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City University London

Numerical Simulation of Fluid Flow and Solid Structure in Screw Compressors

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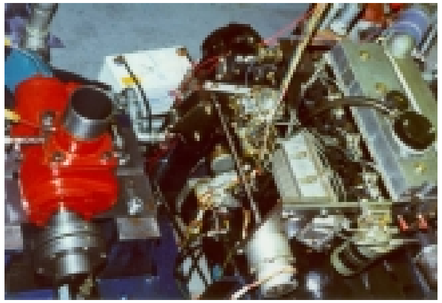
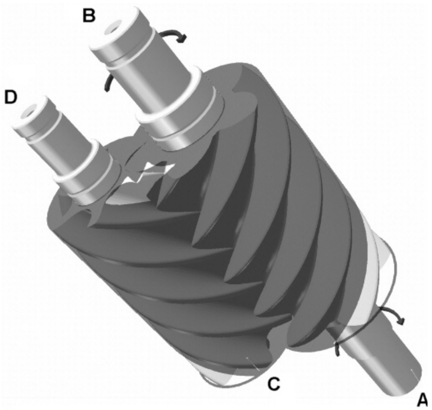
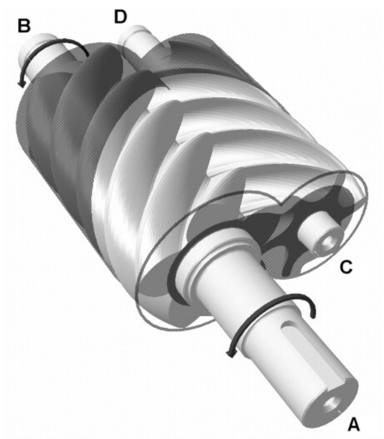
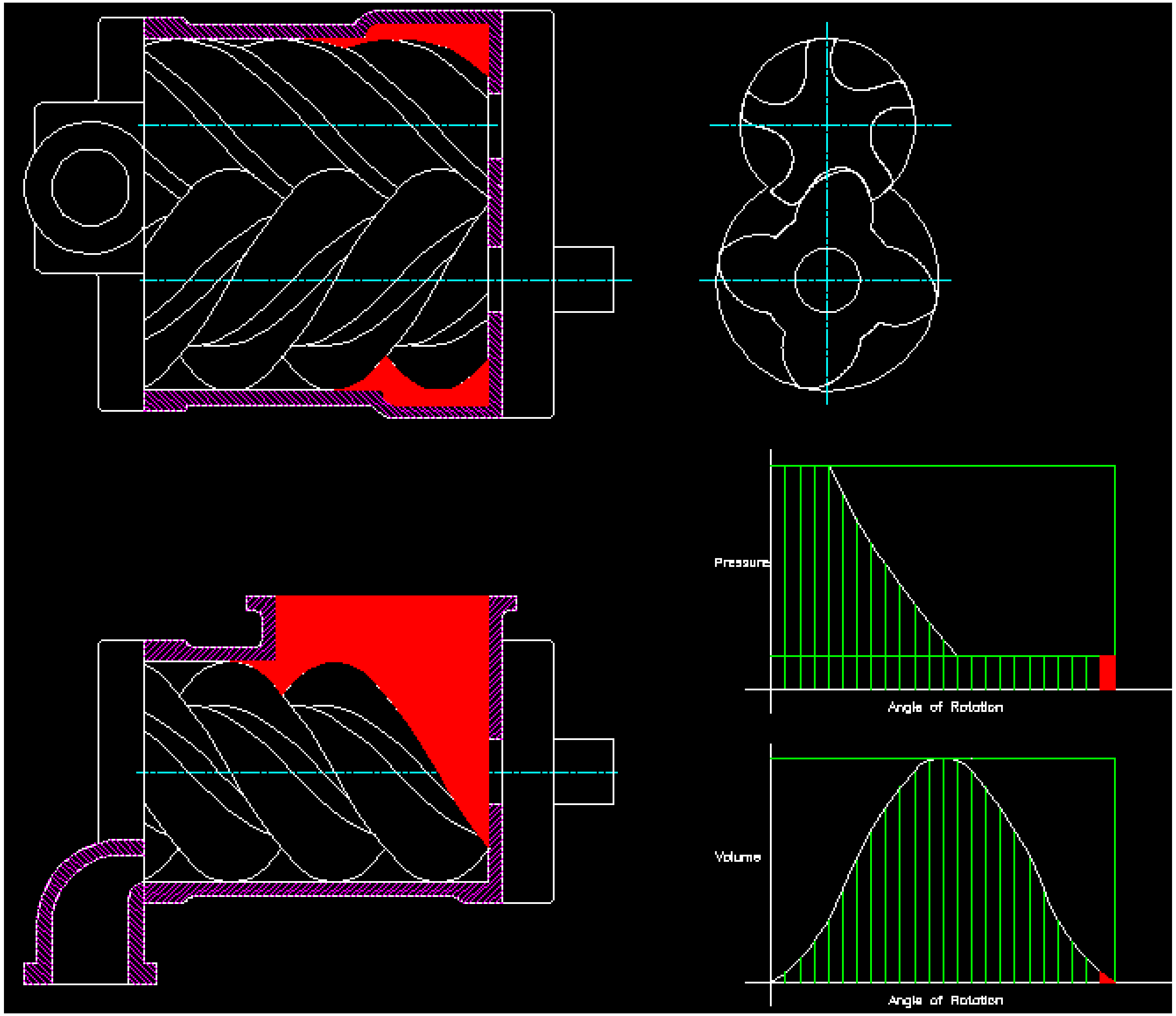
Screw compressor working principle



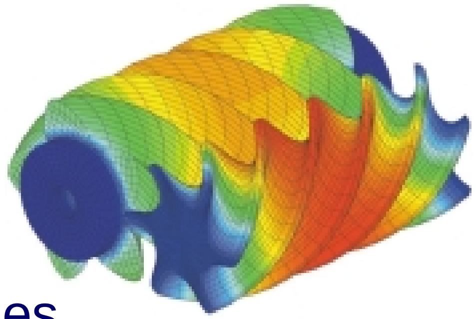






Flow and Deformation

Screw compressor performance is affected by:



- Temperature and pressure field,
- Distortion of rotors and housing,
- Reverse effects to the flow,
- Leakage through the gaps,
- Rotor wear or even seizure in extreme cases

One-Dimensional models assume that:

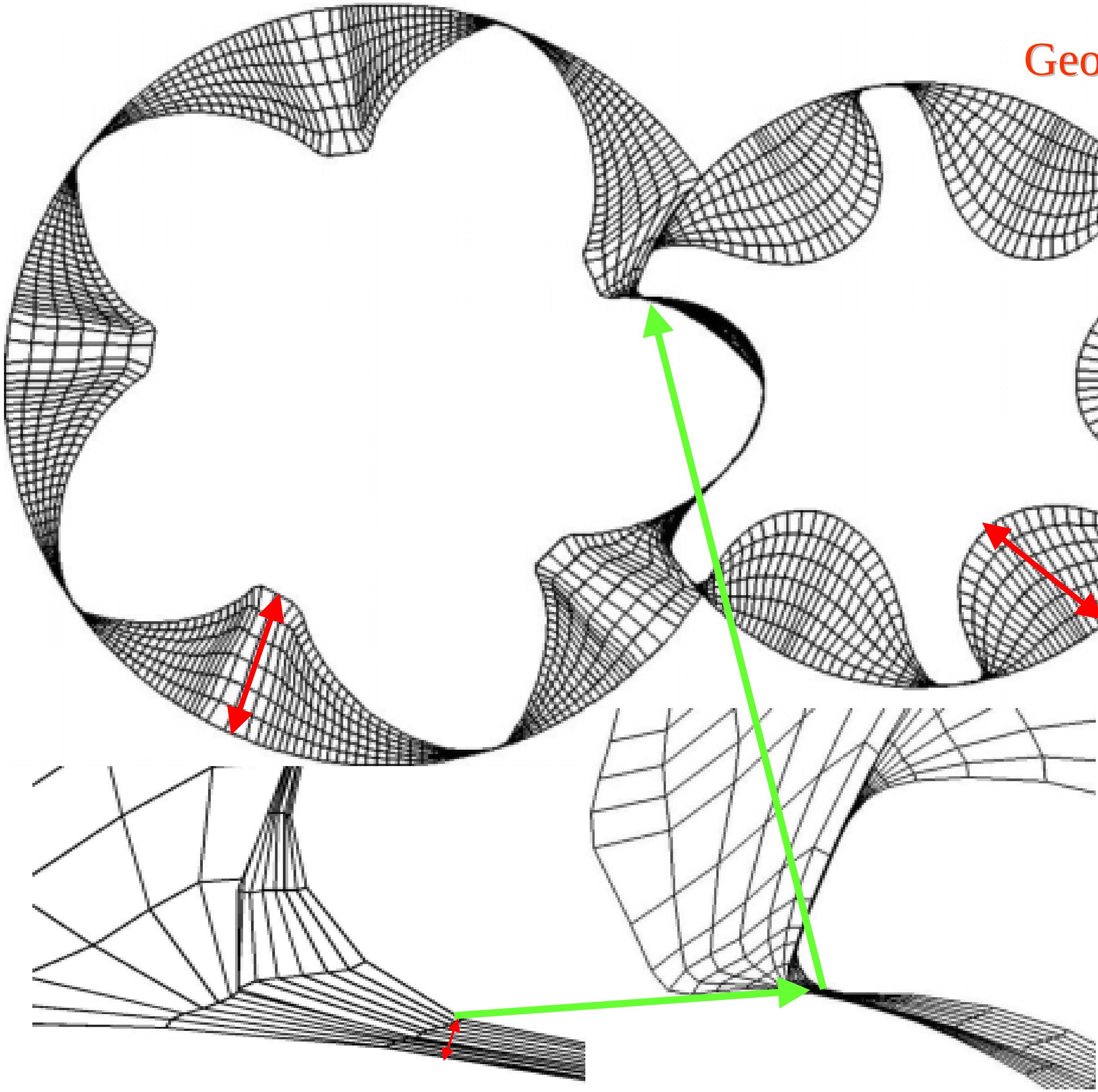
- Effects of pressure and temperature distortions are negligible!?

To overcome that:

3-D flow and stress calculation

CCM (Computational **C**ontinuum **M**echanics**)** ⇒ **FSI (F**luid **– S**olid **I**nteraction**)**

Problems associated with numerical analysis and operation of Screw Machines



Geometry ratio 300-1000

Regions of highly turbulent flow and fully laminar flow

Transonic velocities

Large pressure gradients

High temperature

Rotor distortions

Multi phase flow

CCM in Screw Compressors

- A commercial CCM solver(s) capable for efficient calculation
- "Expert system" for application in screw compressor

- **METHOD:** Advanced Grid Generation & commercial CCM solver
  - Finite volume method, block-structured hexahedral mesh
  - Moving domains, sliding boundaries
  - Automatic running and analysis of the results

- **TOOL:** ***SCORG*** - Analytical grid generation & Pre-processor
  - Multidimensional stretching Hermite transfinite interpolation,
  - Boundary adaptation, smoothing, orthogonalisation and regularity check,
  - Fast and reliable calculation of thermodynamic properties of real fluids
  - Multiphase flow, novel boundary conditions, mesh movement
  - Simultaneous generation and calculation of fluid/solid interaction
  - Automatic transfer to the CCM solver, Post-processing

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Screw Compressor FSI calculations

Conservation laws: continuity, momentum, energy, concentration and space

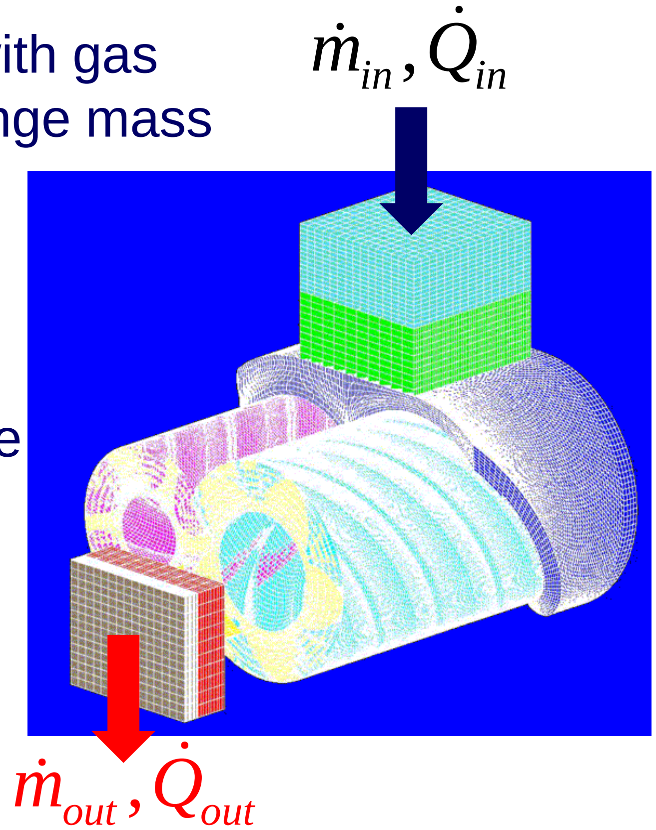
$$\frac{d}{dt}\int_V \rho\phi dV + \int_S \rho\phi(\mathbf{v}-\mathbf{v}_s)\cdot d\mathbf{s} = \int_S \Gamma_\phi \operatorname{grad}\phi \cdot d\mathbf{s} + \int_S \mathbf{q}_{\phi S}\cdot ds + \int_V q_{\phi V}\cdot dV$$

	ϕ	Γ_ϕ	$\mathbf{q}_{\phi S}$	$q_{\phi V}$
Continuity	**1**	**0**	**0**	**0**
Fluid momentum	v_i	μ_{eff}	$\left[\mu_{eff}(\operatorname{grad}\mathbf{v})^T - \left(\frac{2}{3}\mu_{eff}\operatorname{div}\mathbf{v} + p\right)\mathbf{I}\right]\cdot\mathbf{i}_i$	$f_{b,i}$
Solid momentum	$\frac{\partial u_i}{\partial t}$	η	$\left[\eta(\operatorname{grad}\mathbf{u})^T + (\lambda\operatorname{div}\mathbf{u} - 3K\alpha\Delta T)\mathbf{I}\right]\cdot\mathbf{i}_i$	$f_{b,i}$
Energy	e	$\frac{k}{\partial e/\partial T} + \frac{\mu_t}{\sigma_T}$	$-\frac{k}{\partial e/\partial T}\frac{\partial e}{\partial p}\cdot\operatorname{grad}p$	**T: grad v +** h
Concentration	c_i	$\rho D_{i,\text{eff}}$	**0**	s_{ci}
Space	$\frac{1}{\rho}$	**0**	**0**	**0**
Turbulent kinetic energy	K	$\mu + \frac{\mu_t}{\sigma_k}$	**0**	$P - \rho\varepsilon$
Dissipation	ε	$\mu + \frac{\mu_t}{\sigma_\varepsilon}$	**0**	$C_1 P\frac{\varepsilon}{k} - C_2\rho\frac{\varepsilon^2}{k} - C_3\rho\varepsilon\operatorname{div}\mathbf{v}$

$\rho = \rho(p,T), \quad e = e(p,T)$ **Constitutive relations, equation of state and turbulence model.**

Pre-processing

- **Multiphase flow**
  Oil - passive 'species' - exchange heat with gas
  Liquid phase – active 'species' – exchange mass



- **Boundary conditions**
  Suction, discharge, oil port receivers
  Walls close the system
  Mass is added to retain constant pressure

- **Properties of real fluids**
  Based on the reality factor
  Calculate compressibility factor
  2% error, fast calculation

- **User subroutines:** mesh movement, initial conditions, source terms
- **Control parameters** for CCM solver

Performance

- Volume flow (inlet and outlet)

$$\dot{V} = 60 \cdot \sum_{t=t_{start}}^{t_{end}} \dot{V}_f^{(t)} \quad \left[m^3/\min\right], \qquad \dot{V}_f^{(t)} = \sum_{i=1}^{I} v_{fi} S_{fi}$$

- Mass flow (inlet, outlet, oil)

$$\dot{m} = \sum_{t=t_{start}}^{t_{end}} \dot{V}_f^{(t)} \cdot \bar{\rho}^{(t)} \quad [kg/\sec]$$

- Boundary forces

$$F_x = p_b * A_{xb}; \quad F_y = p_b * A_{yb}; \quad F_z = p_b * A_{zb}$$

- Restraint Forces and Torque

$$F_{rS} = \sum_{i=1}^{I} F_{rS}(i), [N]; \qquad F_{rD} = \sum_{i=1}^{I} F_{rD}(i), [N]$$

$$F_a = \sum_{i=1}^{I} F_a(i), [N]; \qquad T = \sum_{i=1}^{I} T(i), [Nm]$$

- Compressor shaft power

$$P = 2 \cdot \pi \cdot n \cdot (T_M + T_F) \quad [W]$$

- Specific power

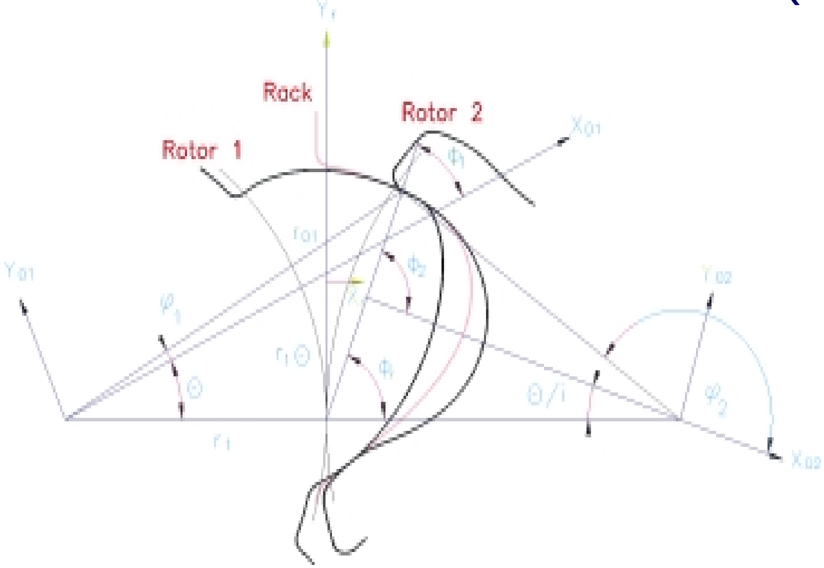
$$P_{spec} = P / \dot{V} \cdot 1000 \quad \left[kW / m^3 \min\right]$$

- Efficiency
  Volumetric and adiabatic

$$\eta_v = \dot{V} / V_d ; \qquad \eta_i = P_{ad} / P$$

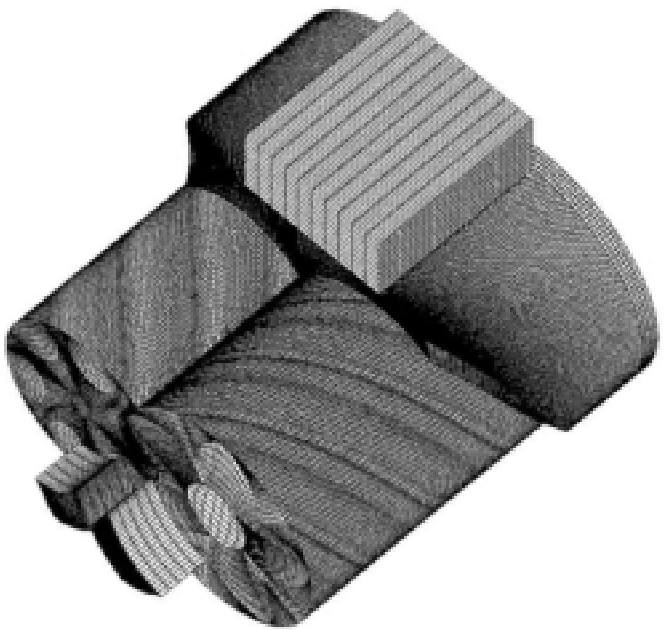
Grid generation

Block structured mesh for solid (rotors) and fluid passages

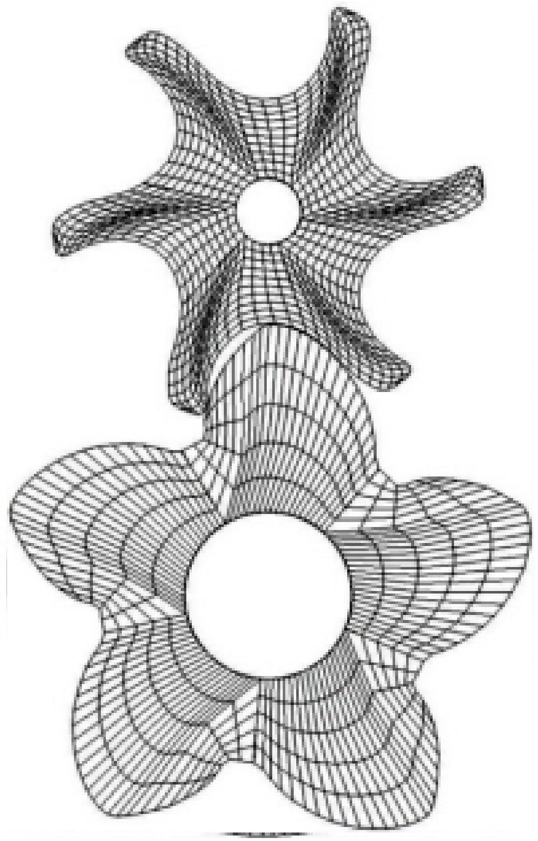


- Rack generating procedure
- Basic geometrical parameters
- Discretisation on boundaries
- Multiparameter adaptation

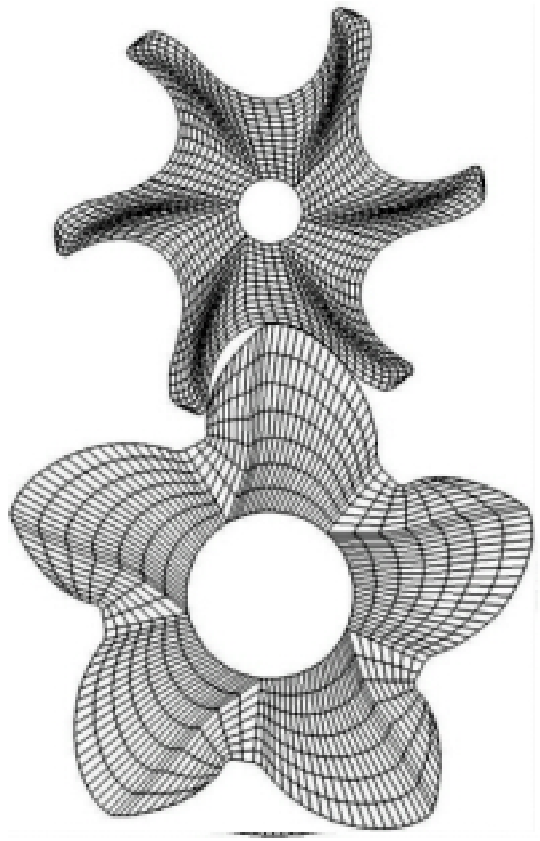
- Transfinite interpolation
- Hermite blending functions
- Multidimensional stretching functions
- Orthogonalization
- Smoothing
- Regularity check



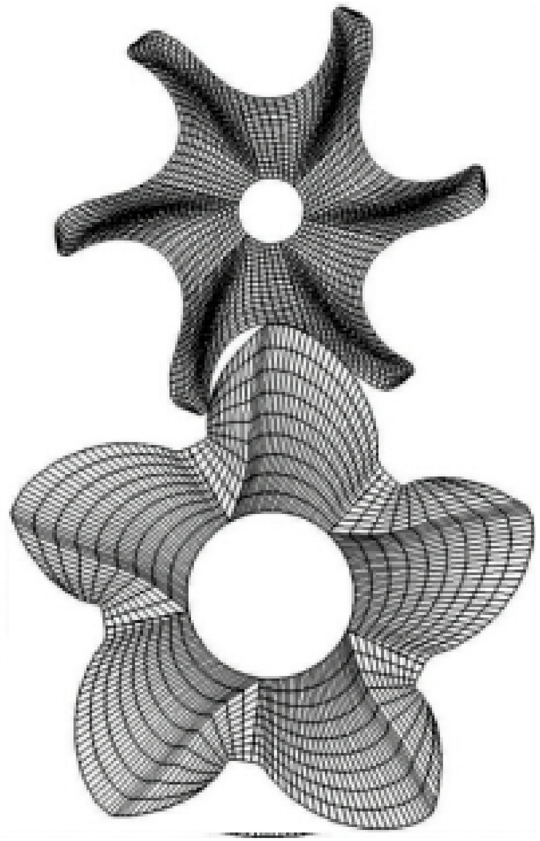
Cross sectional view of numerical meshes



Rotors: 189,144
Entire mesh: 353,084

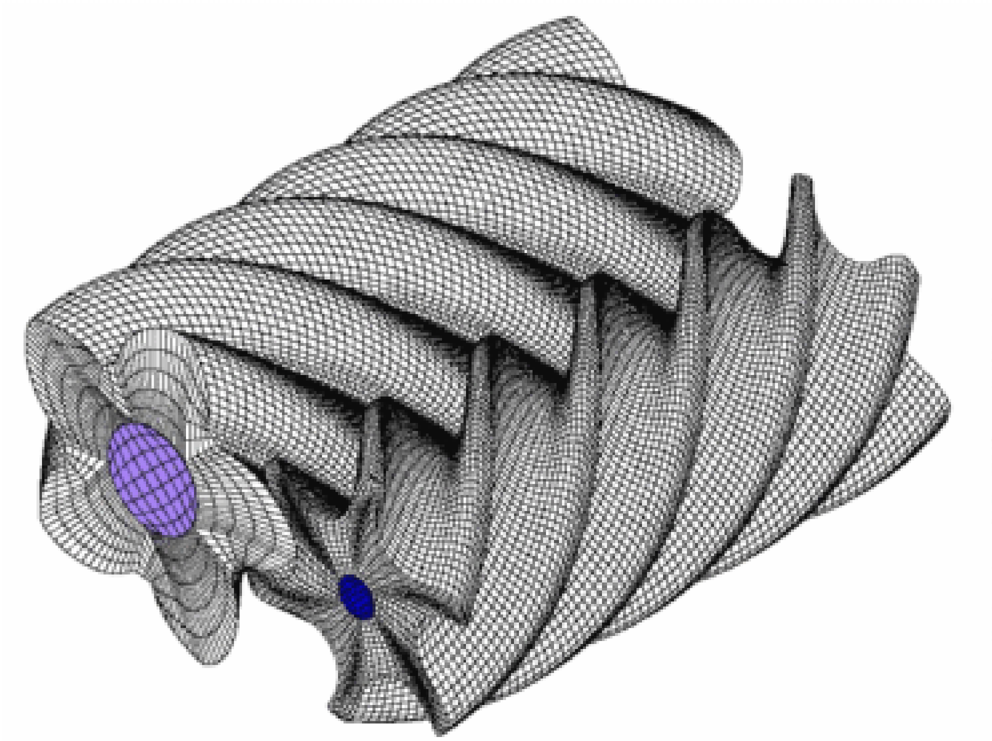


Rotors: 322,560
Entire mesh: 448,830



Rotors: 515,520
Entire mesh: 637,790

Moving mesh generated by SCORG



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SCORG

Screw COmpressor Rotor Geometry grid generator

Rot (nang,nast,naen,irot)	Transf (imin,imax,jmin,jmax,ntr)
Rack (nang,nada)	Simple (imin,imax,jmin,jmax,ntr)
Distr (irot,ka,idi,ma)	Ortho (imin,imax,jmin,jmax)
Mesh (nang,nada,irot,ntr,imesh)	Gridsm (imin,imax,jmin,jmax,ir)
Inlet (irot,fi1c,radd,nn1,nn2, irax,imesh,nang)	Grireg (imin,imax,jmin,jmax,ir)
Outlet (irot,fi1c)	Smooth (ra,ar,fip,fik,dfi,ns,nsp)
Prep (radd,nd,om1,pinl,pout, nang,irax)	**Names** (iang) **Check** (npos,jro,ynew) **Circ** (r,nt,a,fip,fik,dfi,jhoce) **Equal** (mp,m,np,n,j) **Celreg** (i,j)

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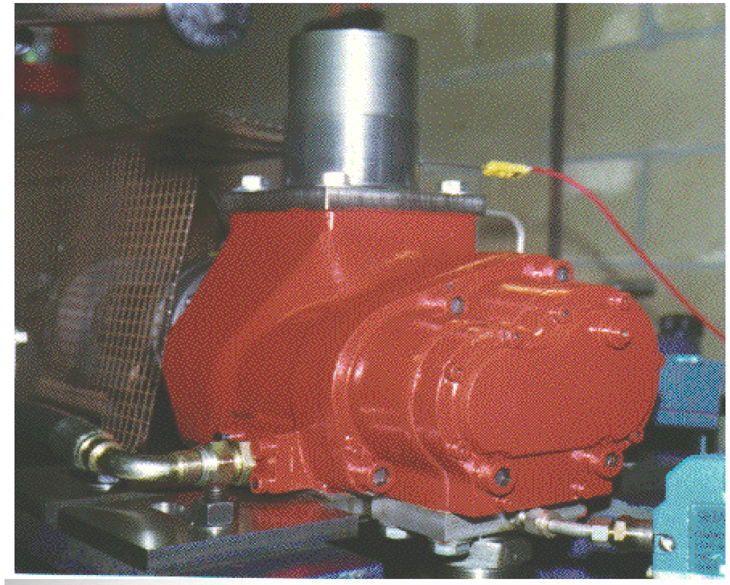
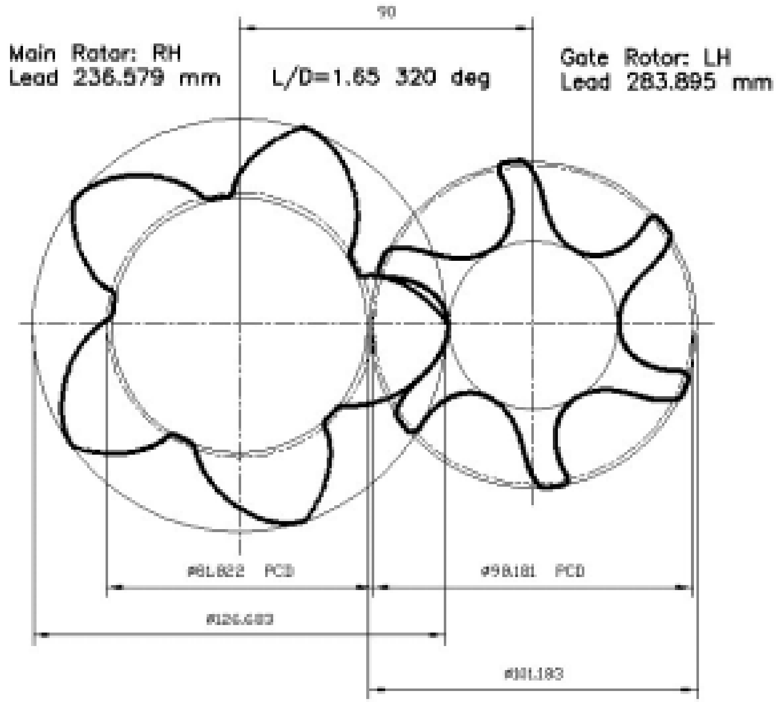
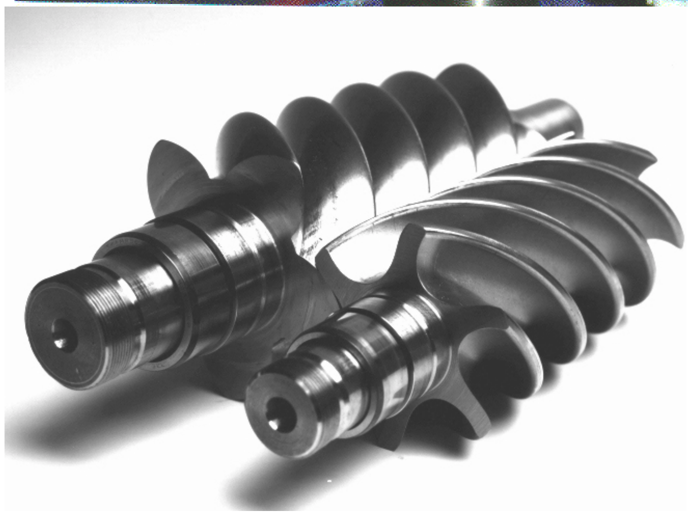
FSI for screw compressor







Configuration 5/6

d_1= 126.7 mm, d_2= 101.4 mm, a= 90 mm

l=212 mm, l/d=1.66, wrap angle=320 deg

Nominal clearance **65** mm

n=5000 rpm

442 130 cells, 25 time steps/cycle

FSI for screw compressor

Examples:

Case 1: Oil injected air screw compressor

P_{inl}= **1** bar, P_{out} = 6, **7**, 8, 9 bar

t_{inl} = 20 degC, t_{out} = 40 degC

Case 2: Dry air screw compressor

P_{inl}= **1** bar, P_{out} = **3** bar

t_{inl} = 20 degC, t_{out} = 150 degC

Case 3: High pressure oil injected screw compressor

P_{inl}= **30** bar, P_{out} = **90** bar

t_{inl} = 0 degC, t_{out} = 40 degC

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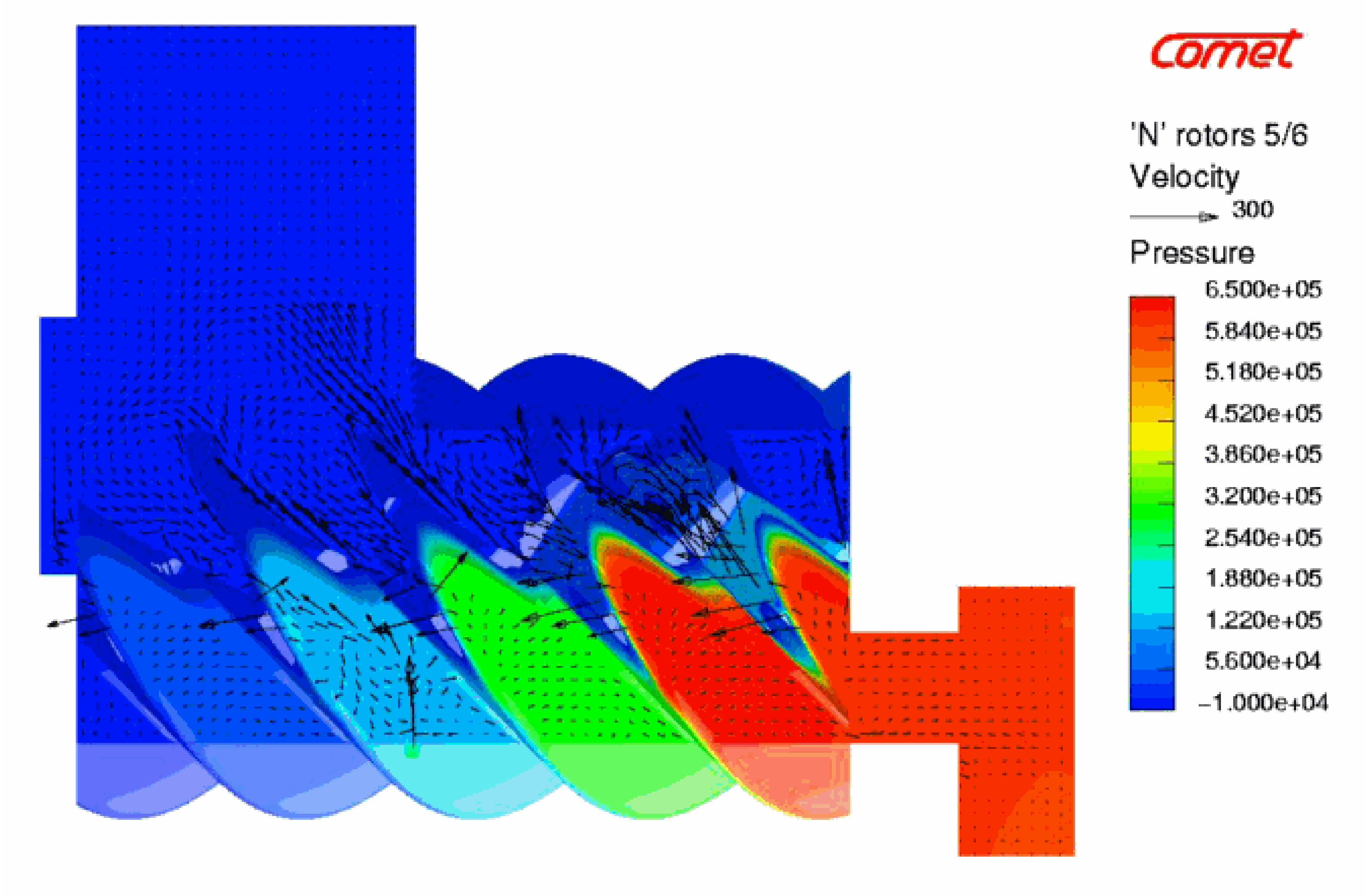
Oil injected – Pressure/Velocity



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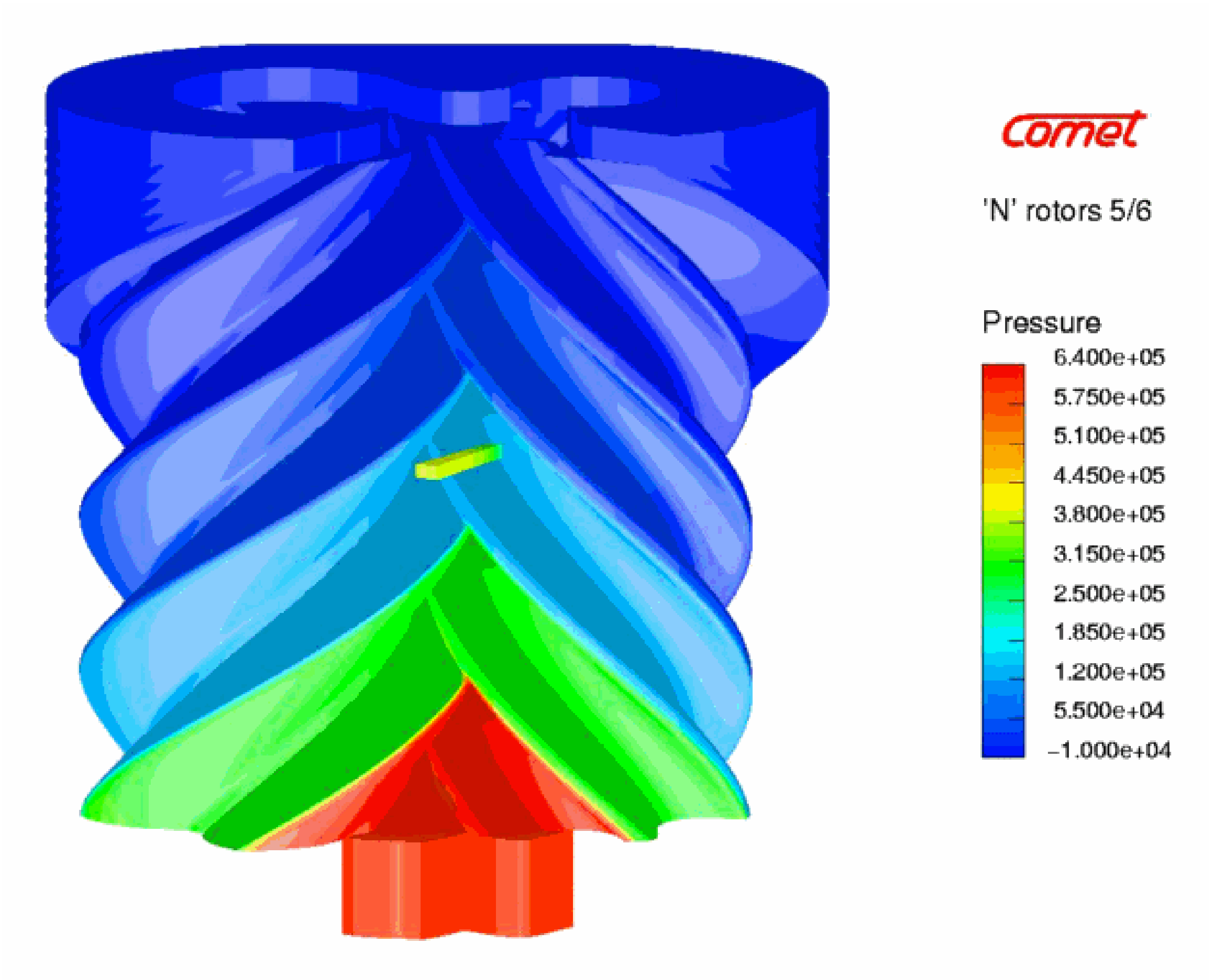
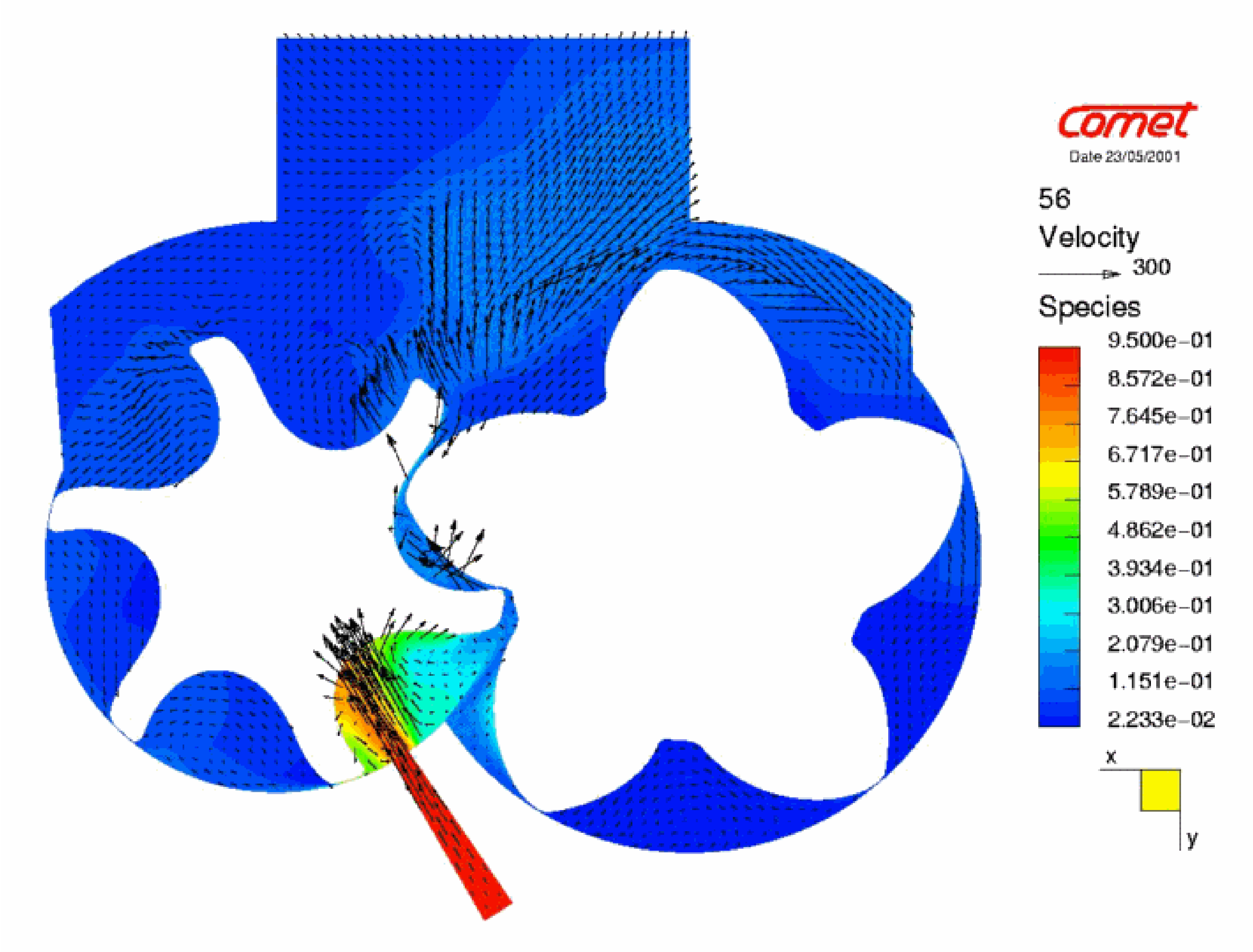
Oil injected - Pressure 3D view



Oil injected - Oil concentration



Oil injected – Concentration/Velocity

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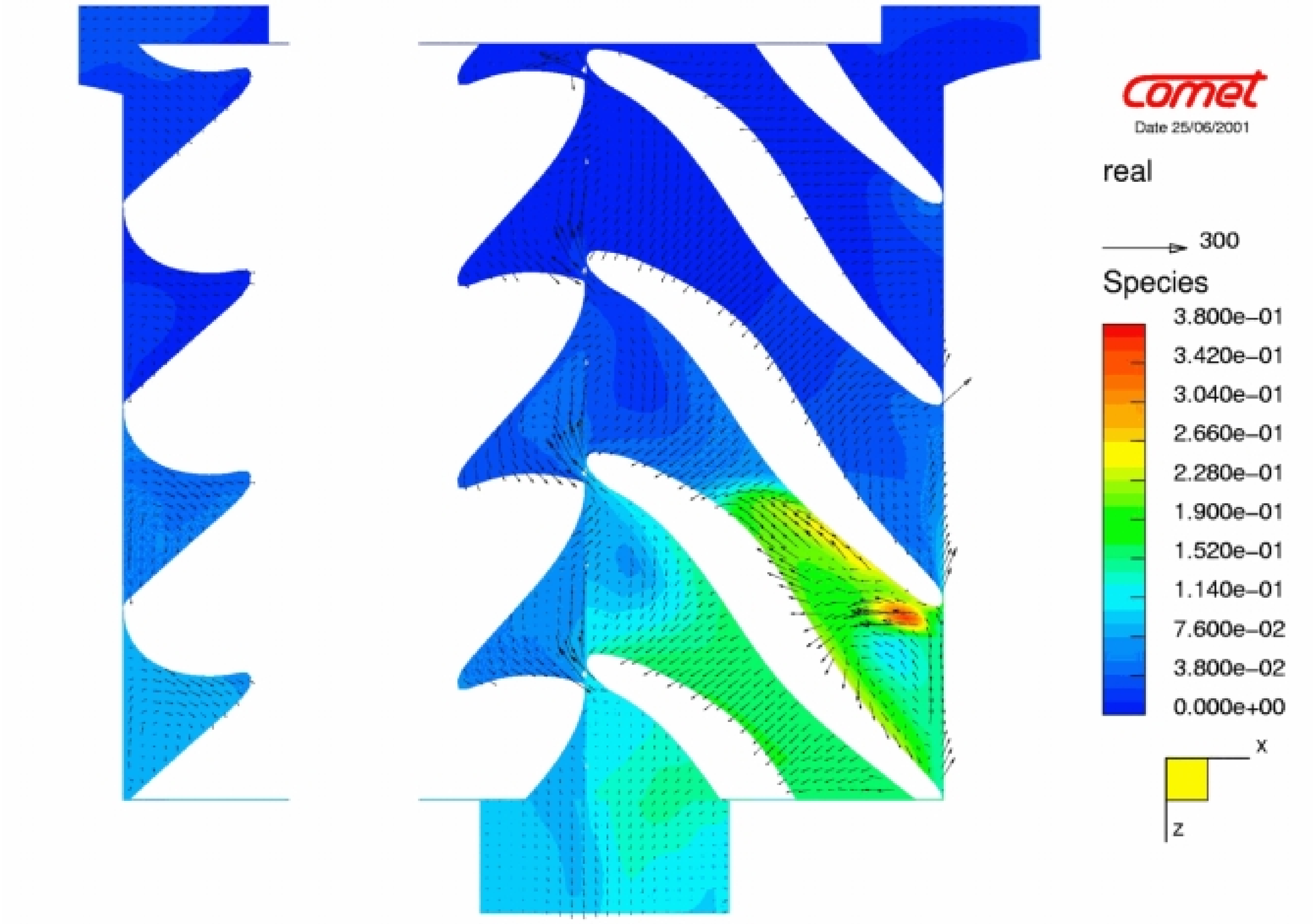
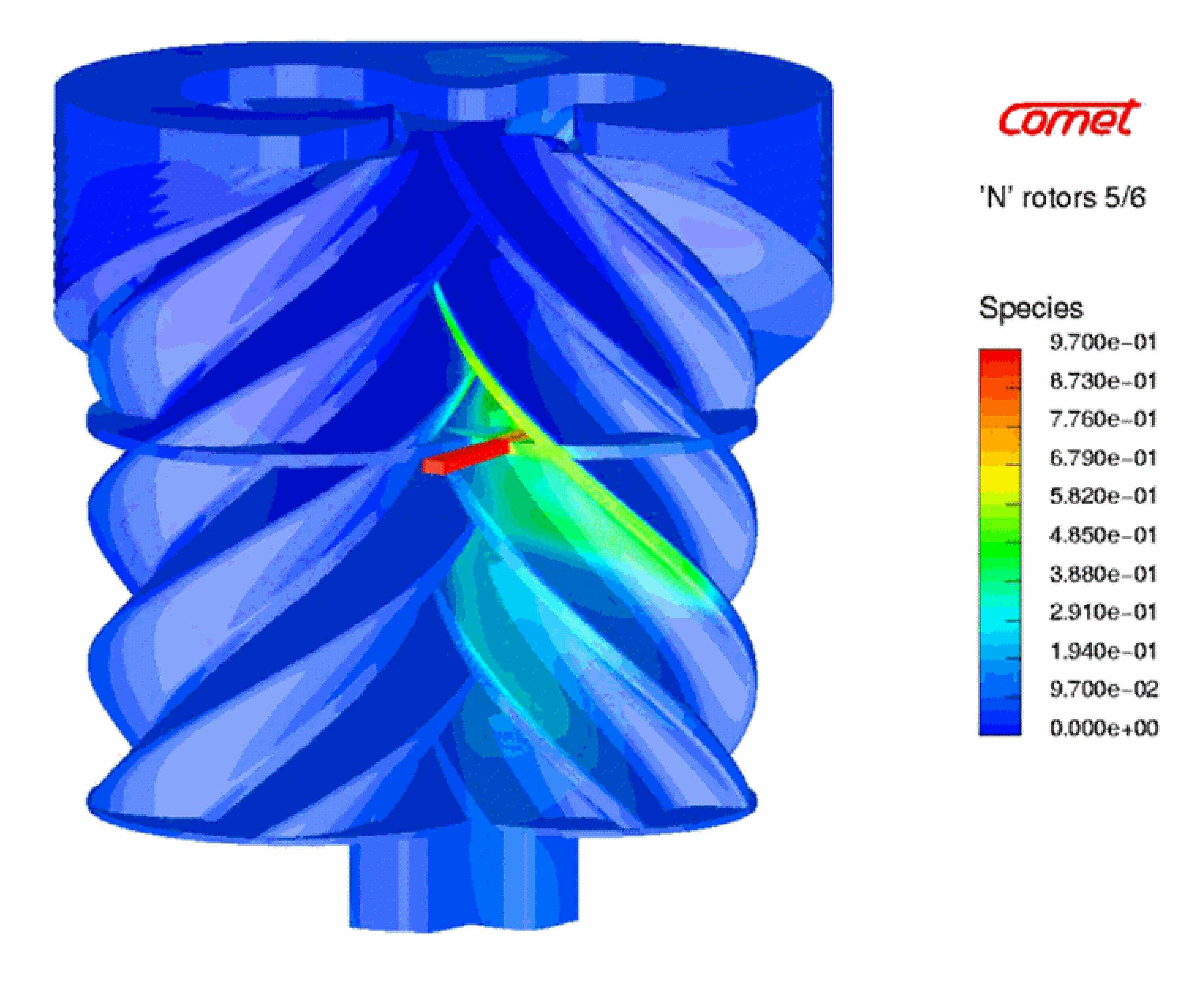
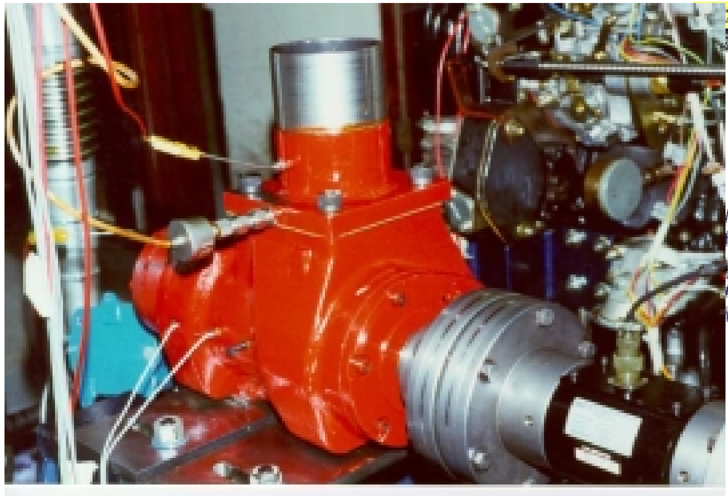
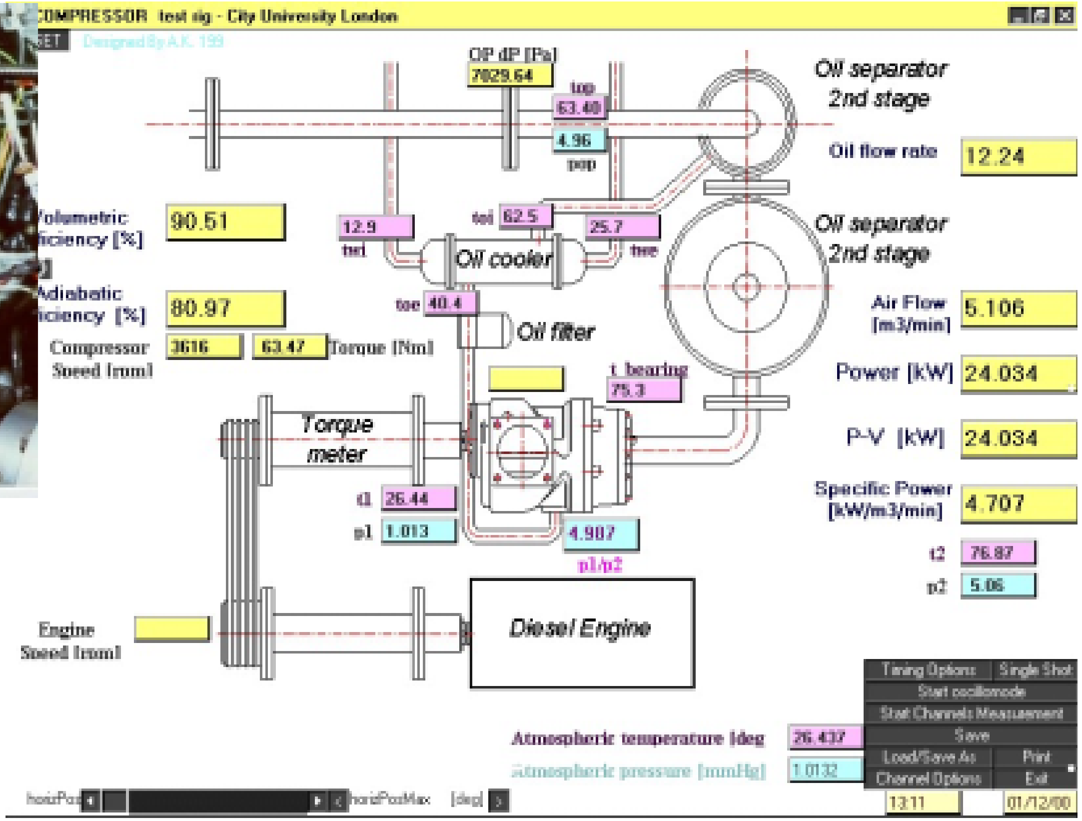


Oil injected - Oil distribution 3D view



Experimental verification





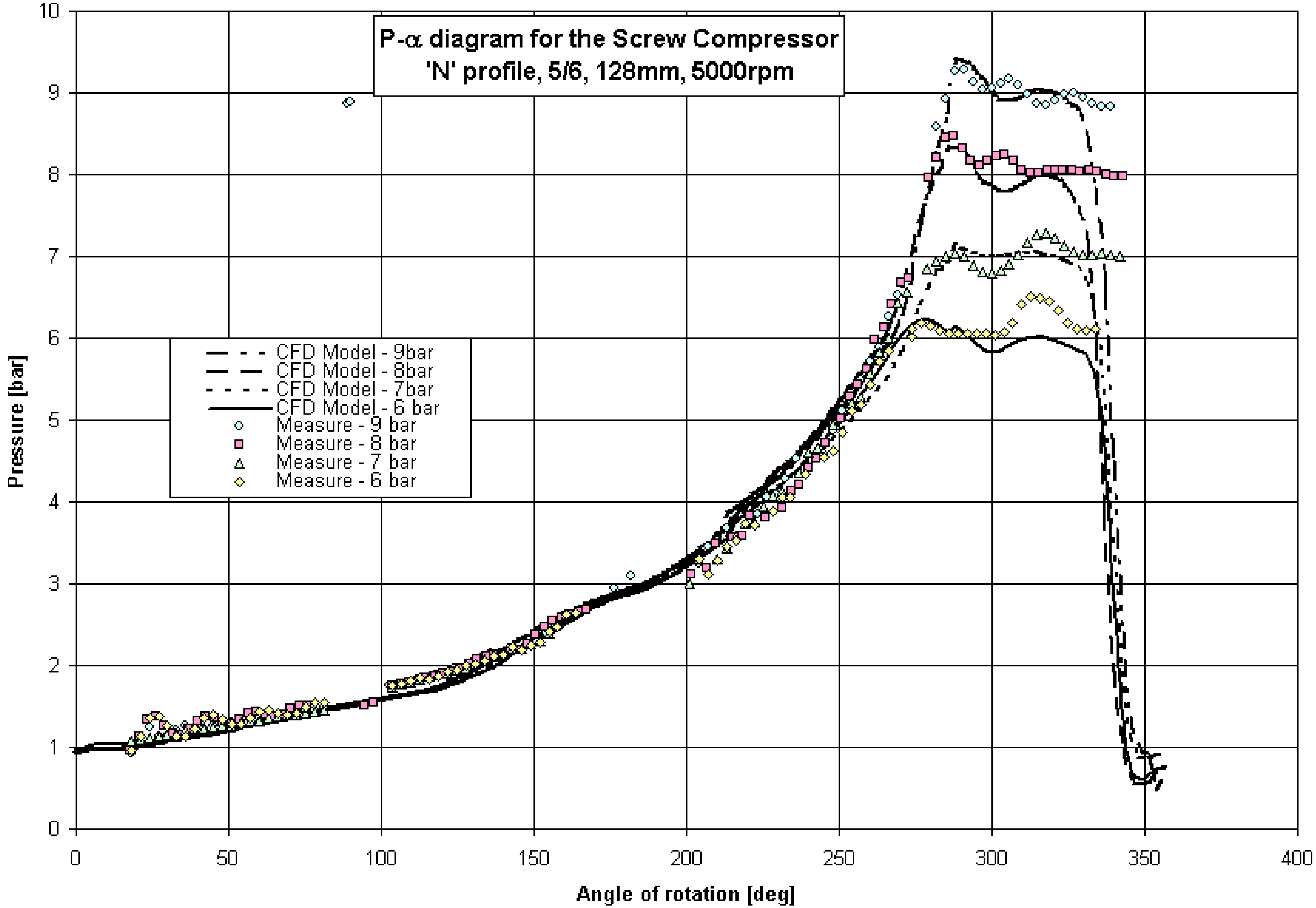
-Test rig enables oil flooded and dry air compressors to be measured. Limits:

- Power <= 100 kW
- Delivery <= 16 m^3/min

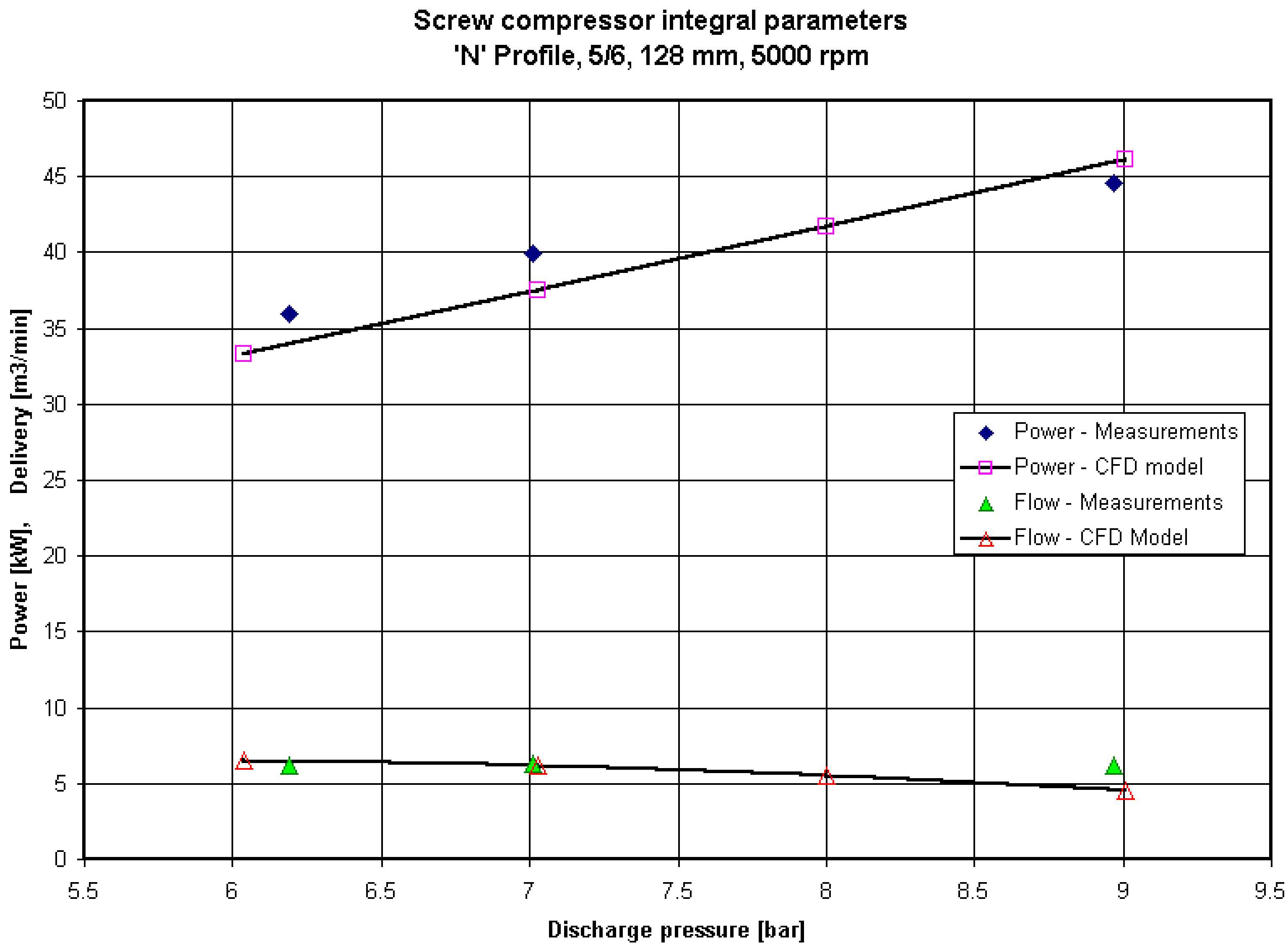
- High accuracy test equipment
- p-α diagram – piezoelectric transducers
- Computerized data logger
- Real time calculation and presentation

- Meets Pneurop/Cagi standards
- Compressor tested to ISO 1706
- Flow measurements BS 5600
- Certified by Lloyd's of London

P-α diagram

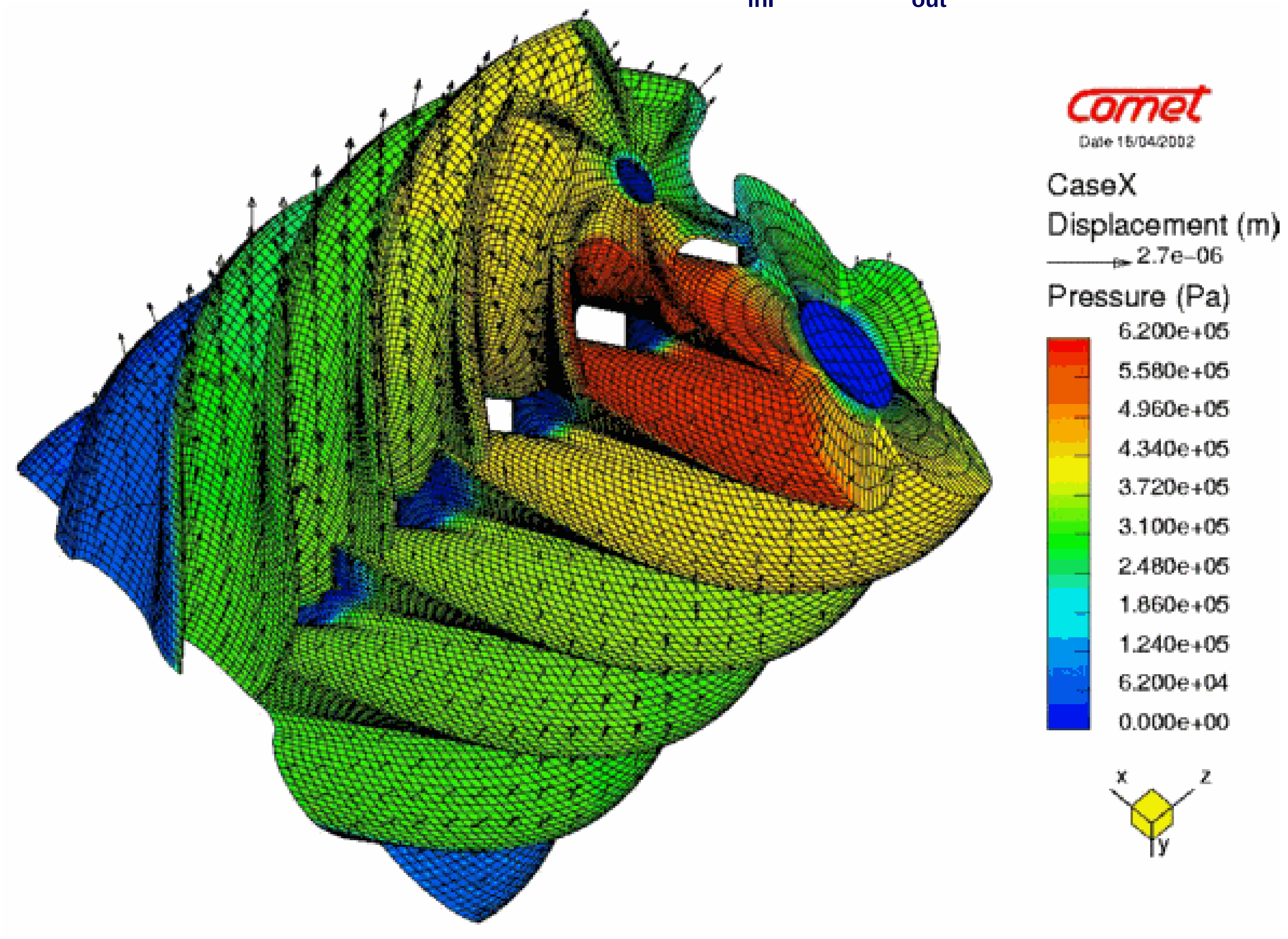

P-α diagram for the Screw Compressor
'N' profile, 5/6, 128mm, 5000rpm
Pressure [bar]
Angle of rotation [deg]
CFD Model - 9bar
CFD Model - 8bar
CFD Model - 7bar
CFD Model - 6 bar
Measure - 9 bar
Measure - 8 bar
Measure - 7 bar
Measure - 6 bar
0
1
2
3
4
5
6
7
8
9
10
0
50
100
150
200
250
300
350
400

Integral parameters – Power, Delivery



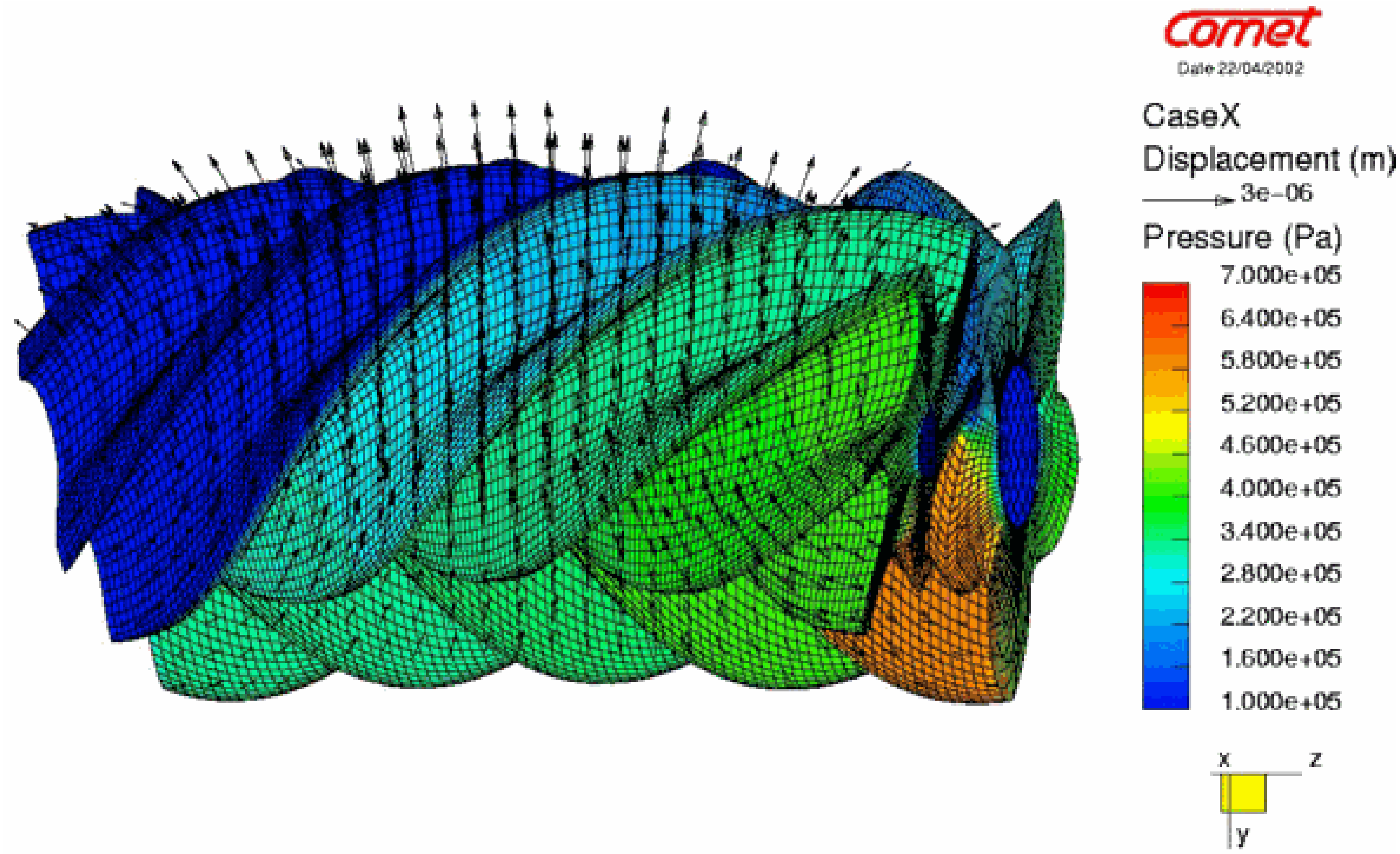
Oil injected

P_{inl}=1 b P_{out}=7 b n=5000 rpm
t_{inl}=20 °C t_{out}=40 °C



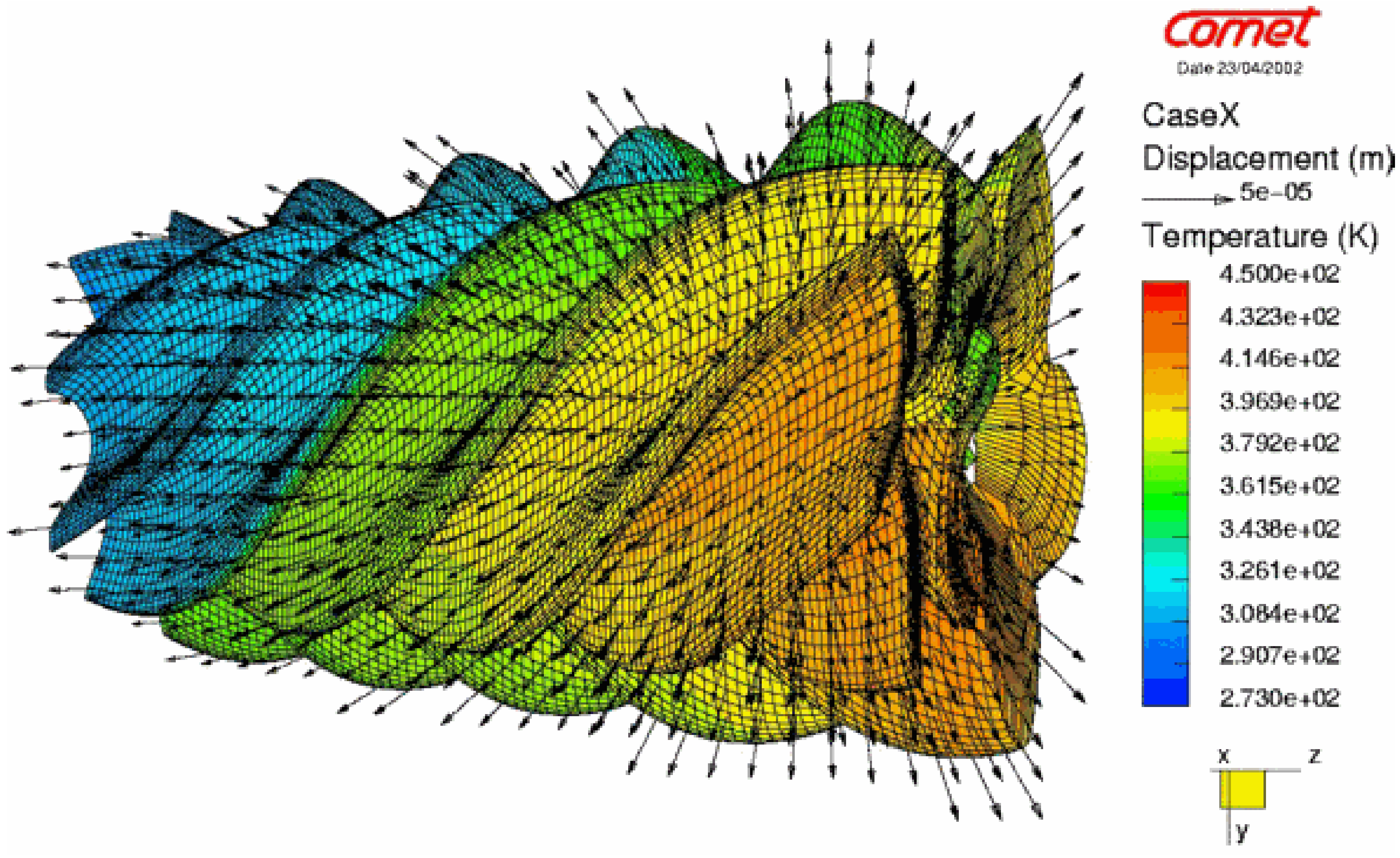
Oil injected

P_{inl}=1 b P_{out}=7 b n=5000 rpm
t_{inl}=20 °C t_{out}=40 °C mag=20,000x



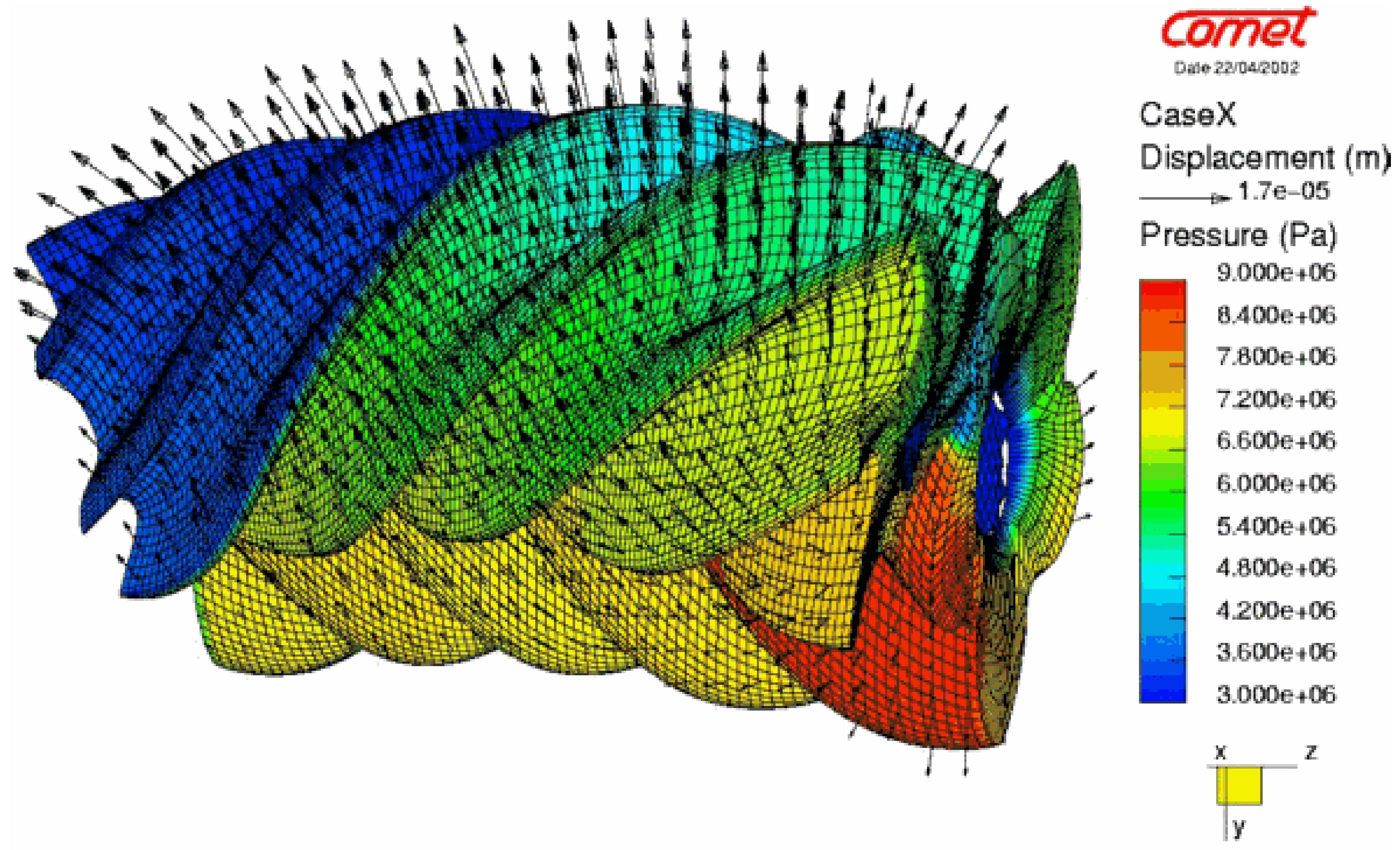
Oil free

P_{inl}=1 b P_{out}=3 b n=5000 rpm
t_{inl}=20 °C t_{out}=150°C mag=1,000x



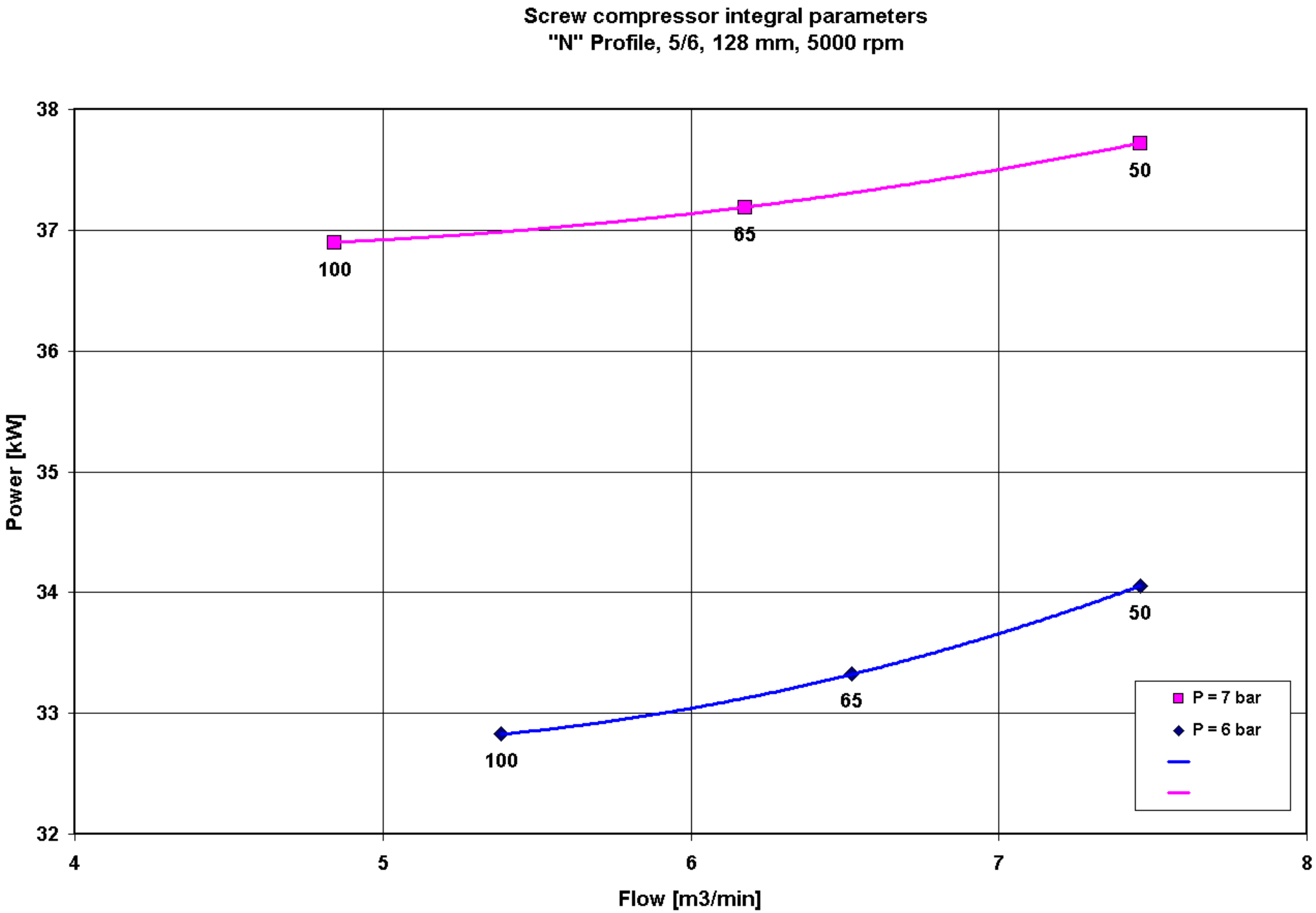
High pressure oil injected

P_{inl}=30 b P_{out}=90 b n=5000 rpm
t_{inl}=0 ºC t_{out}=40 ºC mag=2,000x



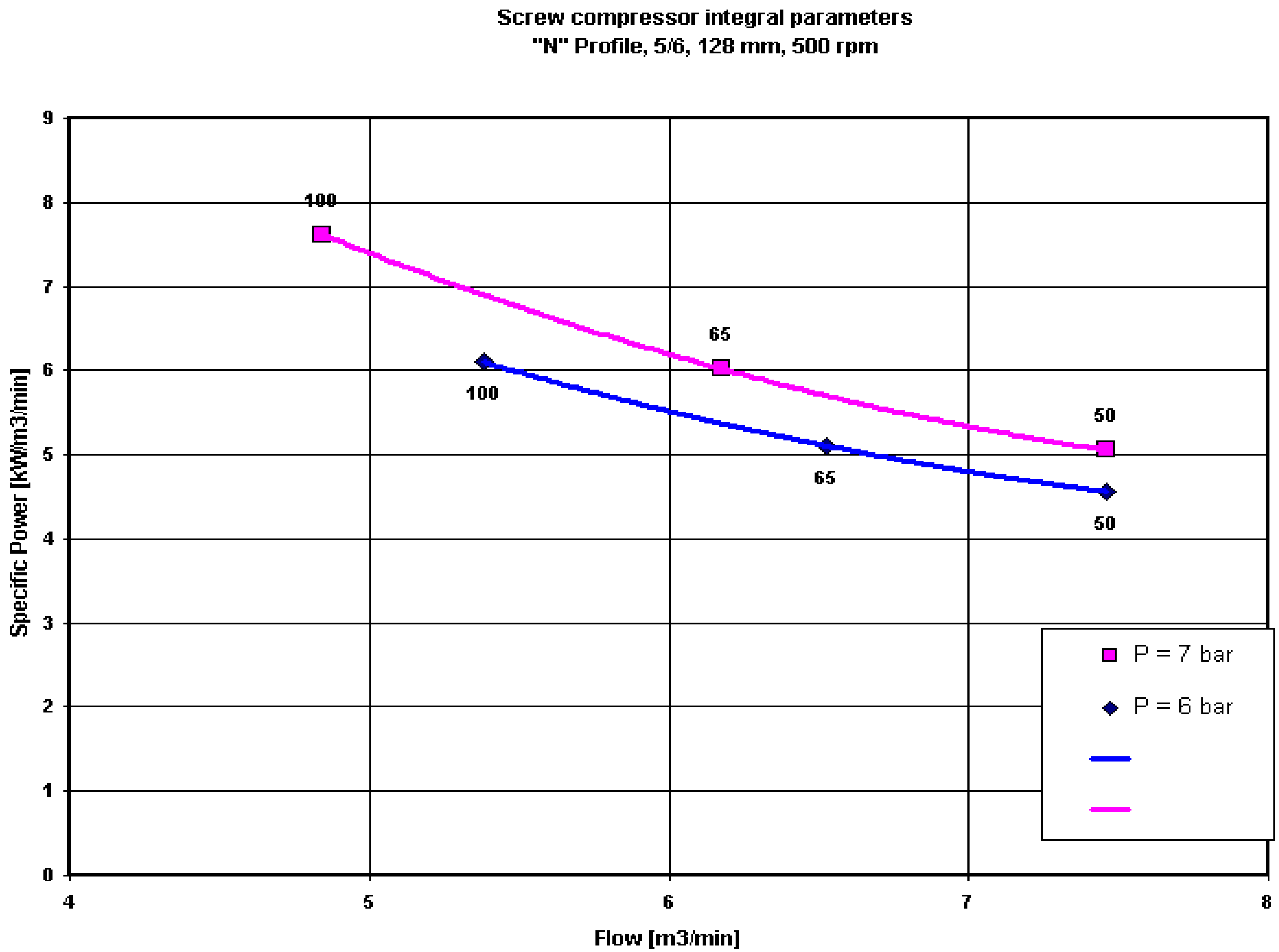
FSI integral parameters

Power-Flow diagram



FSI integral parameters

P_{sp}-Flow diagram



CONCLUSIONS

- Compressor rotors deform. Due to that, clearances change. That influence internal leakage, and deteriorate compressor performance.

- Computational continuum mechanics is employed to analyse interaction between fluid and solid,

- *SCORG* - A stand alone program is developed to transfer screw compressor geometry and parameters to CCM solver automatically;

- *COMET* **GMBH** ICCM was used for CCM calculation;

- Calculation results for oil injected compressor are compared with measurements

- Method is used to estimate influence of rotor deflection on overall screw compressor parameters.