Cmap

Centrifugal Compressor performances evaluation software

How Cmap works

Performance Evaluation Software

IPC INDUSTRIAL PLANTS CONSULTANTS

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		How Cmap Works		Job: 90-20
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1-Introduction, scope and applicability

The main purpose of this paper is to provide some insight about concepts at base of Cmap calculation methods.

This paper is applicable to the version 1 of Cmap, but it has been written with the general purpose to illustrate main concepts at the base of the software philosophy. So while yet now new features are already under implementation for the new Cmap version, we consider that this paper will remain still valid also for next software versions.

In the paragraph 2 the paper will start with a preliminary explanation of the centrifugal compressor performances prediction problem. It will than continue with some necessary basic. In the paragraph 3 Cmap algorithms philosophy will be discussed along with calculation details of main tasks. Main formulation used will be also included. In the paragraph 4 an overall picture of the calculation process will be given.

One of the main target of this paper is to provide, to the Cmap user and to the interested person, a overall understanding of the concept flow processes of centrifugal compressor performances calculations and Cmap calculations method.

2- Cmap calculation processes, preliminary definitions

As known centrifugal compressor performances are strictly linked to compressor inlet reference conditions. Output performances are dependant from inlet gas composition, and inlet gas thermodynamic conditions (i.e, inlet pressure and temperature) and from the character of the compressor itself.

In most cases the evaluation of centrifugal compressor performances is quite difficult. Infact the comparison of field measurements to expected values may become complicated because the expected performances are often expresses with reference to design condition, while field measured performances are referenced to actual condition. In order to correctly compare the expected performances with field measured one its necessary to have both them referenced to the same inlet condition. Than it is necessary adjust one of the two performances to the inlet condition of the other. As example the expected performances should be adjusted to the actual suction conditions.

CMAP software allows, starting from the reference (or design) performances, to predict expected centrifugal compressor performances in actual conditions. In this way it will be possible compare the actual performances to the expected ones with homogeneous inlet condition and consequently analyze quantitatively the machine performances behavior. CMAP provides to the centrifugal compressor analyst or industry user a powerful and easy tool to predict the machine performances under different operative conditions. It also uses these

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information to evaluate how much are acceptable the actual ones. Analysts and engineers that use CMAP will have all quantitative information about machine status necessary useful to define diagnostic strategies and maintenance activities.

With these main tasks in mind, Cmap software has been designed to develop, in a fully automated way, thermodynamic and aero-mechanical calculations necessary to obtain centrifugal compressor performances when inlet conditions differ from reference ones.

Starting from machine performances data in reference operative conditions, Cmap is able also to build a machine model that captures the character of the machine. In other words the obtained compressor model is characteristic of the machine and represents the invariant base of information upon which it is possible to build the predictions of the compressor performances in operative conditions different from the reference ones. In the following pages we'll describe how Cmap accomplishes to this task.

In fact since from long time centrifugal compressor engineers are in search of an invariant performance curve able to represent the compressor under different operative condition. While, when compressibility effect may be considered negligible (low Mach flows), head vs flow curves can be used with technically acceptable results, this method leads to considerable errors for many process gas applications where the compressibility effect becomes important. Also more sophisticated maps like the reduced head vs reduced flow curves shown to be inadequate to correctly predict compressor performances in these conditions.

At today one reliable way to approach the problem is to refer to correlations of head coefficient , polytrophic efficiency, flow coefficient and Mach number. Using these correlations, from a calculation point of view introduces anyway a certain degree of complication. In the following pages it will be shown as the necessary calculation steps cannot be easily developed by hand, and that consequently a computational tool will be useful or necessary in order to manage the problem. Cmap has been designed in order to provide necessary calculation capability necessary to implement this last method for the centrifugal compressor performances prediction problem.

In order to understand concepts at foundation of Cmap calculations, it is necessary to recall some basic definitions. At first we can consider the set of process parameters that describe the compressor inlet condition:

p_1, suction pressure

T_1, suction temperature

$mix(x_1, \ldots, x_i, \ldots, x_n)$, inlet gas mixture composition

($x_1, \ldots, x_i, \ldots, x_n$ molar fractions of each gas mixture component)

We can define this set of parameters as a variable $i = \{P_1 \quad T_1 \quad mix\}$, inlet condition

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Inlet conditions may have different values such as the reference value i_0 and the actual value i_a

$$i_0 = \{P_{10} \quad T_{10} \quad mix_0\}$$

$$i_a = \{P_{1a} \quad T_{1a} \quad mix_a\}$$

Also we can define a set of process parameters that describes the compressor performances at discharge section:

p_2, discharge pressure

T_2, discharge temperature

Discharge performance parameters may be grouped into a variable $\boldsymbol{P} = \{p_2 \quad T_2\}$, compressor performances.

Compressor performances may be expressed also in other terms, as example:

$\boldsymbol{P_p} = \{H_p \quad \eta_p\}$, Polytrophic compressor performances

Also other combinations of output parameters may be used to describe compressor performances, even if for the purpose of this explanation of Camp main features, the two ones mentioned will be sufficient.

As already recalled, discharge performances are consequent to inlet conditions, than for each specific performance variable, it is necessary to specify the associated inlet condition variable:

$\boldsymbol{P_0} = \{p_{20} \quad T_{20}\}$ represents the compressor performance with reference inlet conditions i_0

$\boldsymbol{P_a} = \{p_{2a} \quad T_{2a}\}$ represents the compressor performance with actual inlet conditions i_a

The base concept of Cmap approach is that the compressor performances may be considered as result of a particular operation (D) between two terms: the first is an invariant information that represent the character of the compressor (p) and the second is the particular inlet condition variable considered (i)

Following this base assumption the discharge performances may be expressed with the following notation:

$\boldsymbol{P_0} = \mathrm{D}|_0[p]$

$\boldsymbol{P_a} = \mathrm{D}|_a[p]$

The inverse operation A allows to extract from discharge performances and relevant associated inlet condition, the compressor character p.

$\boldsymbol{p} = \mathrm{A}|_0[P_0]$

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$$\boldsymbol{p} = \mathrm{A}|_a[P_a]$$

Than it is possible obtain for every inlet condition the following relation;

$$\boldsymbol{P_i} = \mathrm{D}|_i[\mathrm{A}|_i[\boldsymbol{P_i}]]$$

Being the calculation process bijective, than

$$\mathrm{A} = \mathrm{D}^{-1}$$

The Cmap method is than based on a calculation process that, using the explained concepts, provides a prediction of compressor performances using integrated aeromechanical and thermo-dynamical computational tools to manage the numerical complexity that arises from the nature of the problem.

3-Cmap algorithm description

In order to develop compressor characterization step, Cmap proprietary algorithm calculates the compressor characteristic 3d performances function:

$$\boldsymbol{p} = \begin{Bmatrix} \psi \\ \eta_p \end{Bmatrix} = \mathrm{C}[\varphi \quad M_u]$$

Where C is the compressor characterization operator.
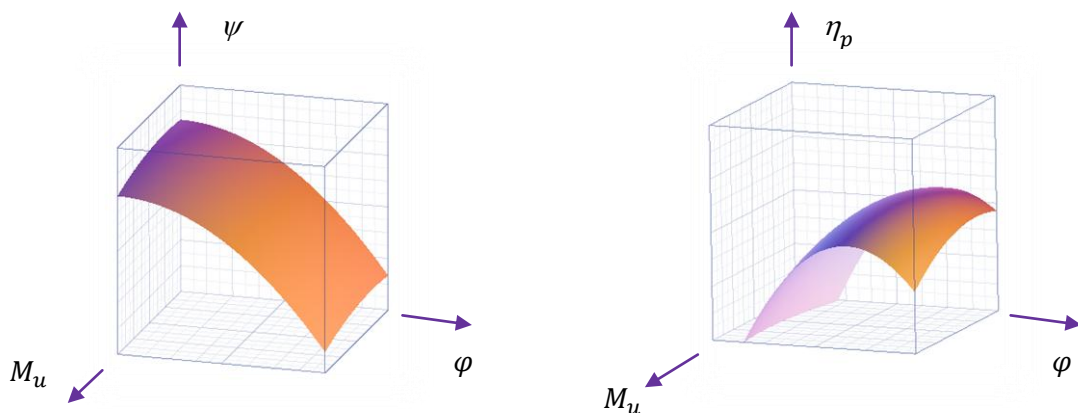
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Where:

$\psi = \frac{gH_p}{u_2^2}$, Head coefficient

$\varphi = \frac{4}{\pi}\frac{Q}{\omega d_2^2}$, flow coefficient

$M_u = \frac{u_2}{\sqrt{k_v z_1 R T_1}}$, Mach Number

$\eta_p = \frac{H_p}{H_i}$, polytrophic efficiency

The compressor characterization function is obtained from performances functions, such as discharge temperature and discharge pressure. Performances functions depend from suction flow and compressor speed.

$$C = A|_i[P_i]$$

$$i = \{\quad p_{1i} \quad T_{1i} \quad mix_i\}$$

Where $P_i = \begin{Bmatrix} p_2 \\ T_2 \end{Bmatrix}$

$p_2 = f(Q,n)$, discharge pressure

$T_2 = f(Q,n)$, discharge temperature

n, compressor speed

Q, inlet volumetric flow

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Cmap calculation capabilities are based on two main tasks:

3.1. Gas mixes thermodynamic properties calculation

3.2. Compressor aeromechanical model calculation

3.1. Task 1: calculation details

The task 1 is developed by Cmap developing 3 calculation steps:

a-gas mixture: using latest formulation for gas mixtures, Cmap determines the mixture parameters necessary for following execution steps. About the Mixing rules, Cmap implements the Kay's mixing. Through these equations, reduced gas mix parameters are calculated.

$$\omega = \sum_j x_j \omega_j$$

$$V_c = \frac{1}{8} \sum_j \sum_k x_j x_k \left(V_{cj}^{\frac{1}{3}} + V_{ck}^{\frac{1}{3}} \right)^3$$

$$T_c = \frac{1}{8 V_c^{\eta}} \sum_j \sum_k x_j x_k \left(\left(V_{cj}^{\frac{1}{3}} + V_{ck}^{\frac{1}{3}} \right)^3 \right)^{\eta} \sqrt{T_{cj} T_{ck}} \, \kappa_{jk}$$

ω, acentrc factor

V_c, T_c, gas mixture pseudo-critical volume and temperature

b-Cmap solves the real gas Equation Of State: Thanks to the availability of parameters calculated at the previous step, it is possible to solve the EOS. Cmap actual version implements the Lee-Kesler equation of state, that provides good results over an extend application range. Cmap also automatically detects an eventual mix saturation in all expected conditions.

After the EOS solution step, the software proceeds to calculate all the requested thermodynamic properties.

Lee Kesler EOS: (modified by Plock,Knapp, Prausnitz and team)

$$Z = Z^{(0)}(T_r, P_r) + \omega Z^{(1)}(T_r, P_r),$$

$$Z = \left(\frac{P_r V_r}{T_r} \right) = 1 + \frac{f_1(T_r)}{V_r} + \frac{f_2(T_r)}{V_r^{\,2}} + \frac{f_3(T_r)}{V_r^{\,n}} + f_4(T_r)[(\alpha + \frac{\gamma}{V_r^{\,2}}) \frac{1}{V_r^{\,m}}] \exp(-\frac{\gamma}{V_r^{\,2}}),$$

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other EOS that will be implemented in next Cmap version:

1. PR: Peng Robinson

2. RKS: Redlich-Kwong-Soave

3. BWRS: Benedict-Webb-Rubin-Starling

4. FREON family

The actual Cmap version (v.0.1.2) works with the following hydrocarbons:

#	Mix Component	11	N-buthane
1	Argon	12	N-decane
2	Carbon Dioxide	13	N-Heptane
3	Carbon Monoxide	14	N-exane
4	Ethane	15	Nitrogen
5	Helium	16	N-nonane
6	Hydrogen	17	N-octane
7	Hydrogen Sulfide	18	N-pentane
8	I-butane	19	Oxygen
9	I-pentane	20	Propane
10	Methane	21	Water

Cmap allows to freely configure a gas mix composition using the above listed hydrocarbons.

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c- Cmap calculates the gas mixture thermodynamic properties necessaries for following machine performances estimation.

Here there is a detail of the main gas mix thermodynamic properties calculated by Cmap actual version:

Isobaric heat capacity

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

Isochoric heat capacity

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

Polytropic volume exponent

$$n_v = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_{\eta_p}$$

Polytropic temperture exponent

$$n_T = \frac{1}{1 - \frac{p}{T}\left(\frac{\partial T}{\partial p}\right)_{\eta_p}}$$

Isoentropic volume exponent

$$k_v = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s$$

Isoentropic temperature exponent

$$k_T = \frac{1}{1 - \frac{p}{T}\left(\frac{\partial T}{\partial p}\right)_s}$$

Specific Gas constant

$$R = \mathscr{R} / M$$

Gas compressibility factor

$$p \cdot v = z \cdot R \cdot T$$

Calculated thermodynamic properties will than change with the configured gas mixture composition and as function of the considered thermodynamic properties.

As consequence even all the following performances calculation will depend also from the particular gas mix composition configured. Diversely from other calculation tools, this allows to Cmap to provide performances calculation always fitted to the actual operative conditions.

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3.2. Task 2: Calculation details

Cmap develops the performances calculation using the aero-mechanical compressor model $\mathbb{C}$.
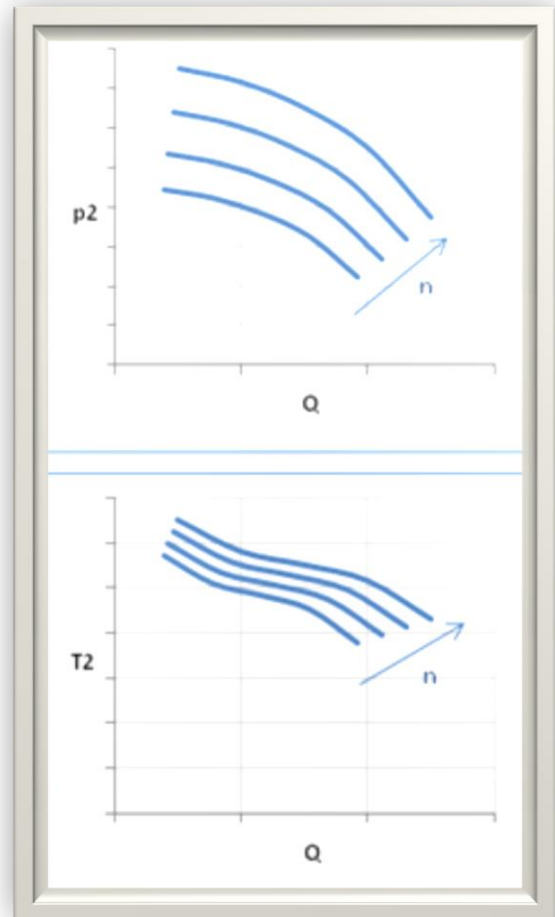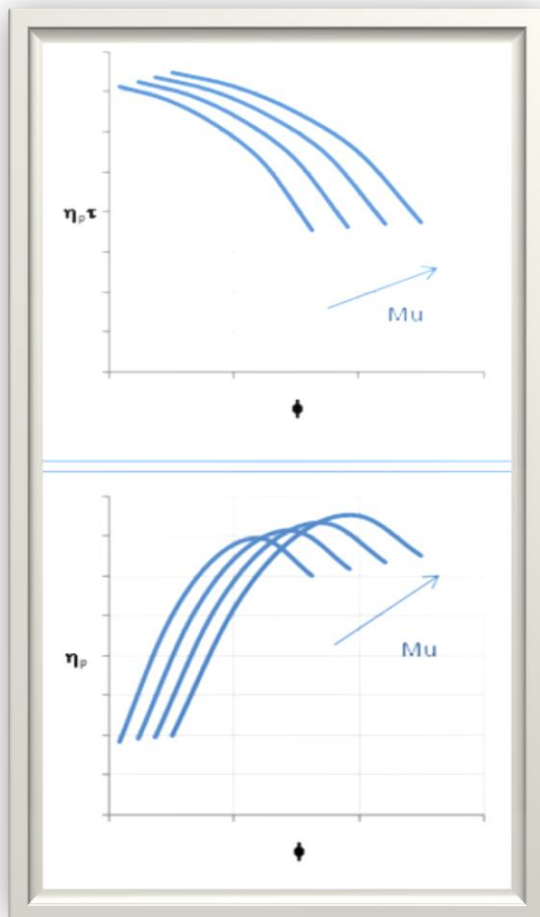
$$\mathbb{C}$$

$$\eta_p \tau = f(\varphi, Mu)$$

$$\eta_p = f(\varphi, Mu)$$

$$p_2 = f(Q, n) \qquad H_p = f(Q, n)$$

$$T_2 = f(Q, n)$$

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Performances parameters are calculated using also the following machine equations:

$$p_2 = p_1 \cdot \beta$$
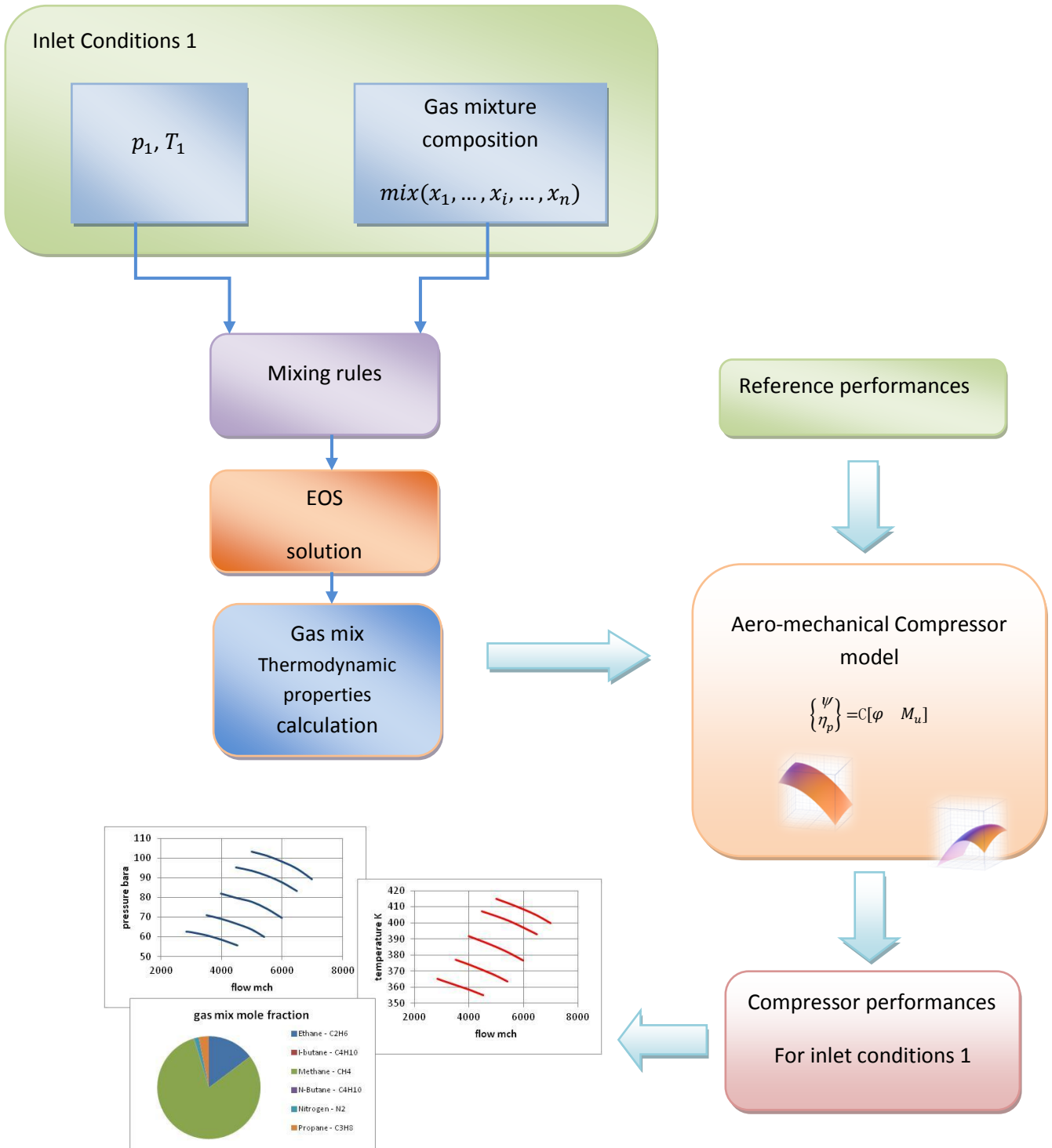
$$T_2 = T_1 \cdot \beta^{\frac{n_T - 1}{n_T}}$$

$$\beta = \left[1 + \frac{H_p}{z_1 R T_1} \cdot \frac{n_V - 1}{n_V} \right]$$

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4. Overall calculation flow process

The following diagram shows the concept flow for thermodynamic properties calculations:

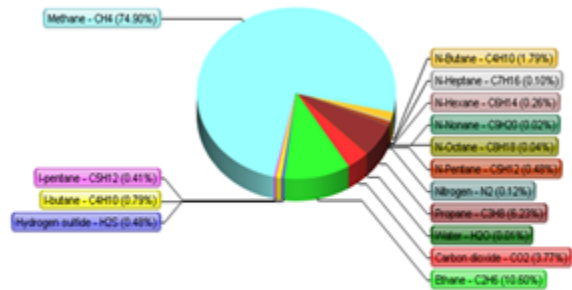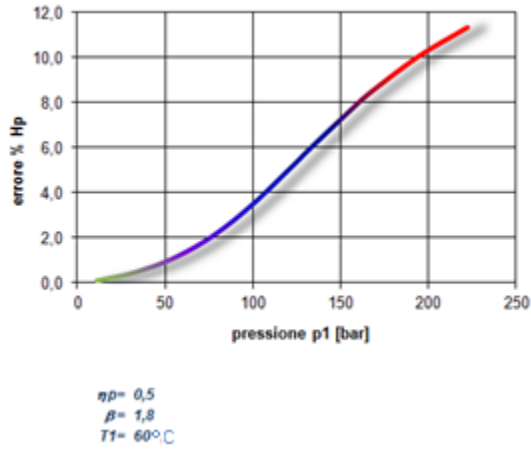| 0	issue		GP	PP	MDF	02/07/12	TNS730-MRK-PRG720-CMP-How Cmap works-ENG-PRG250-rev.0.	
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5-Notes

Cmap determines the compressor performances using as starting reference information the compressor aero-mechanical model and applying the machine performance equations. These equations recall the gas thermo-dynamic properties. Cmap calculates these properties as function of the gas mix composition, solving the relevant equation of state. May be its useful clarify that all Cmap calculations take in consideration the gas mix chemical composition and the suction condition of pressure and temperature, not only the overall mix molecular weight. Cmap calculations are then dependent not only form the mix molecular weight but from the overall gas mix composition. This means that for instance it could happen to manage two different mixes with different composition but with the same molecular weight. In this case, even if the two gases have the same molecular weight, Cmap will calculate different thermodynamic properties for each one of them.

Conventional centrifugal compressor performances calculation methods are based on simplified formulations that model the gas transformation trough the isentropic and polytrophic transformation exponents. These approximate formulations may be acceptable in limited operating ranges where the gas behavior is similar to the ideal gas model. The simplifications used in the current practice may be considered acceptable when working in low pressure ranges or, in more general way, in low compressibility flow conditions. But these simplified theories become progressively more approximate, especially when approaching the high pressures range where introduced errors do not allow to provide enough accurate predictions necessary.

Diversely Cmap, using the most recent thermodynamic approach for real gases, calculates isentropic an polytrophic exponents for temperature and volume transformation. This approach is applied always for the specified gas mix composition and provides accurate gas and machine behavior prediction and finally a reliable compressor performances prediction in actual suction conditions. *Cmap approach provides very precise calculation especially at high pressure ranges where traditional formulation introduce considerable errors*

The following figure shows the error on calculated polytrophic efficiency between traditional simplified calculation methods and the Cmap detailed calculation method.

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$\eta p = 0,5$
$\beta = 1,8$
$T1 = 60°C$

For more severe applications this capability becomes upmost important. In fact traditional approximated calculation method fail in correctly predict the compressor performances. In these cases introduced errors become important, because they may cause a lack of analytical support capability for evaluation of machine healthy and performances.

Cmap allows to overcome these problems providing full calculation power without limiting approximations.

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6-Reference documents

For further insight please refer also to the following IPC papers:

- CMAP_draft_quick guide rev1

- Cmap UG notes on method

- Cmap User Guide

- TR 230_12 - validation case-rev0

- BRO-SPS-PRG250-additional notes on SPS-rev5

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