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Fast Design Methodology For Supersonic Turbines With Strong Real Gas Effects

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Abstract :

This work describes a fast 2-D design methodology for supersonic axial Organic Rankine Cycle (ORC) turbines. A Method of Characteristics (MOC) generalized to gases governed by complex equations of state (EOS) is used to generate both stator and rotor blades. A steady viscous numerical simulation of a turbine stage designed using the proposed methodology is carried out by using the ANSYS CFX solver. The results show that the viscous effects represent the main source of isentropic efficiency drop, since the accurate MOC design allows to minimize losses due to shock waves.

Keywords : dense gas, turbomachinery, method of characteristics, supersonic nozzle

Introduction

In recent years, the Organic Rankine Cycle (ORC) technology has received great interest from the scientific and technical community because of its capability of generating electric power using low temperature sources with good performances. For compactness, mechanical design simplicity and cost reasons, ORC plants often use single stage expander characterized by high pressure ratios, which leads to supersonic flow conditions. Furthermore, ORC working fluids are often molecularly complex organic fluids characterized by the so-called dense-gas effects (see, e.g. [1] and references cited therein). Specifically, dense gas are defined as single phase vapors in thermodynamic conditions close to saturation curves, characterized by complex molecules and moderate to large molecular weights. The dynamics of dense gases can be described through a key thermodynamic property, known as the Fundamental Derivative of Gas

Dynamics [2]:

$$\Gamma = 1 + \frac{\rho}{a} \left(\frac{\partial a}{\partial \rho} \right)_s \quad (1)$$

Eq. (1) represents a measure of the rate of change with density of the local speed of sound. For light fluids, $\Gamma > 1$. This is the case of perfect gases, which have a constant $\Gamma = (\gamma + 1)/2$. For fluid with sufficient molecular complexity, $\Gamma < 1$, which leads to a reverse behaviour of the speed of sound in isentropic perturbations with respect to classical case: a decreases in isentropic compressions and grows in isentropic expansions. The aerodynamic modelling of such a system is made difficult by real gas effects characterizing the thermodynamic behaviour of the working fluid in the vicinity of the critical point and the saturation curve.

The aim of this work is to develop a methodology for the design of axial supersonic ORC impulse turbine blade shapes which takes properly into account dense gas effects based on the Method Of Characteristics (MOC).

Real-gas MOC

The MOC for dense gases proposed here for turbine stage design is developed under the hypotheses of 2-D, homentropic, steady and inviscid flow.

For the transonic stator design, the system of conservation laws is numerically integrated in the characteristic reference system by means of a second-order accurate Heun predictor-corrector algorithm. All the thermodynamic properties are described through multi-parameter EOS based on Helmholtz free energy contained in the software NIST-REFPROP (REF) ver. 9.1 [3]. With this methodology the divergent part of a De Laval nozzle is determined. The final blade shape is obtained through geometrical post-processing of the nozzle geometry previously calculated. More details are provided in [4].

The supersonic real-gas rotor blades are designed by considering a vortex flow inside the blade vanes. This assumption simplifies the methodology allowing to not solve numerically the system of conservation laws but using geometrical considerations based on the characteristic lines (see [5]). The flow passes from uniform inlet conditions to vortex conditions going through a transition zone, which is the one calculated by means of the MOC extended to real gases. After the vortex region, the flow is newly transitioned towards a uniform outlet condition using MOC. Once again, the REF thermodynamic equations are coupled to the algorithm in order to provide all the required thermodynamic properties.

Although the calculations required for the REF model are more complex than the ones required for other gas models, this algorithm remains very fast and only few seconds are required for obtaining results on a single-processor machine.

Results

Figure (1) presents examples of blade designs for stator and rotor. The organic working fluid is R245FA, which represents a typical choice for ORC turbines working at heat temperature of the order of 350-400 K. The full stage and rotor design parameters are shown in table 1 and table 2, respectively. The results are compared to those obtained using the perfect gas model. Significant differences are observed especially for the stator blades, which operate at pressures and temperatures for which R245FA exhibits strong deviations from a perfect gas behaviour. For the rotor, the differences are much smaller in the present case because the expansion through the stator drives the fluid toward the dilute gas region.

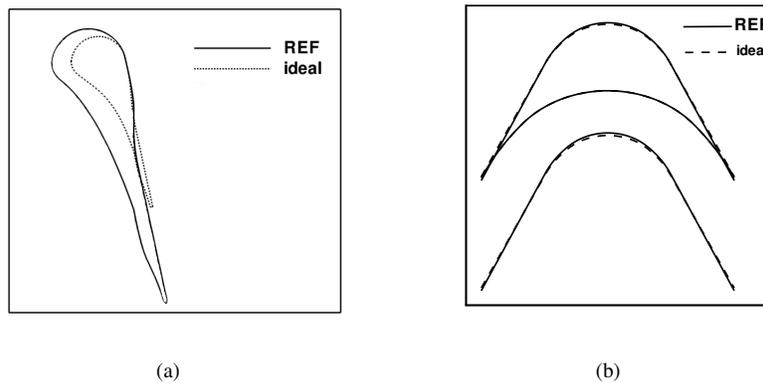


Figure 1: Examples of ORC turbine blade vane calculations and comparison between dense gas and perfect (ideal) gas results for R245FA working fluid: (a) Stator blades. (b) Rotor blades.

Table 1: Main turbine full stage working parameters.

Parameters	Values
Inlet total reduced pressure	1.2
Pressure ratio	20.6
Inlet total reduced temperature	1.1
Stator nozzle outlet design Mach number	2.4
Stator stager angle [°]	70
Rotor blade speed [m/s]	141.37

Figure 2 shows the relative Mach number distribution for the full turbine stage viscous simulation carried out involving a supersonic rotor blade row and a supersonic sta-

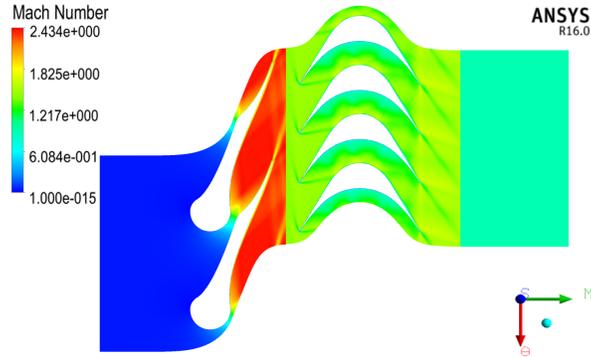


Figure 2: Relative Mach number distribution for full turbine stage with R245FA fluid.

Table 2: Rotor blade design parameters.

Parameters	Values
Inlet total relative pressure [bar]	6
Inlet total relative temperature [K]	393.15
Inlet relative Mach number	1.5
Inlet relative flow angle [°]	60
Suction side circular arc Mach number	1.9
Pressure side circular arc Mach number	1.1

tor blade row both designed by the means of the MOC procedure presented in this work. The total temperature, the total pressure and the velocity components are imposed at the inlet. Average static pressure is set at the outlet and a mixing-plane boundary condition is set at the stator-rotor interface. The turbulence model used is k-omega SST (Shear Stress Transport). The flow is accelerated in the stator vanes up to the design absolute Mach number of 2.4 and, thanks to the accurate design with the MOC algorithm, no normal shocks are formed in the divergent part of the nozzle. However, weak oblique shocks are generated at the trailing edge of the stator due to the thick rounded trailing edge. These shocks interact with the viscous wake, visible on the stator outlet. Due to the mixing plane interface, interactions of the latter with the rotor row can not be observed. The flow in the rotor vanes is characterised by weak oblique shocks departing both from the leading and trailing edge of the blades due to the finite thickness of the actual rotor geometry. Nevertheless, these shocks have only a minor impact on the overall flow behaviour. The turbine is found to be in a "started" configuration, so that a normal shock at the rotor inlet is avoided and the flow inside the rotor vanes is supersonic [6]. The calculated total to total isentropic efficiency for this turbine is 92.9%. In order to assess the main source of losses in the turbine stage, the entropy deviation $(S - S_{in})/S_{in}$ has been analysed, with S_{in} the specific entropy at rotor inlet. The entropy deviation is shown in figure 3a for the isolated rotor. Entropy is mainly generated

with the viscous boundary layers and wakes, whereas entropy generation across shocks is extremely weak. This demonstrates that the proposed methodology provides blade designs with negligible shock losses.

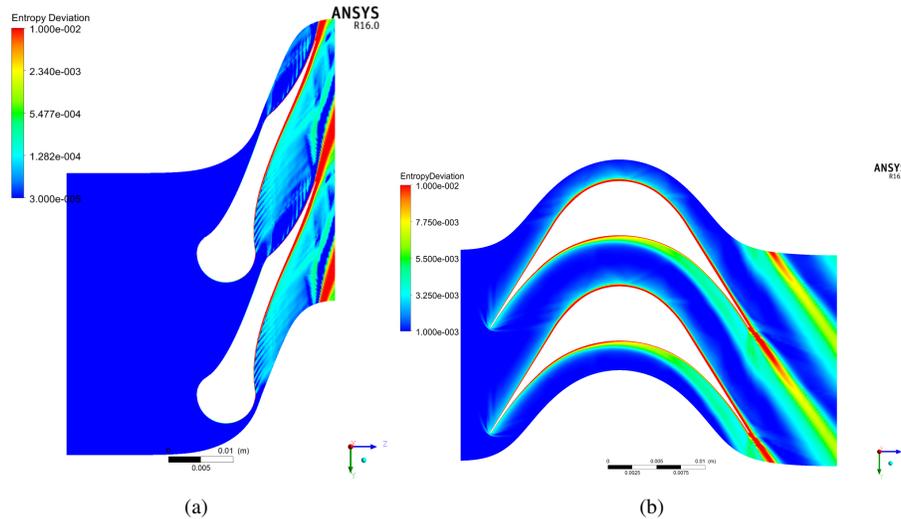


Figure 3: Entropy deviation contour plot for stator (a) and rotor (b).

Conclusions

The proposed methodology allows for a fast preliminary design of stator and rotor blades of ORC turbines involving strong real gas effects. Results show that the resulting blade designs are characterized by very low wave losses at the nominal conditions. As future work, the MOC design procedure will be coupled to an uncertainty quantification method such as Probabilistic Collocation, sparse-grid Non-Intrusive Polynomial Chaos method, adaptive Simplex Stochastic Collocation method, Kriging-based response surface method and a second-order-accurate Method of Moments in order to assess the sensitivity in terms of performances of the ORC system to stochastic variations of the working conditions. Besides, the coupling of these methods with an optimizer based on genetic algorithms will provide a robust optimized geometry with performances near the nominal ones, with relatively low sensitivity to operating condition variations.

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