 2: design map compressor 1: discharge pressure vs inlet flow*

The following table indicates the inlet design gas conditions of Compressor 1.

| | |
|---|---|
| • Pressure: | 40.2 bar a |
| • Temperature: | 50°C |
| • Gas Mixture (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*

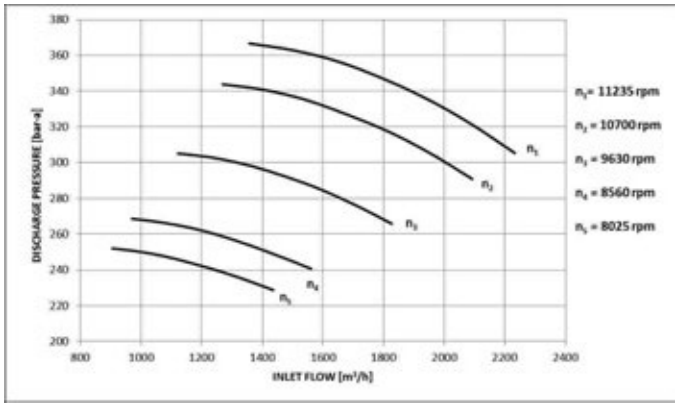



*Fig 3: Design map compressor 2: discharge pressure vs inlet flow*

The following table indicates the inlet design gas conditions of Compressor 2.

| | |
|---|---|
| • Pressure: | 150 bar a |
| • Temperature: | 37°C |
| • 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*

Considering the above maps, the expected performance curves in the off-design conditions have been calculated.

The following tables are indicative of the off-design inlet condition for Compressor 1 and Compressor 2.

| | |
|---|---|
| • Pressure: | 43 bar a |
| • Temperature: | 47°C |
| • 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: | 154 bar a |
| • Temperature: | 30°C |
| • 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*

The following picture compares the performance curves (discharge pressure vs inlet flow) in design and off-design condition:

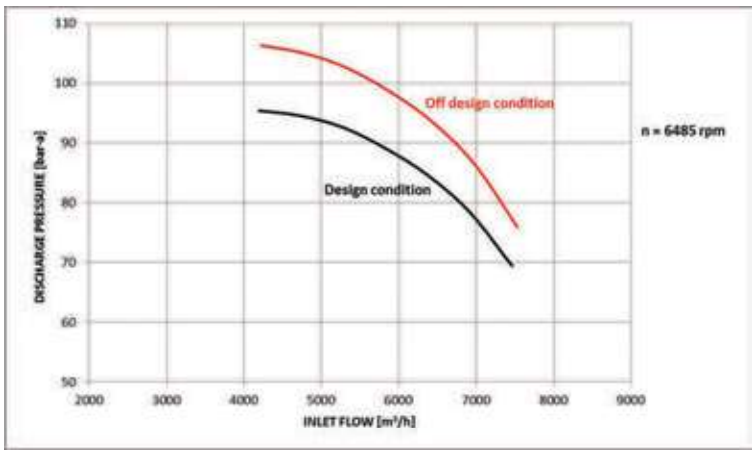



*Fig 4: Comparison of discharge pressure between design and off-design condition (Compressor 1)*

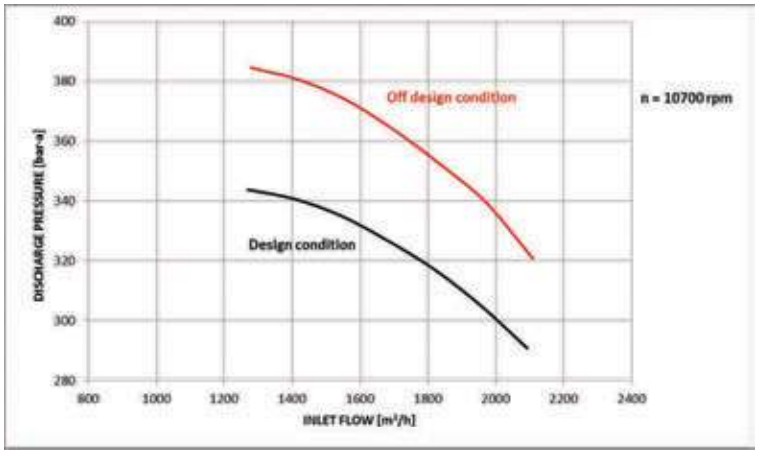



*Fig 5: Comparison of discharge pressure between design and off-design condition (Compressor 2)*

The Cmap software allowed the calculation, at the actual flow, the values of expected pressure, temperature, Head and efficiency in the actual (off-design) conditions and then compares it to the measured ones.

With reference to the field values, the following table compares the pressures and temperatures as read from transducers to the value predicted by Cmap software:

Compressor 1

| Properties | Field value | Cmap predict value | Percentage 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 | Percentage error |
|---|---|---|---|
| Discharge pressure [bar a] | 240.5 | 263.7 | - 8.8 |
| Discharge temperature [°C] | 99 | 102 | - 2.9 |

The same comparison has been executed for Head and Polytropic efficiency.

In the previous tables it can be noted how for Compressor 1 the maximum error calculated is less than 1% and for Compressor 2 the error calculated is about 9%.

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

The analysis developed using Cmap also allowed to obtain 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 advantageously used to predict compressor performances and to support planning of machinery maintenance activities.

Cmap allows compressor performance prediction using different equations of state (EOS) depending on the 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.

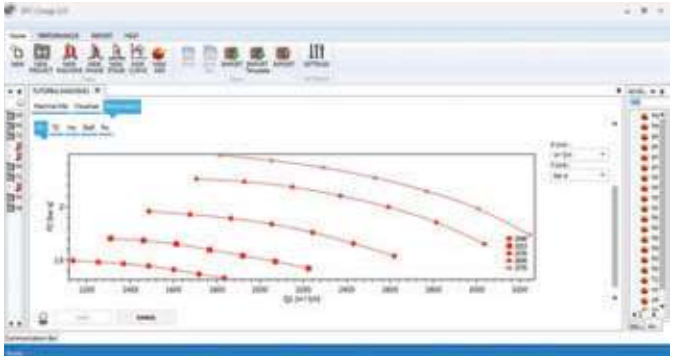


*Fig 6 Screenshot Cmap 2.0*

## Conclusions

Experiences 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. Also experience showed that in most cases the deviation of a parameter such as the efficiency, indicates the eventuality of a problem on the machine.

The proposed method may be used in a fully automated way, and could provide high 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 gives the possibility to provide a continuous monitoring of the machine performance and therefore exert an automated surveillance and diagnostic. Also the compressor protection from surge can be automatically and continuously updated to actual inlet conditions overcoming limitation of actual systems (see SPS surge protection system - IPC™, all rights reserved).

Methods proposed and described in this paper can allow to:

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

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