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Design of an expander for internal power recovery in cryogenic cooling plants

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Abstract

The electrical power consumption of refrigeration plants is evaluated to be in the order of 15% of the total electricity consumption worldwide. For this reason, many efforts are spent in the development of energy saving techniques to be applied to refrigeration and air conditioning systems. This paper deals with the development of a device which allows an internal recovery in cryogenic plants, reducing their power consumption. Such a device consists in a Compressor-Expander Group (CEG) developed on the basis of automotive turbocharging technology.
According to the rules of the similarity theory, a preliminary CEG design has been realized modifying commercially available components. The critical CEG component is the expander. In order to address the new requirements, a turbocharger expander wheel has been strongly modified and equipped with supersonic variable nozzles, designed to have a radially inflow full admission. To verify the performance of such a machine and suggest improvements, a numerical fluid dynamic model has been set up. The commercial Ansys-CFX software has been used to perform steady-state 3D CFD simulations.
In this paper all the numerical results are presented, compared with available experimental data and discussed.

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*Keywords*Vapour Compression Systems, Energy Saving, Refrigeration Plant, Organic Fluids, Radial Turbine, Transonic flow

1. Introduction

Large Vapor Compression Refrigeration (VCR) systems are used in a wide range of industrial and service sectors [1-3], consuming about 15% of electricity produced worldwide [4]. Therefore, in the last decades, many efforts have been spent for the energy saving in such a field. Some proposals are focused on the set up of a better system control [5,6], while other ones take cycle modifications into account.

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Among VCR system power saving proposed methods, some are based on the increase of subcooling (where possible) [7], the adoption of ejector loops [8], multistage compressions [9] or the replacing of the throttling valve with an expander to reduce the power demand [10].

The present work is related to the development of a device for internal power recoveryfor a R404a industrial cryogenic plant. The concept isbased on Ascani's patent [11].

2. Reference plant and machinery selection

VCR plants are based on vapor compression inverse cycles. In figure 1a, a simplified plant scheme is reported. The main components are an evaporator (E), a compressor (C), a condenser (K) and an expansion device (DL). Cycle improvements proposed by Ascanilead to a VCR cycle with internal power recovery as shown in fig.1b. In such a cycle there are two bleeds in the primary flow before the throttling valve (stations 5 and 6). A certain amount of liquid is extracted and heated in two heat exchangers (components HE1 and HE2). Once evaporated, the first one enters the expander (component EX) and, then, exhausts in the main flow before going into the Main Compressor (C). The expander mechanical power is used for a pre-compression of the main flow, reducing the main compressor power demand. The cycle thermodynamic optimization has been carried out simultaneously with the preliminary sizing of the Compressor-Expander Group (CEG).

Before the optimization process, the selection of machines commercially available which can match the plant requirements has been carried out. Positive displacement machines and turbomachines have been taken into consideration and, finally, the adoption of machines from automotive turbocharging technology has been decided. The selection has been made taking similarity rules into consideration.

Information from the application of similarity ruleshave been implemented in the tool developed for the cycle optimization [12-16]. In such a way, once the cycle layout has been established, the optimization process gives the optimum of the cycle parameters together with the selection of machines for a preliminary design. In [17, 18] procedures and results are widely described and discussed.

For 100 kWc, power required by the main compressor in an optimized cycle with internal recovery is about 26% less than in a simple cycle (75 kW instead of 101.5 kW). Evaporating and condensing temperatures have been fixed at -40°C and +40 °C respectively.

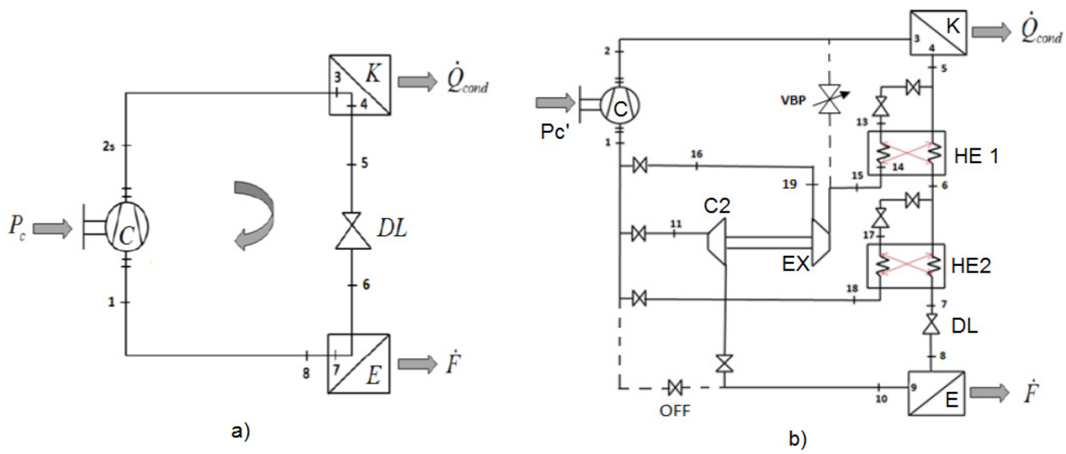

Fig. 1. (a) VCR simple cycle; (b) VCR cycle with internal power regeneration

In the modified cycle, the expander (EX) has been identified as the critical CEG component, having a small nominal mass flow (0.31 kg/s) and a nominal pressure ratio (3.32) which can lead to a transonic flow inside the machine. In order to address the actual requirements, a turbocharger expander wheel has been strongly modified and equipped with supersonic variable nozzles, designed to have a radially inflow full admission. To verify the performance of such a machine and suggest improvements, a numerical fluid dynamic model has been set up.

3. The expander analysis

Turbocharging expander wheels are welded with the shaft. The selection of a suitable machine was conducted taking the transmitted torque into consideration. The choice of a proper shaft stem was the first mandatory step. The selection of the expander wheel was a consequence. Then, in order to address the expected performance, the prototype expander geometry was achieved reducing the blade height of a Garrett GT3582 wheel. The rotor was equipped with transonic nozzle vanes, added to reach the required velocity and the flow angles at the bladeinlet [12,18]. In order to explore a wide range of running conditions, the prototype was equipped with variable nozzle vanes. In figure 2a a 3D view of the full geometry is given. On such a geometry viscous turbulent steady-state CFD simulations were carried out by using the commercial software ANSYS-CFX.A O-H 3D computational mesh for the simulation of two stator vanes and three rotor blade passages was generated (figure 2 b-c). The domain was extended in front of stator vanes and beyond the rotor exit section of a distance equivalent to one rotor inlet diameter. At the interface between stator vanes and rotor blades a frozen rotor interface was set. Steady-state 3D viscous flow simulations were set up using a high resolution advection scheme for the discretization of Navier-Stokes equations. In order to achieve preliminary information on the prototype capabilities a standard k-ε model with scalable wall function was set up.

A preliminary comparison between experimental and numerical data was performed running the expander prototype on a compressed air test bench. Such a test bench was set up at Roma Tre University for a pioneering demonstration of the CEG prototype capabilities in terms of continuous and safe running. In fig. 3expander characteristics from simulations and from experimental tests are shown (figure 3a) and compared (figure 3b).

Their good agreement opened the way to a second simulation campaign, replacing the fluid model to take R404a properties into consideration. To describe the refrigerant, the real gas cubic equation Aungier Redlich Kwong Model was chosen [19]. Such a model provides a reasonable prediction of the real fluid behavior in the cases of interest.

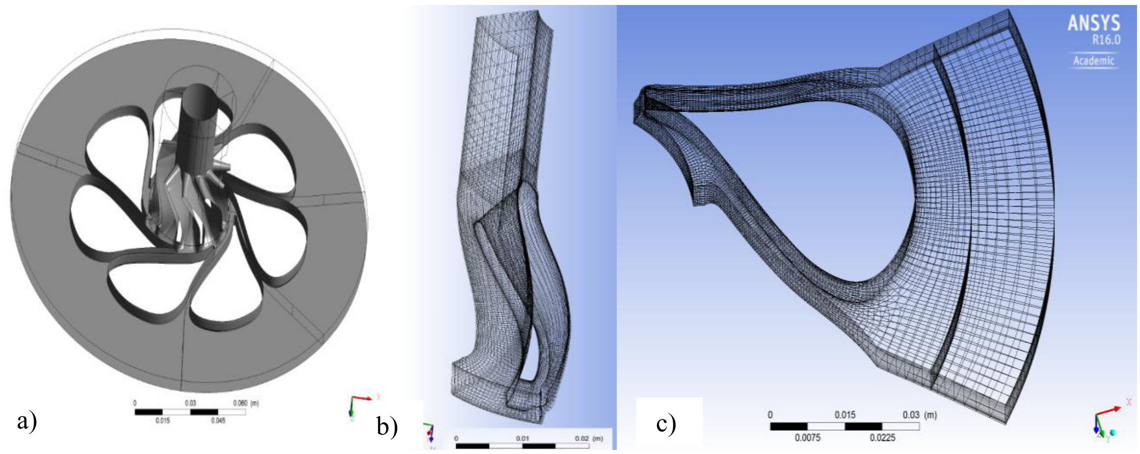

Fig. 2. (a) expander preliminary geometry; 3D view of O-H grids (b) rotor blade and(c) stator blade

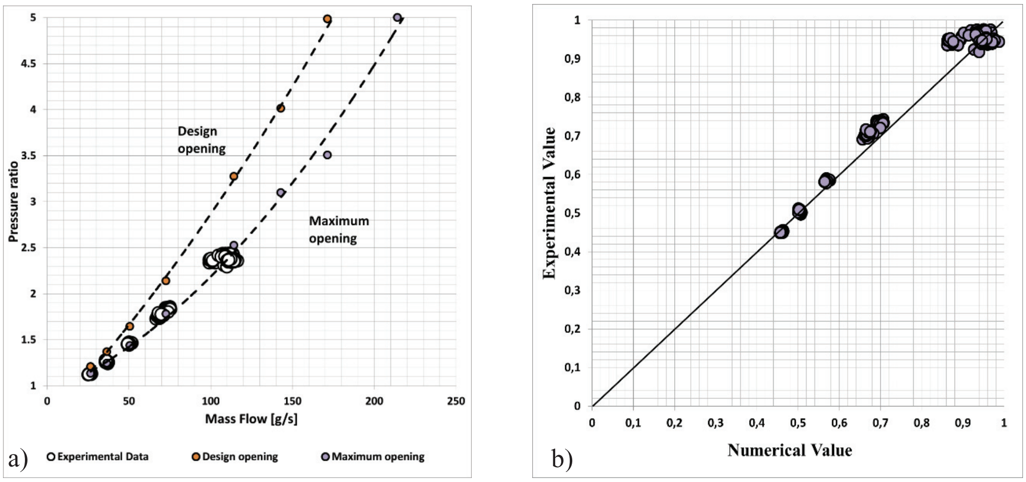

Fig. 3. (a) Expander simulated and tested characteristics with air: pressure ratio vs. mass flow;(b) Parity plot.

Three rotational speeds (30, 60–nominal- and 90krpm) were assumed for calculations. The total inlet pressure and temperature, the inlet velocity direction and the static pressure at the exit were specified.

In Figure 4a, simulation results have been compared with experimental results achieved on a CEG prototype installed in a 50 kWc refrigeration plant. Since the CEG prototype was designed for a 100 kWc plant, it was possible to test the expander only in steady-state off-design conditions. In such tests, the expander speed depends on the equilibrium running with the secondary compressor C2 (fig.1b). Moreover, expander characteristics simulated at73%, 100% and 170% of the nominal nozzle opening are reported. The pressure ratio versus mass flow is shown in figure 4a, while in figure 4b the total-to-total isentropic efficiencyversus pressure ratio is given.

Although tests have given a positive response verifying the patent concept, the simulation campaign highlighted that some improvements in the expander geometry have tobe adopted. In fig. 5athe Mach number at mid-span at nominal condition(design opening, 60 krpm, pressure ratio 3.32) is presented. The nozzles do not accelerate the fluid as expected and a shock wave before exiting the passage reduces the absolute velocity to subsonic values. Thus, the relative velocity at the rotor inlet is twisted in respect to its design direction. Such a new average direction, together with the non-optimizedrotor blade leading edge profile, causes a stall with a large vortex on the blade suction side, reducing the profile loading.Thus, the nominal efficiency is quite low (about 70%) as shown in figure 4b. Performance increases opening the stator vane. At maximum opening, the efficiency raises (up to 80%) due to the better flow incidence on the rotor leading edge (Figure 5b).Efficiency drops drastically at low-pressure ratios because of the stall growth inside the rotor. On the contrary, it is limited at high-pressure ratios (more than 2.5) by a transonic flow and a shock wave before the rotor exit section (figure 4b).

4. Conclusions

The paper presents the results of numerical simulations related to the first prototype of an expander for power recovery in industrial cryogenic plants. Simulations have been validated by means of experimental data achieved on a test bench that can operate with compressed air and with data achieved installing the prototype on a 50 kW plant.

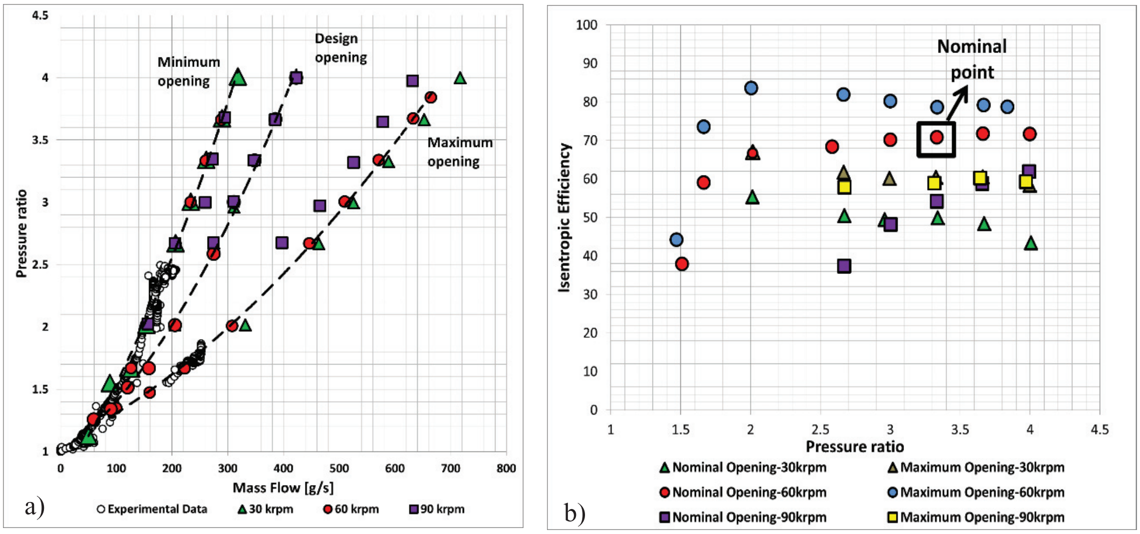

Fig. 4. Expander characteristics: (a) Pressure ratio vs. mass flow (b) isentropic efficiency vs. pressure ratio

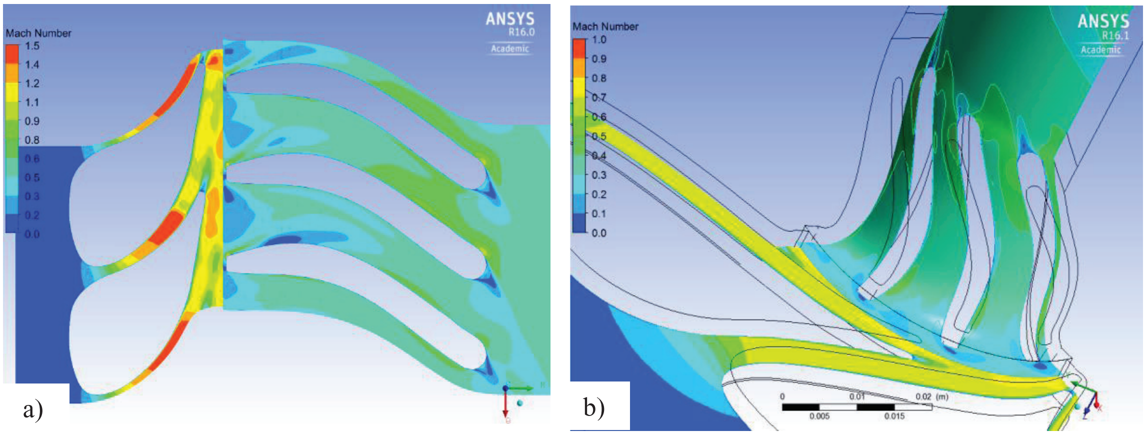

Fig. 5. Mach number at mid-span: (a) nominal point; (b) maximum opening, 60 krpm, pressure ratio 2.

The concept of power recovery in such industrial plants has been verified observing a relevant energy saving (10-12% in CEG de-rated conditions). Nevertheless, the 3D steady-state simulations have highlighted some critical aspects in the fluid dynamic behavior of the pioneering expander geometry.

Modifications in the nozzle vane shape and in the exit blade angle could increase significantly the expander performance, enhancing the power recovery at nominal and off-design operating conditions. In order to improve the expander performance a new set of nozzle vanes is under design.Moreover, a modification of rotor blade leading and trailing edge shapes isnecessary.

Therefore,a second prototype generation is under construction and will be tested in the near future.

Acknowledgements

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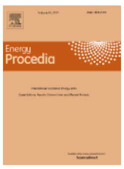

Biography

Ambra Giovannelli is currently Assistant Professor in Fluid Machinery in the Department of Engineering at ROMA TRE University. She is involved in research projects manly focused on Concentrated Solar Power production, Energy Saving in refrigeration plants, Turbomachinery design and optimization.