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- EX LABORE FRUCTUS -

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MODELLING OF SCROLL MACHINES: GEOMETRIC, THERMODYNAMICS AND CFD METHODS

M. Morini, C. Pavan, M. Pinelli,
E. Romito, A. Suman

Dipartimento di Ingegneria
Università degli Studi di Ferrara (Italy)

Introduction

The ***ORC systems*** are becoming more common for the exploitation of energy sources with low enthalpy and for ***very small size*** applications (<10 kWel)

The ***scroll*** fluid machine seems to be suitable for this applications due to:

- the small number of moving parts
- low noise and vibrations

Higher efficiency standards could be achieved by specific studies on:

❖ ***kinematic***

❖ ***thermodynamic***

spiral geometry, flank and axial ***gaps*** play a key role on the final performances

CFD simulations could represent a very "new" ***useful method***

Aims & Issues

- ***Geometric comparison*** between two methods for the design of the scroll spiral profiles

- ***Thermodynamic comparison*** of the two scroll compressor by evaluating overall performances

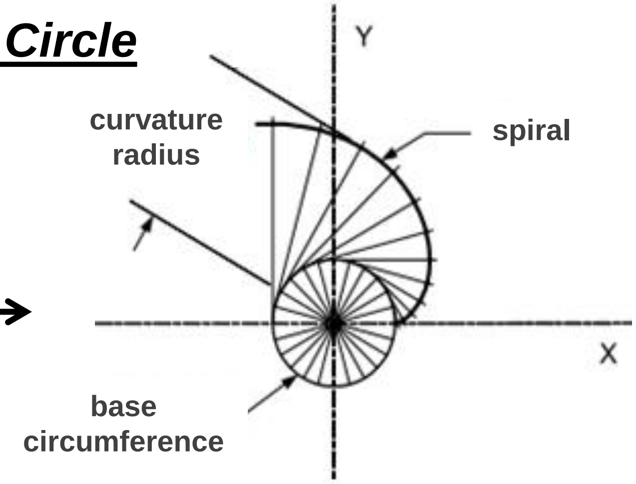
- Implementation of a ***CFD transient simulation*** with ***Dynamic Mesh*** strategy

- ***Sensitivity analysis*** on time discretization in terms of overall performance and fluid dynamic phenomena

Geometrical methods

Both the two methods are obtained by a ***Involuted Circle*** method

the spiral curve radius varies with a linear law starting from a base circumference centered in the origin of the reference system →



❖ ***Method 1****
Non-Linear Method (NLM)

equations governed

by ***non-linear coefficients***

❖ ***Method 2*****
Linear Method (LM)

equations governed

by ***linear coefficients***

* Liu, Y. et al., 2012, "Optimum design of scroll profiles created from involute of circle with variable radii by using finite element analysis", *Mech. Mach. Theory*, 55, pp. 1-17.

** Blunier, B. et al., 2006, "Novel Geometrical Model of Scroll Compressors for the Analytical Description of the Chamber Volumes", *ICEC* 2006, 1745.

Method 1 – Non Linear Method (NLM)

	Fixed scroll equations	***Mobile scroll equations***
❖ Outer spiral	$\begin{cases} x_{f,out} = a_{out}\,cos\phi + \rho_{out}\,sen\phi \\ y_{f,out} = a_{out}\,sen\phi - \rho_{out}\,cos\phi \end{cases}$	$\begin{cases} x_{m,out} = -x_{f,out} + r_{ob}\,sin\theta \\ y_{m,out} = -y_{f,out} - r_{ob}\,cos\theta \end{cases}$

Coefficients (outer) $a_{out} = a_o + \delta_0(\phi + \alpha)^k$ $\qquad \rho_{out} = a_o(\phi + \alpha) + \frac{\delta_0}{k+1}(\phi + \alpha)^{k+1}$

❖ Inner spiral	$\begin{cases} x_{f,in} = a_{in}\,cos\phi + \rho_{in}\,sen\phi \\ y_{f,in} = a_{in}\,sen\phi - \rho_{in}\,cos\phi \end{cases}$	$\begin{cases} x_{m,in} = -x_{f,in} + r_{ob}\,sin\theta \\ y_{m,in} = -y_{f,in} - r_{ob}\,cos\theta \end{cases}$

Coefficients (inner) $a_{in} = a_0 + \delta_0(\phi - \pi + \alpha)^k$ $\qquad \rho_{in} = a_o(\phi - \alpha) + \frac{\delta_0}{k+1}[(\phi + \alpha - \pi)^{k+1} - (\pi - 2\alpha)^{k+1}]$

where: a_0 base circumference radius,

θ orbit angle and r_{ob} orbit radius defined as: $\qquad r_{ob} = a_0(\pi - 2\alpha) - \frac{\delta_0}{k+1}(\pi - 2\alpha)^{k+1}$

The coefficents k, δ_0 allow to **control** the spiral thickness variation:

- ❖ k = distance between the inner and outer spiral
- ❖ δ_0 = variation of the spiral thickness as function of θ

Method 2 – Linear Method (LM)

Outer spiral

Fixed scroll

$$\begin{cases} x_{f,out} = a_0(cos\phi + \phi sen\phi) \\ y_{f,out} = a_0(sen\phi - \phi cos\phi) \end{cases}$$

Mobile scroll

$$\begin{cases} x_{m,out} = a_0[\cos(\phi+\pi) + \phi\ sen(\phi+\pi)] + r_{ob}\cos(\theta + 3\pi/2) \\ y_{m,out} = a_0[\mathrm{sen}(\phi+\pi) - \phi\ cos(\phi+\pi)] + r_{ob}\,\mathrm{sen}(\theta + 3\pi/2) \end{cases}$$

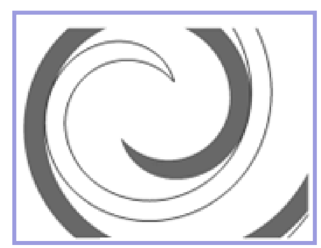
Inner spiral

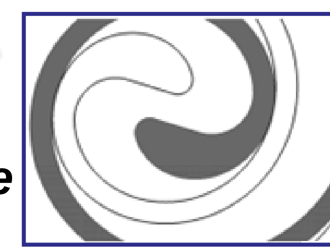
Fixed scroll

$$\begin{cases} x_{f,in} = a_0[\cos(\phi+\alpha_{i0}) + \phi sen(\phi + \alpha_{i,0})] \\ y_{f,in} = a_0[\mathrm{sen}(\phi+\alpha_{i0}) - \phi cos(\phi + \alpha_{i,0})] \end{cases}$$

Mobile scroll

$$\begin{cases} x_{m,in} = a_0[\cos(\phi+\alpha_{i0}+\pi) + \phi\ sen(\phi+\alpha_{i0}+\pi)] + r_{ob}\cos(\theta + 3\pi/2) \\ y_{m,in} = a_0[\mathrm{sen}(\phi+\alpha_{i0}+\pi) - \phi\ cos(\phi+\alpha_{i0}+\pi)] + r_{ob}\,\mathrm{sen}(\theta + 3\pi/2) \end{cases}$$





Perfectly Meshing Profile*** **(PMP)**

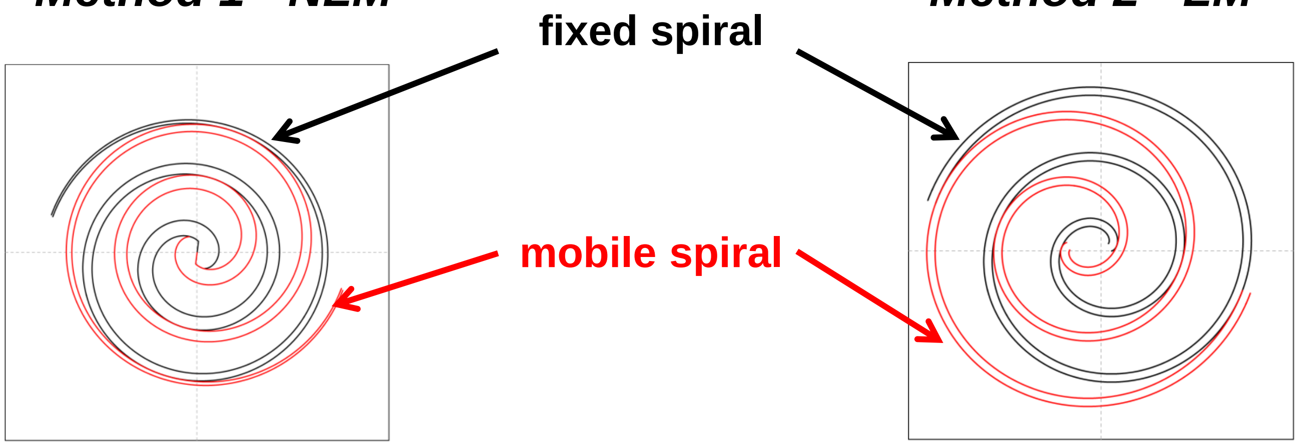
connect the inner and outer profile. The PMP influence the ***spiral geometry***, ***leakage*** and ***structural resistance***

*** Liu, Y. et al., 2010, "Study on involute of circle with variable radii in a scroll compressor", *Mech. Mach. Theory*, 45, pp. 1520-36.

Comparison

All the ***geometric features influence*** the ***overall performance*** of the scroll

Method 1 - NLM | ***Method 2 - LM***



Method 1 - NLM: Volume ratio = 2.47

The ***end-plate*** of the scroll is ***less*** than the diameter obtained by the LM method*

Method 2 - LM: Volume ratio = 2.53

The ***distance between*** the ***inner*** and ***outer*** spiral is lower than the NLM method*

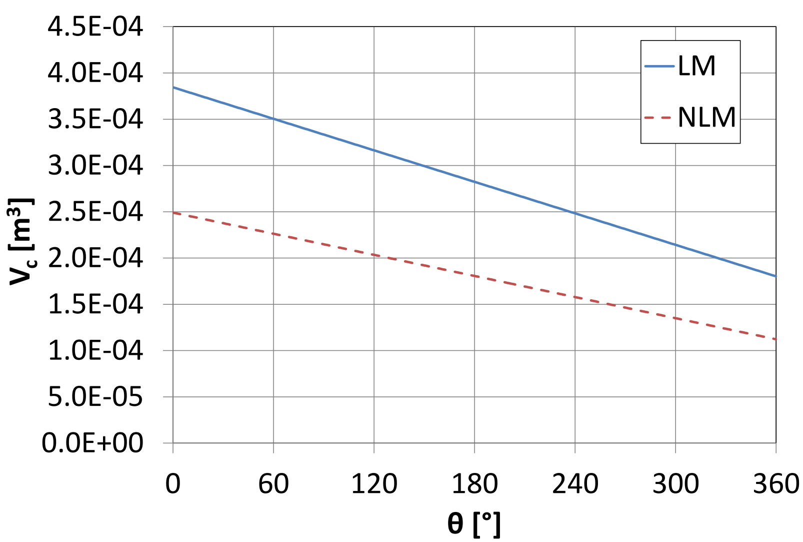
* for given base circumference radius, blade height, involute ending angle and inner spiral initial angle

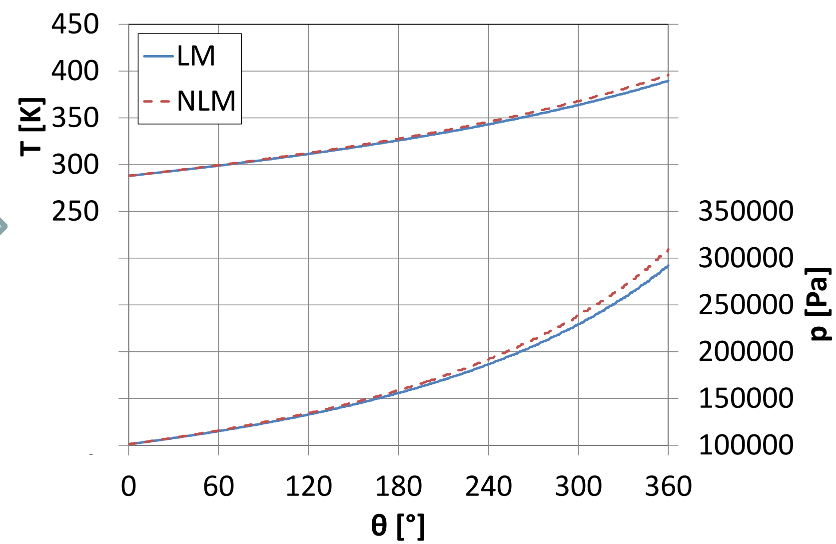
Thermodynamic analysis

Simplified thermodynamic model of an energy balance in an open control volume:

- no heat exchange
- constant fluid properties at inlet and outlet sections
- air ideal gas @ standard conditions
- partial derivatives approximated by finite differences

$$\frac{\Delta T}{\Delta \theta} = \frac{1}{m\,c_v}\left\{-T\left(\frac{\Delta p}{\Delta T}\right)_v \frac{\Delta V}{\Delta \theta}\right\} = \frac{1}{c_v}(-T)\,R\,\frac{1}{V_c}\frac{\Delta V_c}{\Delta \theta}$$





Same performance, different mass flow rate

CFD analysis – LM numerical model

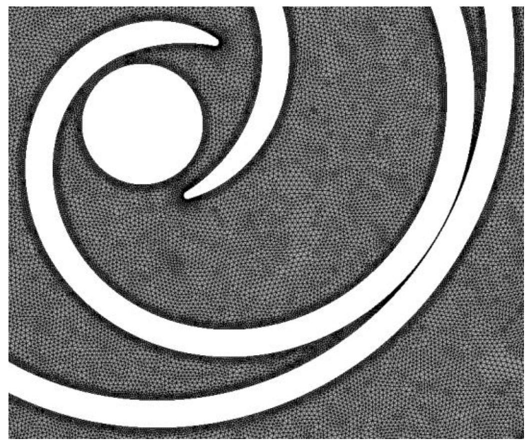
***CFD peculiarity*: 2D transient simulations by using a __Dynamic Mesh__ strategy

can reproduce the real operation of the machine through

a sequence of different positions by imposing an angular increment **$\Delta\theta$**

Mesh with ***local refinement***

- 302,000 tetrahedral elements
- regenerated each time step
- MAX skewness < 0.47
- min orthogonal q.lty > 0.68

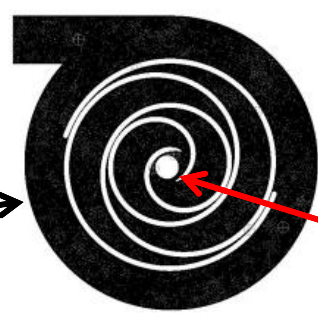


Mesh deformation

closely related to the step amplitude $\Delta\theta$

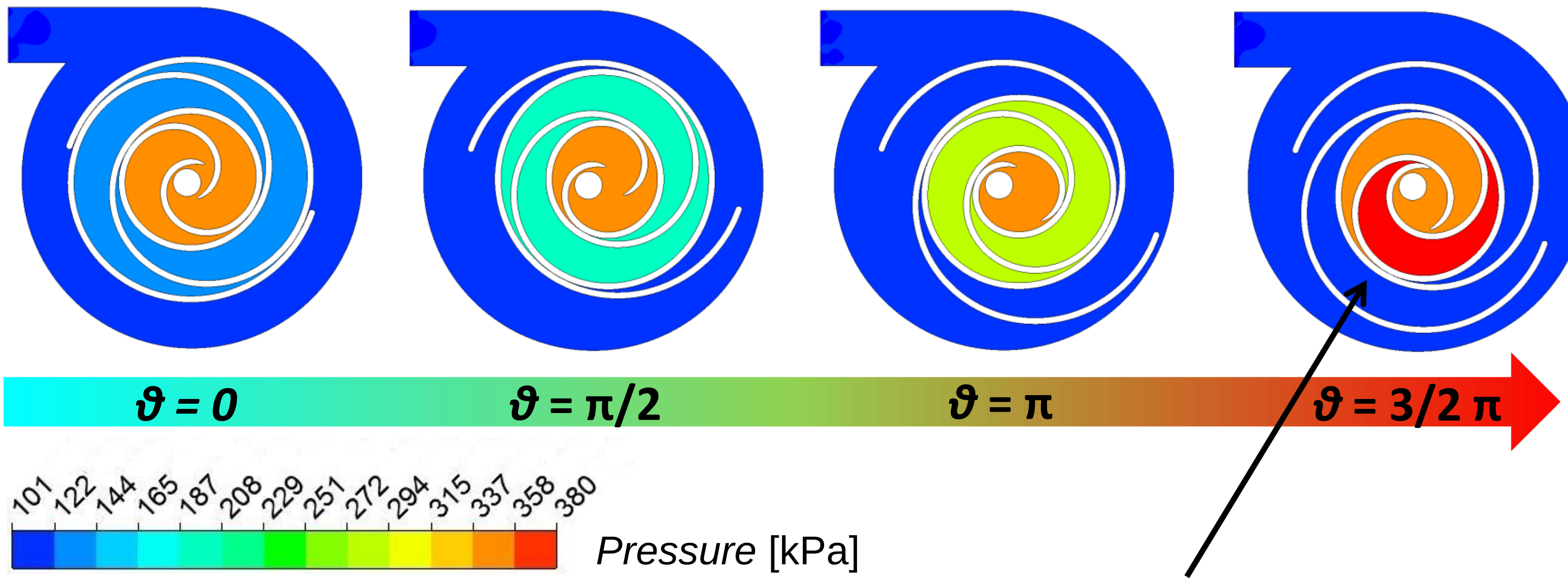
4 different $\Delta\theta$

- $\Delta\theta = 0.2500°$
- $\Delta\theta = 0.1250°$
- $\Delta\theta = 0.0625°$
- $\Delta\theta = 0.0417°$



CFD analysis – Global pressure

DM strategy = ***pressure increment*** during the scroll orbit



Compression chambers with ***different pressure*** *due to the asymmetric* ***inlet position***

imbalanced load for the mobile spiral

Noise & vibrations

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CFD analysis – Local pressure

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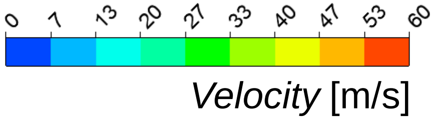
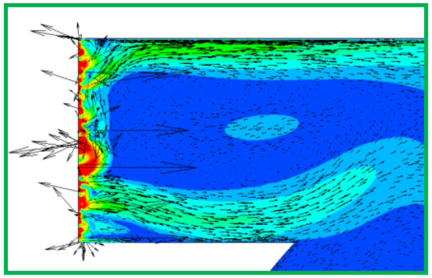
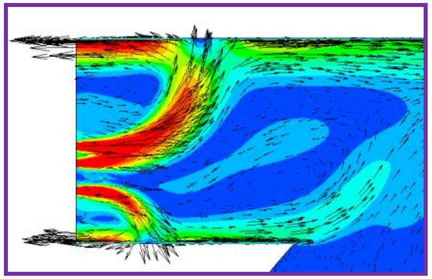


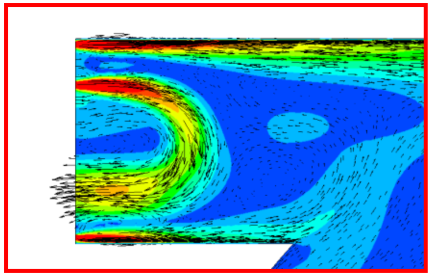
Δθ = 0.0625



Δθ = 0.0417



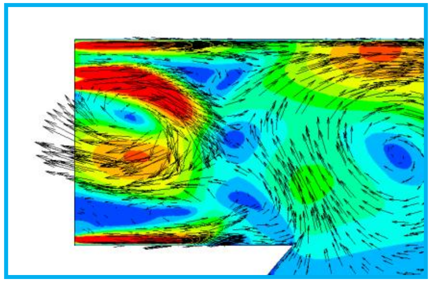
Δθ = 0.2500

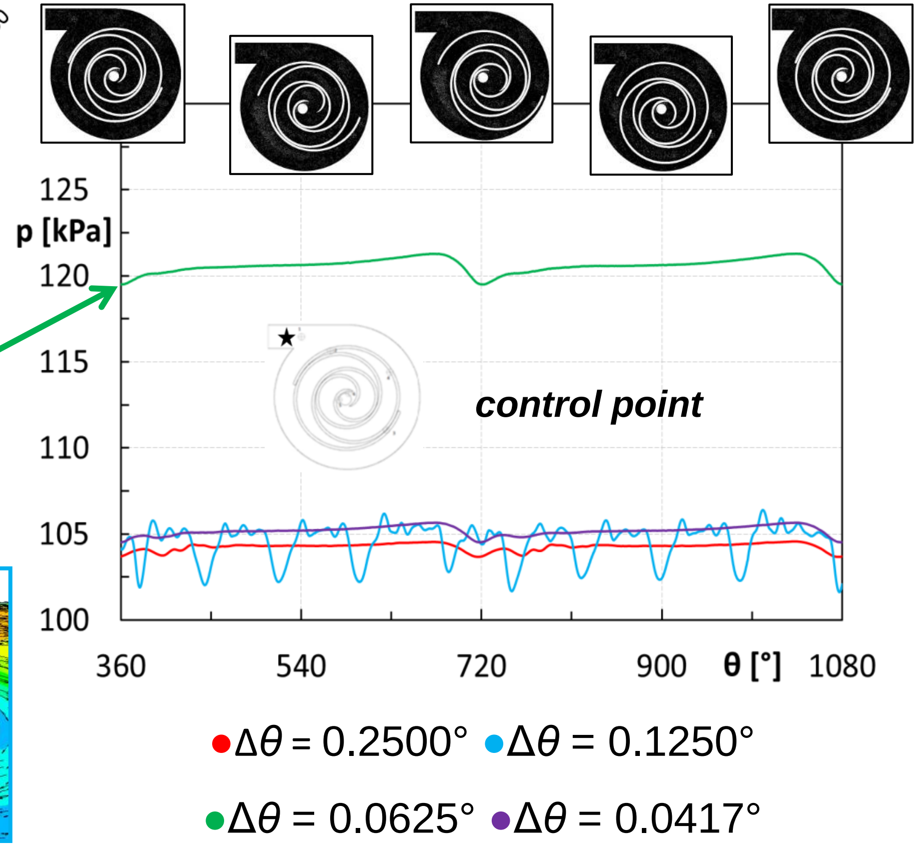


higher pressure

$\Delta\theta = 0.0625°$

Δθ = 0.1250





❖ local solution affected by $\Delta\theta$ and the turbulence model (k-ε)

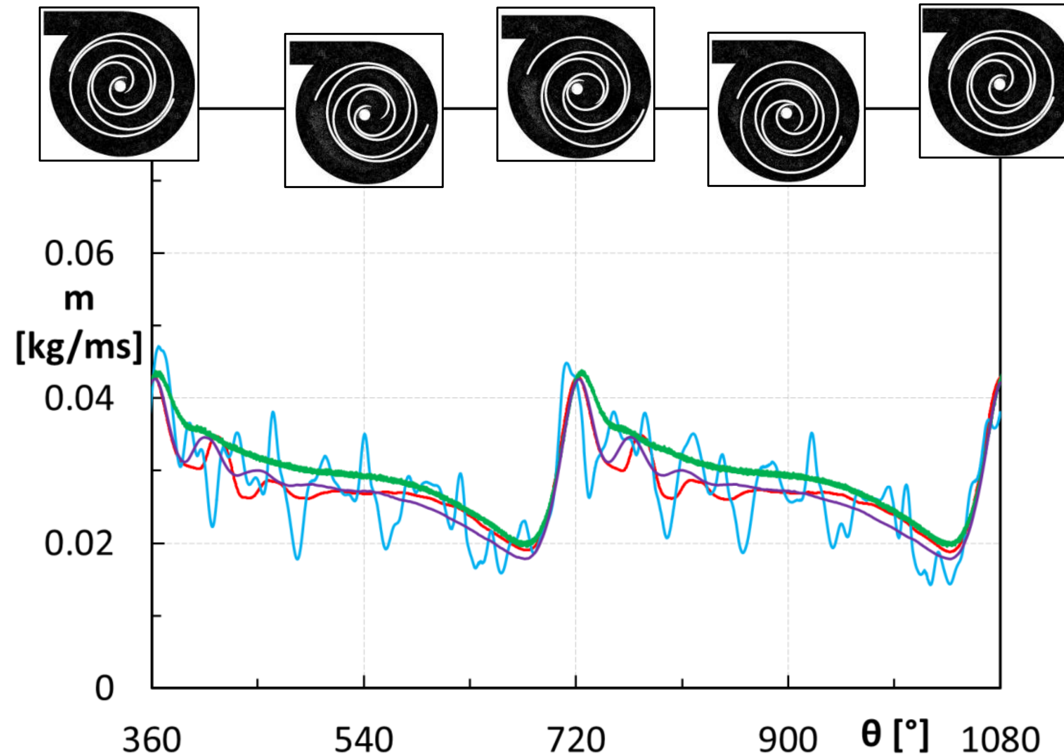
❖ wide recirculation zones with reversed flow are present at the inlet section

CFD analysis – Mass flow rate

Mass flow rate @ inlet for the2nd and 3rd orbit

● $\Delta\vartheta = 0.2500°$ ● $\Delta\theta = 0.1250°$

● $\Delta\theta = 0.0625°$ ● $\Delta\theta = 0.0417°$

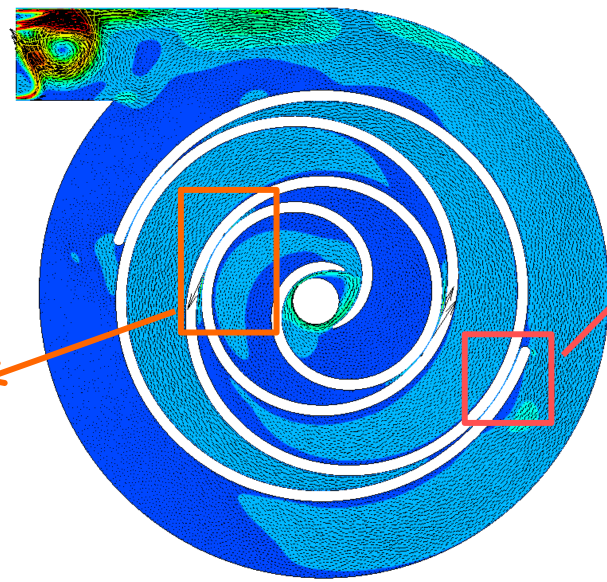


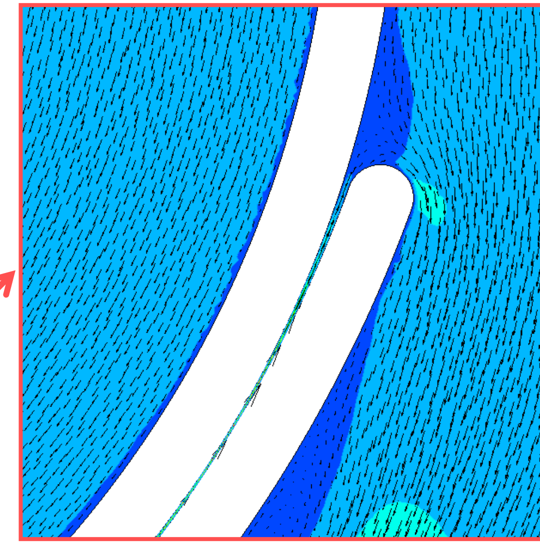
- The ***Δθ = 0.1250°*** simulation presents ***greatest fluctuations***
- Every $\Delta\theta$ shows the ***same trend*** of the mass flow rate
- The global ***mass flow rate*** was affected by the ***flank leakage*** due to the ***flank gap*** (equal to ***78 μm*** for the LM Scroll geometry)

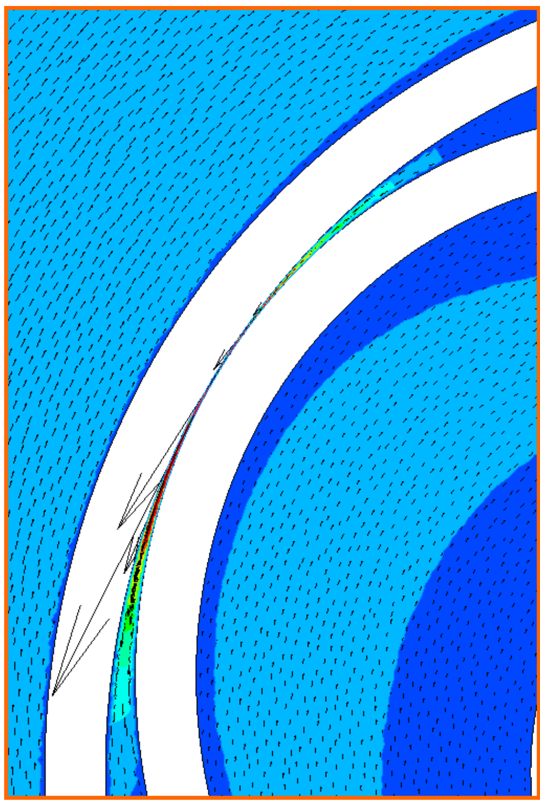
CFD analysis – Flank leakage

The ***flank gap*** (equal to ***78 µm***) determines the ***leakage*** that ***reduce*** the ***volumetric efficiency***

Velocity [m/s]
$\Delta\theta$ = 0.0125°







from the ***suction chamber*** to the ***external volume*** (casing) of the scroll compressor

from the ***compression chamber*** to the ***suction chamber*** of the scroll compressor

Conclusions

- The geometric methods analyzed showed significant differences in geometric structure of the scroll compressor, while the overall performance (in terms of compression ratio, temperature, …) were the same

- A CFD method was developed by means of a transient Dynamic Mesh strategy

- The sensitivity analysis showed that overall performances are not influenced by the $\Delta\theta$, but local mesh deformation can lead to different local fields of pressure and velocity

- CFD simulations allowed the evaluation of time profile of the mass flow rate and pressure fluctuations in every point of the domain
  - ✓ study and optimization of the shape of the spiral profile
  - ✓ study and optimization of the shape and the position of inlet and outlet ducts
  - ✓ analysis and optimization of the noise and vibration of the ORC system