Theory, design and CFD analysis of a multi-blade screw pump evolving liquid lead for a GEN-IV LFR Nuclear Power Plant

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European Lead-cooled Fast Reactor

ELFR KEY DESIGN GUIDELINES	
Sustainability of the fuel cycle	Waste minimization and management
Economics	Simpler design solutions/Lower life cycle cost
Safety and reliability	Passive – no offsite emergency response required
Proliferation resistance	Fuel bearing MAs

ELFR KEY DESIGN PARAMETERS	
Power	1500 MW(th), 600 MW(e)
Thermal efficiency	~42%
Core diameter	4.5 m
Core height	1.4 m
Core fuel	MOX (1st load)
Coolant temperature	400/480 °C
Maximum cladding temperature	550 °C
Core breeding ratio (CBR)	~ 1

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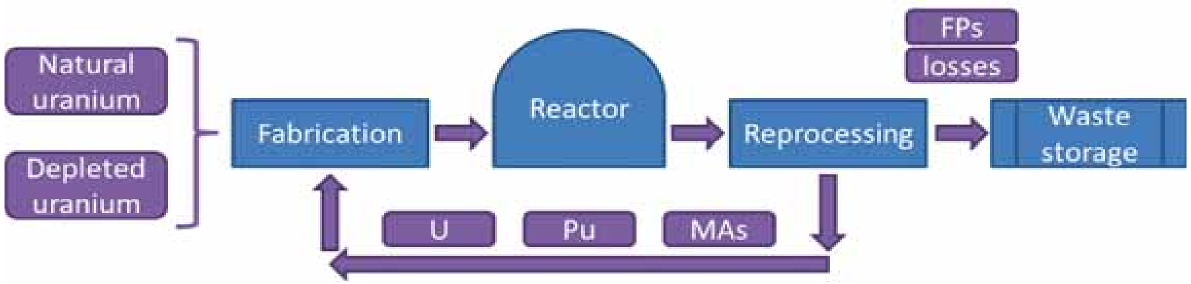
European Lead-cooled Fast Reactor: Adiabatic Reactor concept



The ELFR enables the closure of the fuel cycle.

- Multiple Recycling of the long-lived and high radiotoxicity wastes.

- Discharge of the sole fission products (500 kg/year) for a simplified storage (decay: 400 years).

- Fabrication of fresh fuel only by addition of natural Uranium -using 1/100 of current usage- or addition of depleted Uranium -without affecting the current resources-.

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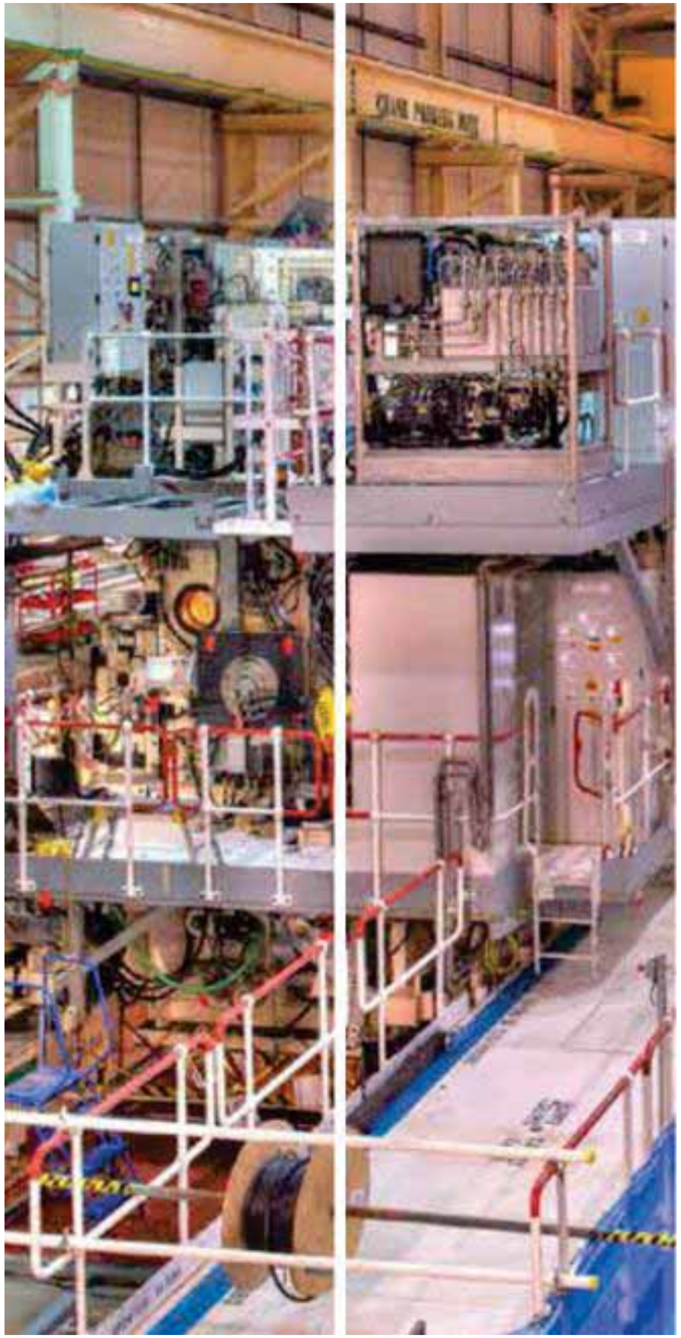
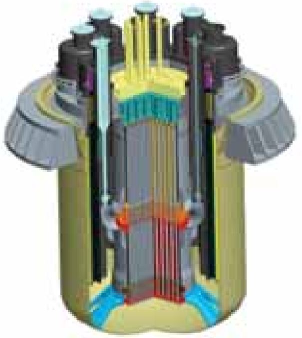
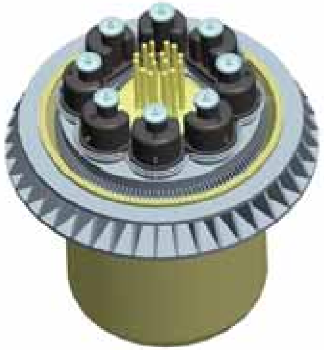
ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator)

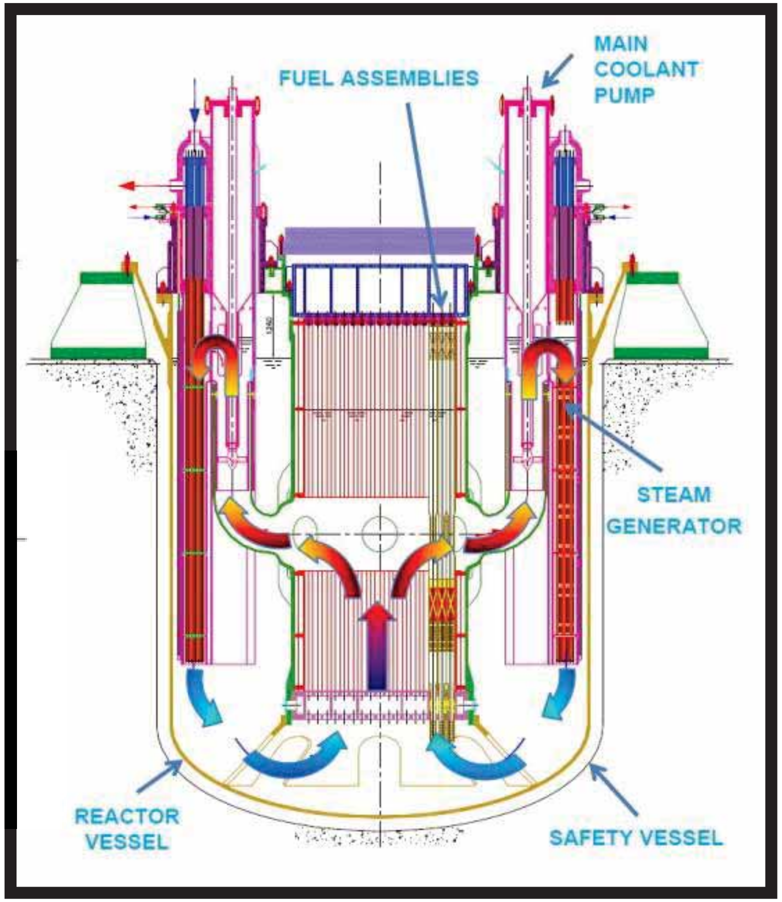
ALFRED KEY PARAMETERS AND COMPONENTS LAYOUT		
Power	300 MW(th), ~120 Mw(e)	
Thermal efficiency	~42%	
Primary system	Pool type, compact	
Primary coolant	Fluid	Pure lead
	Circulation at power	Forced (mechanical pumps)
	Emergency circulation	Natural circulation
Coolant temperature	400 / 480 ºC	
Primary system pressure loss (at power)	< 1.5 bar	
Primary coolant circulation for DHR	Natural circulation	
Fuel	MOX (1st load)	
Fuel cladding material	15-15 / Ti as a reference	
Steam Generators	8 or 4 , integrated in the main vessel	
Secondary cycle	Water-superheated steam at 180 bar, 335-450 ºC	
Primary pumps	8 or 4, mechanical, integrated in the Steam Generators, suction from hot collector	
Internals	All internals removable	
Inner vessel	Cylindrical	
Hot collector	Small-volume, enclosed by the Inner Vessel	
Decay Heat Removal	4 independent, redundant and passive DHR systems, 3 out of 4 loops of each system are capable of removing the decay heat	



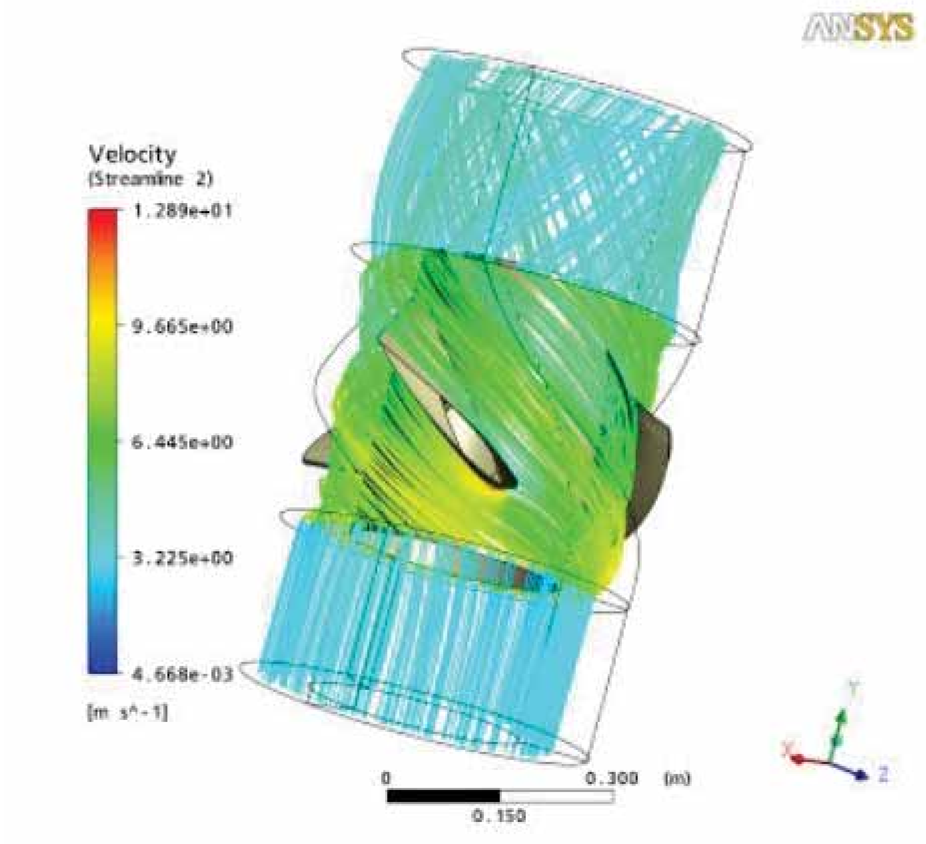
ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator)

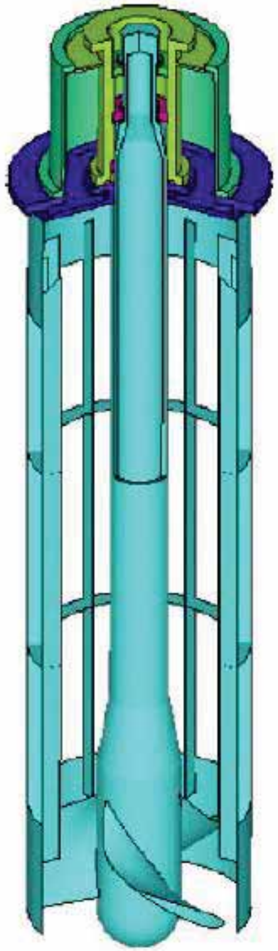




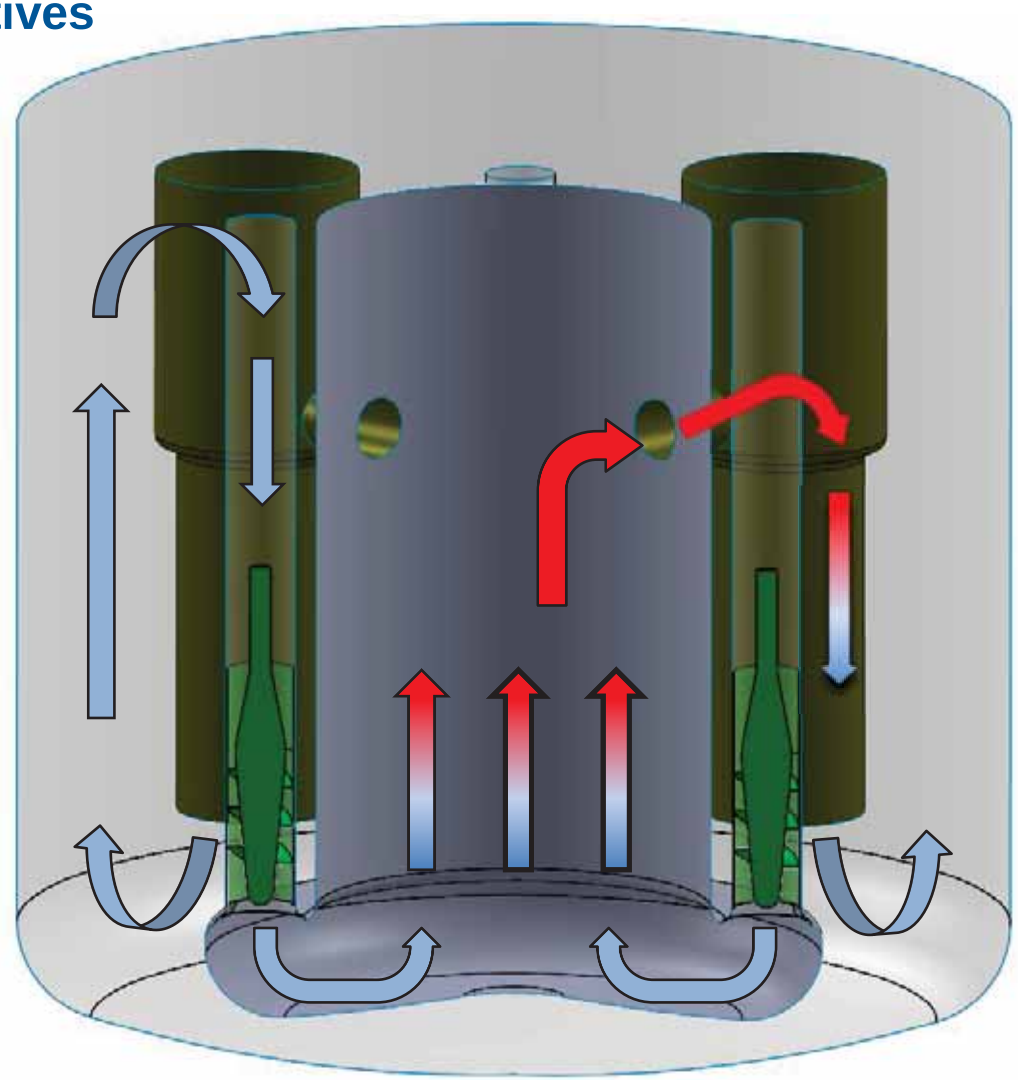


Primary Pump: Analysis of Alternatives
Option A: pull the coolant via blade pump

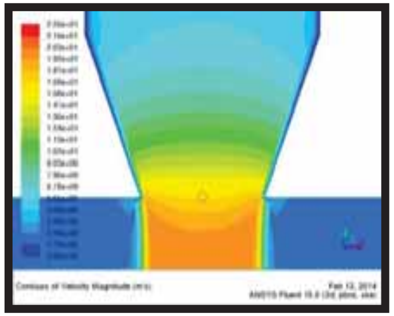


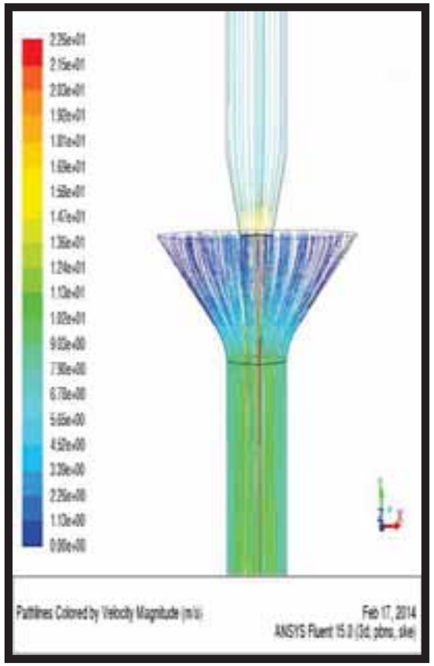


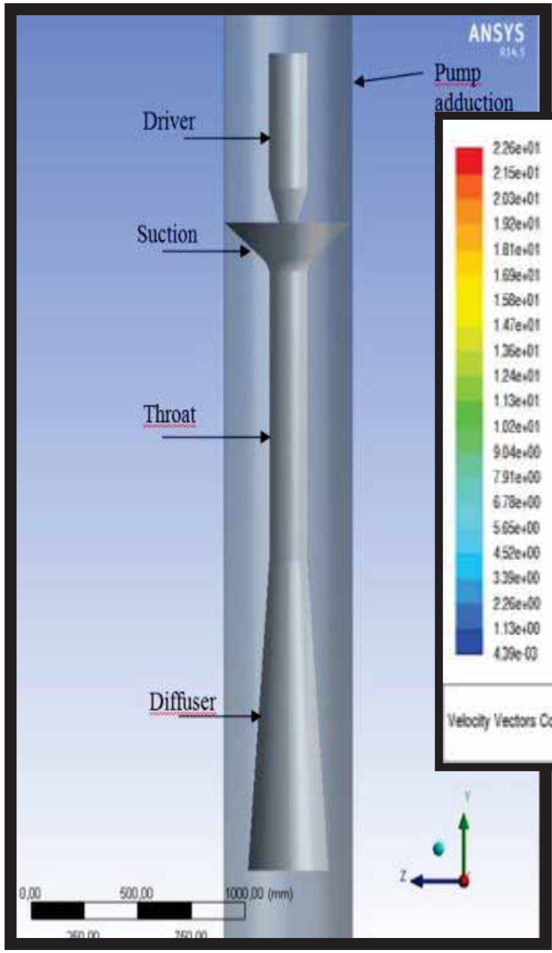
Primary Pump: Analysis of Alternatives
Option B: push the coolant
Architectural layout

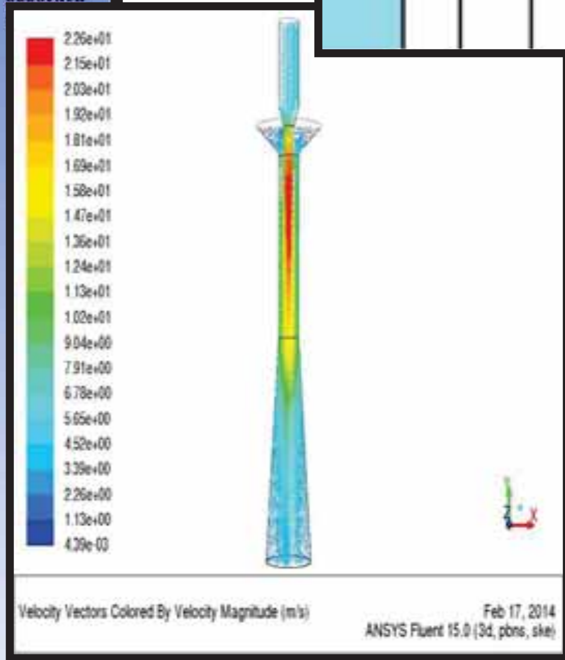


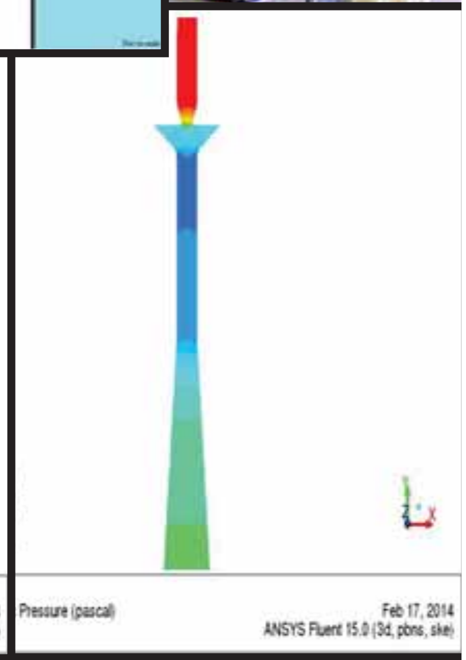
Primary Pump: Analysis of Alternatives
Option B/1: push the coolant via jet pump

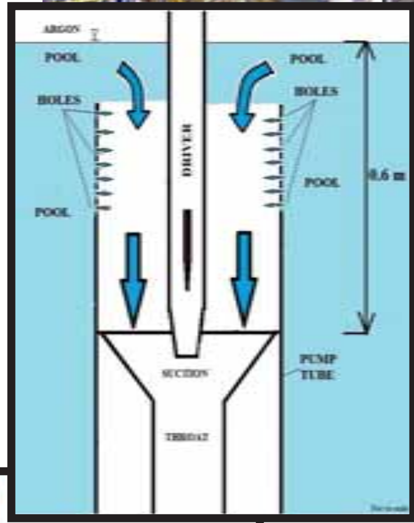












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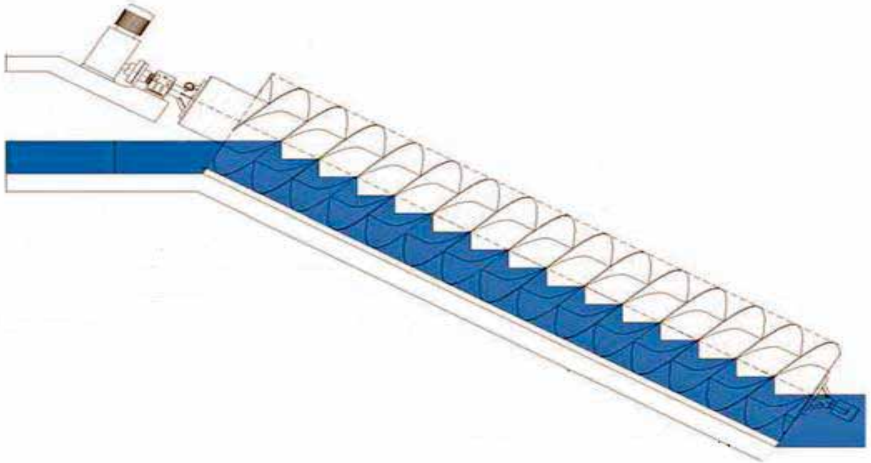
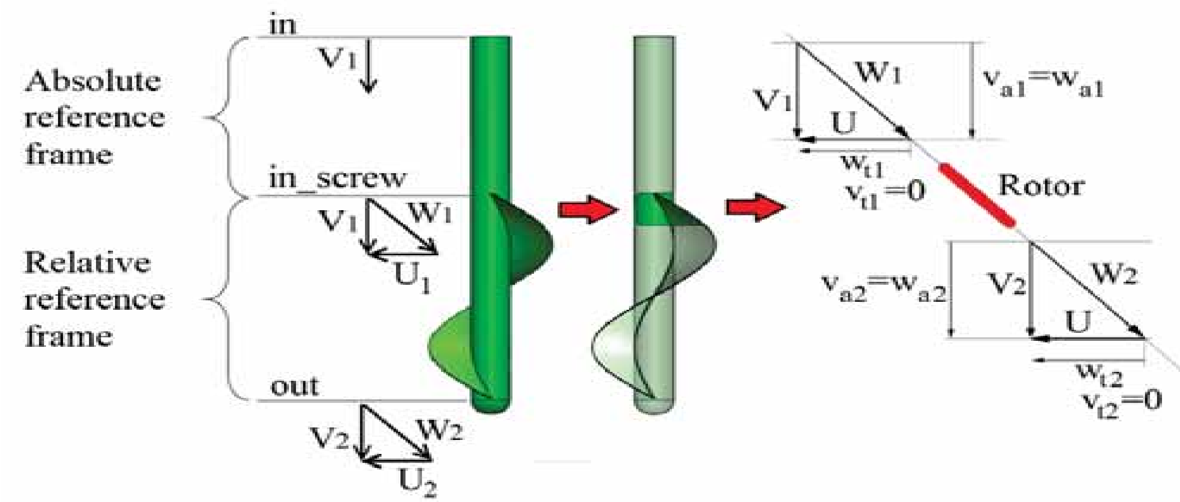
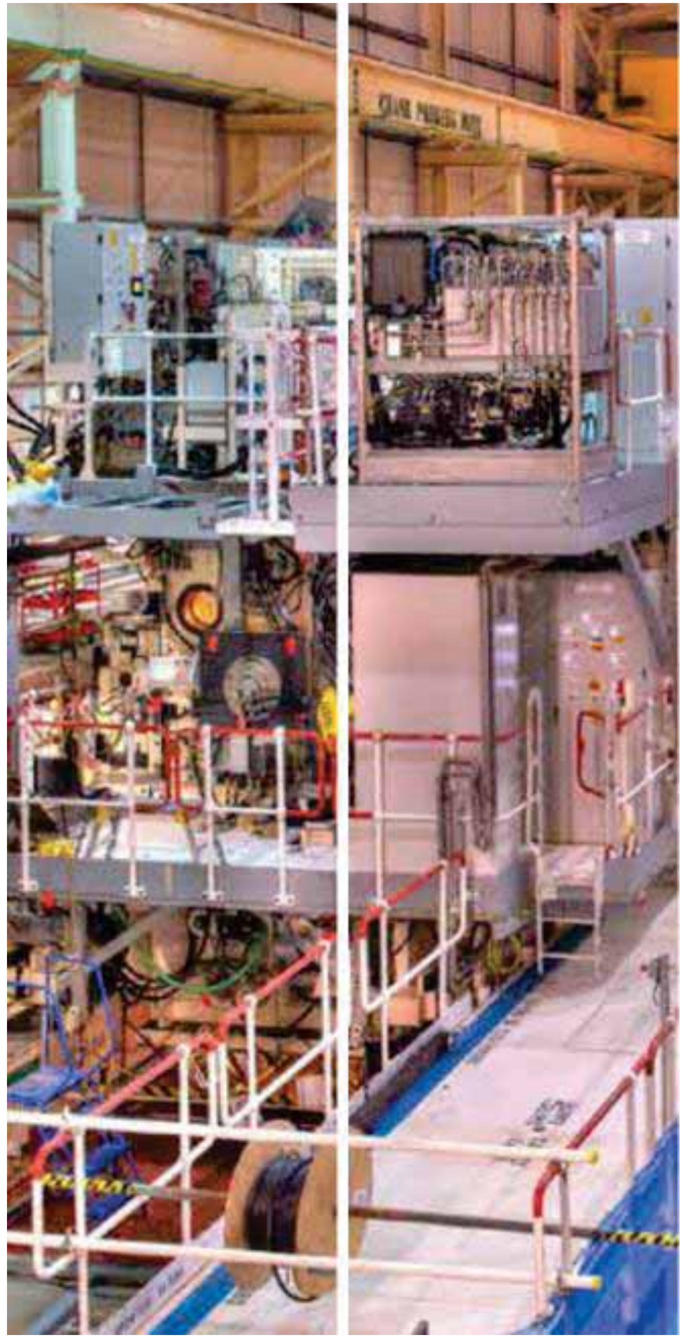
Primary Pump: Analysis of Alternatives
Option B/2: push the coolant via screw pump







Screw pump: Governing equations

- Conservation of mass

$$\dot{m} = \rho * V * A = constant$$

- Conservation of energy

absolute reference frame

$$p_{tot\_abs} = constant$$

$$p_{tot\_abs\_out} = p_{tot\_abs\_in}$$

$$p_{out} + \frac{1}{2} * \rho * V_{out}^2 = p_{int} + \frac{1}{2} * \rho * V_{in}^2$$

relative reference frame

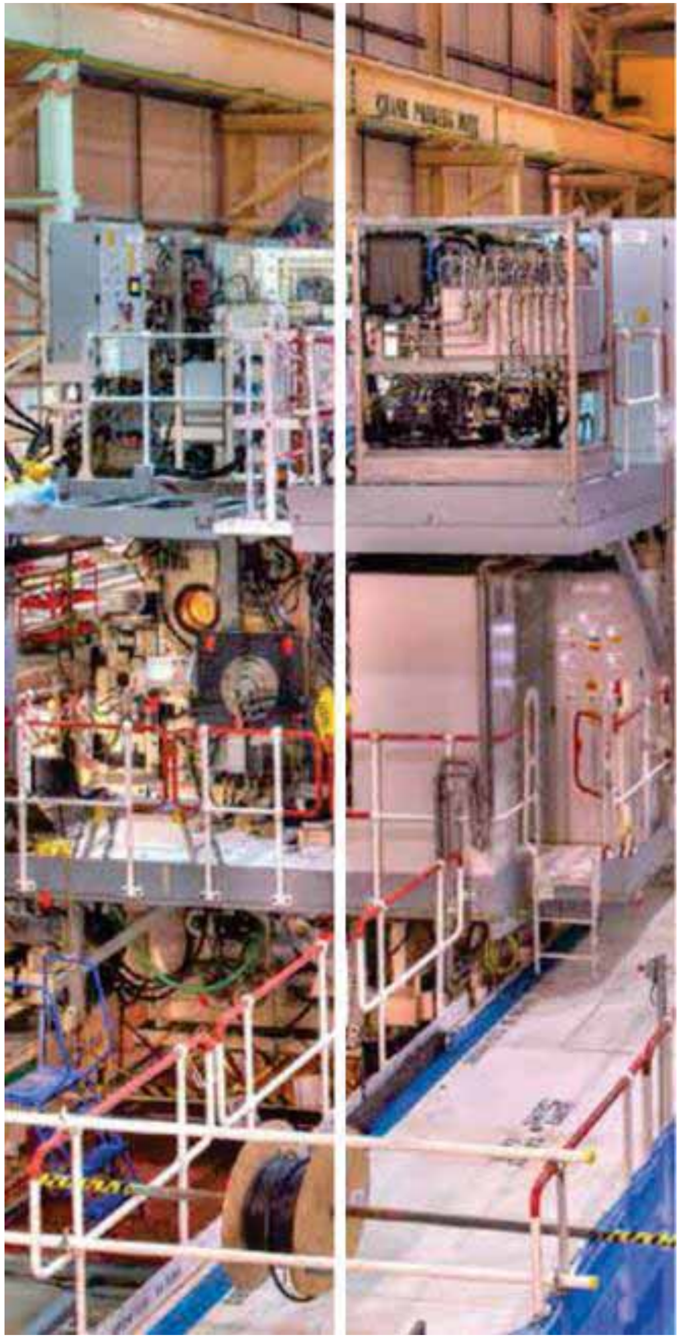
$$p_{tot\_rel} = constant$$

$$p_{tot\_rel\_out} = p_{tot\_rel\_in}$$

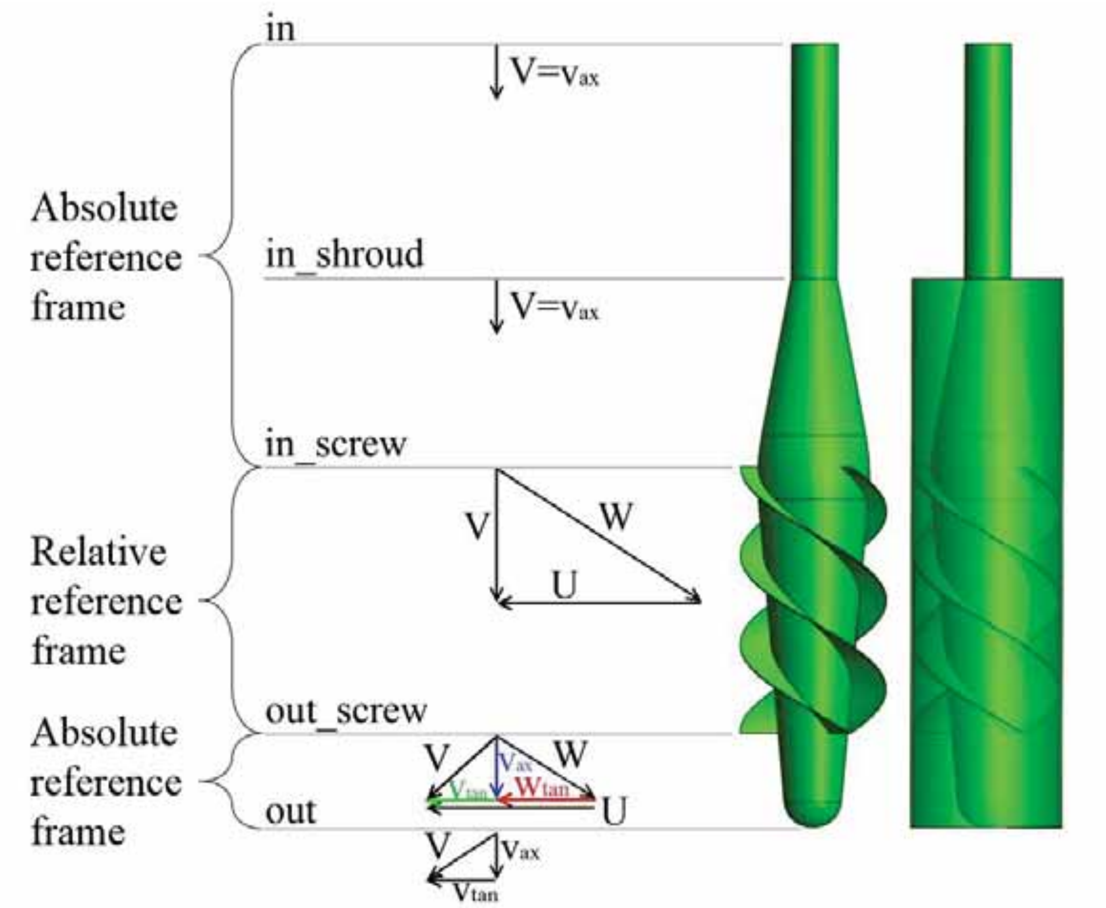
$$p_{out} + \frac{1}{2} * \rho * W_{out}^2 - \frac{1}{2} * \rho * U_{out}^2 = p_{int} + \frac{1}{2} * \rho * W_{in}^2 - \frac{1}{2} * \rho * U_{in}^2$$

- Conservation of angular momentum

$$L_{sp} = (U_{out} * v_{t\,out}) - (U_{in} * v_{t\,in})$$



Screw pump: absolute vs reference frame



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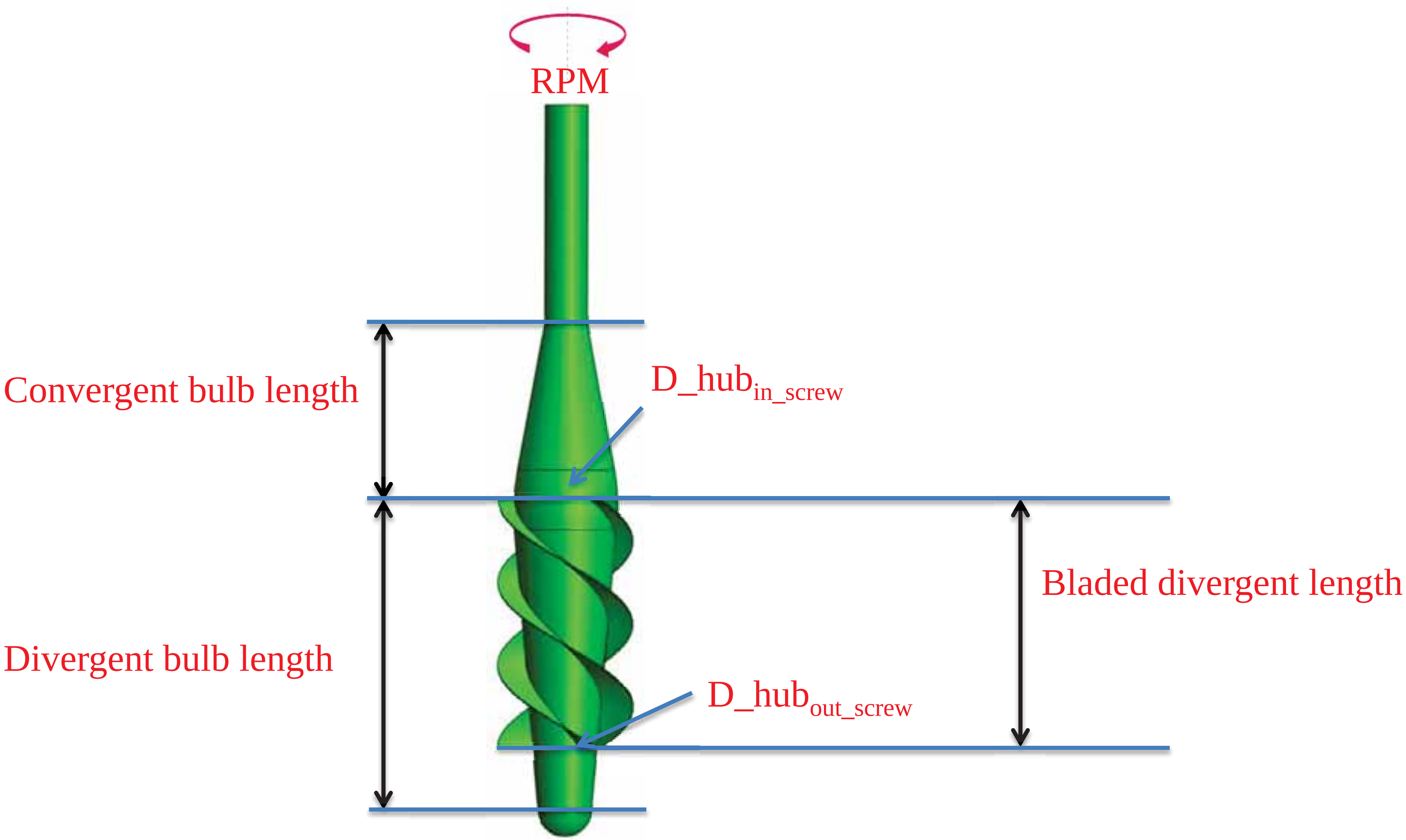
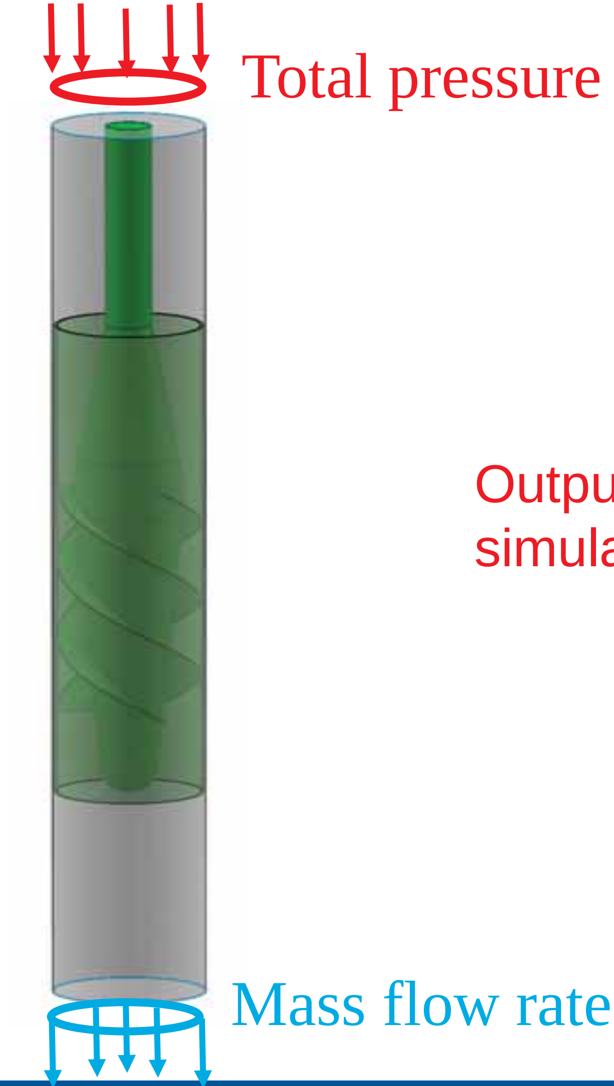
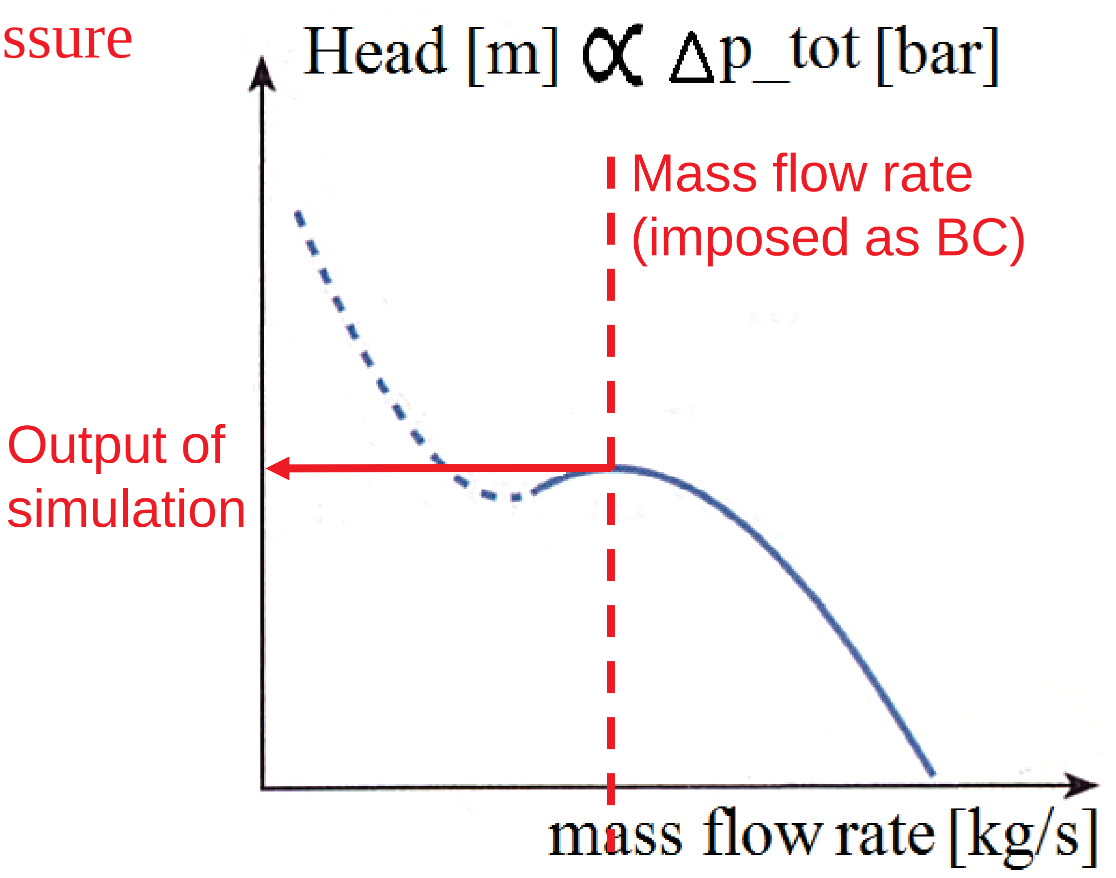
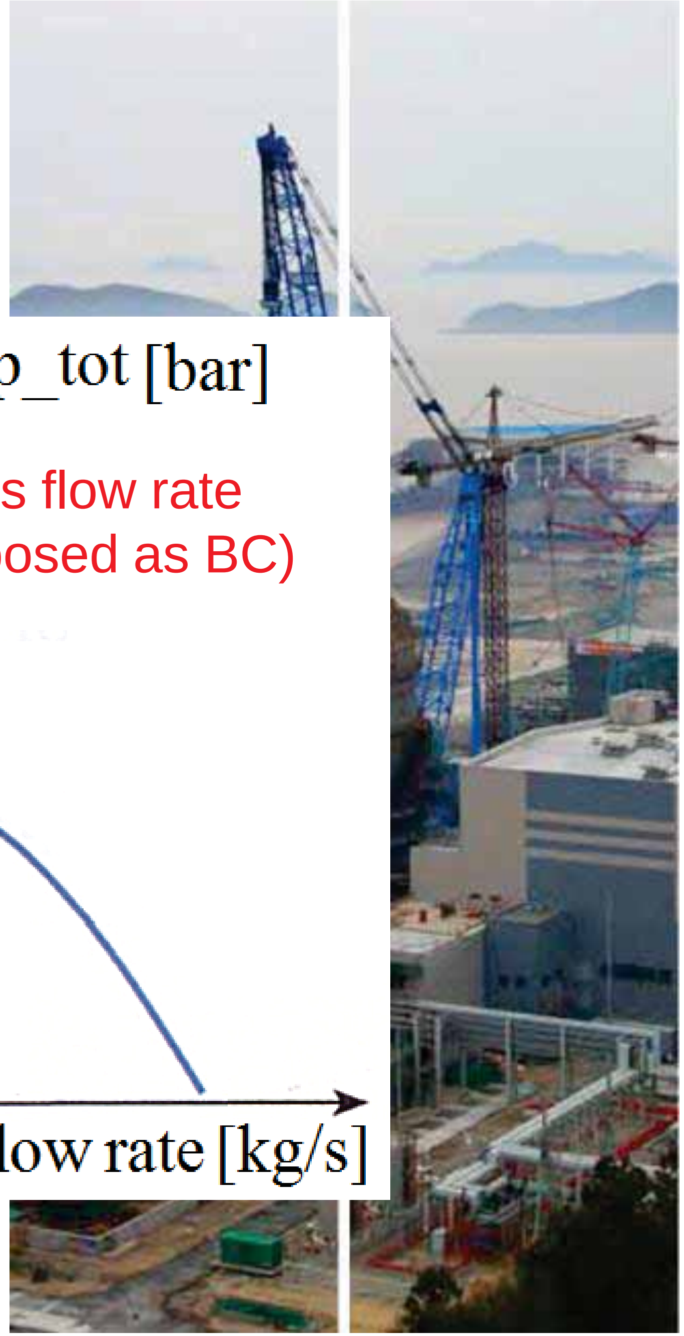
Screw pump: degrees of freedom



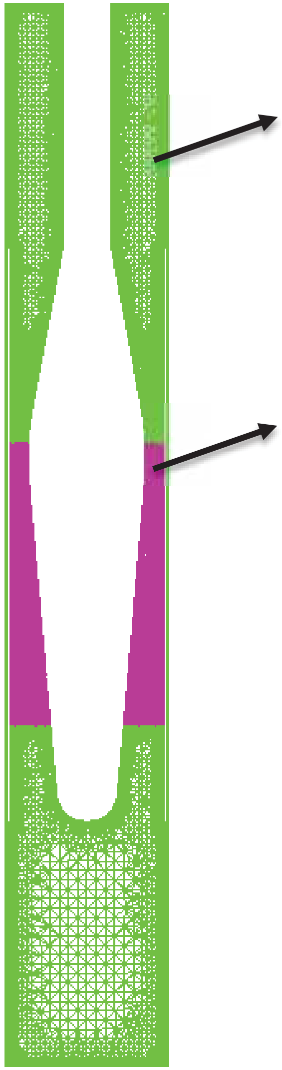
Screw pump: BCs





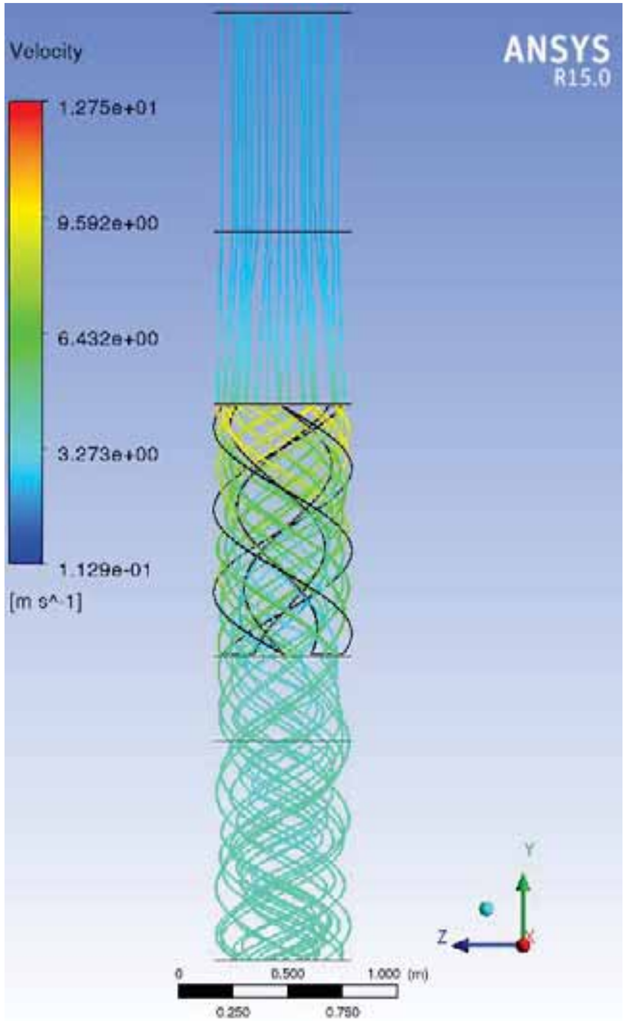


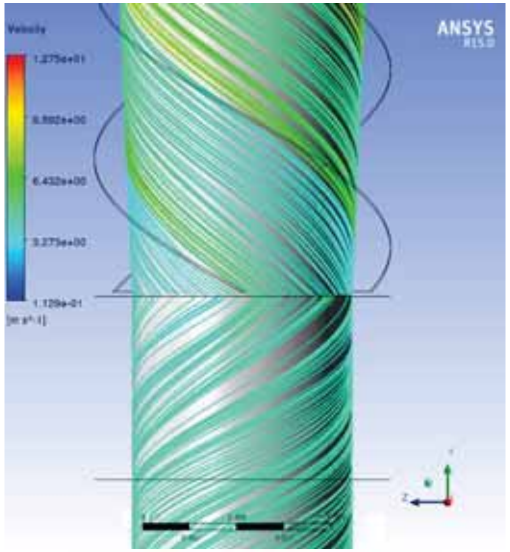
Screw pump: stationary vs rotating domain

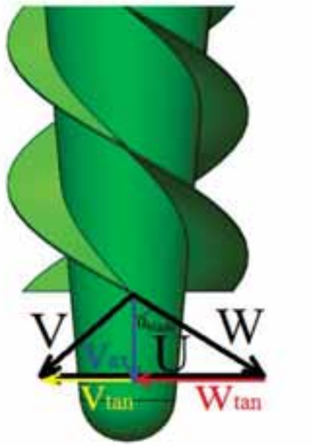


Frame change:
Frozen rotor

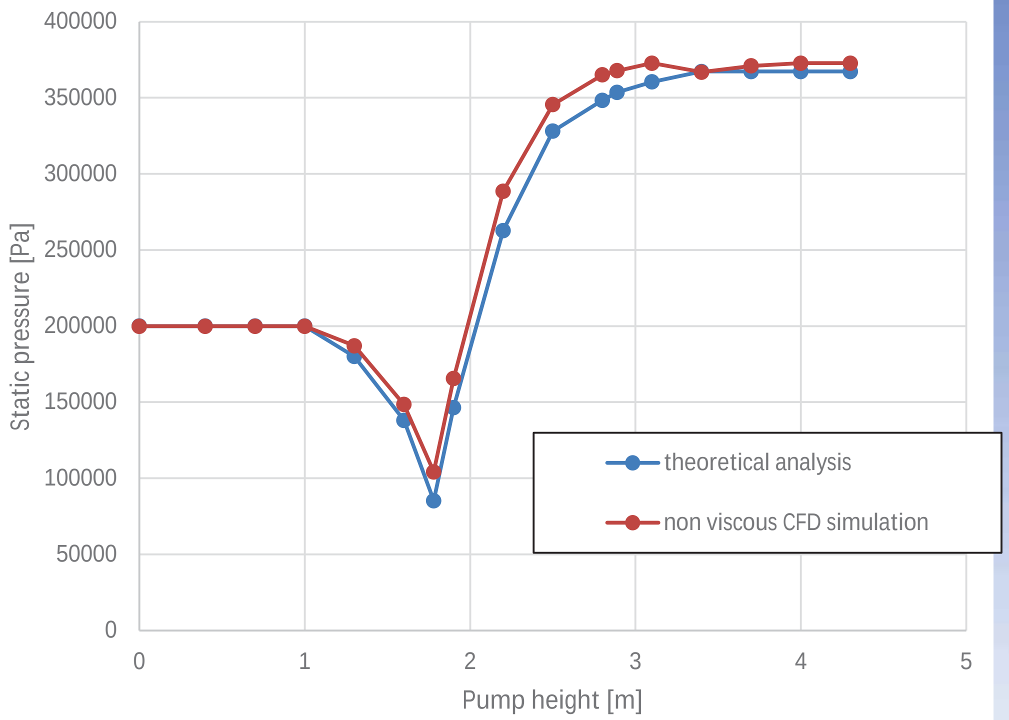
Reference case: 280 RPM, non viscous

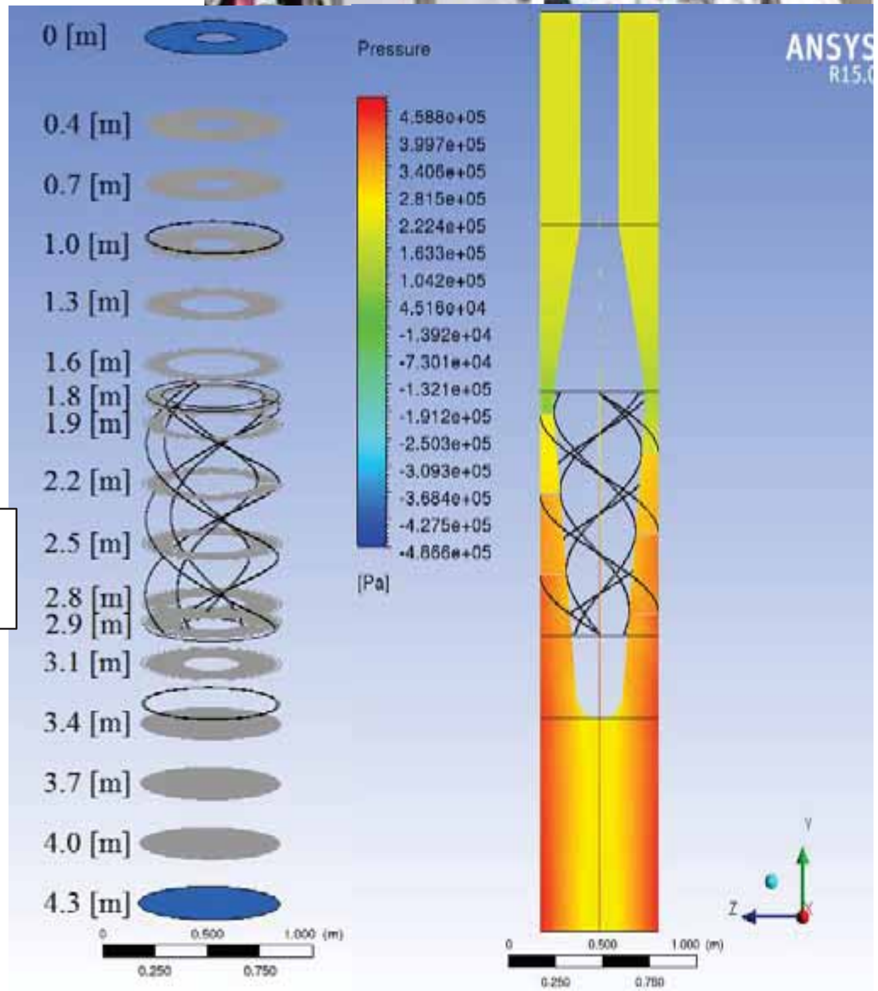




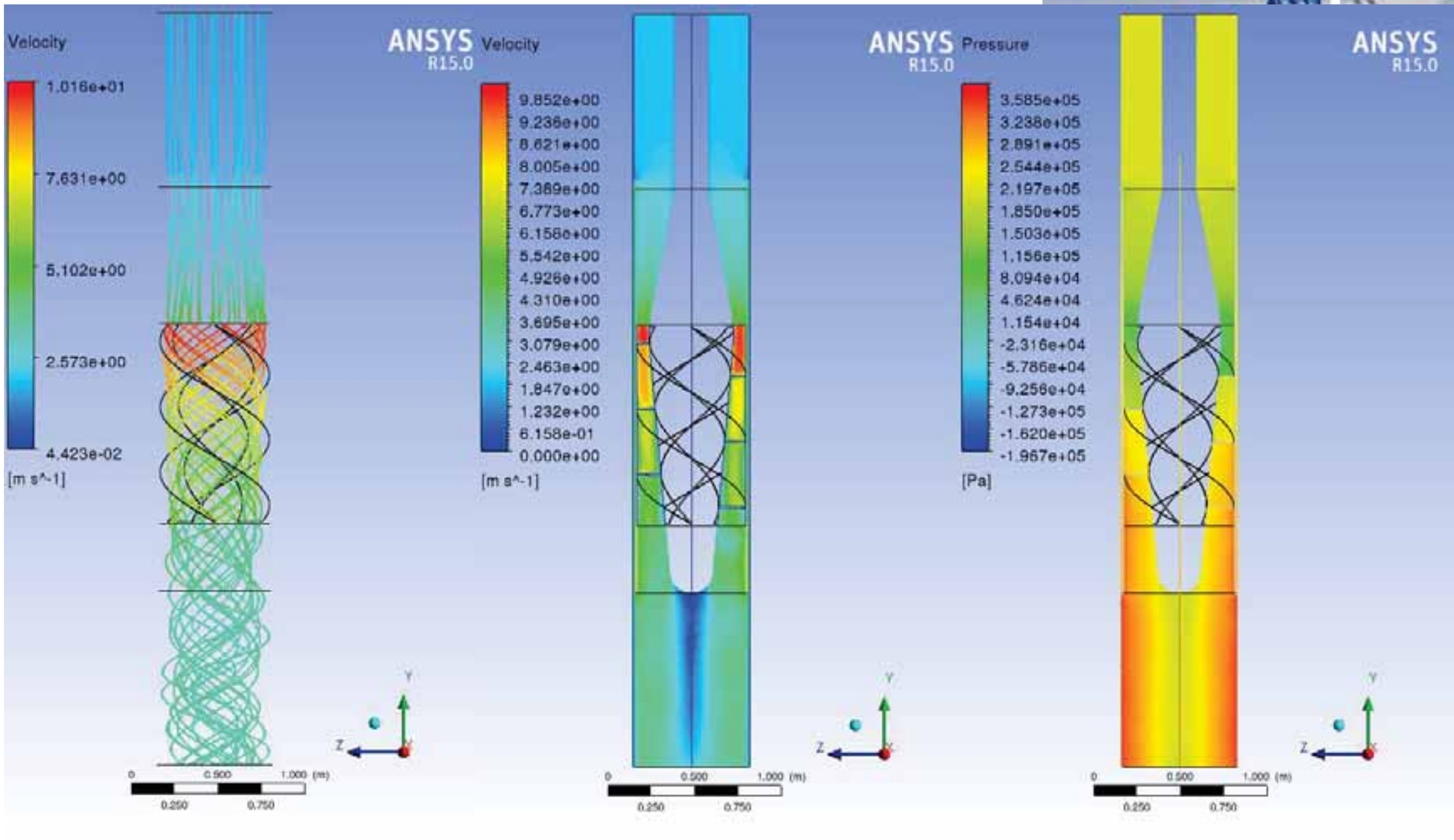


Reference case: 280 RPM, non viscous

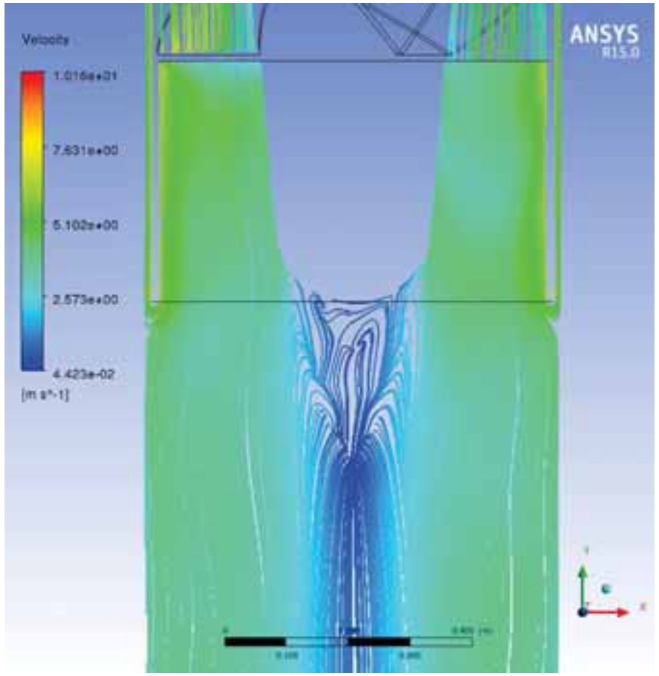


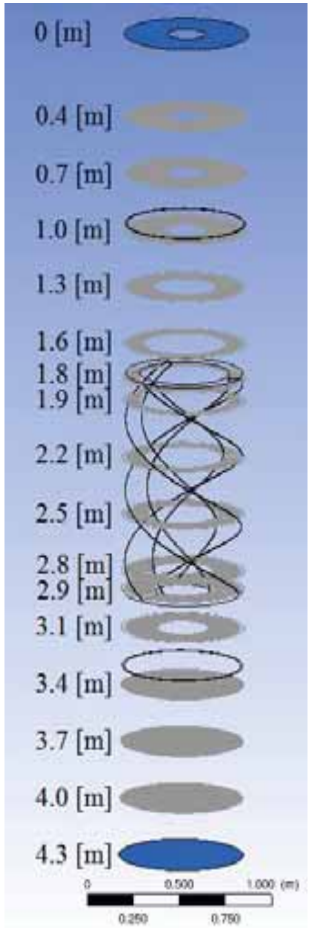


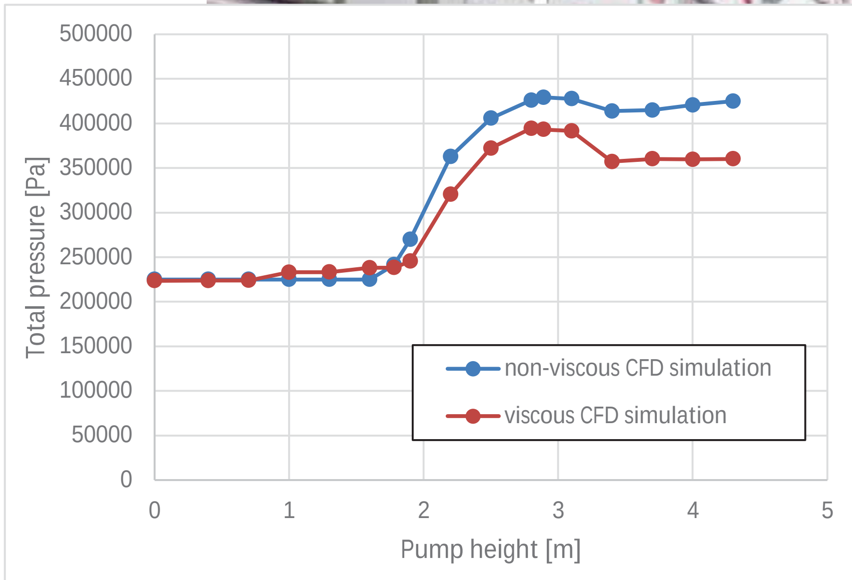
Reference case: 280 RPM, viscous



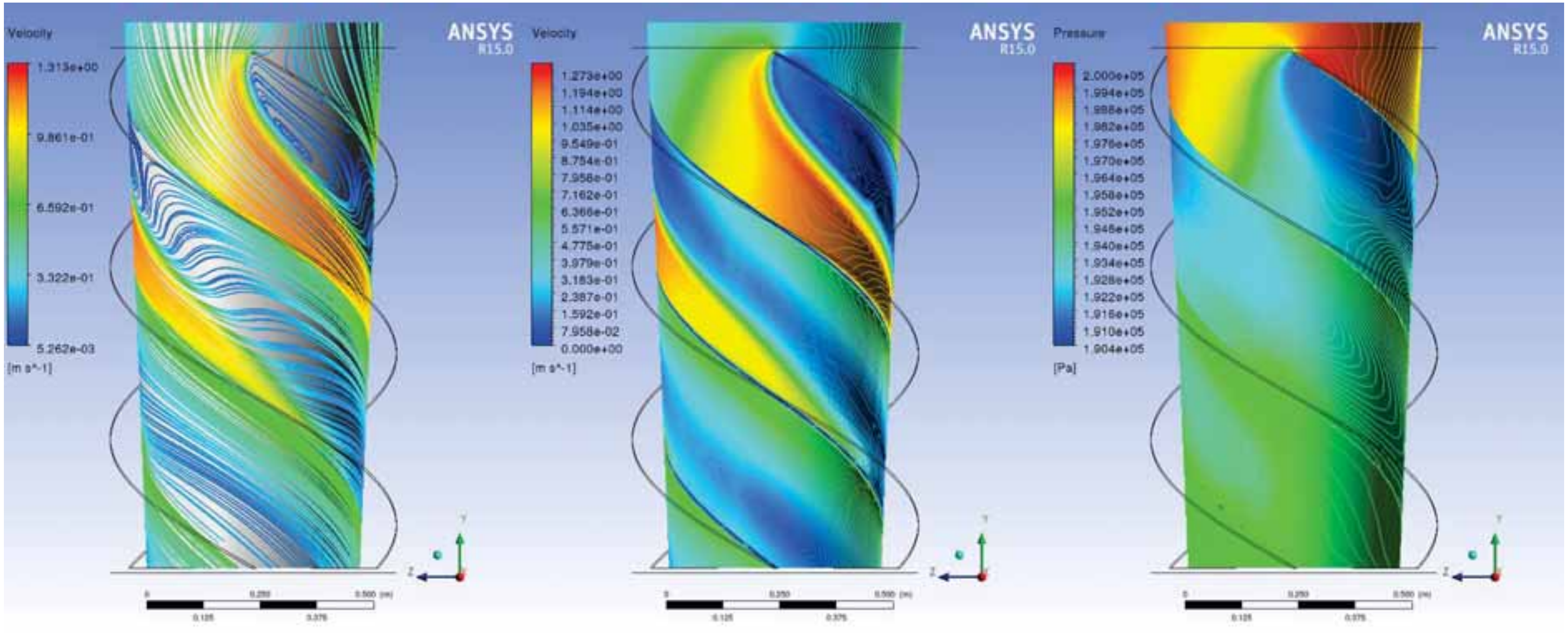
Reference case: 280 RPM, viscous







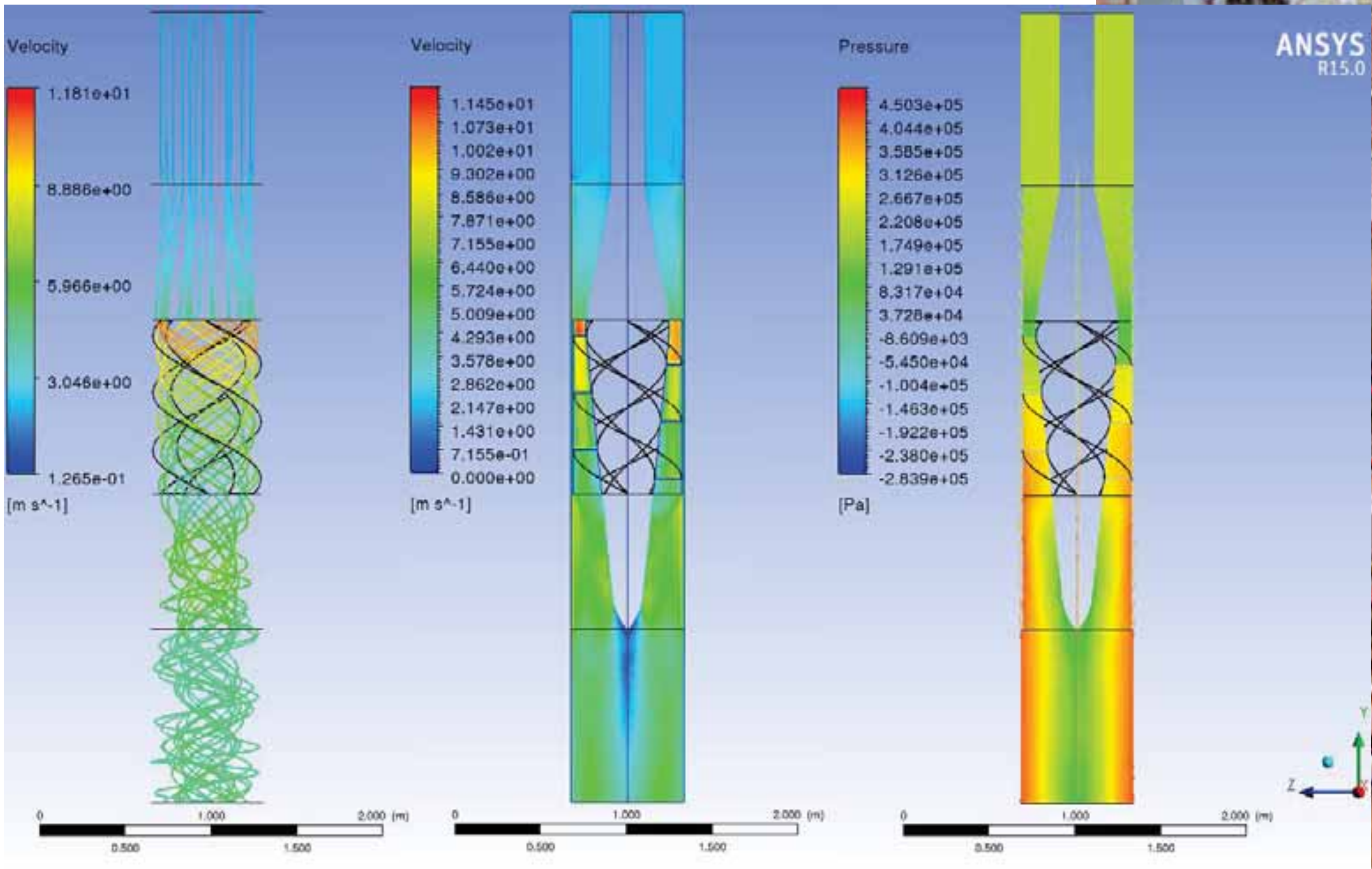
Reference case: 280 RPM, viscous - *Pressure losses at locked rotor conditions*

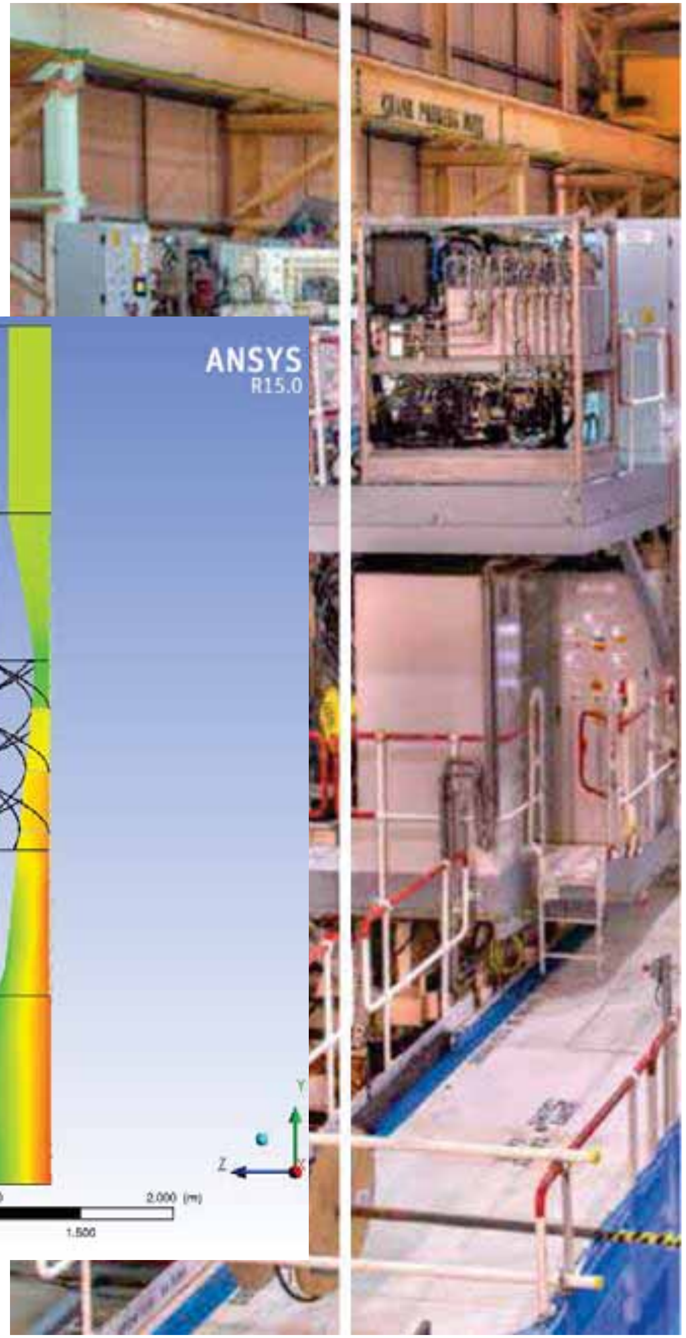


mass flow rate = 644,7 [kg/s]
(10% of nominal mass flow rate)

differential pressure = 0,04 [bar]

Improved design: 315 RPM, geometrical adjustments





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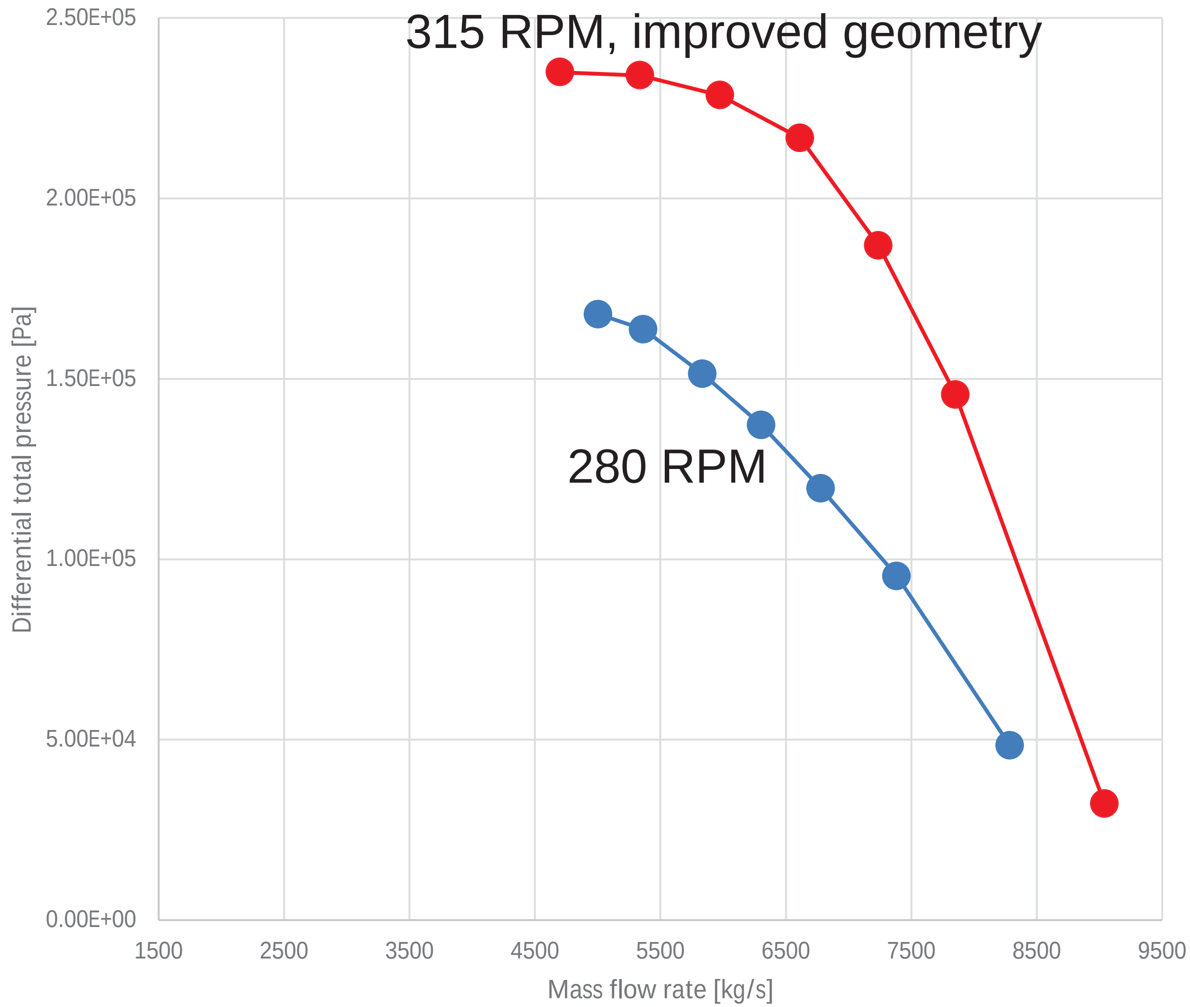
Improved design: 315 RPM, geometrical adjustments



Conclusions and future work

- The ANSYS CFX 3D simulations confirm the results of the theoretical analysis.
- The improved design of the screw pump delivers the required $\dot{m}$ and Δp, keeping velocities within acceptable values.
- ANSYS CFX has shown a significant ease of use, stability and effectiveness.
- The next step is the integration of the screw pump in the overall system.

Final remarks

“ALFRED will represent the first time that a critical heavy liquid metal cooled reactor would provide electricity to the grid”

Strategic Research and Innovation Agenda (February 2013)