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Development of turbomachines for renewable energy systems and energy-saving applications

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Abstract

Turbomachines play a significant role in some key sectors as aircraft and marine propulsion, power production, heat ventilation and air conditioning and chemical processing. The success of dynamic machines is connected to the wide variety of demands that they can cover, together with their compactness, reliability and availability.

In this respect, such machines are the favourite candidate to support an efficient exploitation of some renewable energy sources and the development of energy-saving systems. Innovative plants require machines which can work with new fluids (e.g. Organic Rankine Cycle systems) or in new operating conditions (e.g. high-flexibility or new pressure ratios) and it poses new challenging aspects in the preliminary machinery design. Moreover, another challenging aspect is how innovative techniques (e.g. high-integrated design systems, 3D printing) can be integrated in the design process and how much they can affect the machine development and final performance. Two case studies are presented to focus the attention on such aspects, discussing preliminary design and prototyping of "unconventional" turbomachines.

Keywords: Turbomachinery design; renewable energy; energy saving systems

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1. Introduction

Turbomachines play a significant role in some key sectors as aircraft and marine propulsion, power production, heat ventilation and air conditioning, chemical processing. Just to have in mind the total value of production and reasonable mid-term projections, some numbers can be cited: Analyst Stuart Slade reports $84.3 billion for the overall gas turbine market worldwide, predicted to reach $100.6 billion by 2032 [1]. The air compressor market, valued at around $19.8 billion in 2016 and projected to reach at $26.8 billion by 2023, in 2016 was constituted for around 24% by centrifugal-based turbomachines [2].

The success of dynamic machines is due to the wide multiplicity of requirements that they can cover (e.g. type of fluids, elaborated mass flow rates, pressure increase/decrease) as well as to their compactness, reliability and availability. Although after more than a century of technology development in any traditional arena the most prevalent innovations consist of improving efficiency, efficacy and flexibility [3-5], new prospects are growing nowadays.

According to the International Energy Agency (IEA) reports [6], renewable energy net capacity has been growing dramatically worldwide, reaching around 165 GW in 2016 and predicted to expand by 43% by 2022. China, USA, India and EU are expected to lead this "energy revolution" by means of focused policies: examples are federal incentives and state-level policies in USA [7] and a new regulatory framework in EU which includes a renewable energy target of 32% for 2030 with an upward revision by 2023 [8, 9]. Excluding PV plants, the efficient exploitation of renewable energy sources (wind, concentrated solar power, hydropower, geothermal, tide, biofuels) requires efficient machines suitable for such purposes.

Moreover, the application of energy-saving techniques to any sector has become a priority to reduce the environmental impact of mankind activities. In particular, the industrial sector consumes more energy than any other one: it was estimated that in 2011 it consumed about 37% of the world's delivered energy [10]. Each country has adopted its own Energy Policy to improve the energy saving in the national key sectors. For example, to boost the European economy and protect the climate [11], the new regulatory framework in EU includes an Energy Efficiency target of 32.5% for 2030. Obviously, plants based on innovative concepts ask for efficient machines which, in some cases, have to work with new fluids (e.g. Organic Rankine Cycle systems) or in new operating conditions (e.g. very high-flexibility or new pressure ratios). Such requirements lead to new challenging aspects in the machinery design and manufacturing.

In some cases, the prevalent technology change is incremental and it leads to improvements in efficiency flexibility and reliability of the specific component. It is what has been happening to wind turbines [12, 13], steam turbines for Concentrated Solar Power Plants (CSP) [14, 15] or gas turbines for CSP and biofuels [16-18]. In other cases, technology changes are more "radical" and they involve the design of new machines like for supercritical Carbon dioxide (sCO_2) power cycles [19] or Organic Rankine Cycles (ORCs) for Waste Heat Recovery systems, CSP or geothermal [20-22]. In the first instance, design procedures are consolidated and the development is limited to a technological upgrade of existing machines. On the contrary, for the second category, many challenging aspects affect any step of the design and development of a new machine.

2. Design Process for Turbomachines

The design process of a turbomachine can be divided into four main levels, as reported briefly in Figure 1. Passing from level 1 to level 4, the more the machine is designed in detail, the more applied models should correspond to real physical phenomena inside any component. The process requires continuous judgment by the designers and, according to their experience and confidence with the specific design problem, many iterations from one level to another one could be necessary. Eventually, one or more prototype rig testing activities will verify the component performance and they will be used to tailor the models applied at levels 1, 2 and 3 to the specific design case.

At level 1, similarity rules are usually applied for the preliminary selection of reference machines. It is well known that performance parameters like power, efficiency and pressure ratio are correlated to a certain number of independent variables. Such parameters are expressed as function of two non-dimensional groups. Dimensionless relationships commonly refer to a "flow capacity", a "blade Mach number", the Reynolds number (Re) and to the ratio of fluid specific heats (γ) [23, 24] as reported in eq. 1. Charts are usually given in literature in a simplified form for turbulent flows, a fixed working fluid and a specific machine. Therefore, performance parameters are expressed as function of just two independent variables (a "corrected flow" and a "corrected speed") no longer dimensionless, as shown in equation 2.

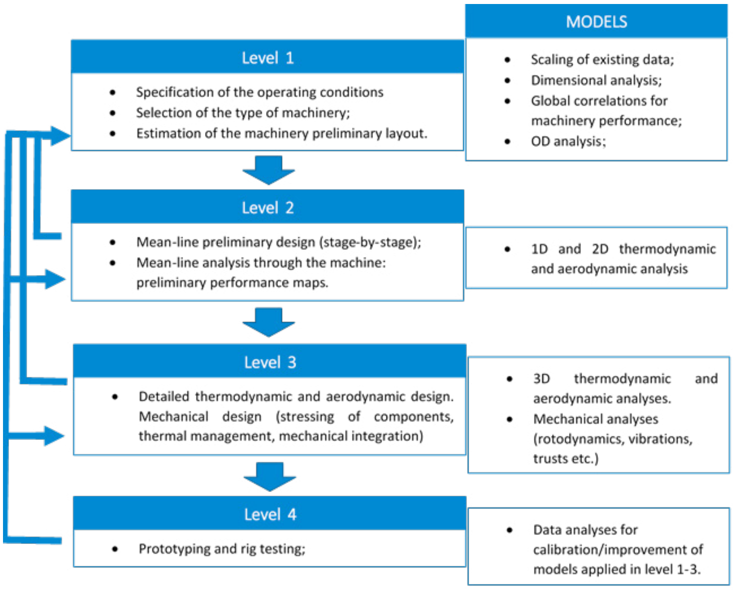


Fig. 1. Design process for a turbomachine.

$$\frac{p_{0out}}{p_{0in}}, \eta, \frac{\Delta T_0}{T_{0in}} = f\left(\frac{m\sqrt{\gamma R T_{0in}}}{D^2 p_{0in}}, \frac{ND}{\sqrt{\gamma R T_{0in}}},\ Re, \gamma\right) \tag{1}$$

$$\frac{p_{0out}}{p_{0in}}, \eta, \frac{\Delta T_0}{T_{0in}} = f\left(\frac{m\sqrt{T_{0in}}}{p_{0in}}, \frac{N}{\sqrt{T_{0in}}}\right) \tag{2}$$

Although such charts (e.g. Balje's charts [25]) are powerful tools for the selection or the estimation of the preliminary layout of a machine, they cannot be used as they are for new working fluids or for machines to be applied under operating conditions far from the traditional ones. Therefore, for renewable energy systems and energy-saving applications, several pitfalls must be carefully avoided. First, charts given in literature must be converted in non-dimensional form. Second, to take into consideration that machines can handling different fluids, corrections due to Re and γ must be taken into consideration. It means that the general dimensionless relationship given in eq 1 is necessary and if charts are given according to eq. 2, they must be converted in the general form. Nevertheless, machine selection and preliminary performance estimation can be strongly affected by some secondary effects. For ORC turbines, one of the most common concerns is related to the working fluid low sound speed which leads the expander in transonic/supersonic conditions. It implies some compressibility effects that could totally undermine the similitude with known machines. Moreover, new working fluids often works in thermodynamic conditions near saturation or close to the critical point. It means that all the thermodynamic properties (especially density) vary significantly for small increase/decrease in pressure. Therefore, the "reality" of the fluid makes the application of similarity rules less reliable. In the next chapter some classic examples are presented.

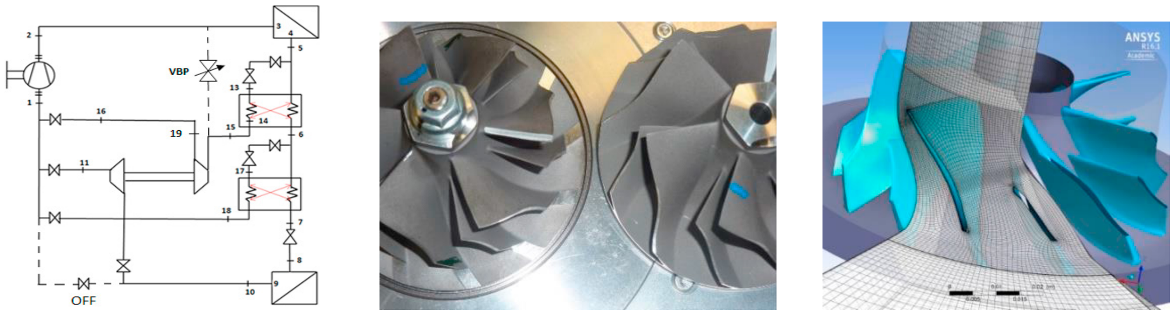
At level 2 and 3 the design procedure has been changing dramatically for the last years. More reliable and detailed 2D and 3D CFD analyses integrated with Finite Element Analysis have replaced semi-empirical correlations, reducing design iterations and reliance on prototype testing [26, 27]. At those levels the design process will involve a multi-disciplinary optimization that can take into consideration performance, component life, cost and other criteria useful for any specific design case (e.g. acoustics criteria, component size and weight). Moreover, new manufacturing techniques have speeded up the prototyping phase (lead time reduction is estimated to be up to 90%) and made several products more economic or customized. OEMs [28-32] have announced that 3D printing has become a standard and additive manufacturing has been applied also to serial production process. Such techniques reduce the path from an innovative design to a finished product and, therefore, can be applied successfully also to innovative turbomachines for renewable energy sources and energy-saving systems.

3. Case studies

Two case studies are presented in detail in the next paragraph to better understand what the design of a machine for RES or Energy-saving systems implies, starting from a traditional one or giving a completely new design.

3.1. Case one: recovery system for industrial cooling plants

The present case study deals with the development of an innovative internal recovery system for large Vapor Compression Refrigeration (VCR) plants based on Ascani's patent [33]. As shown in Figure 2a, the VCR system is modified adding working fluid extractions at the condenser exit. The first extracted flow is expanded and heated by means of a recovery heat exchanger (13-15). Then, the expansion is completed by means of an expander (15-19) before entering the main compressor. The main flow, sub-cooled in the recovery heat exchangers, passes through the main expansion valve and the evaporator. Then, it is pre-compressed into an auxiliary compressor (10-11). Such a compressor is connected and moved by the expander. The flows are mixed together before entering the main compressor.



(a) (b) (c)

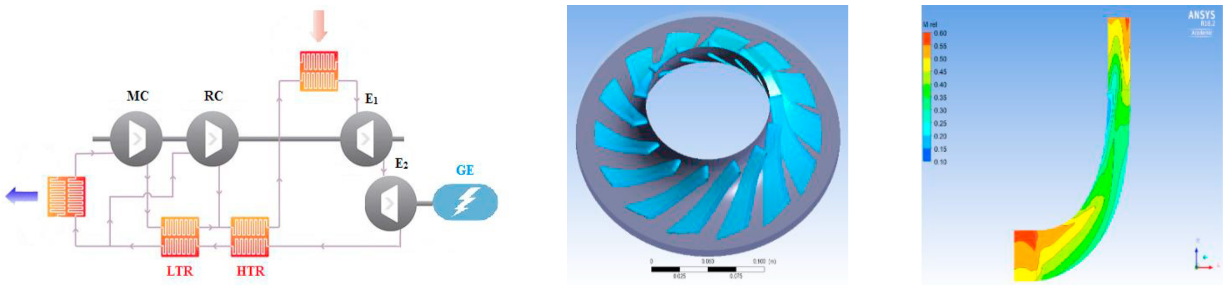
Fig. 2. (a) VCR layout with the internal recovery; (b) Modified compressor impeller near the original one and (c) 3D mesh for CFD analysis

At the beginning, both positive displacement machines and dynamic machines have been taken into consideration for the design of the recovery system. Similarity rules have been applied for the preliminary selection of reference machines, according to what has been explained in the previous Chapter. A radial layout has been selected for compressor and expander. Since there are not suitable components available on the market, it was decided to carry on modifying a turbocharging group. A deep re-design process both for the compressor and the expander was necessary because of the working fluid (R404a) thermo-fluid dynamic properties, the design mass flow rates and pressure ratios, far from any other application. The expander was designed first: the low inlet volumetric flow rate imposed a constraint to a full admission geometry. Furthermore, the high expansion ratio (about 3.32) and the low R404a sonic speed could lead to a supersonic flow inside the machine. The selection of the commercial rotor has been carried out on the basis of the transmitted torque. Once the proper shaft stem was selected, the corresponding expander wheel was given consequently, since turbochargers usually have the rotor welded with the shaft. Then, the expander was modified reducing the blade height at the inlet section and along section by section to meet expected fluid dynamic conditions. Moreover, the rotor was equipped with nozzle vanes to reach the expected velocities and flow angles at the rotor inlet [34]. The design was verified at level 2 and 3 by means of CFD analyses. Some iterations were necessary due to the transonic behaviour of R404a (a mixture of several fluids with different physical properties) inside the expander. Once the expander prototype design was ready, a suitable compressor impeller was modified accordingly (fig.2b). A 1D analysis at the mean line was carried out. In this way, the preliminary selection has been specified taking the R404a real properties into consideration. The resulting modifications were verified by means of 3D CFD analyses (fig. 2c).

Finally, the compressor impeller was reduced, cutting the channels near the outlet section to achieve the expected pressure ratio (it became a mixed-flow impeller) and reducing the blade height from inlet to outlet (fig. 2b). Moreover, the original compressor volute was replaced with a vaneless diffuser for the recovery of the outlet kinetic energy and the machine was equipped with an Inlet Guide Vane to provide the better nominal inlet velocity direction [35].

3.2. Case two: turbomachines for sCO_2 power plants

The design of turbomachines for sCO_2 cycles has several fluid dynamic and mechanical challenges. The compressor operation is close to the critical point, while turbine operation is at high pressures, temperatures and CO_2 density. Such conditions lead to a compact machinery configuration quite far from traditional gas turbines or steam turbines. For example, the density at the turbine exit can be 100 times greater than for a gas turbine and 10000 times greater than for a condensing steam turbine. Therefore, the design of CO_2 machines is outside the existing knowledge for any other dynamic machine. In [19] several existing prototypes for small, medium and large- scale plants are presented and discussed. The development of all of them as well as the preliminary design carried out by the Author for a 15 MWe system [36] have followed the design procedure reported in Figure 1. The selection of one or more suitable layouts have been carried out taking non-dimensional charts [25] into consideration. Since secondary effects are relevant and semi-empirical OD and 1D correlations developed for traditional machines are not reliable for such applications. Therefore, 2D and 3D CFD analyses have been widely used for the design of the first prototypes (fig 3 a-c). Nowadays, the first test campaigns are providing valuable information on the operation of such machines and will be applied for the calibration of models used at all design levels.



(a) (b) (c)

Fig. 3. (a) sCO2 plant layout for solar applications; (b) Example of compressor impeller designed for the system and (c) CFD simulations

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