Engine ORC Consortium

Improved scroll expander model for exhaust heat recovery

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EXOES

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EXOES

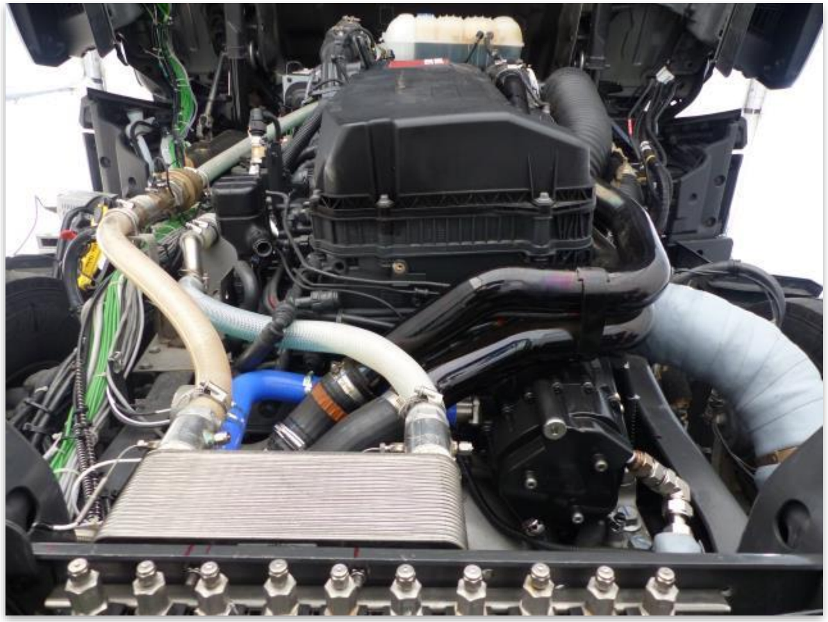
at a glance

MAN RENAULT TRUCKS faurecia Valeo TENNECO SANDEN

Latest project

Demo vehicle tested in 2017 (shown at EORCC last year)

thanks to a collaborative project with Faurecia and Renault Trucks



Component development

Expander development program

2016: single acting piston

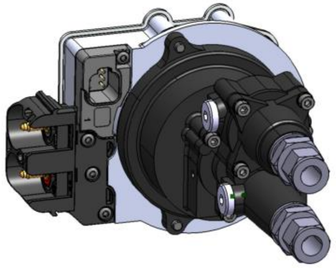
2014: double acting pistons

2013 : swashplate architecture & lubricant

2012 : Inlet valves & materials

Batteries for E-ORC

HP pump



Scroll expander

Expander model description

Literature

- Presentation based on EVE-T 3 design
- Literature:
  - University of Liège: Vincent Lemort, Leonardo Cutini, Arnaud Legros
  - Ian Bell, Thesis [1]
  - J. E. McCullough [2]

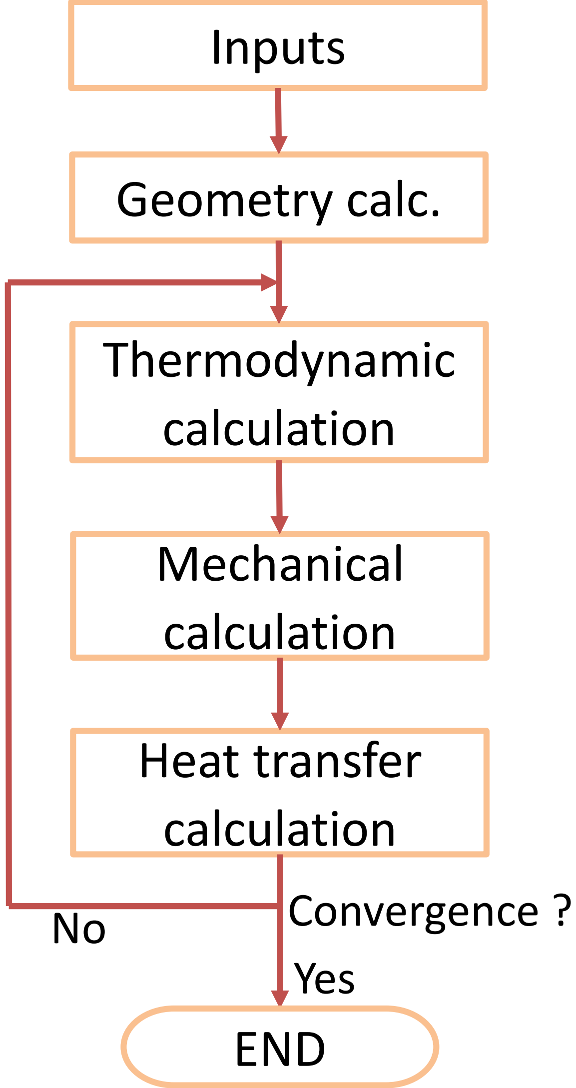
EVE-T3 Datasheet

Speed range (RPM)	1,000 – 6,000
Shaft power range	<15 kW
Eff. Is. efficiency range	Typ. 55 - 75%
Size	< D220xL130mm
Weight w/o coupling	18kg
Working fluid	Ethanol Cyclopentane
Oil circulation rate	Typ. 5%
Expansion ratio	4,30 -
Displacement	134 cc

Scroll expander modelling

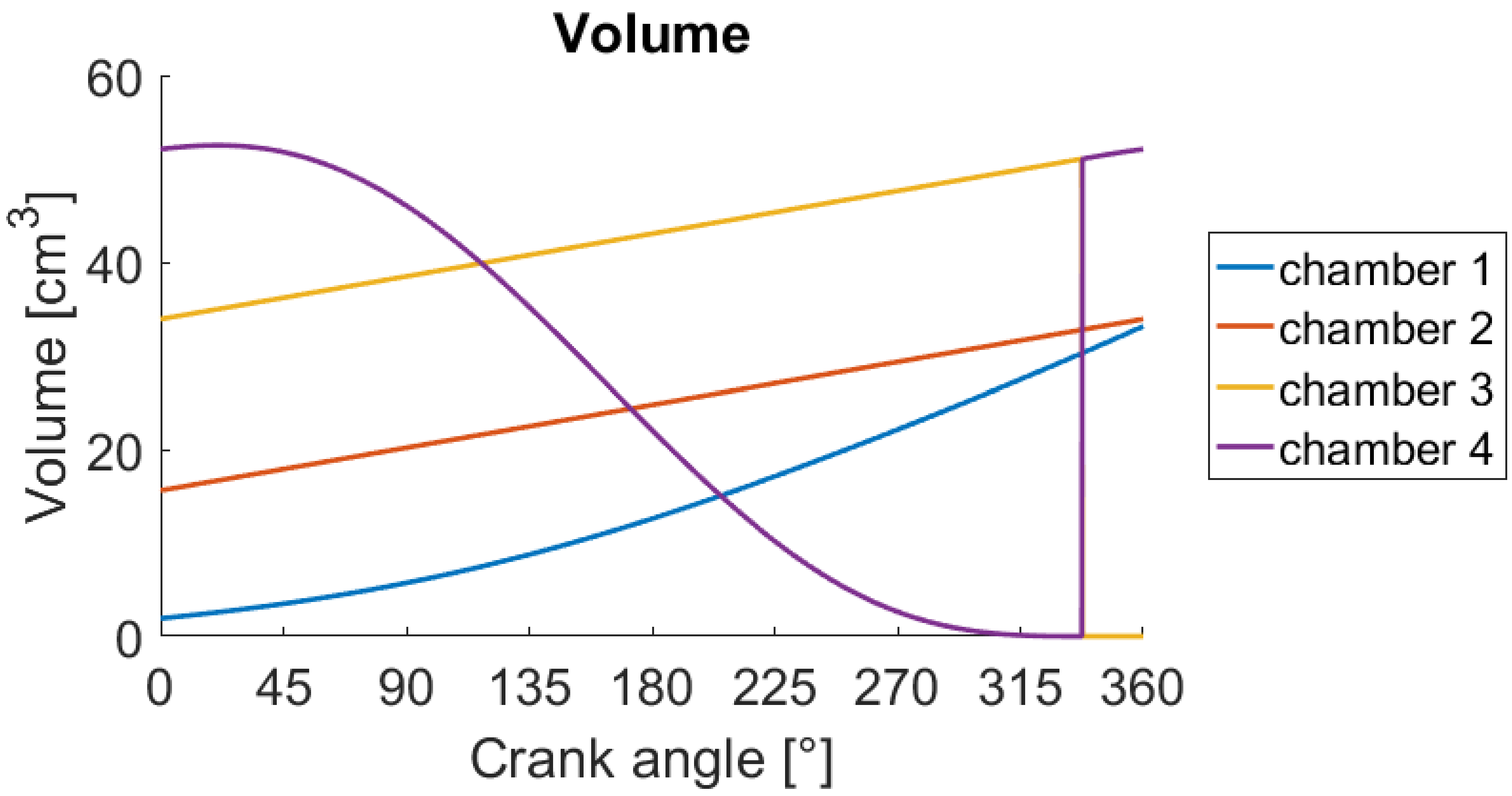
Improvement of a scroll model

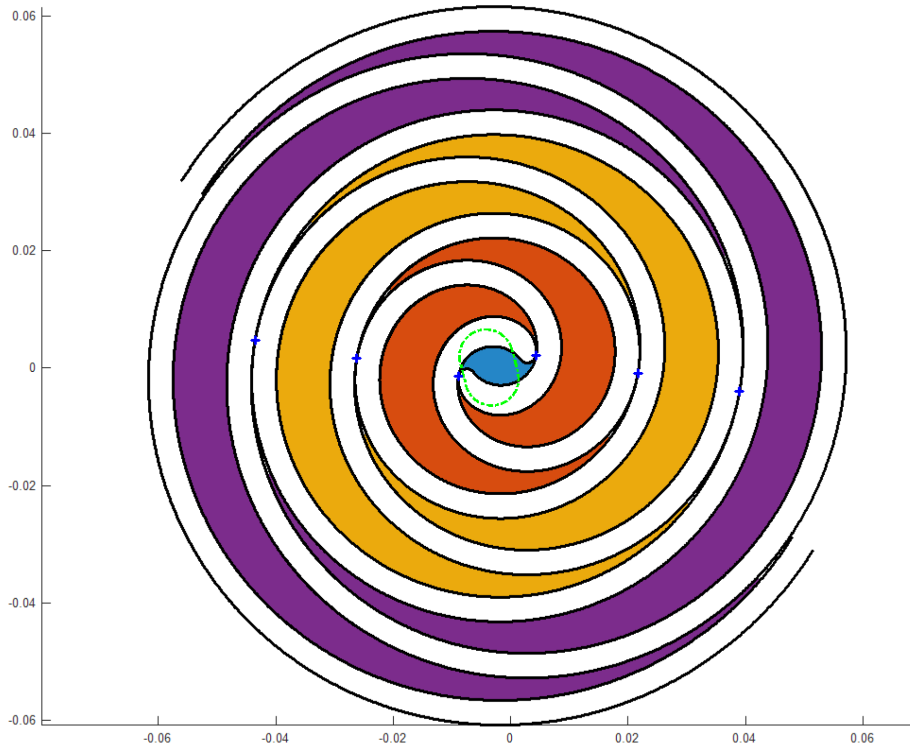
- Original model from University of Liège:
  - Matlab based model (linked with Coolprop)
- The scroll model includes:
  - Geometry description, incl. tip & inlet port
  - Conservation of energy and mass
  - Leakage
  - Mechanical model
  - Heat transfers
- We added / improved:
  - Leakages, mechanics and heat transfers
  - “double pocket” description



Geometry description

Pocket volume calculation

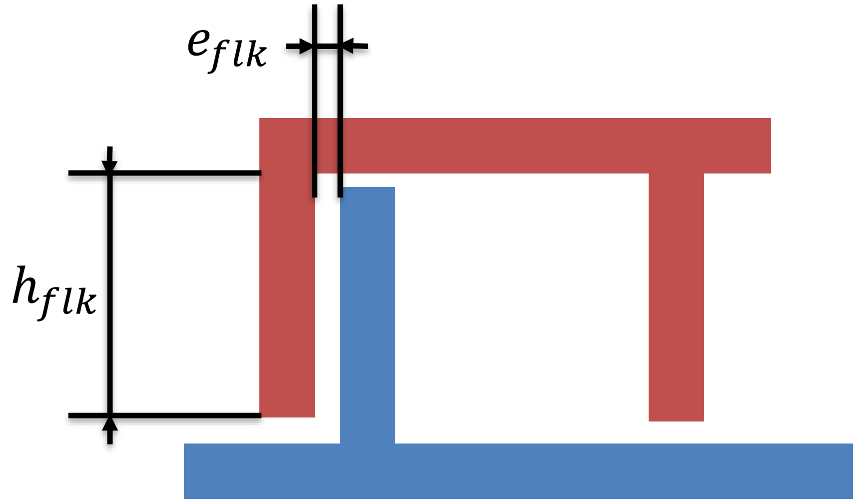




- Chamber volume calculated according to [1]

- Flank leakages: nozzle equation (perfect gas)

$$\dot{M}_{flk} = h_{flk}.e_{leak}\sqrt{2P_h\rho_h\frac{\gamma}{\gamma-1}\left[\left(\frac{P_{thr}}{P_h}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{thr}}{P_h}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$



Flank leakage areas

Flank leakage areas

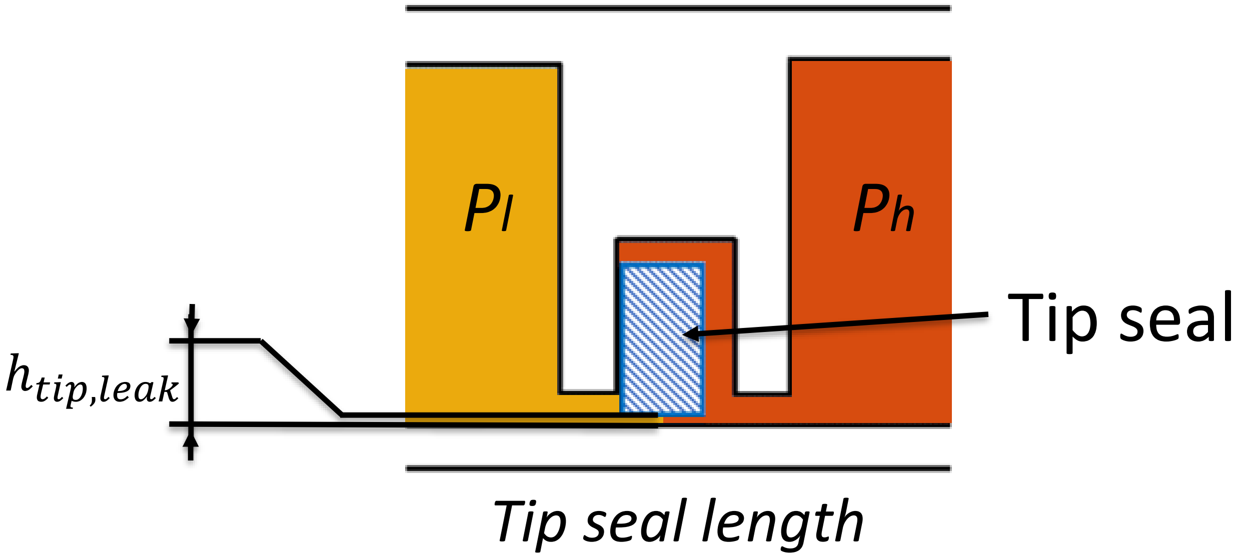
Tip seal leakages

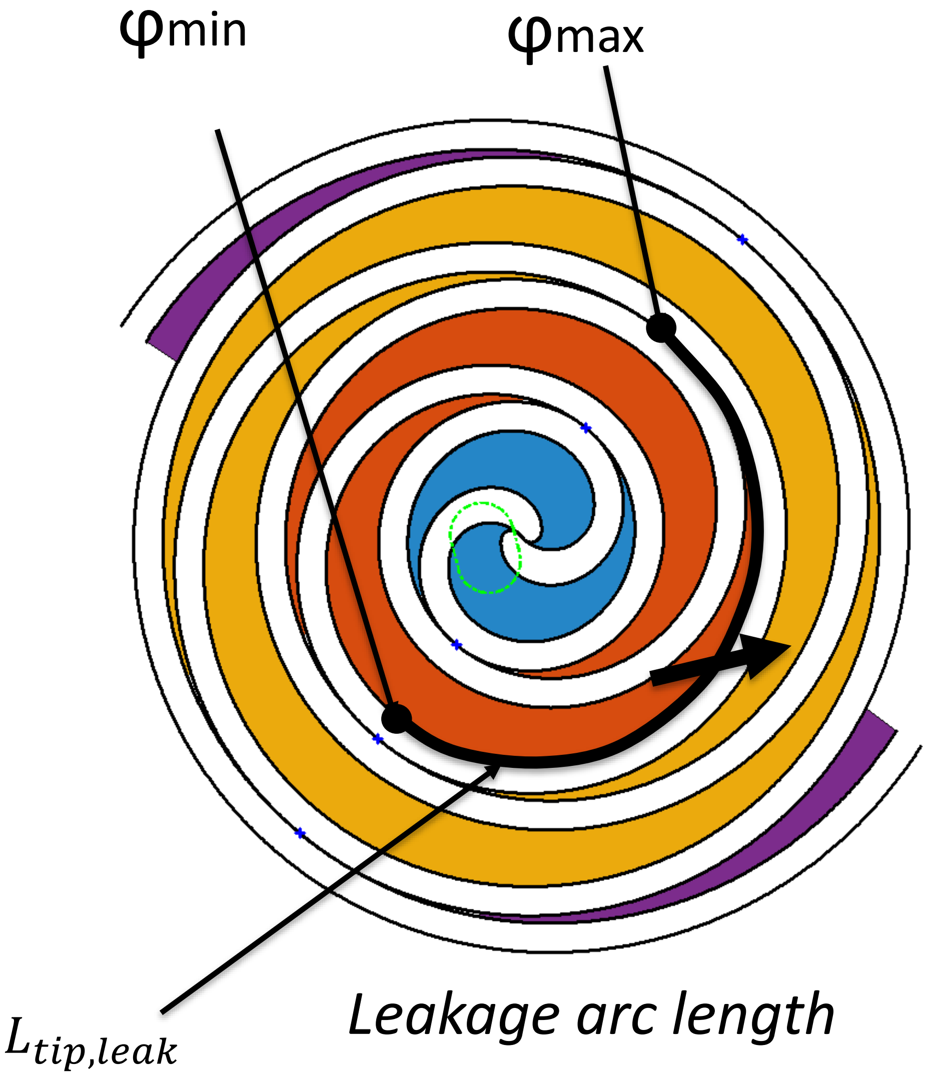
Tip seal & flank leakages

- Tip seal leakages: Hagen-Poiseuille equation

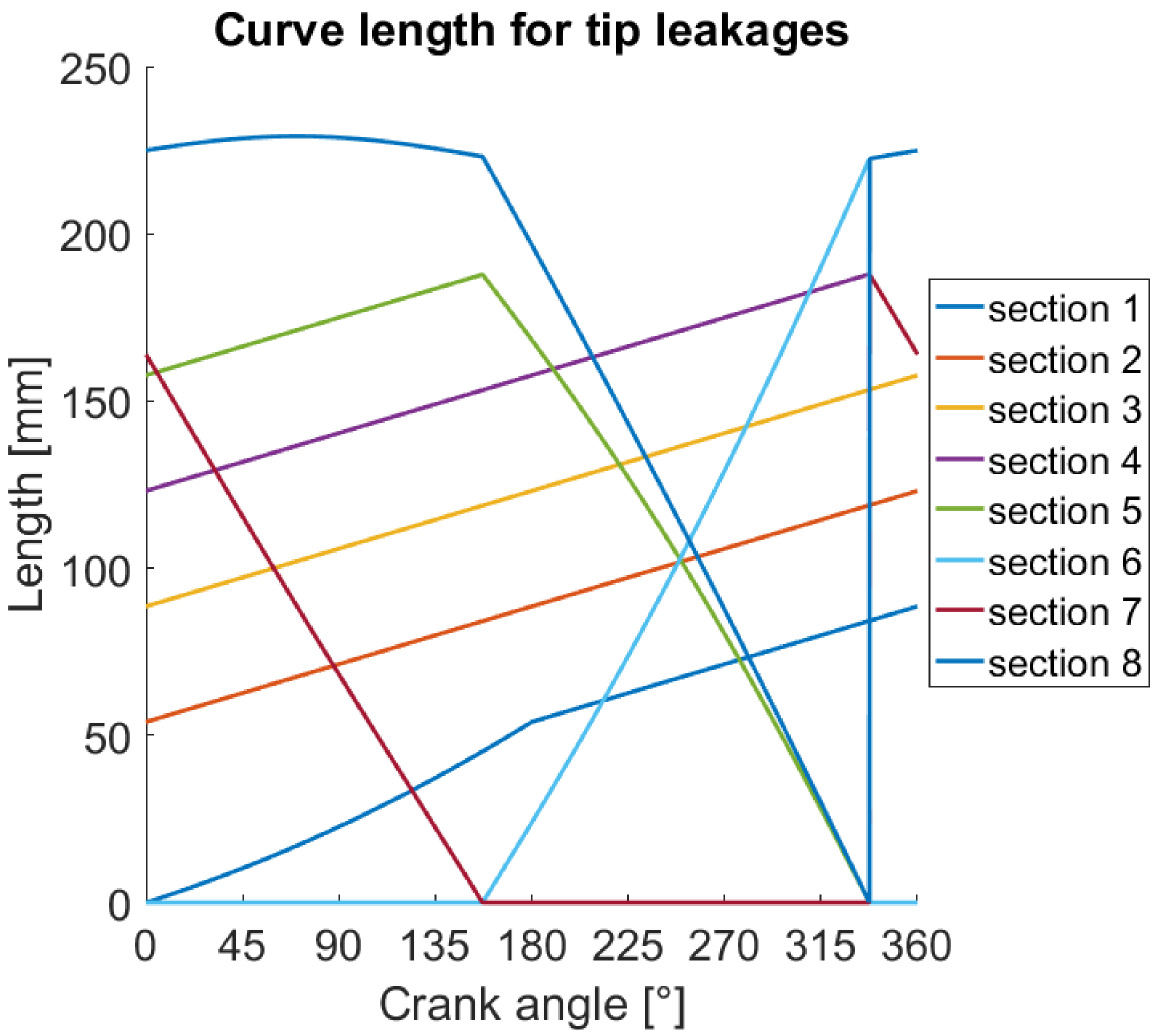
$$L_{tip} = r_b\left(\frac{1}{2}(\varphi_{max}^2 - \varphi_{min}^2) - \varphi_0(\varphi_{max} - \varphi_{min})\right) \quad [1]$$

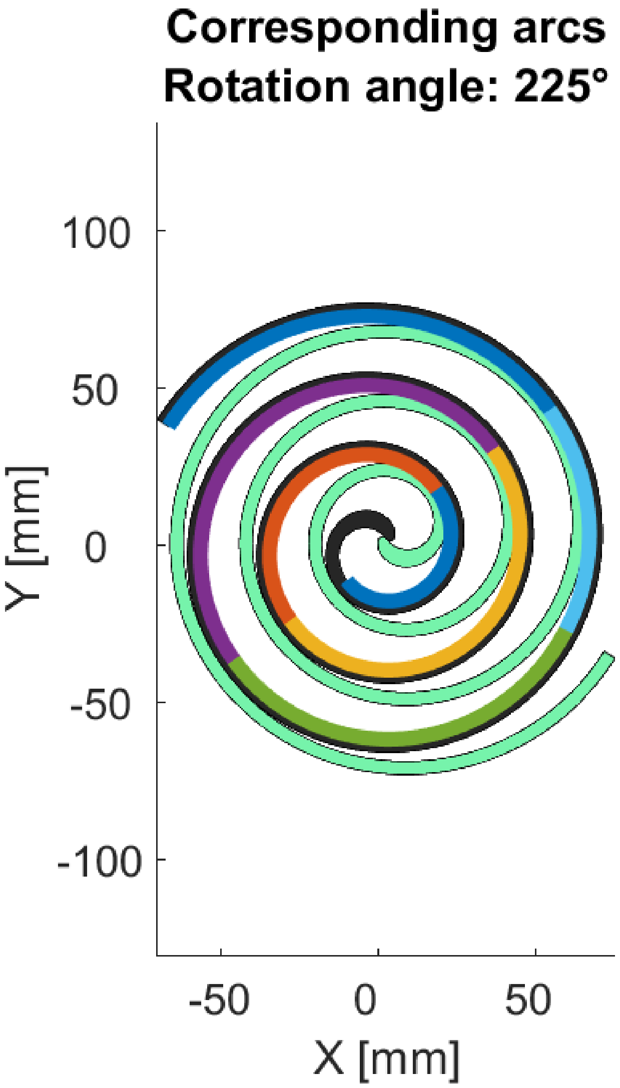
$$\dot{M}_{tip} = L_{tip}.h_{tip,leak}\sqrt{\frac{2D_h.\rho.\Delta P}{f.t}}$$





Tip seal leakages

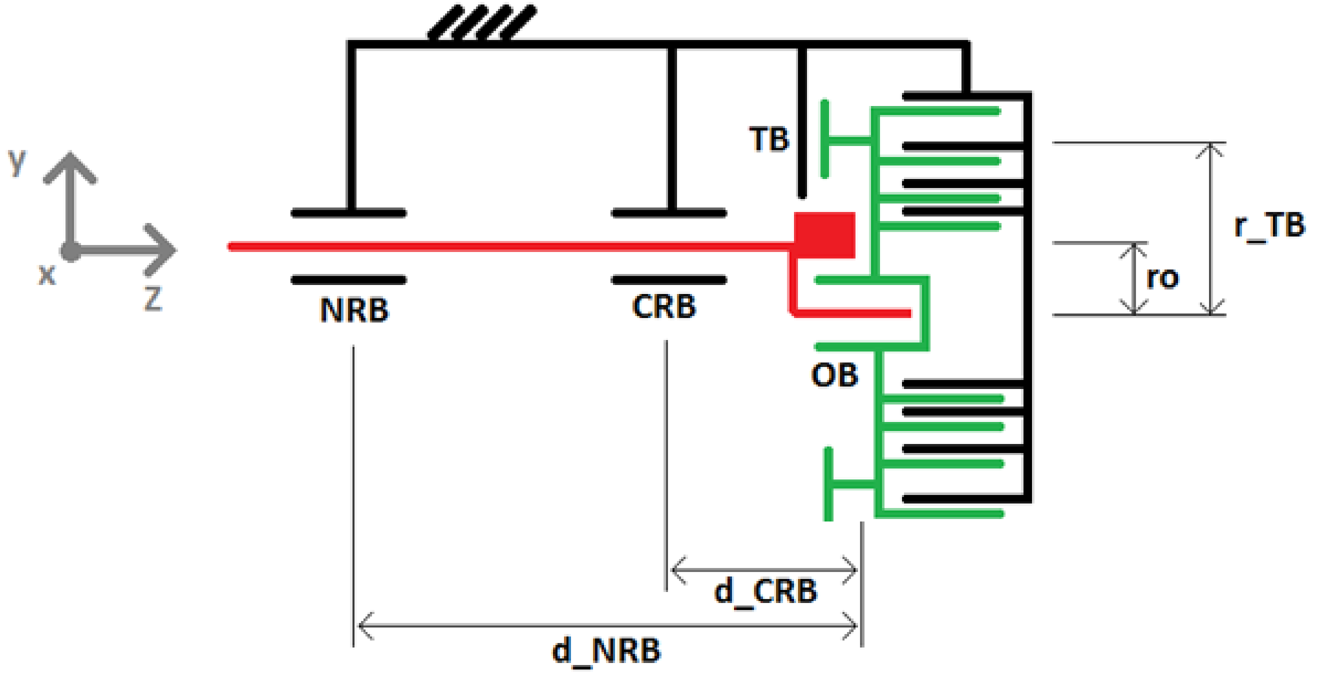




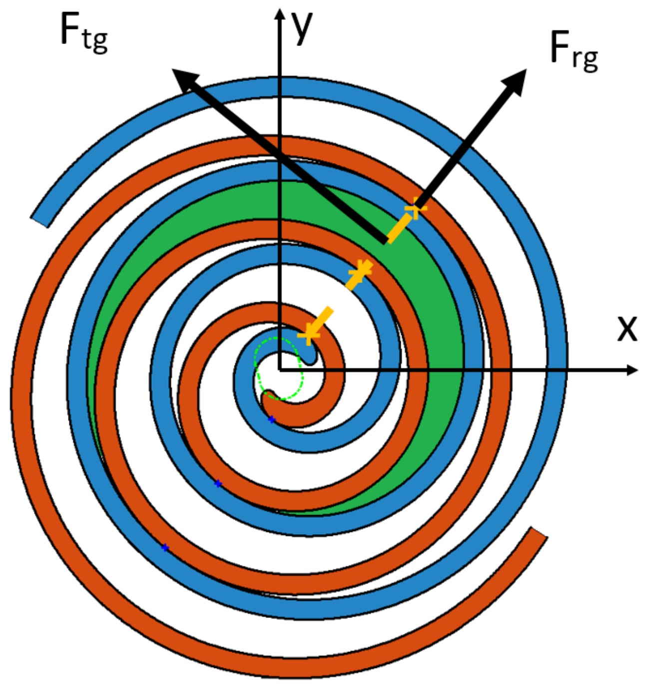
Mechanical model

Mandatory for a scroll design

- Loads on the mobile scroll calculation [1]
- Loads on the bearings
- Heat losses correlations



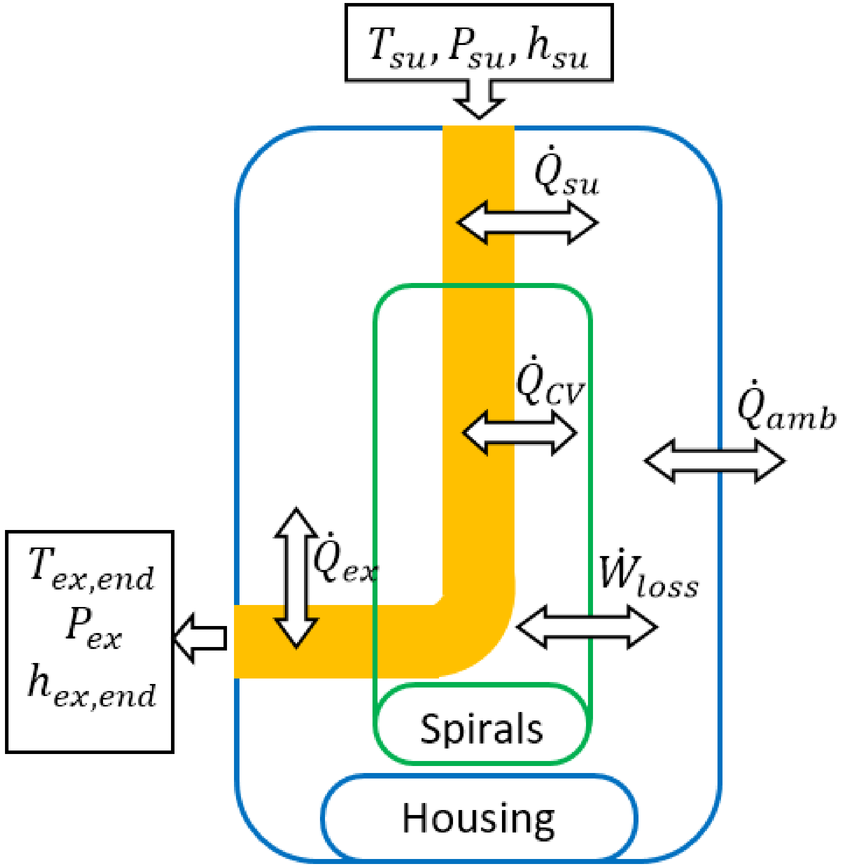
Expander kinematics



Tangential & radial forces representation

Heat transfer

- Heat transfer in the control volume [1]
  - Between the fluid and the scroll wrap and the base plate.
  - Linear drop of wall temperature from inlet to exhaust
  - Base plate temperature calculated function of wall temperature
- Heat transfers in the housing [1]
  - Between fluid exhaust and supply, spirals, housing, ambiant air
  - Lumped housing temperature
  - Integration of the energy of the mechanical losses



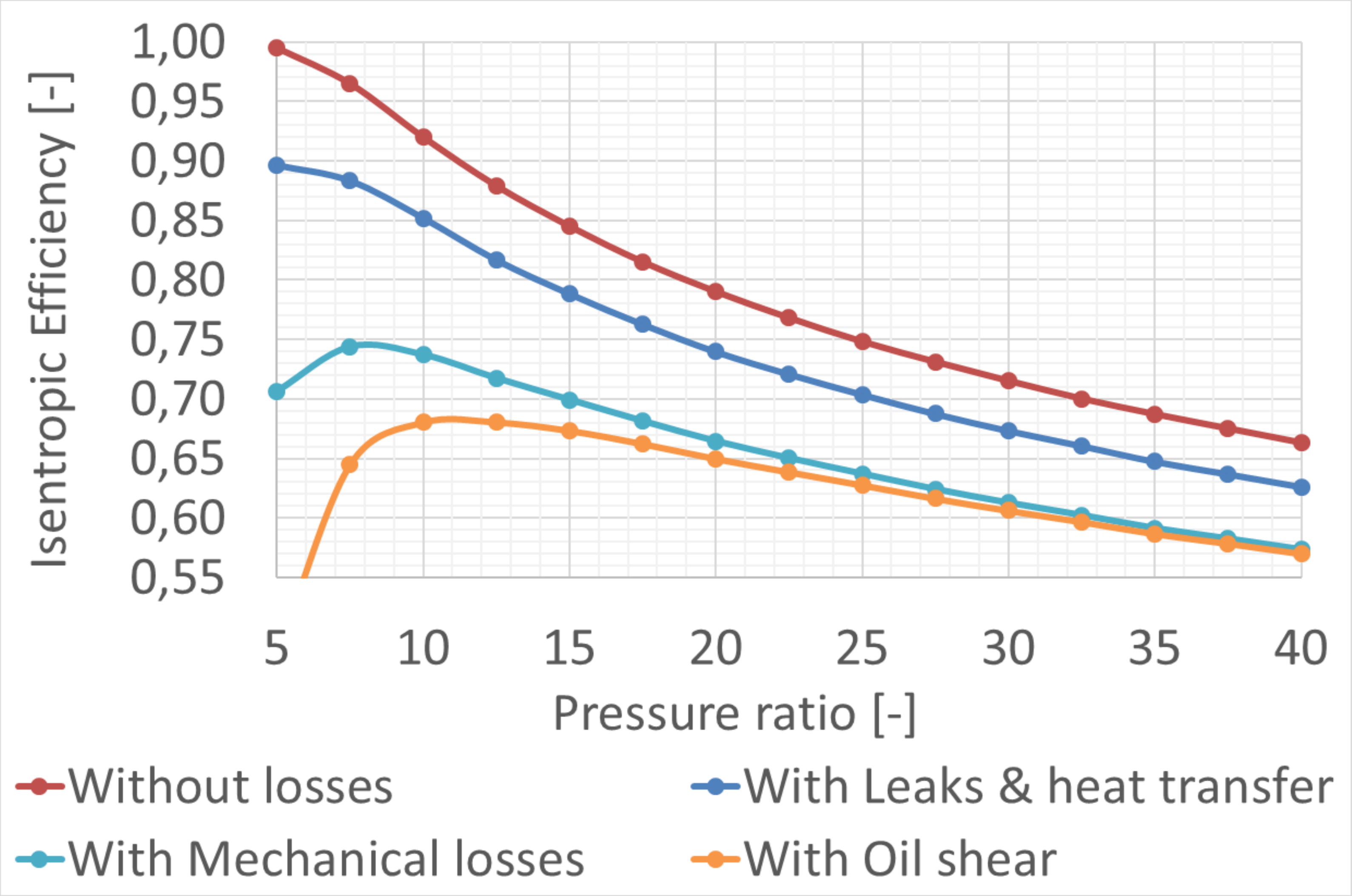
Heat transfer representation

$$\dot{Q}_{spirals} - \dot{Q}_{amb} - \dot{W}_{loss} + \dot{Q}_{ex} + \dot{Q}_{su} = 0$$

Simulation results

Scroll calculation for truck ethanol ORC

- Inputs:
  - Ethanol 95.5%wg
  - 3,600 rpm
  - 20°C Superheat
  - Exhaust press. 1 BarA
- Outputs:
  - Mechanical power
  - Mass flow
  - Isentropic efficiency

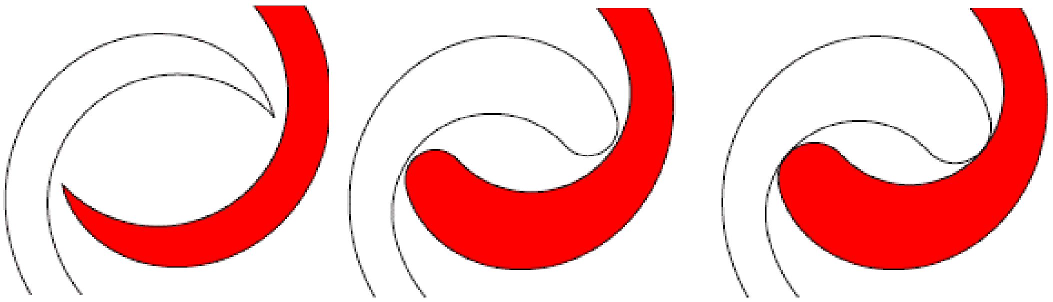


SCROLL NOSE TIP & INLET PORT OPTIMIZATION

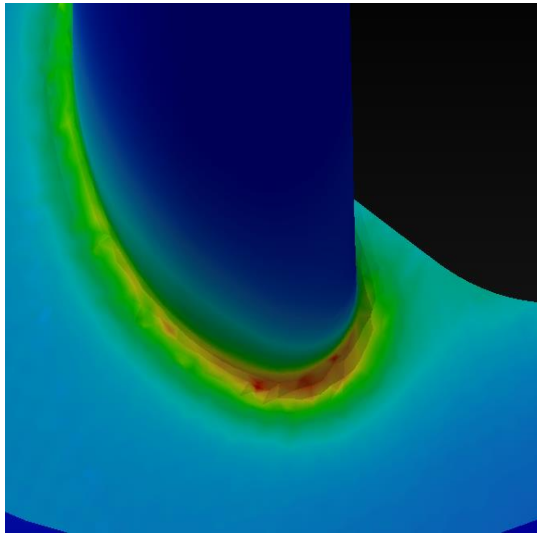
Scroll nose tip and inlet port

are key for a high performing expander

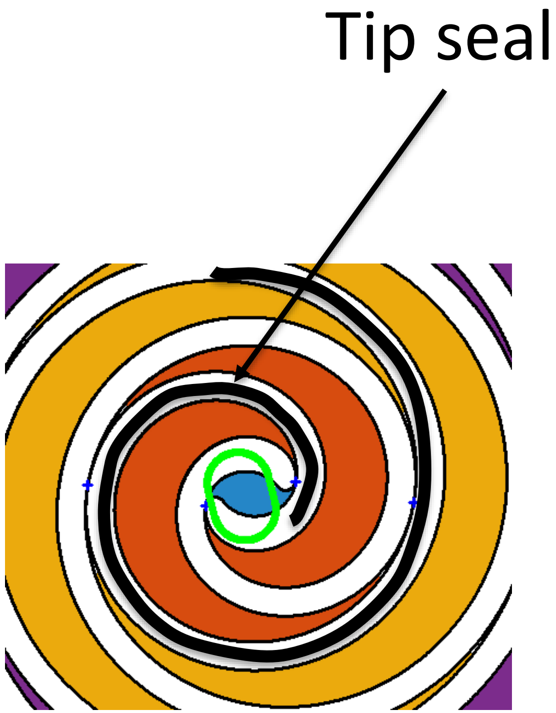
- Accurate nose modeling to withstand mechanical stress
- Detailed leak model on the tip seal



Different scroll tip nose thicknesses [1]



FEA - Nose stress



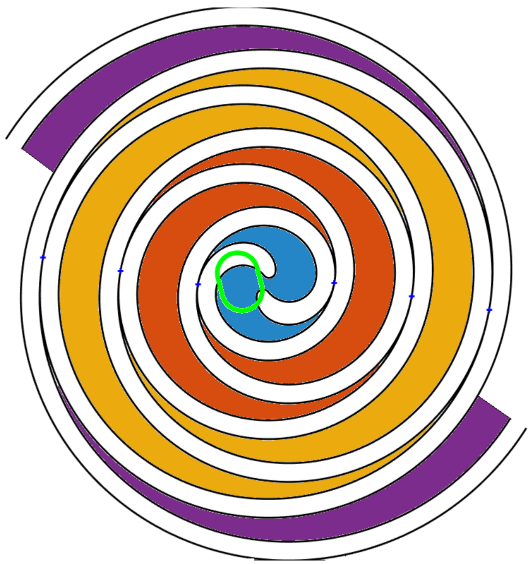
Nose tip seal

⇨ Simulation and FEA needed to find a tradeoff between efficiency and mechanical strength

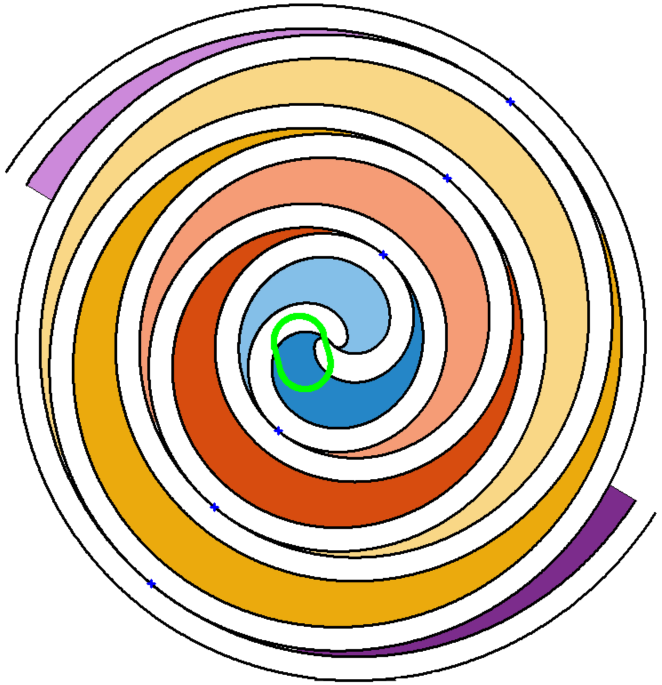
Geometric decomposition

Why introducing this refinement ?

- Problem to be solved:
  - Dissymmetric chamber → Supply process too optimistic
  - Vibrations



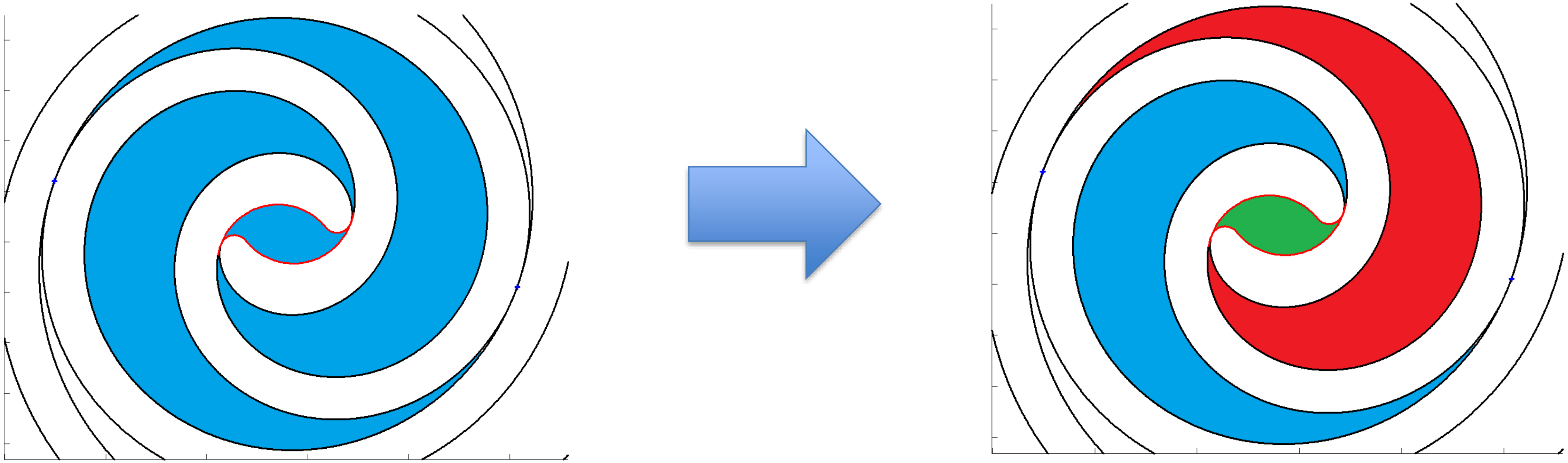
Supply port position @ 180°



Supply port position @ 240°

Geometric decomposition

- Resolution proposition
  - Geo. decomposition of the first pocket
  - Central pocket at supply pressure



Single pocket model @330°

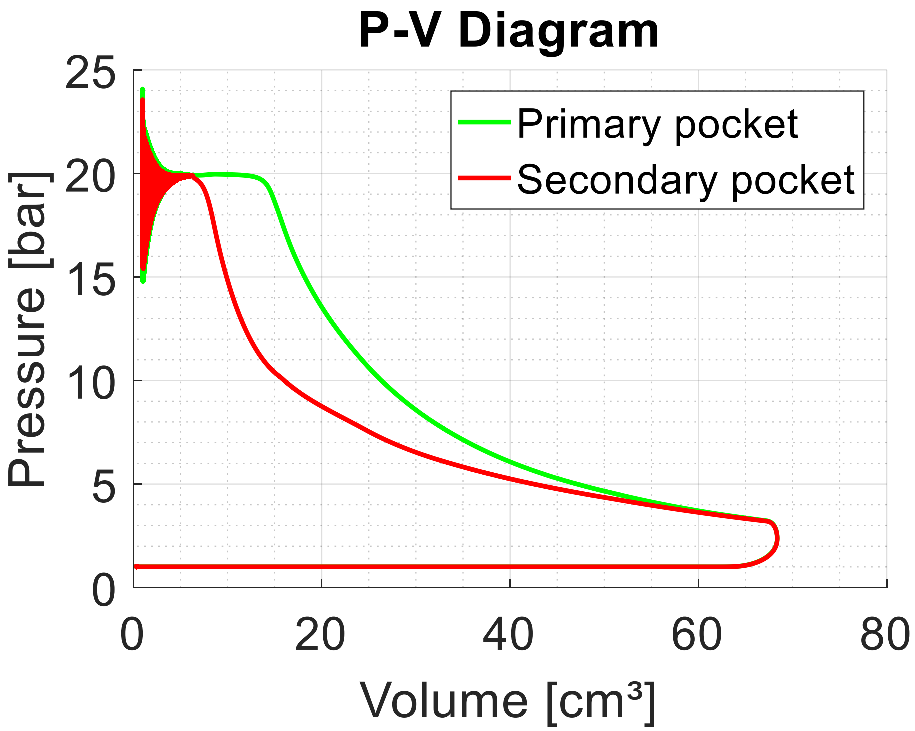
Double pocket model @330°

"Double pocket" concept

Simulation results

- Results:
  - Better design of supply process
  - Pressure difference negligible if supply process well designed

- Inputs:
  - Ethanol 95.5%wg
  - 3,600 rpm
  - 20°C Superheat
  - Supply press. 20 BarA
  - Exhaust press. 1 BarA



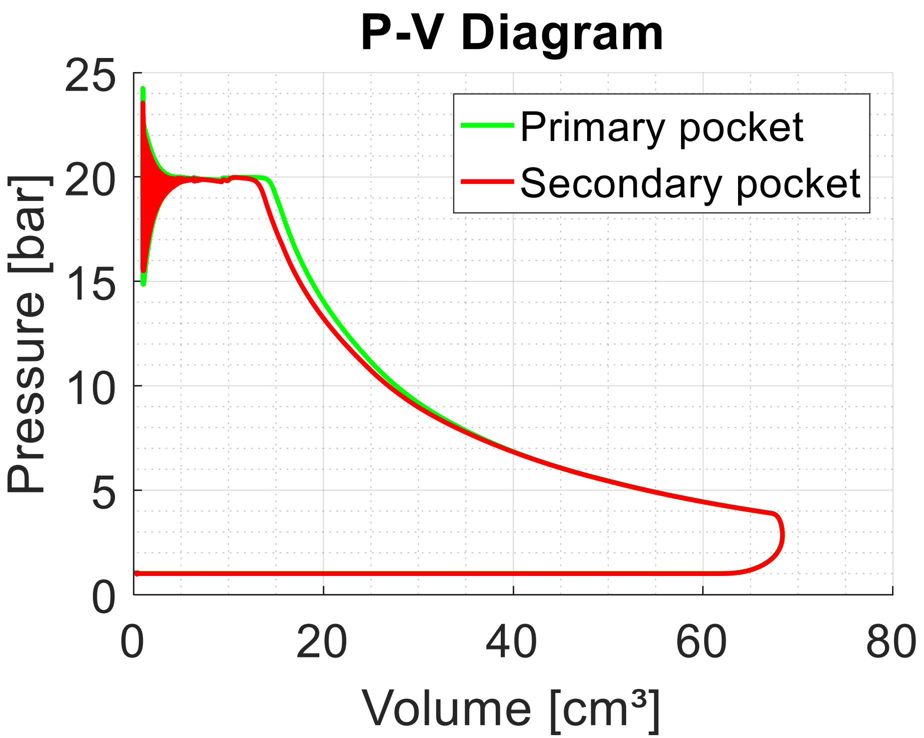
Example of <u>a non optimized</u> supply process

“Double pocket” concept

Simulation results

- Results:
  - Better design of supply process
  - Pressure difference negligible if supply process well designed

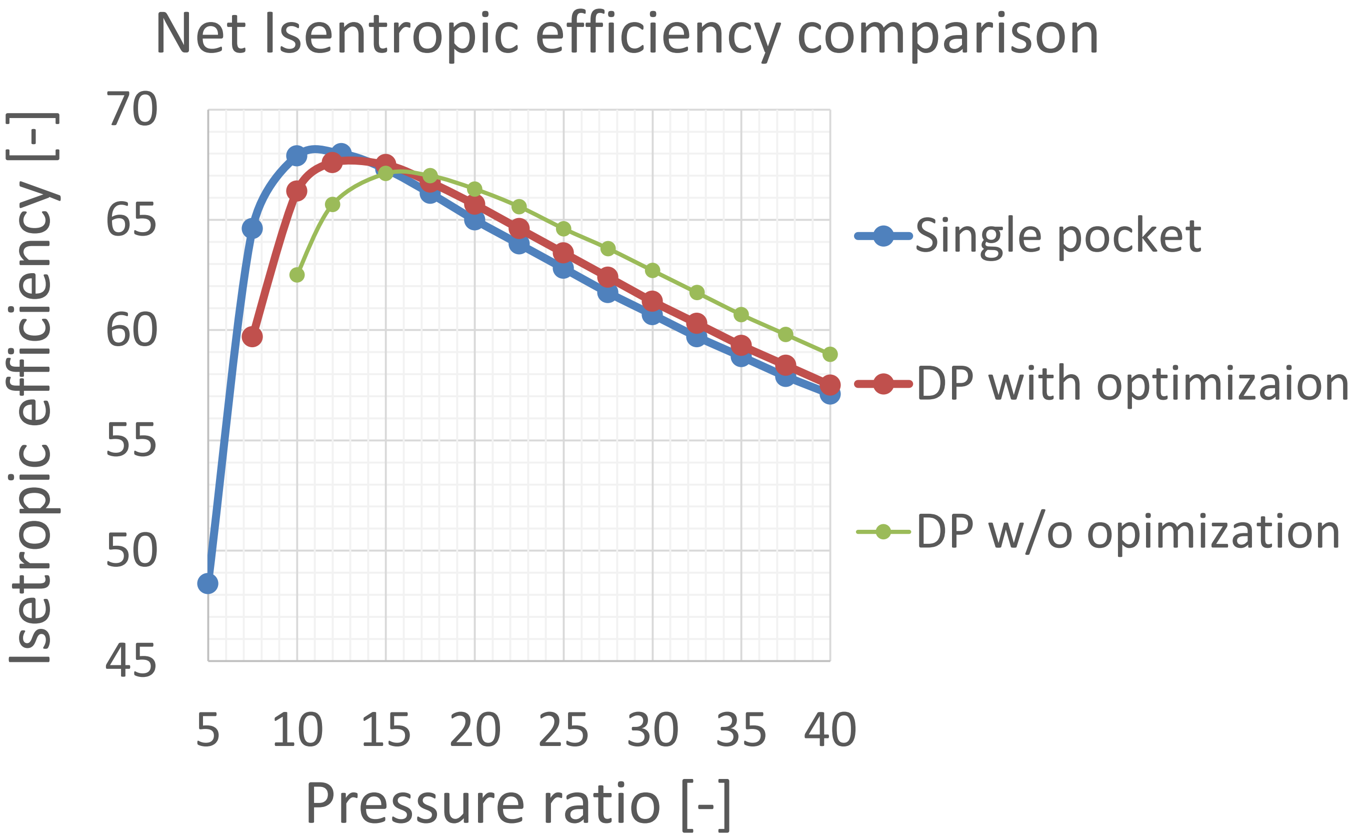
- Inputs:
  - Ethanol 95.5%wg
  - 3,600 rpm
  - 20°C Superheat
  - Supply press. 20 BarA
  - Exhaust press. 1 BarA

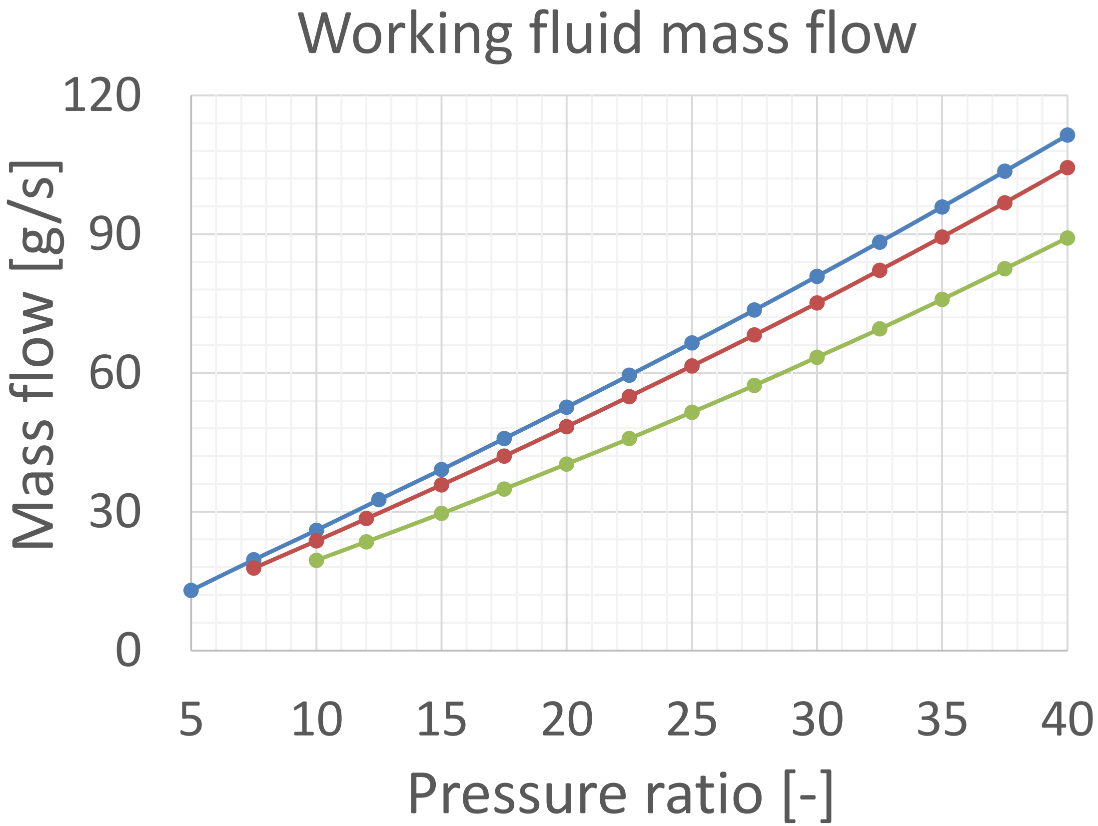


Example of
<u>an optimized</u> supply
process

“Double pocket” concept

Simulation results





Impossibility to optimize the expander mass flow & mechanical power without double pocket model.

Conclusion

- Exoès developed a scroll expander model with double pocket decomposition which allows a:
  - Better supply process prediction
  - Better mass flow prediction / mechanical power prediction

- Coupling with FEA tool is mandatory for an efficient design

- Next step: Model calibration with experimental data

Conclusion

Thank you for your attention

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References

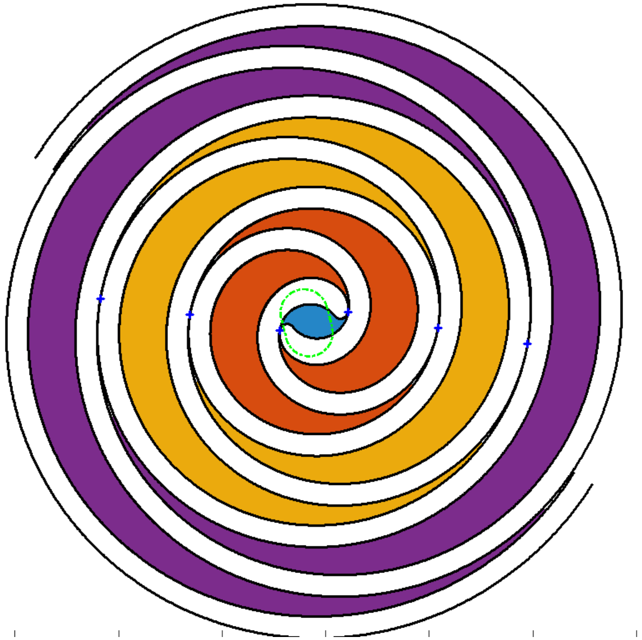
- [1] I. H. BELL, «Theoretical and experimental analysis of liquid flooded compression in scroll compressors» 2011.
- [2] J. E. McCullough, « Scroll Compressor development program » 1977

NRB: Needle Roller Bearing
CRB: Cylindrical Roller Bearing
TB: Thrust Bearing
OB: Orbiting Bearing
ro: orbiting radius

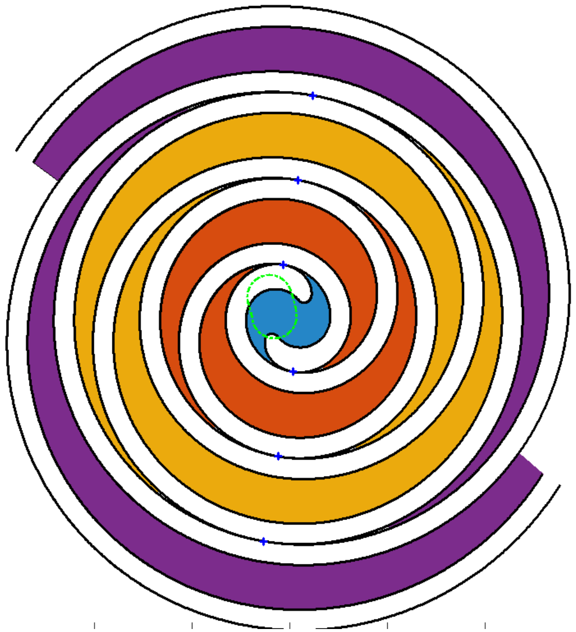
D: distance
Ftg: Tangential force
Frg: Radial force

ANNEXES

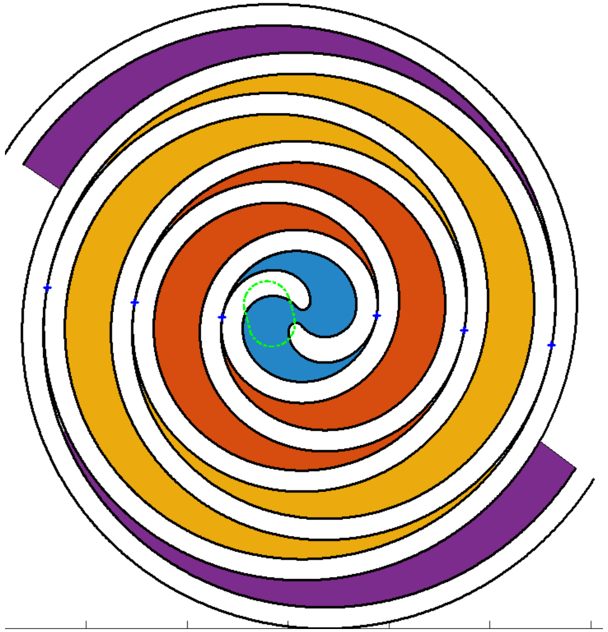
Scroll positions



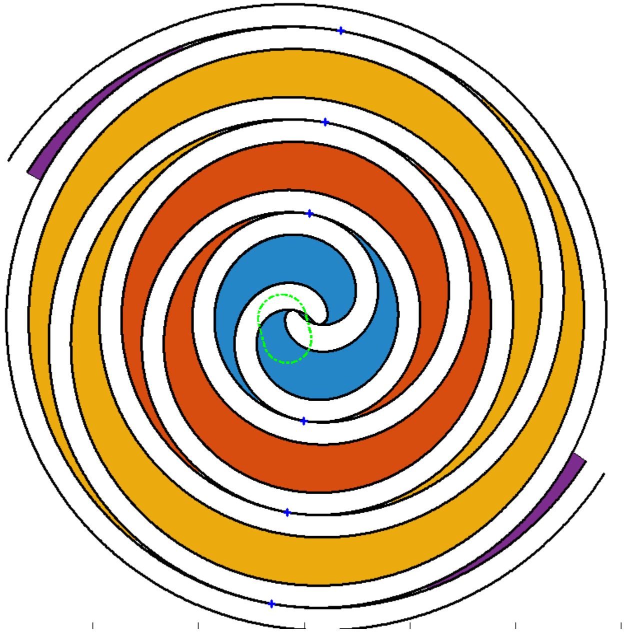
Rotation angle: 0°



Rotation angle: 90°



Rotation angle: 180°

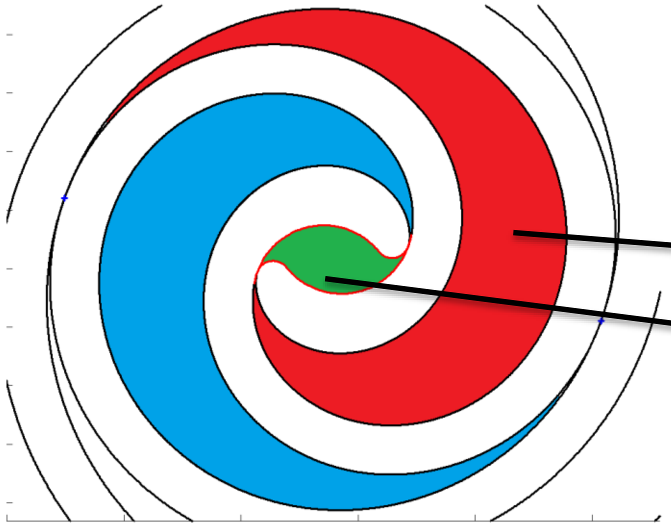


Rotation angle: 270°

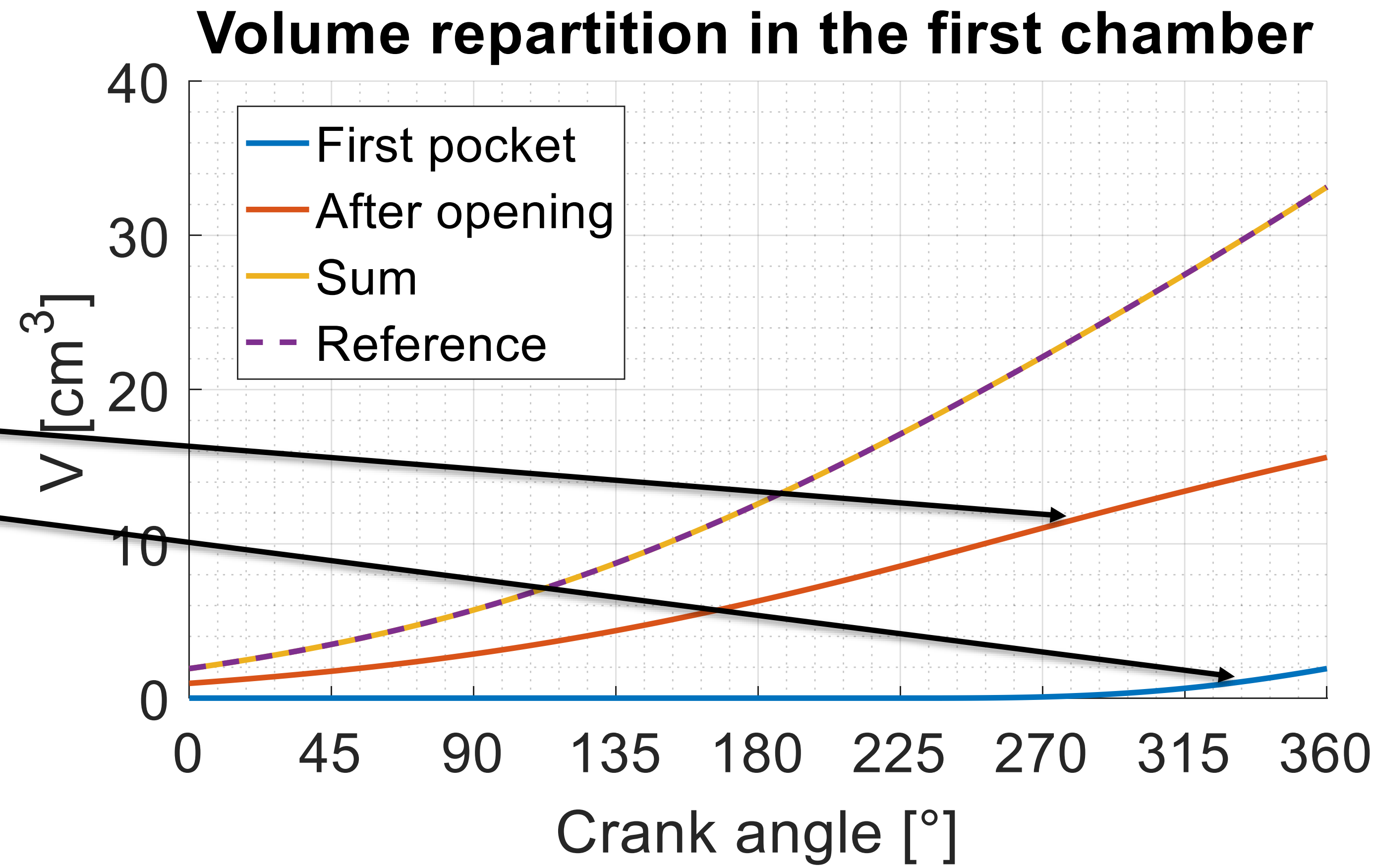
"Double pocket" concept

Simulation results

- Volume repartition in the first chamber



1st pocket volume decomposition



Conservation of Energy and Mass

Very standard description

– Mass conservation:

$$m_{i+1} = m_i + m_{su} + m_{ex} + m_{leaks}$$

– Energy conservation:

$$m_{i+1}.U_i = m_i.U_i + (m_{su}+m_{leak,i,su}).h_{su} + (m_{ex}+m_{leaks,i,ex}).h_i + Q_i - P.dV$$

Mechanical model

Calculation results

- Inputs:
  - Ethanol 95.5%wg
  - 3,600 rpm
  - 20°C Superheat
  - Psu: 20 BarA
  - Pex: 1 BarA