FAST DESIGN METHODOLOGY FOR SUPERSONIC ROTOR BLADES WITH DENSE GAS EFFECTS

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Context

- ORC small/medium-scale applications need for compact and efficient expanders
- To increase the power density and cycle efficiency of ORC systems, high pressure-ratio single-stage turbines are required
- Supersonic impulse turbines are the best compromise between geometrical size requirements and power output
- Problem: poor know-how about the behaviour of supersonic flow passing through turbine vanes with molecularly complex working fluids
- Accurate design is required in order to take into account the influence of strong real gas effects

Objectives of this work

- Design of impulse ORC expander and rotor with **dense gas effects**
  - development of an accurate methodology through a Method Of Characteristics (MOC) generalized to real gas models, suitable for **fast preliminary blade design**;
  - dense gas effects have to be taken into account because of their influence on geometry and fluid-dynamics [Guardone et al., 2013]
  - modifications of existent design methodologies [Wheeler et al., 2013] for supersonic stators is proposed, along with a **new procedure** for impulse rotors under dense gas effects
- Design of a complete ORC turbine stage
- Assessment of performances through numerical simulations

Dense gas dynamics

- Fundamental derivative of gas dynamics [Thompson, 1971]:

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

  - Classical behaviour if $\Gamma > 1$
  - Non-classical behaviour if $0 < \Gamma < 1$ or $\Gamma < 0$ (expansion shocks allowed)

- Flow properties are described with multi-parameter Equations Of State (EOS) based on Helmholtz free energy (REFPROP reference equations for several fluids [Lemmon et al., 2013])

ORC expander design with MOC

Flow equations:

- No body forces
- Isentropic and steady flow
- 2-D planar flow

$$\frac{dy}{dx} = tan(\varphi \pm \alpha) \tag{1}$$

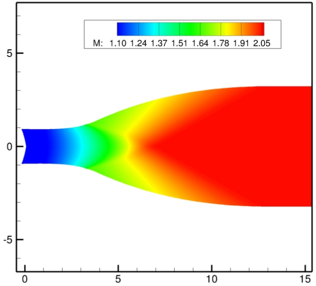
$$d\varphi \pm \sqrt{M^2 - 1}\frac{dV}{V} = 0 \tag{2}$$

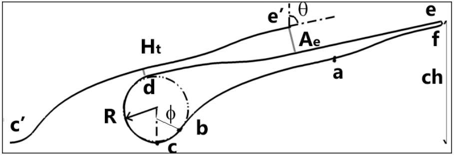
Can be analitically integrated for a perfect-gas model, leading to the Prandtl-Meyer function.

What if a dense gas model is taken into account?

Features of the generalized MOC algorithm **for stators**:

- Numerical integration of the governing equations (1)-(2) through a second-order accurate predictor-corrector solver. Sensitivity analysis to operating conditions and geometric fluctuations has been assessed [Bufi et al., 2015]
- Nozzle divergent part design and geometrical post-processing for the final blade (design parameters: massflow, total conditions, pressure distribution)

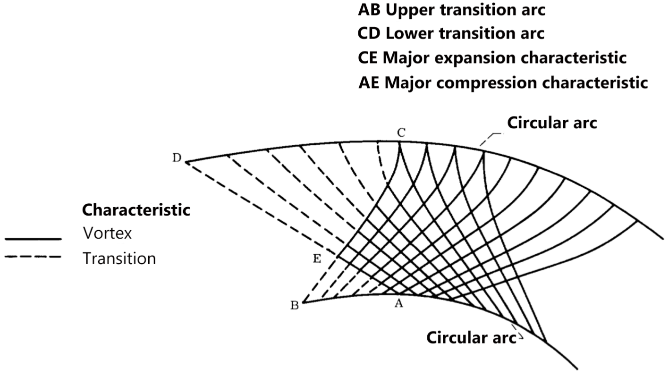




ORC rotor design with MOC

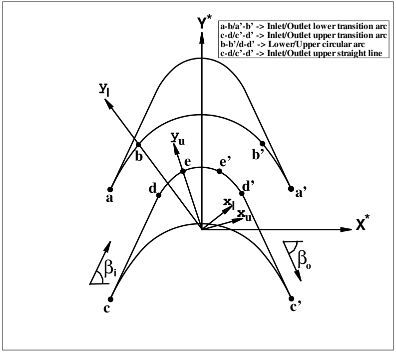
General assumptions **for rotors**:

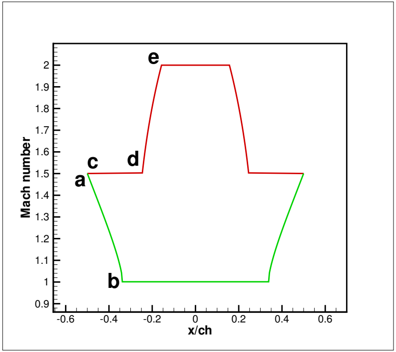
- Uniform supersonic flow at blade inlet and outlet
- Vortex flow in the blade passage ($V \cdot R = constant$, with R the radius of curvature of a streamline and V the constant velocity along it)
- Numerical solution of equations (1)-(2) in the transition region as generalization of the perfect gas design [Paniagua et al., 2014; Goldman, 1968] to real gases
- Iterative procedure based on the calculation of the major expansion/compression characteristic curves



ORC rotor design with MOC

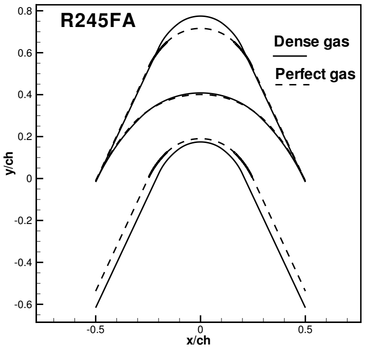
- Input parameters
  - inlet total pressure and temperature
  - inlet outlet relative flow angle β_i,β_o
  - inlet outlet Mach number M_i,M_o
  - lower arc Mach number M_l
  - upper arc Mach number M_u

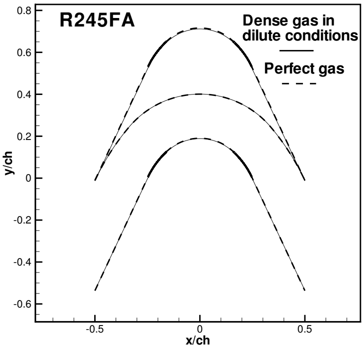




Rotor blade designs with dense gas effects

Blade designs for R245FA fluid at operating conditions ($p_r^0 = 1.05$, $T_r^0 = 1.05$) (a) and at conditions ($p_r^0 = 0.055$, $T_r^0 = 1.15$)(b)





Rotor blade designs with dense gas effects

Geometrical output parameters for four different organic fluids under the same operating condition ($p_r^0 = 1.28$, $T_r^0 = 1.28$, $M_{in} = M_{out} = 1.5$, $M_l = 1$, $M_u = 2$,$\beta_{in} = \beta_{out} = 65°$)

	R245fa	**R227ea**	**R134a**	**R236fa**
σ	1.82	1.81	1.85	1.82
ch^*	2.31	2.32	2.30	2.31
ph^*	1.27	1.28	1.24	1.27
$M_w[g/mol]$	134.05	170.03	102.03	152.04

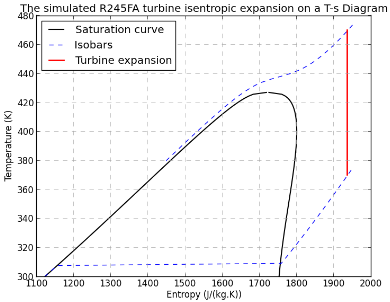
The lower is the fluid molecular complexity, the higher is the solidity.

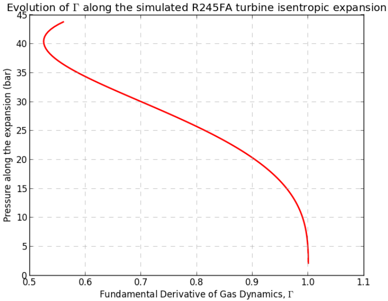
CFD results for R245FA

Turbine stage design 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 stagger angle [deg]	70
Rotor blade speed [m/s]	141.37
Degree of reaction	0

CFD results for R245FA

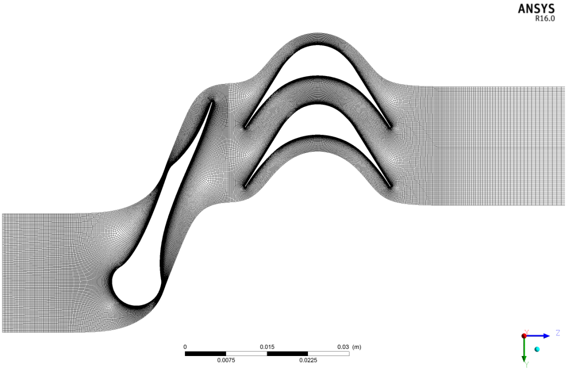




CFD results for R245FA

Simulation settings:

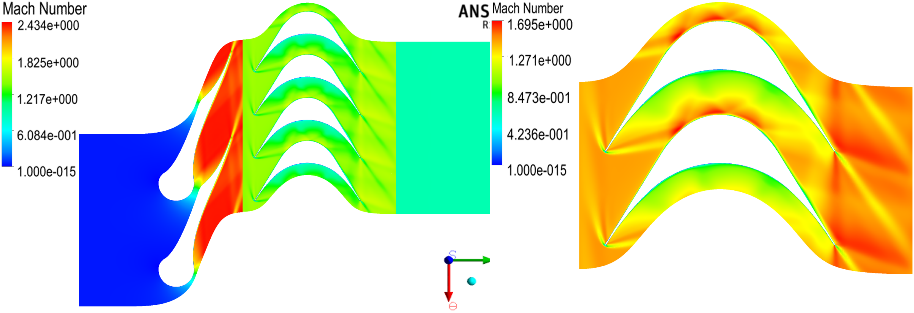
- Viscous 2-D turbulent flow ($k - \omega SST$ turbulence model)
- Real gas properties provided by external library
- Structured mesh: 330066 total number of elements, C-shaped blocks around the blades and H-shaped blocks at stage inlet and outlet
- y+ values less than 1 at the blade walls



CFD results for R245FA

Boundary conditions:

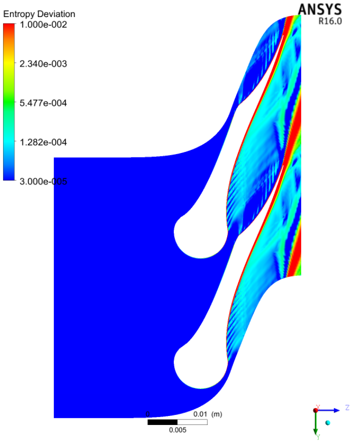
- total temperature, total pressure and velocity components are imposed at the inlet
- average static pressure is set at the outlet
- mixing-plane boundary condition is set at the stator-rotor interface

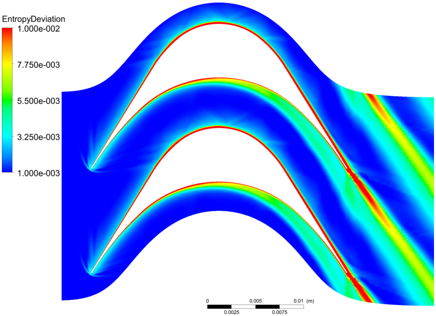


Performances: η_{is}=0.929

CFD results for R245FA

Entropy deviation analysis: $(S - S_{in})/S_{in}$





Conclusions

- Development of design methodology for ORC expander injectors and rotors with dense gas effects
- Significant differences are found between geometries obtained with the ideal and dense gas models
- The numerical simulations show that an accurate blade design in the dense gas flow regime allows accounting for dense gas phenomena during expansion and avoids the focusing of characteristic lines into shocks inside the blade vanes
- The main source of losses is represented by viscous phenomena

Other developments:

- Sensitivity analysis of the ORC expanders designed with MOC to fluctuations of the operating conditions through Uncertainty Quantification techniques
- Boundary-layer correction for the blade shapes

Future work:

- Robust optimization of the ORC turbine geometry by using MOC design as baseline shape
- Design of the entire 3-D turbine stage
- Study of rotor-stator interaction through unsteady simulations

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Thank You for the attention!