Realize LIVE

SPH-based design exploration for integrated oil spray cooling

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Simulation and Design Analysis of complex systems for engineering and industrial applications

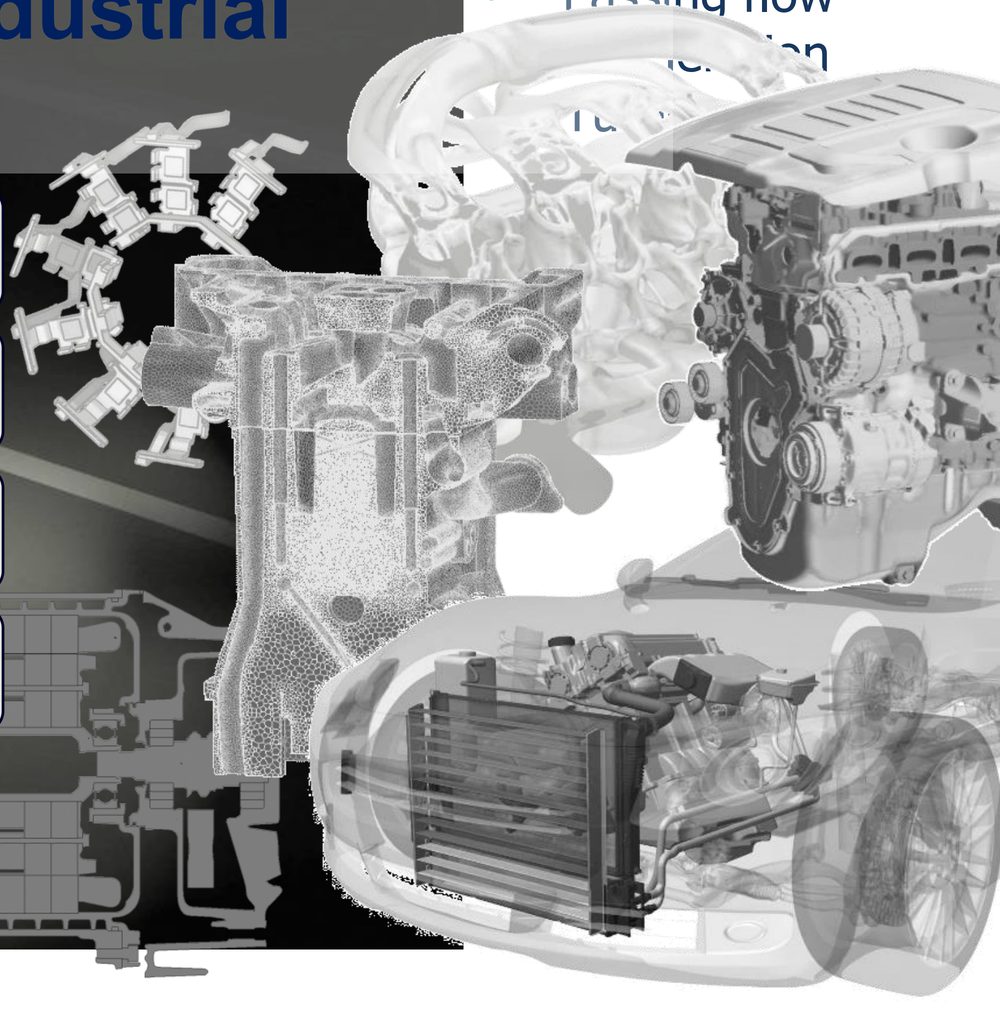
- Aerodynamics
- Passing flow

Fluid Flow & Heat Transfer

Hydro & Aerodynamics

Thermal & Energy Management

Air-borne Acoustics & Sound Design



SPH example

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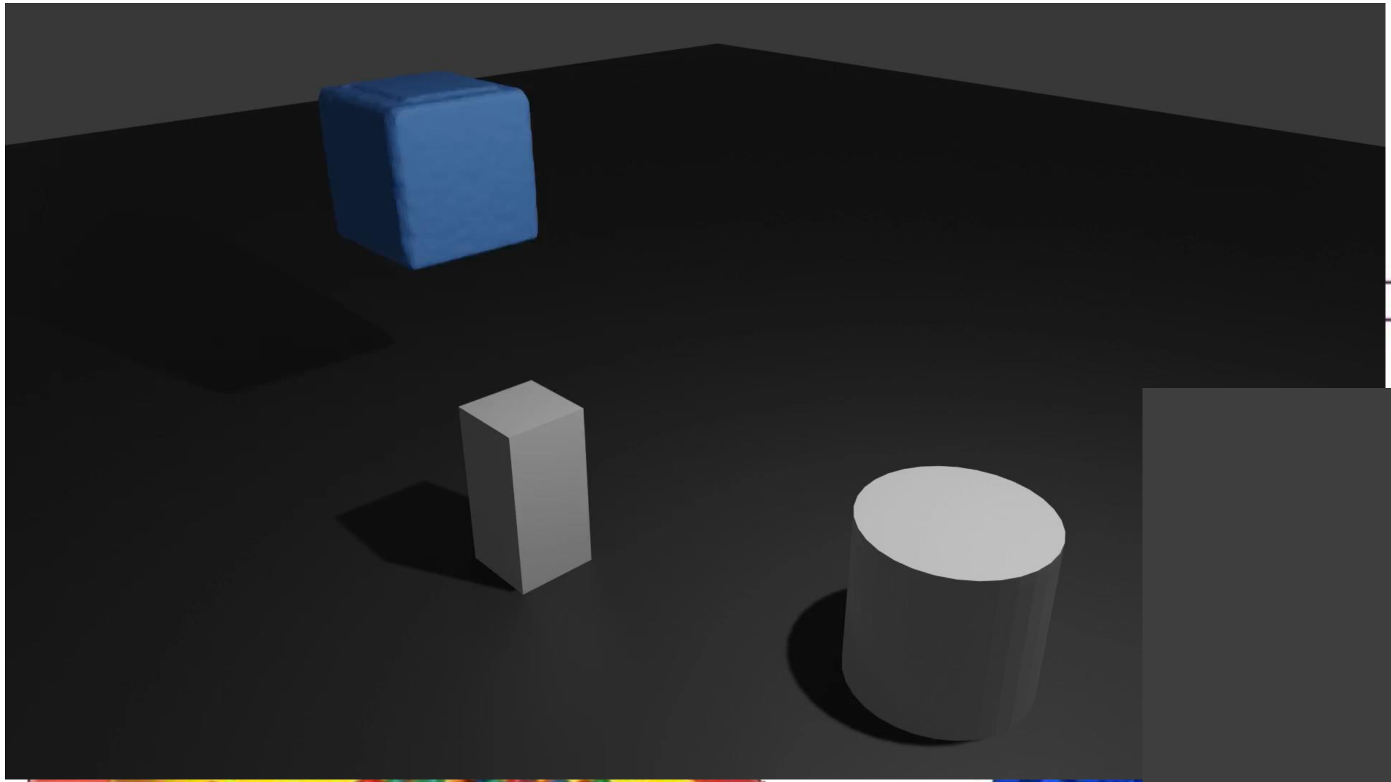
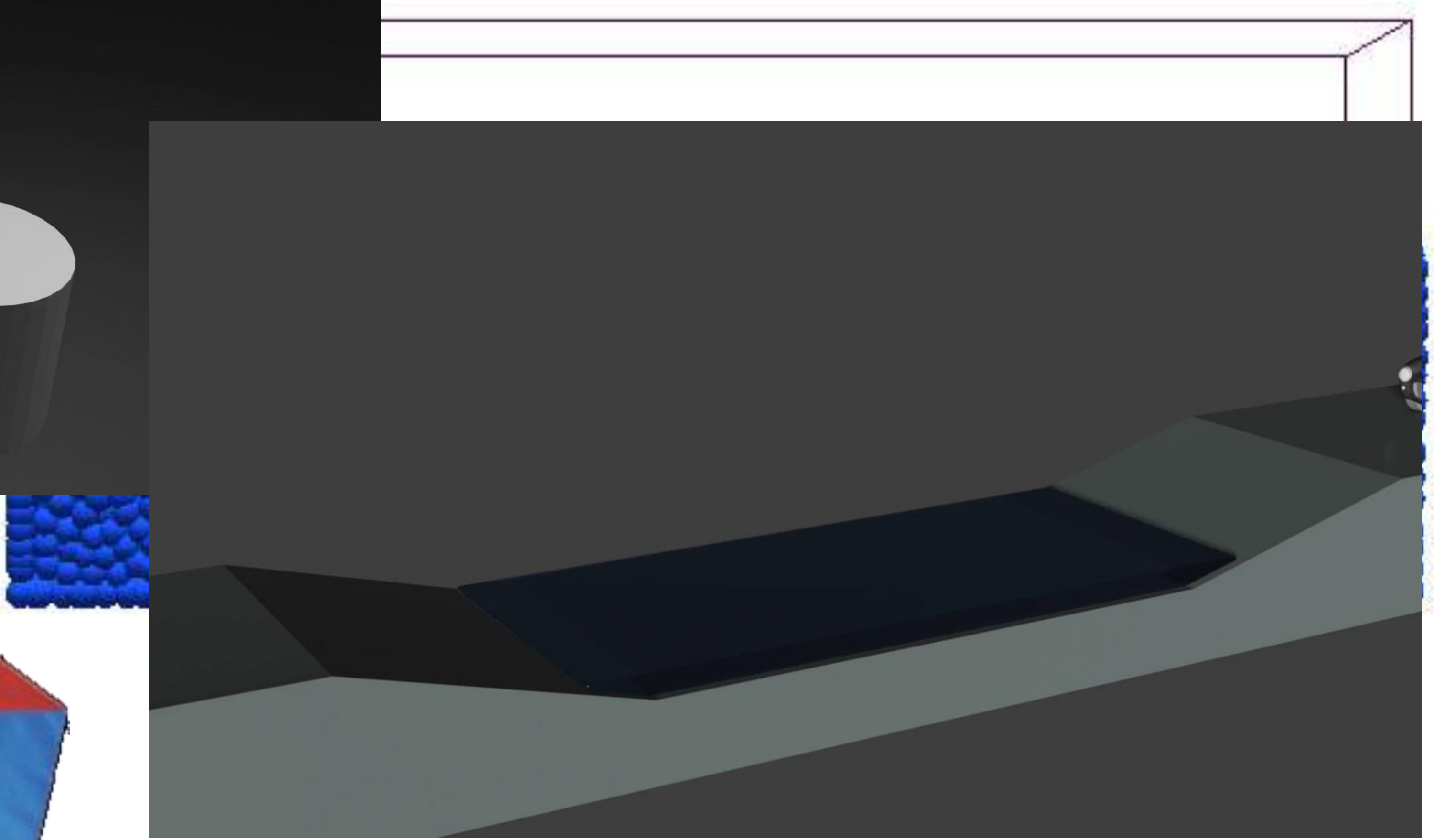


- Approximation of a medium (liquid) using many small "balls"—analogous to a ball pit in a children's play area.
- The smaller the "balls," the more accurate the approximation.



Behind the "pictures"

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$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g}$$

Grid based CFD
(finite volume CFD)

- Fixed mesh
- Fluxes across cell faces
- Mesh quality affects accuracy

Interface tracking,
Efficient for confined flows

Meshless SPH
(Lagrangian based)

- Particle interactions
- No mesh distortion

Natural free surface,
Suitable for problems involving
- Large free-surface deformation
- Fragmentation and coalescence
- Complex moving boundaries
- Strong fluid-structure interaction

Same Physics, different approach

- Kernel Approximation: Continuous fluid is represented by discrete particles.
- Each particle interacts only with neighboring particles within a support radius (smoothing length h).
- Physical quantities are obtained by a weighted interpolation using the kernel function W(r,h).
- Neighboring particles have a stronger influence than distant particles.
- The kernel is compact: outside the support radius, its value is zero.
- Spatial derivatives (gradient, divergence, Laplacian) are evaluated directly from the kernel function.

Behind the “pictures”

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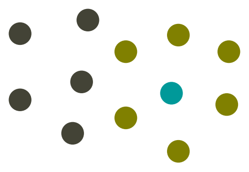
$$A_i = \sum_j m_j \frac{A_j}{\rho_j} W_{ij}$$

- W_{ij}: kernel weighting function
- h: smoothing length
- Sum over neighboring particles only



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PANDORA 4 CYLINDER ENGINE W/ OIL NOZZLES

Fig: SPH simulation (Star-CCM+ v2506) of oil nozzles positioned in Pandora 4 Cyl and resulting SPH particle velocity magnitude

MOTIVATION

- Use case: leveraging meshless SPH simulation in combination with a meshfree kinematics solver to position oil nozzles in the crankshaft housing

BASIC SETUP

- Particle Size: 0.3 mm
- Surface Sampling Factor: 0.1
- Constant Mass Flow for all 4 Injectors @ 0.05 kg/s (total)
- Constant Density (adiabatic/non-thermal walls)

PANDORA 4 CYLINDER ENGINE W/ OIL NOZZLES

Fig: Animation of oil nozzles SPH simulation in Star-CCM+ 2506

LIMITATIONS

- No 1-way coupling (influence of air flow on SPH particles) → undetermined influence on particles
- No solving of energy equations
- No local particle refinement

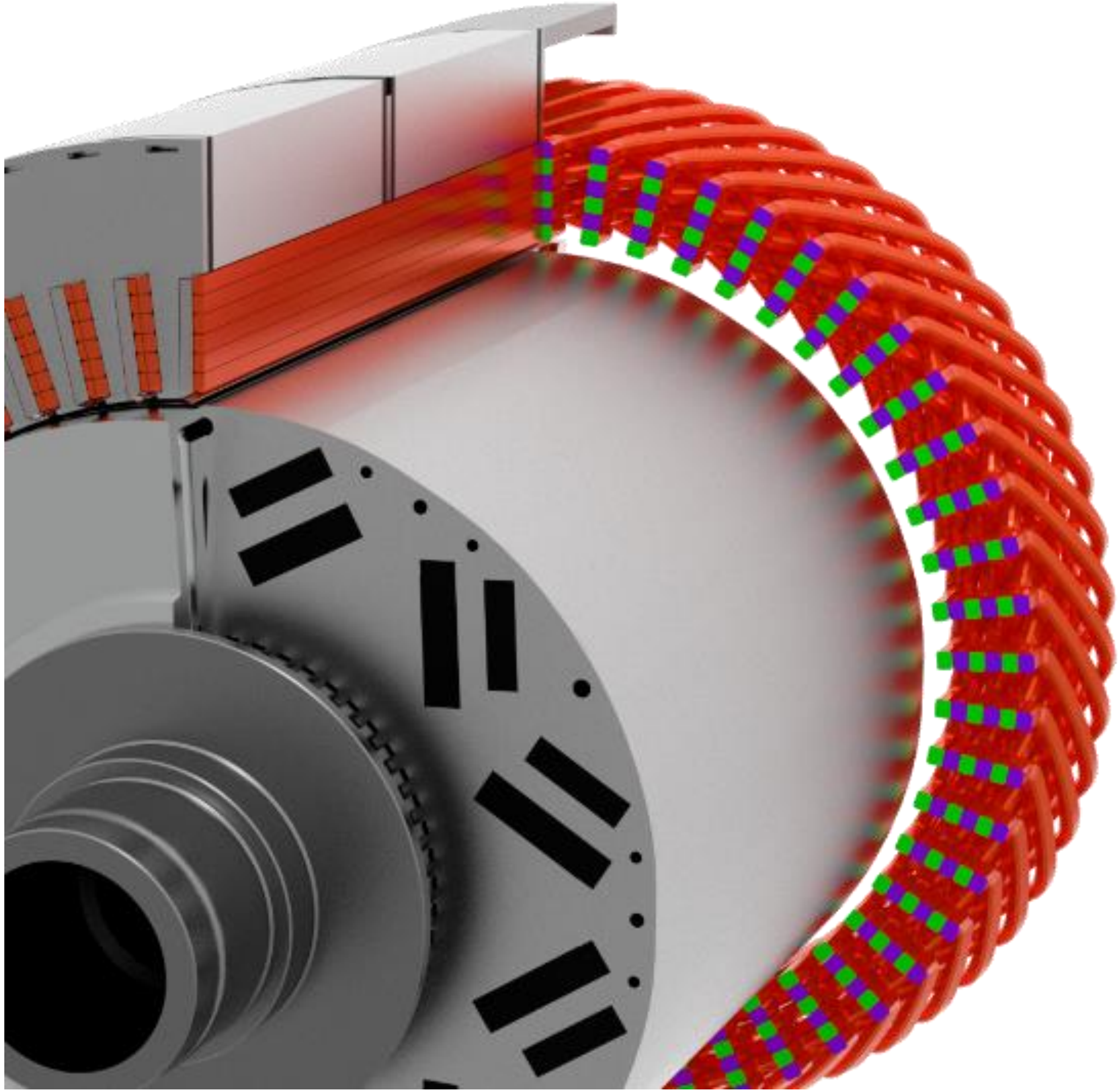
ADVANTAGES

- Efficient positioning of oil nozzles possible
- Easy setup of SPH domain

CHALLENGES

- Fragile/Challenging setup of Kinematics Solver
- Fine settings necessary to reduce surface penetration of particles

PANDORA-E evo



PM motor

Rotor:

- 6 pole, each wit 4 magnets (V-shape 125° deg)
- Diameter: 159 mm, active length: 160 mm
- Oil cooled shaft and yoke
- Oil spray for end-winding

Stator:

- 54 slots, 2 coils
- 6-layer copper winding hair pins
- Oil cooled yoke
- Oil spray for end-winding

Power: 330 kW @ 5300 rpm

Torque: 600 Nm @ 5300 rpm

PANDORA-E EDU: OPTIMIZATION OIL NOZZLES
Geometry + Oil Nozzles

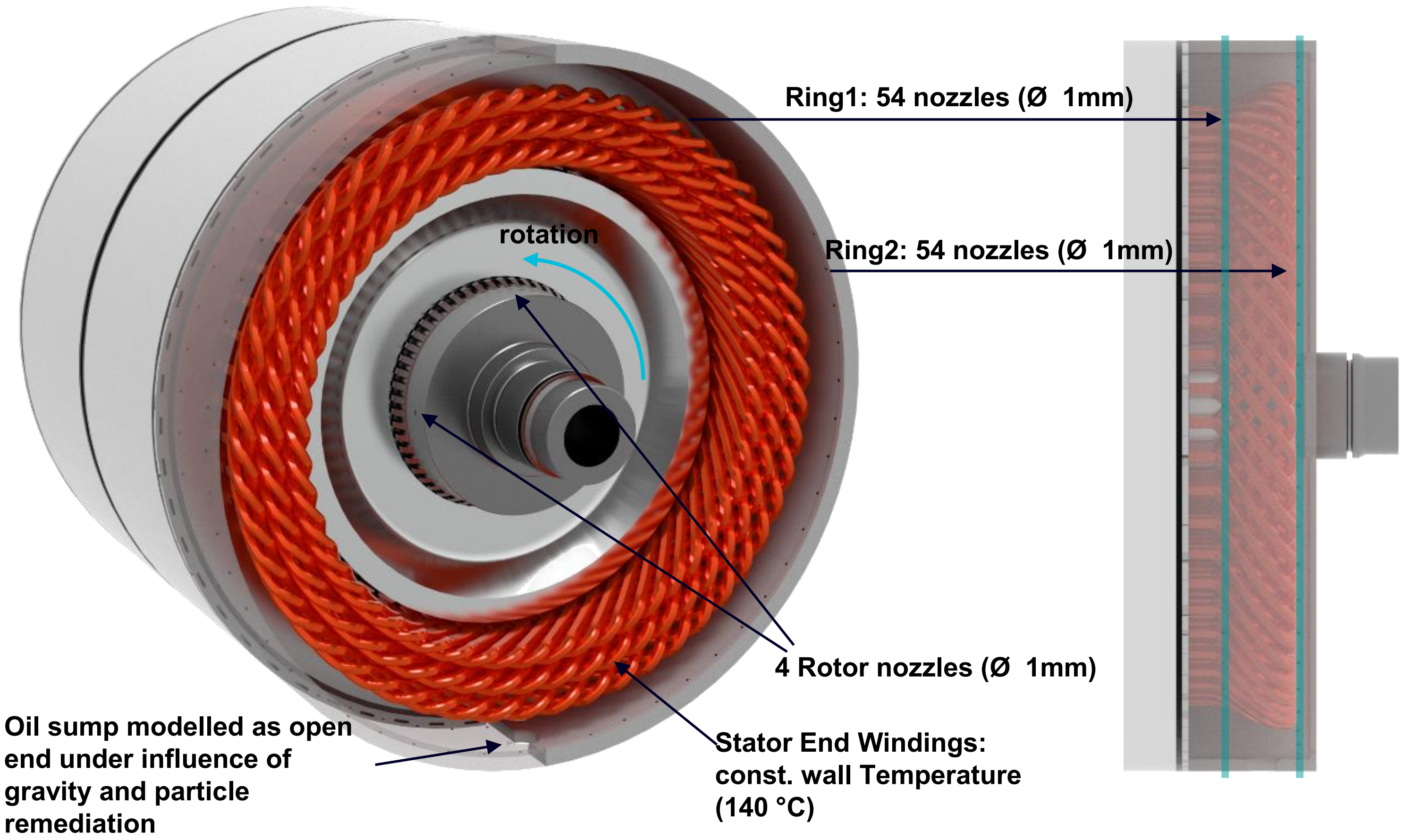
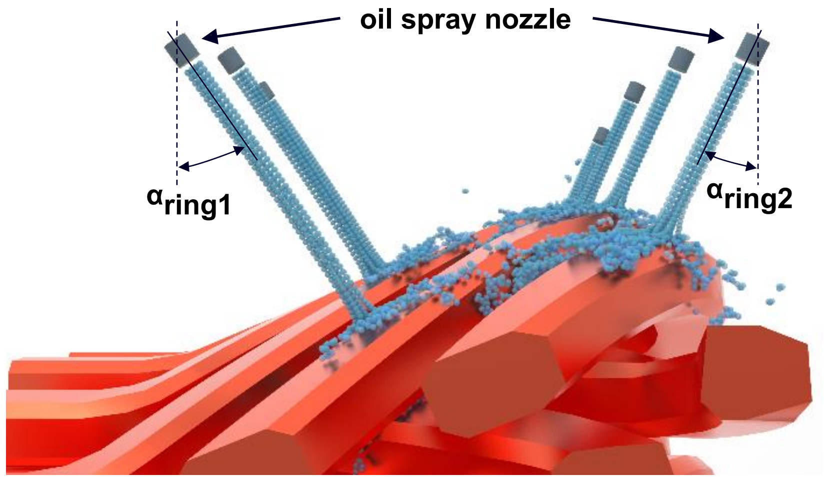


Fig: Stator Endwinding A-side of EDU and defined nozzles (left), axial position of circumferential nozzles ring 1 and 2 (right)

- 54 nozzles in 2 axially positioned rings around stator windings of EDU A-side
- 4 nozzles in rotor to supply EF Segment w/ oil
- Nozzle diameter 1 mm for all nozzles
- Typically, 2 fixed nozzle angles for Ring 1+2
- Oil flow stator: 6 l/min (60° C)
- Oil flow rotor: 3 l/min (60° C)
- Rotor: 4000 rpm



PANDORA-E EDU: OPTIMIZATION OIL NOZZLES
Reduced SPH Model for HEEDS Optimization

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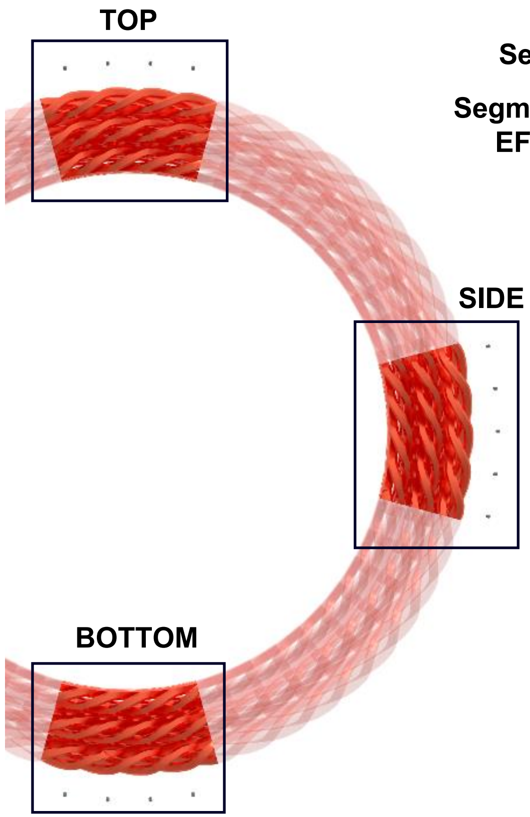


Fig.: 3 segments of stator end windings for HEEDS nozzle angle optimization

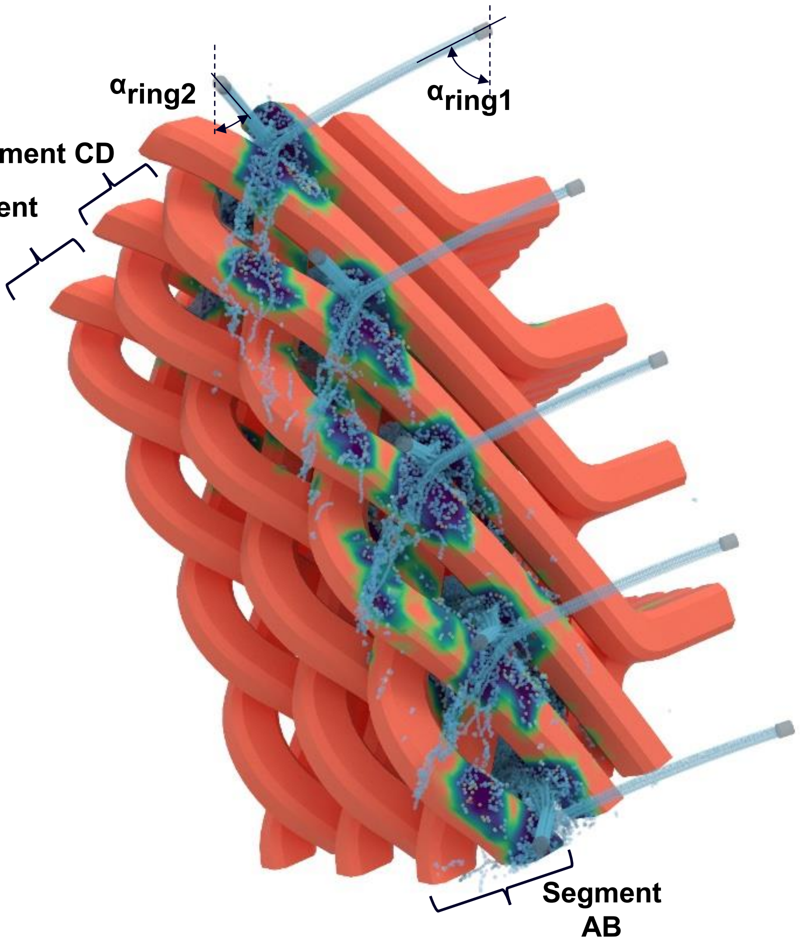


Fig.: SIDE segment (Design Case 22) w/ SPH particles and volume fraction of oil on stator end windings

GOAL: Identification of the optimum nozzle angles ($Ring_{1,2}$) for the 3 segments and the best wetted area (cost function)

APPROACH:

- Definition of a cost function
- 3 separate HEEDS optimizations with nozzle angles for Ring 1 and Ring 2 ($\alpha_{ring1,2}$)
- Polynomial fitting of nozzle angles from top to bottom to simulate the half-model of the stator end windings
- **HEEDS Cost Function:** The cost function prioritizes the penetration of oil particles through the winding on segment CD. This ensures that particle penetration due to nozzle position is better accounted (wA = wetted area).

$$CostFunction = \frac{1}{3} wA_{AB} + \frac{2}{3} wA_{CD}$$

PANDORA-E EDU: OPTIMIZATION OIL NOZZLES
Extrapolation of HEEDS results / individual nozzle angles

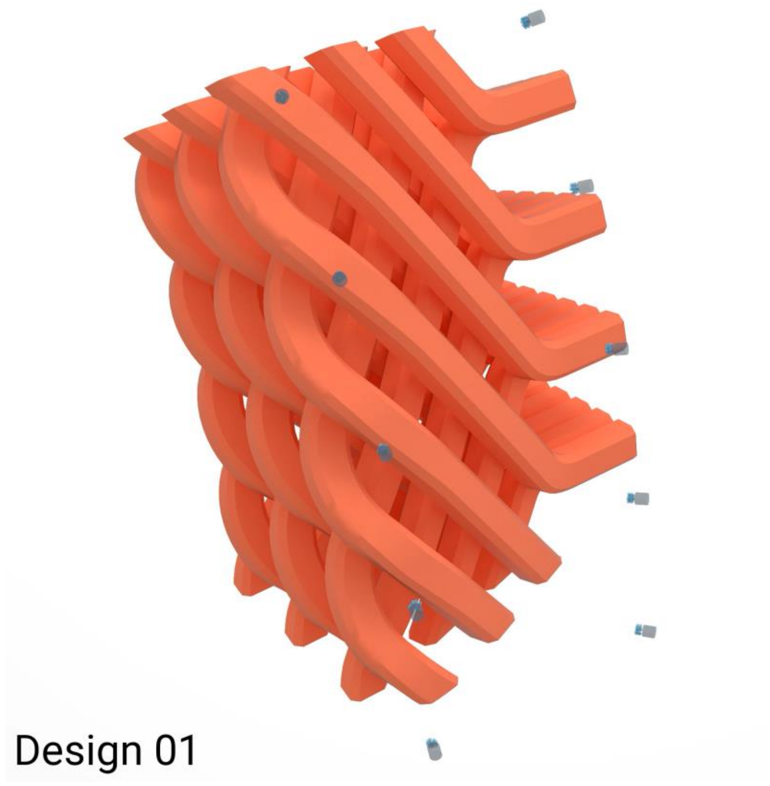
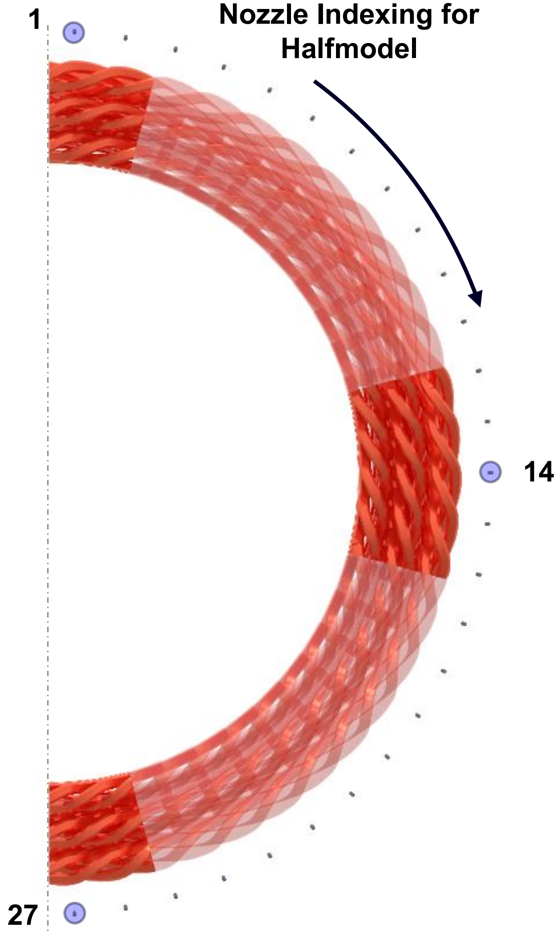


Fig.: Animation of the design optimization for selected designs resulting in the best design



Based on the HEEDS optimization for 3 segments, a polynomial fitting has been performed to determine the individual nozzle angles for the intermediate nozzle positions.

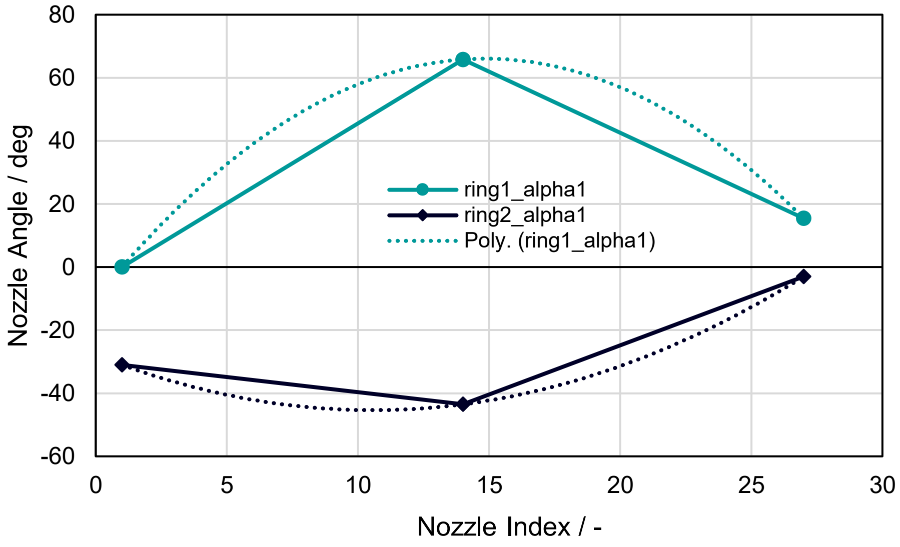
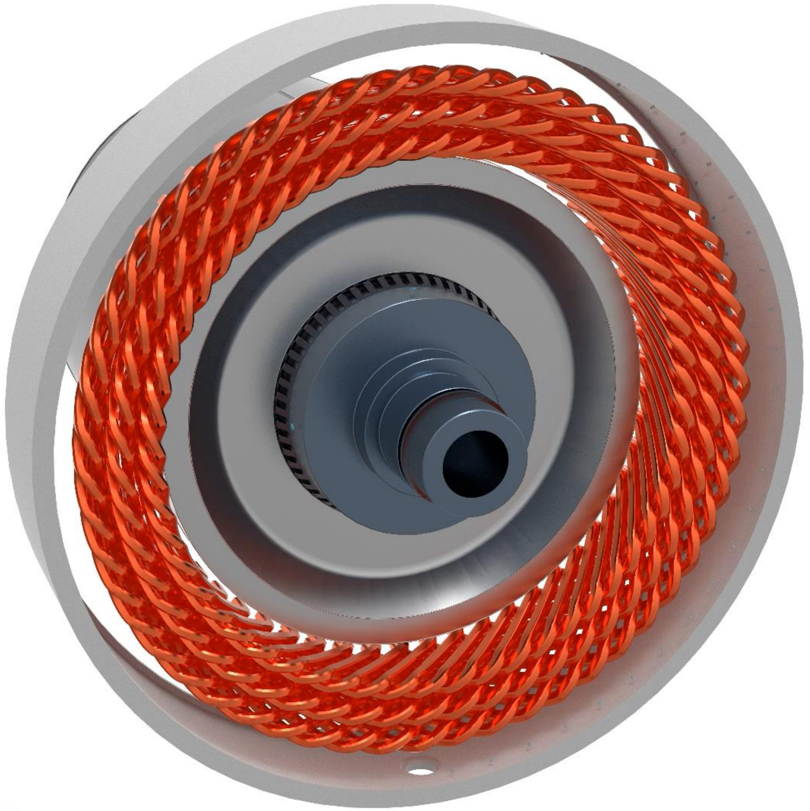


Fig.: HEEDS segments and resulting nozzle indices for the half-model and polynomial fitting

PANDORA-E EDU: OPTIMIZATION OIL NOZZLES
SPH Simulation w/ optimized nozzle angles



SPH simulation of optimized nozzle angles for half circumferential nozzles (top to bottom) to reduce computational costs

BOUNDARY CONDITIONS

- Oil flow stator: 6 l/min (60° C)
- Oil flow rotor: 3 l/min (60° C)
- Rotor: 4000 rpm
- Wall temperature stator end windings: 140 °C
- Particle size: 0.25 mm
- „stationary“ particle count after 2 sec (~ 3.5 Mio)

PANDORA-E EDU: OPTIMIZATION OIL NOZZLES
HTC and (in between) Conclusion

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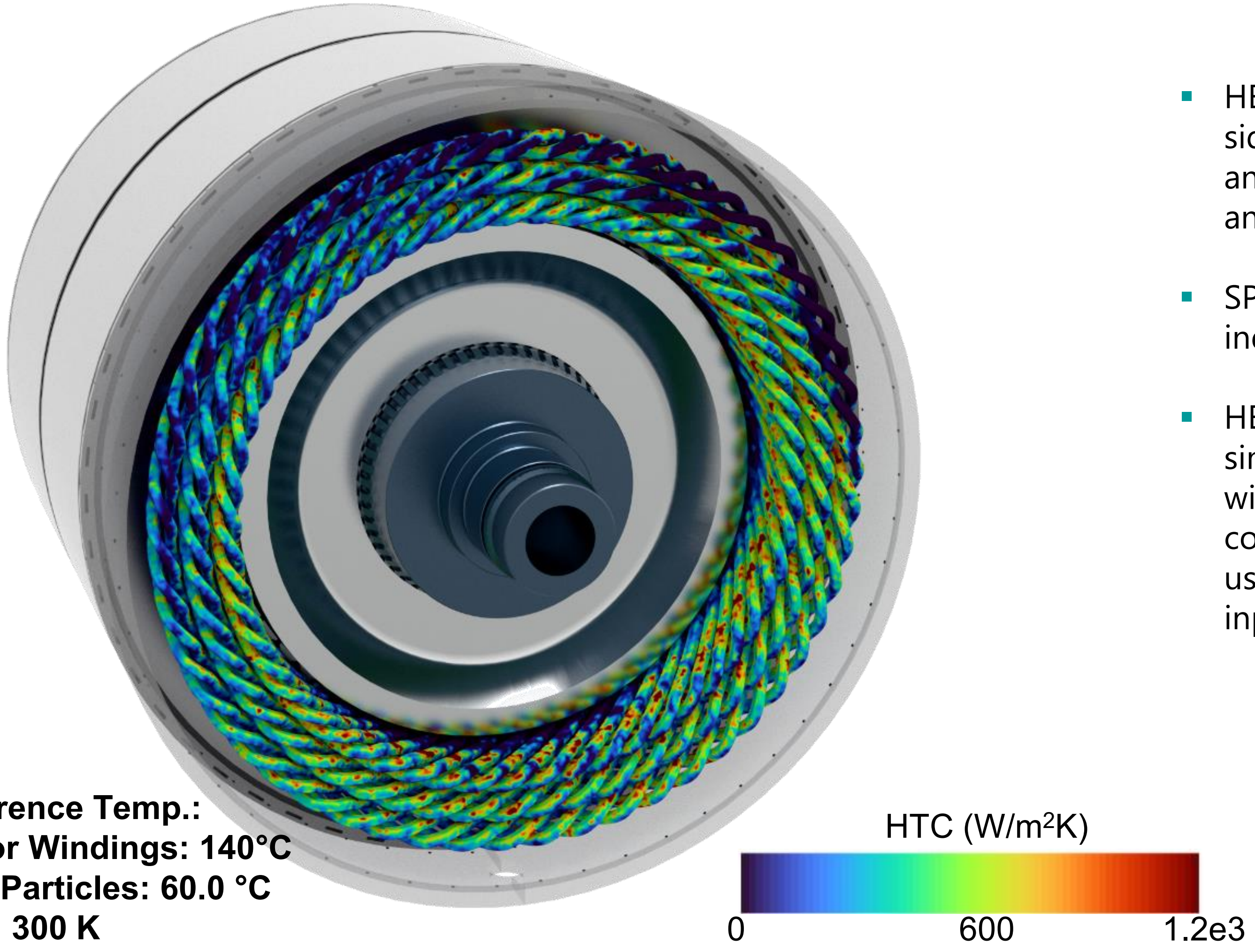

Reference Temp.:
Stator Windings: 140°C
SPH Particles: 60.0 °C
HTC: 300 K

- HEEDS optimization regarding three stator segments (top, side, bottom) led to the conclusion that individual nozzle angles around the circumference can increase the wetted area and as a result the HTC of the stator windings.
- SPH is an effective preliminary investigation tool to adjust individual nozzle angles w/o necessary meshing.
- HEEDS could be an interesting tool to couple different simulation models to cover thermal effects and heat sources within an EDU. This would allow previously missing physics couplings in SPH (e.g. Ohmic heating) to be addressed by using SPH for preliminary sizing and extracting HTC values as input for a subsequent FVM simulation.

PANDORA-E EDU (STAR-CCM+ v2606)
Coupling of AERO DRAG + SPH + EMAG

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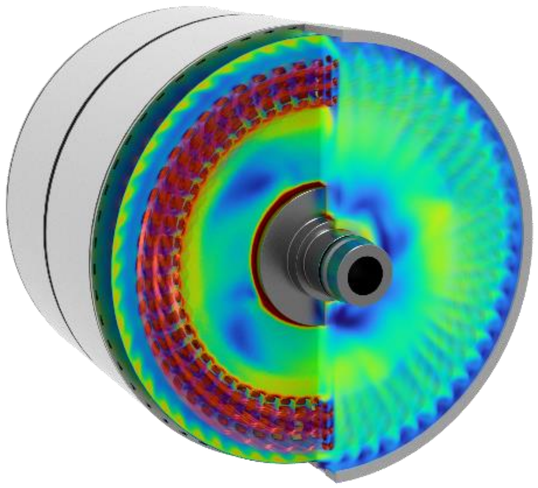
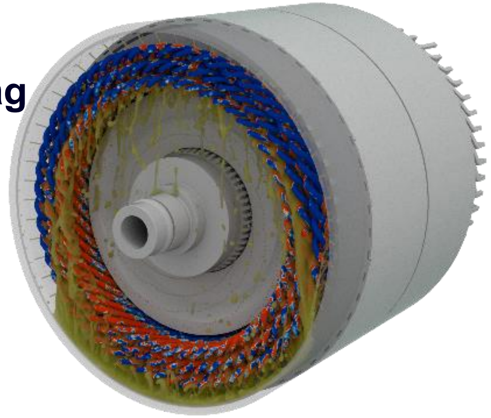


FV AIR Model:
Determine the velocity field of air as input for 1-way coupling of aerodynamic drag on SPH particles

OUTPUT: Steady state air field

Aerodynamic Drag

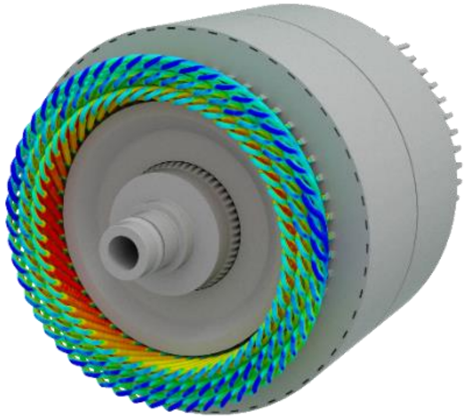
Wall Temperature



SPH Model:
Determine boundary heat flux from stator end windings to oil with respect to aerodynamic forces from FV Air

INPUT: Wall temperature from EMAG
OUTPUT: Boundary heat flux of stator end windings

Boundary Heat Flux



EMAG Model:
Determine Solid Temperature of stator end windings due to Ohmic Heating with regards to boundary heat flux due too oil nozzle cooling (evaluated with SPH)

INPUT: Boundary Heat Flux from SPH
OUTPUT: Wall Temperature stator end windings

Fig: FV Air (velocity magnitude), SPH (Boundary Heat Flux + SPH particles, EMAG (Specified Ohmic Heating))

PANDORA-E EDU: COUPLING OHMIC
Finite Volume Model of Air (A-side)

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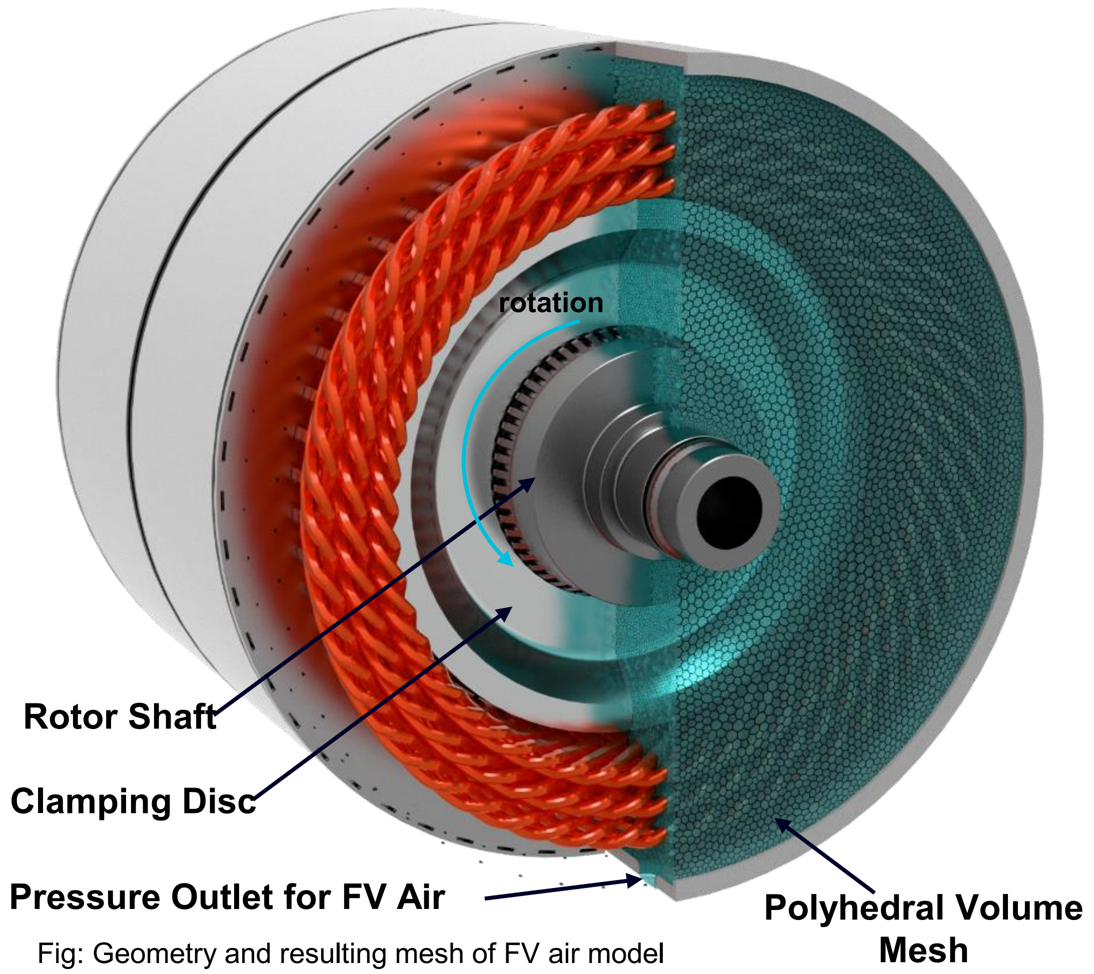

Fig: Geometry and resulting mesh of FV air model

PHYSICS MODEL

- Air (Constant Density)
- Segregated Flow
- RANS (SST k-omega)
- Steady State

BOUNDARY CONDITIONS

- Rotor: 8000 rpm
- Motion applied as Tangential Velocity on clamping disc and rotor
- Adiabatic walls
- Outlet: Pressure outlet (0.0 Pa)
- Front and Back (Symmetry Plane)

MESH

- Polyhedral mesh (~27 Mio cells)
- Thin Mesher to discretize air space between windings

PANDORA-E EDU
Finite Volume Model of Air (A-side)

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Vortex structure with locally elevated velocity can influence the oil jet from the nozzle toward the outer stator windings

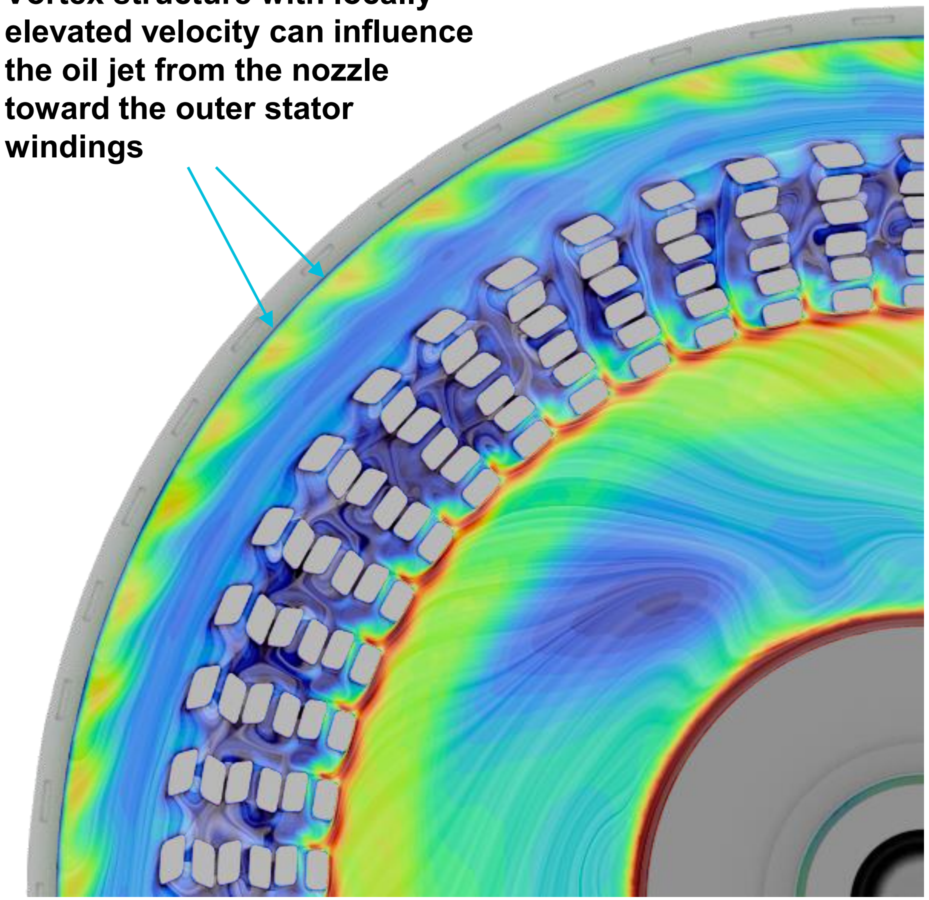
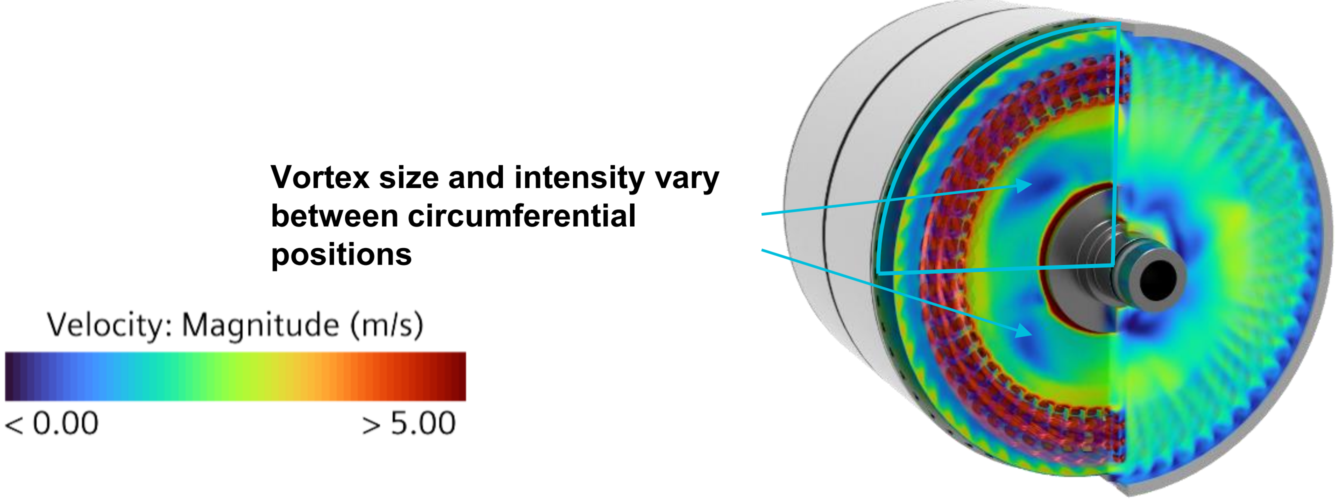


Fig: Velocity magnitude distribution of FV air model

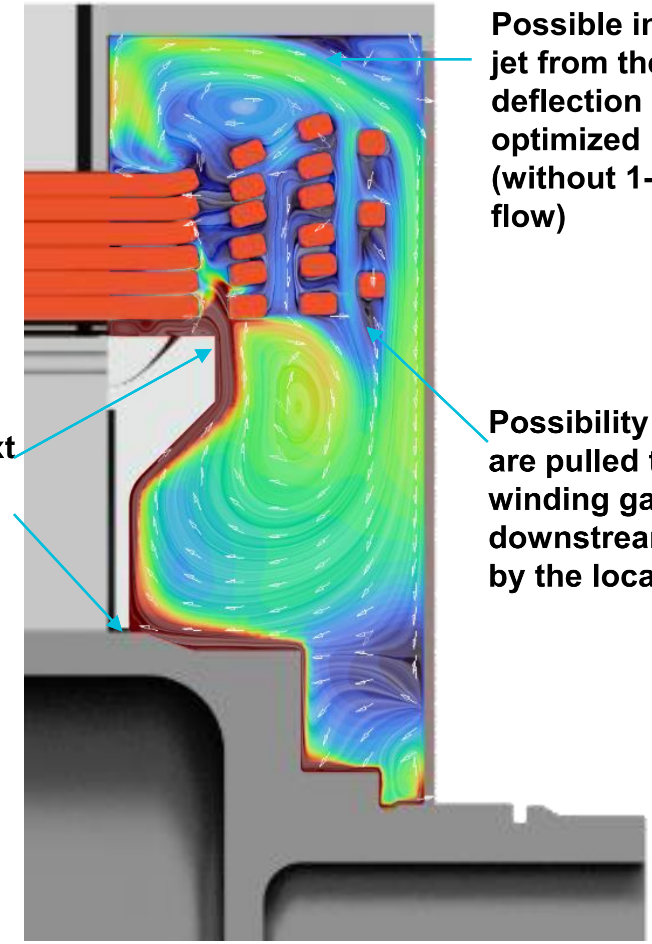
- High air velocities and expected drag forces on particles next to the rotating parts (rotor, clamping disc)
- Air velocity is also expected to influence the oil jet coming out from the nozzles in the stator
- Vortex structures vary non-uniformly around the circumference, which may cause asymmetric drag forces on the particles
- Other influences may be expected due to the implementation of surface tension in combination with Liu's drag on the particles

Detail view

Vortex size and intensity vary between circumferential positions



PANDORA-E EDU
Finite Volume Model of Air (A-side)



Possible influence on the oil jet from the nozzle due to deflection of the previously optimized nozzle angle (without 1-way coupling of air flow)

Possibility that oil droplets are pulled through the winding gaps, drawn downstream toward the rotor by the local air flow

High air velocities next to the rotating parts (clamping disc and rotor shaft)

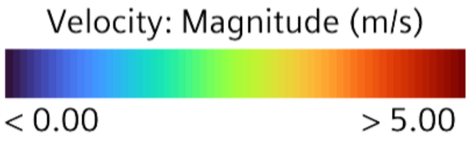
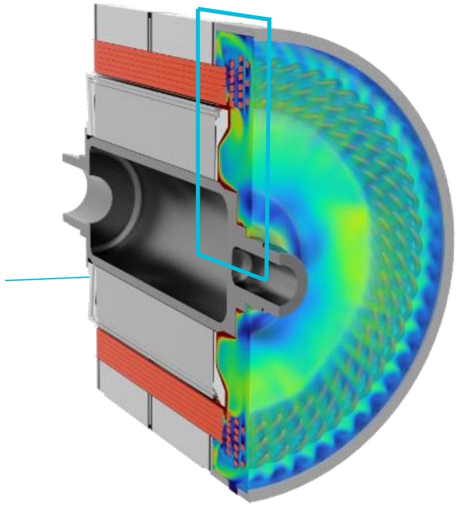


Fig: Velocity magnitude distribution of FV air model

- Recirculation vortex at the clamping-disc step is assumed to locally trap air in a closed, rotating flow path
- SPH particles entering this zone could be deflected and partially entrained due to aerodynamic drag
- Small, low-inertia particles might follow the air rotation closely → potentially increased residence time
- Larger, higher-inertia particles are presumed to pass through with only minor deflection

Detail view



PANDORA-E EDU
EMAG Model

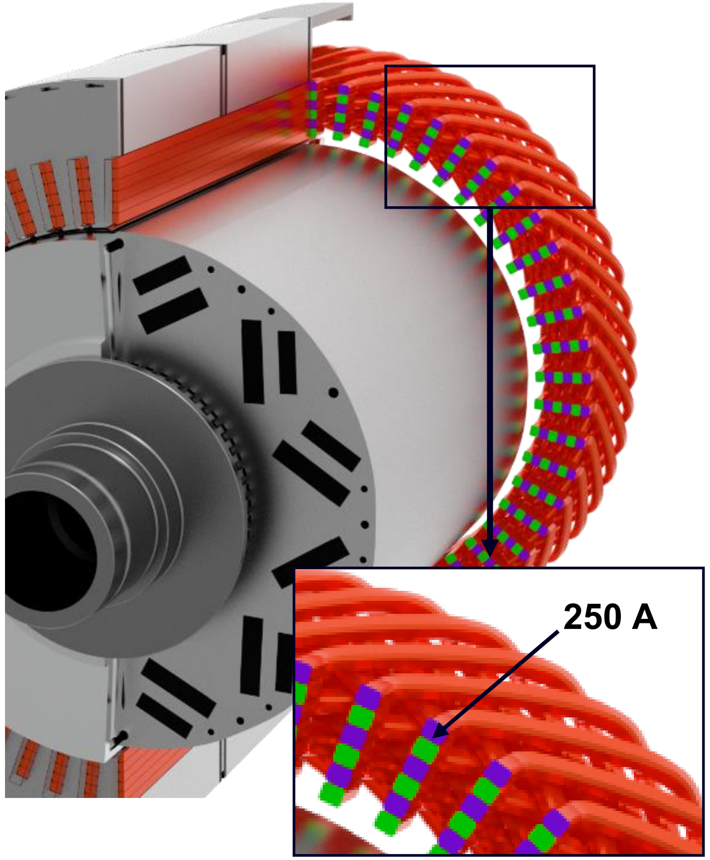


Fig: view of the backside of the stator end windings (A-side) with applied BC, e.g., current, on the end winding

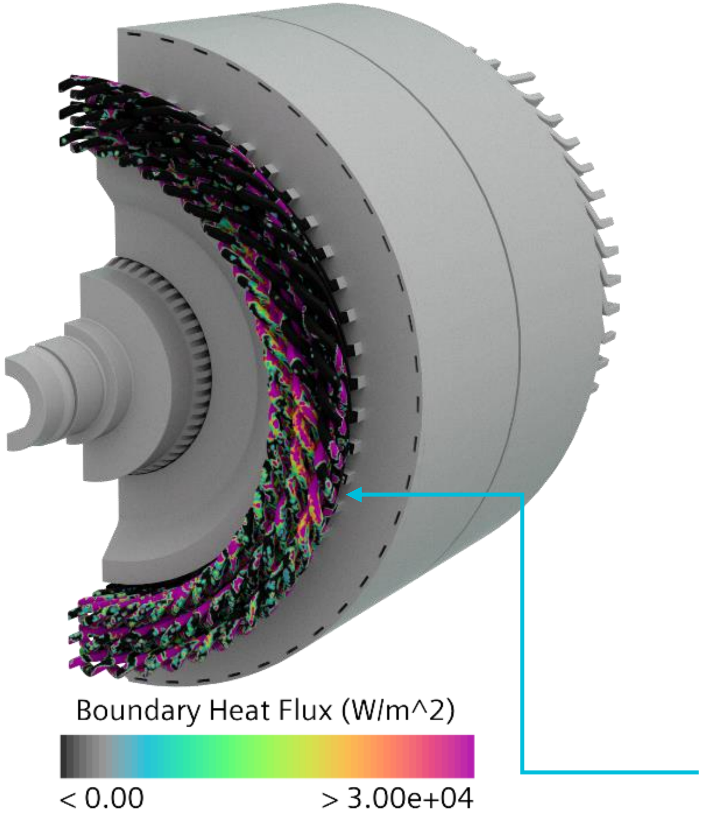


Fig: Boundary Heat Flux (from SPH) which is applied in the EMAG simulation as BC on the stator end winding walls

GOAL

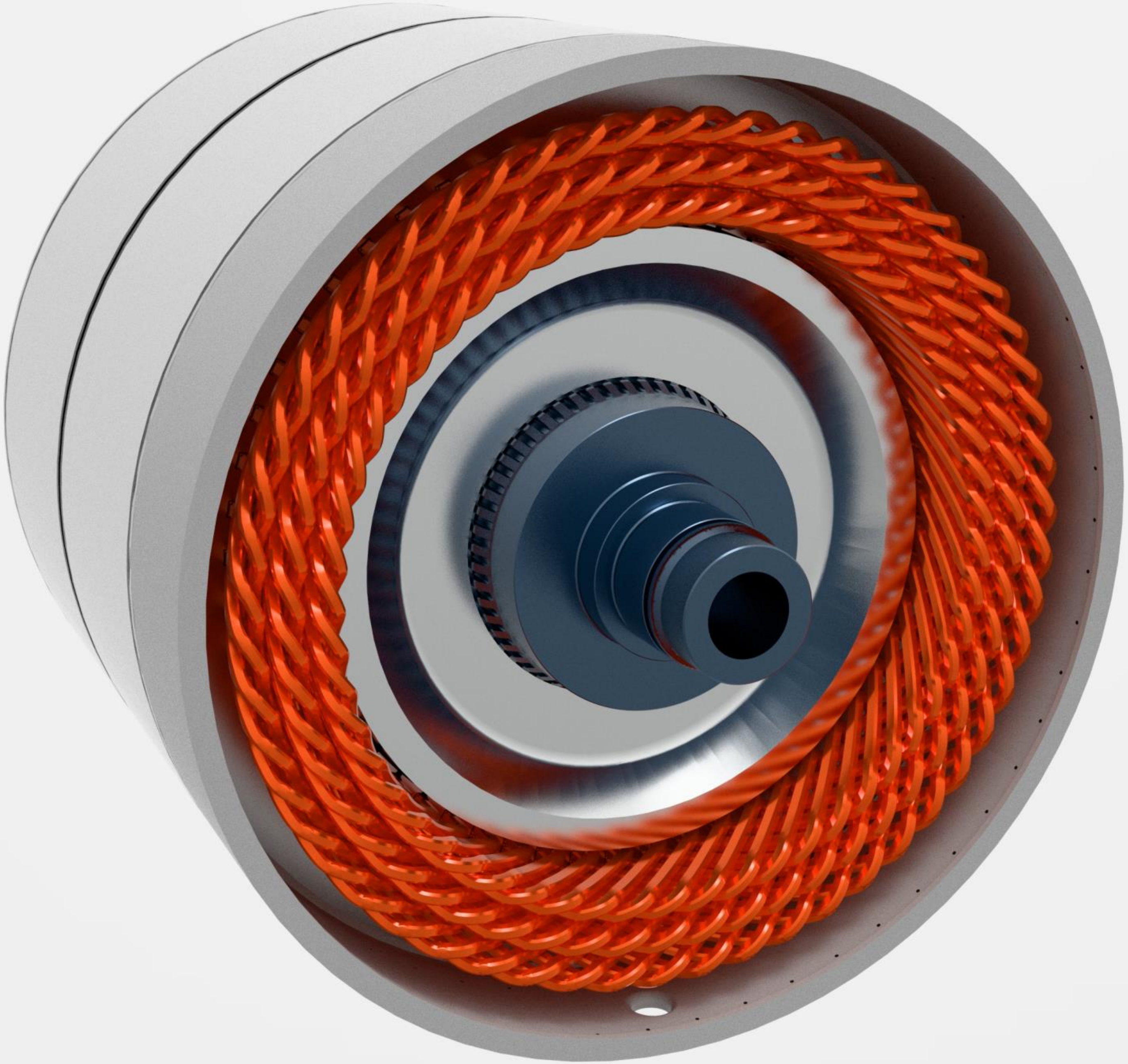
Determine the boundary temperature induced by Ohmic heating, to be applied on the stator end winding walls in the SPH simulation

PHYSICS MODEL

- Electrodynamic Potential
- Electromagnetism
- Ohmic Heating
- Segregated Solid Energy
- Copper (Electrical Conductivity = f(Temperature))

BOUNDARY CONDITIONS

- Ohmic Heating simulation of stator windings with constant current
- Thermal Specification Wire Walls: Heat Flux (from SPH simulation, figure right)



PANDORA-E EDU
SPH Model:

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Velocity magnitude (@ 0.97 sec)

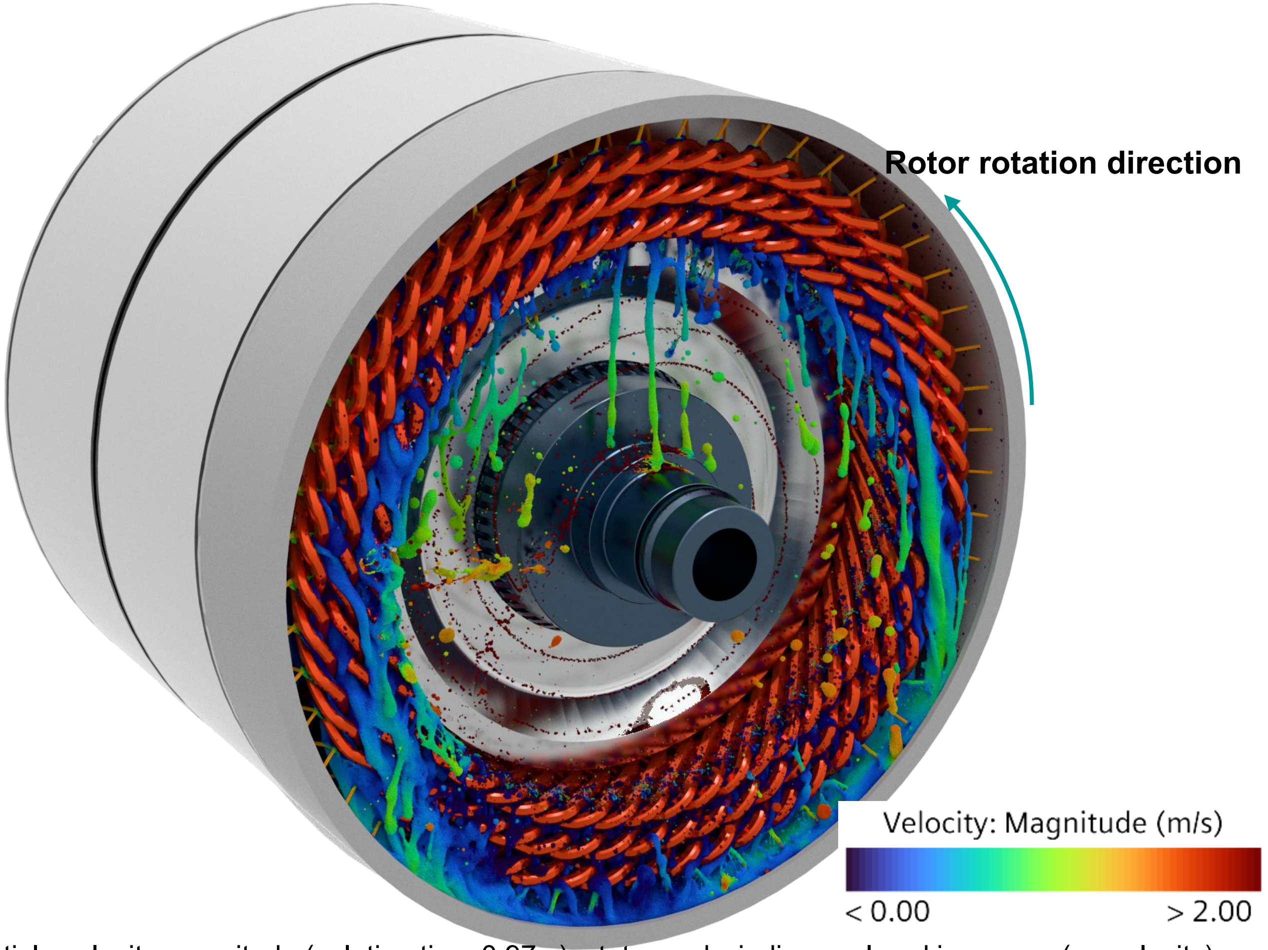

Fig: Particle velocity magnitude (solution time 0.97 s), stator end windings colored in copper (no velocity)

SPH SETTINGS

- Particle Base size: 0.25 mm
- Segregated Multiphase Temperature
- Implicit Solver
- Boundary Formulation: Boundary Integral Method
- Drag Force Method: Liu (TAB Distortion + TAB Breakup)

BOUNDARY CONDITIONS

- Vol. Flow Stator nozzles: 7 l/min (2x 54 nozzles)
- Vol. Flow Rotor nozzles: 5 l/min (4 nozzles)
- Particle Temperature: 60 °C
- Stator End Winding wall temperature: Mapped from EMAG simulation
- Rotor: 8000 rpm
- Outlet: Open End → Position based particle remediation

PANDORA-E EDU
SPH Results: Temperature (@ 0.97 sec)

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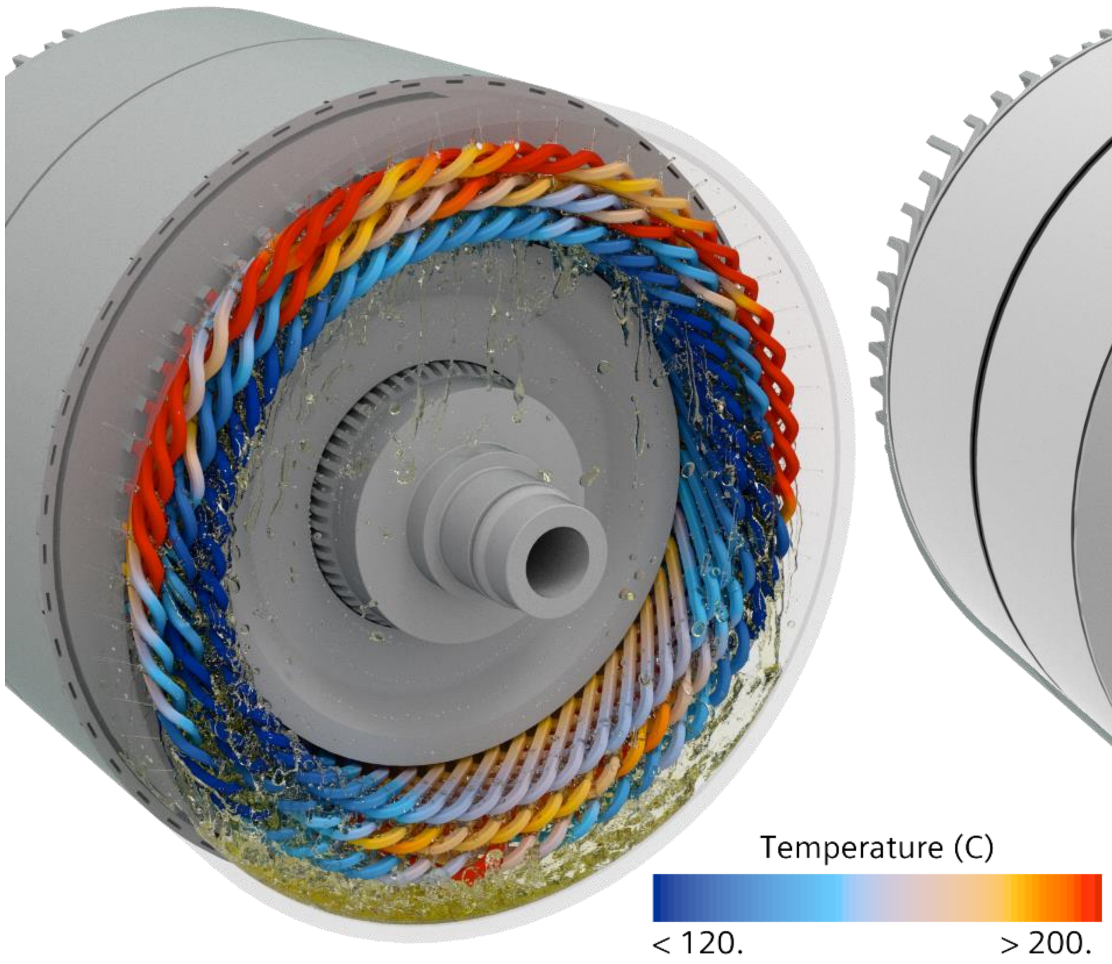
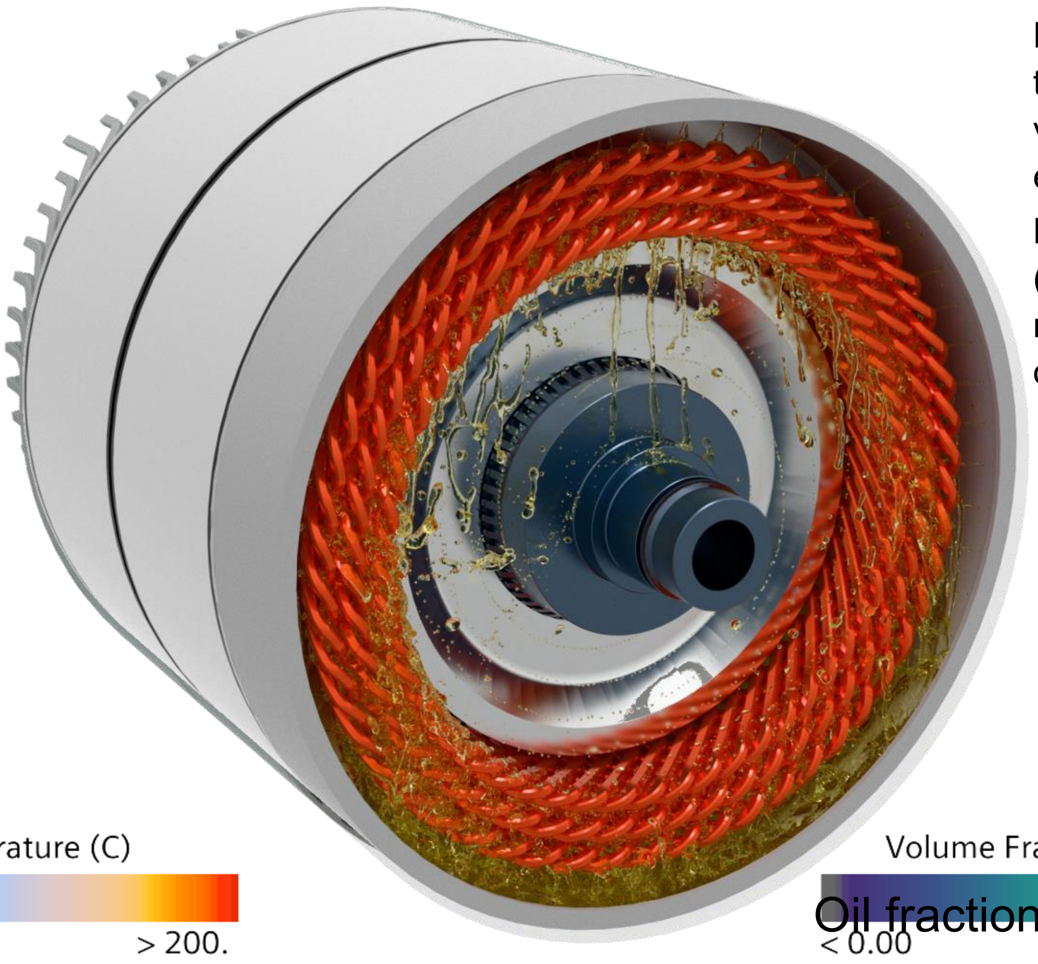


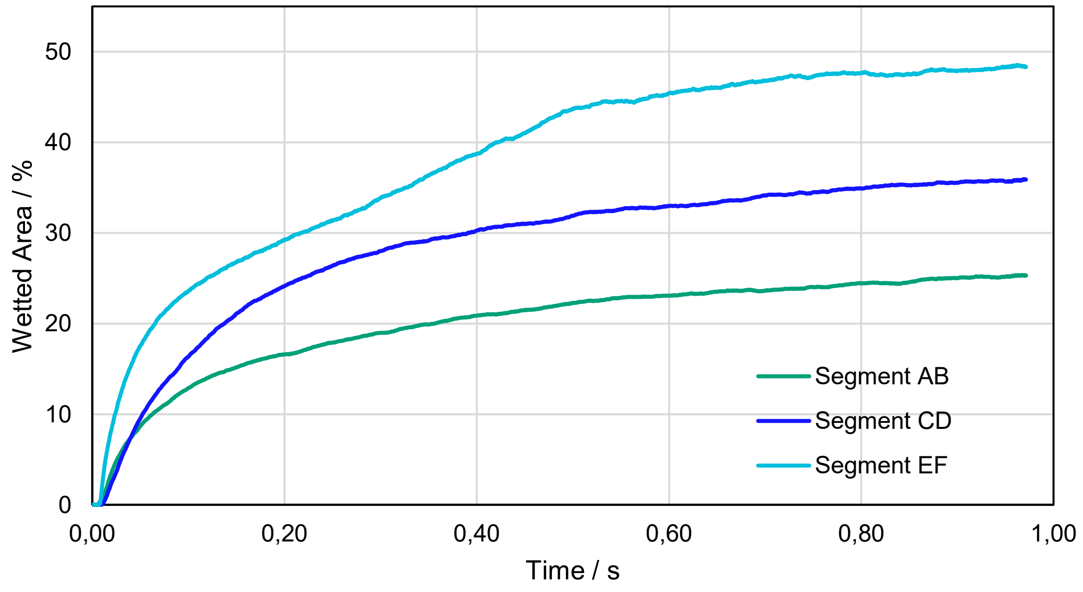


High correlation between high temperatures and wetted area / volume fraction of oil on stator end windings

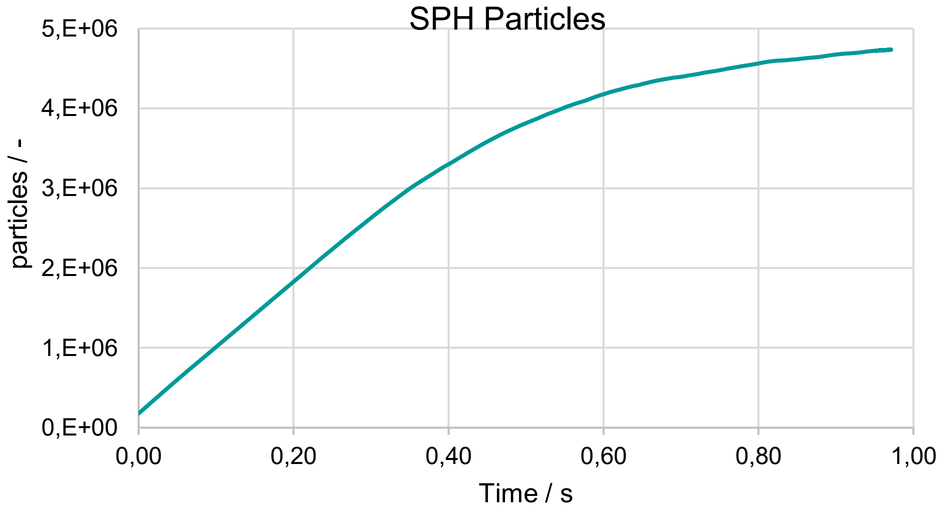
Particularly outer windings (segment AB) in the upper half need improvement of oil distribution

Fig: left: Temperature distribution on stator end windings, right: Volume Fraction of oil with isosurface of oil (solution at 0.97 sec)

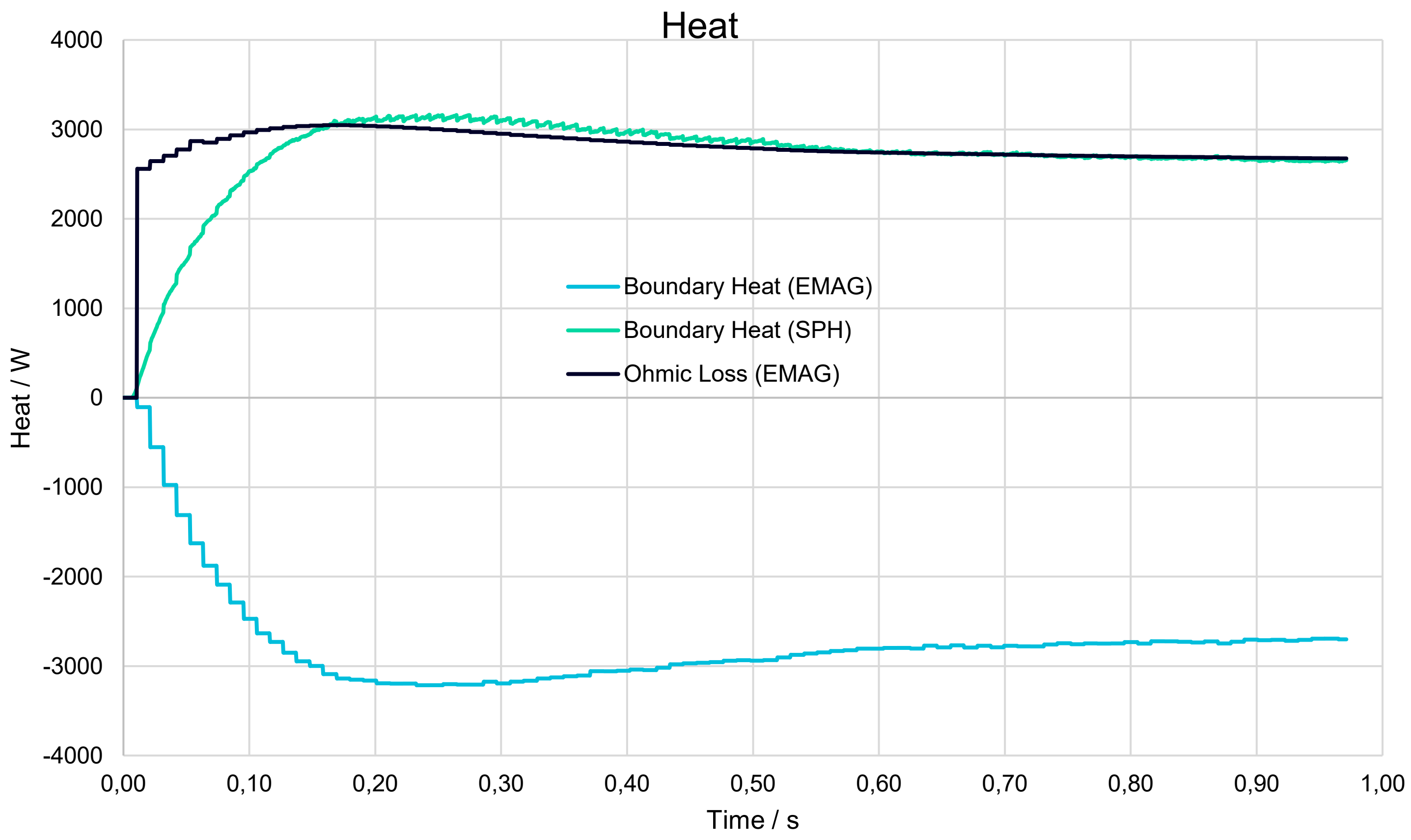
PANDORA-E EDU
SPH/EMAG Results: Wetted Area (@ 0.97 sec)



- Further temperature decrease expected with increase of simulation time. Actual particle counts show a continuing increase of particles with time, which means that still more particles are added to the simulation domain than removed.
- Outer windings (segment AB) could need further nozzle angle optimization. Difference in wetted area reasonable due to optimization cost function which weights the wetted area of the middle windings (segment CD) with 2/3.



PANDORA-E EDU
SPH/EMAG Results: Heat (@ 0.97 sec)



- Ohmic losses (EMAG) stabilize at ~3000 W after the initial transient (t < 0.2 s) and decrease slightly toward ~2600 W. Heat is added to the system by Ohmic heating (positive)
- Expected behavior due to the temperature-dependent electrical conductivity (σ = f(T)): temperature rises, conductivity drops and losses increase. Due to cooling, conductivity recovers.
- Boundary Heat (EMAG) is negative → heat is removed from the winding wall via the oil cooling boundary condition; its magnitude converges toward the Ohmic loss over time, indicating the coupled system is approaching thermal balance between heat generation and oil cooling
- The stepwise pattern at the beginning of Boundary Heat (SPH) reflects SPH particles progressively wetting the winding surface, gradually increasing the extracted heat flux

PANDORA-E EDU
SPH Analysis: Aerodynamic Drag Forces (@ 0.97 sec)

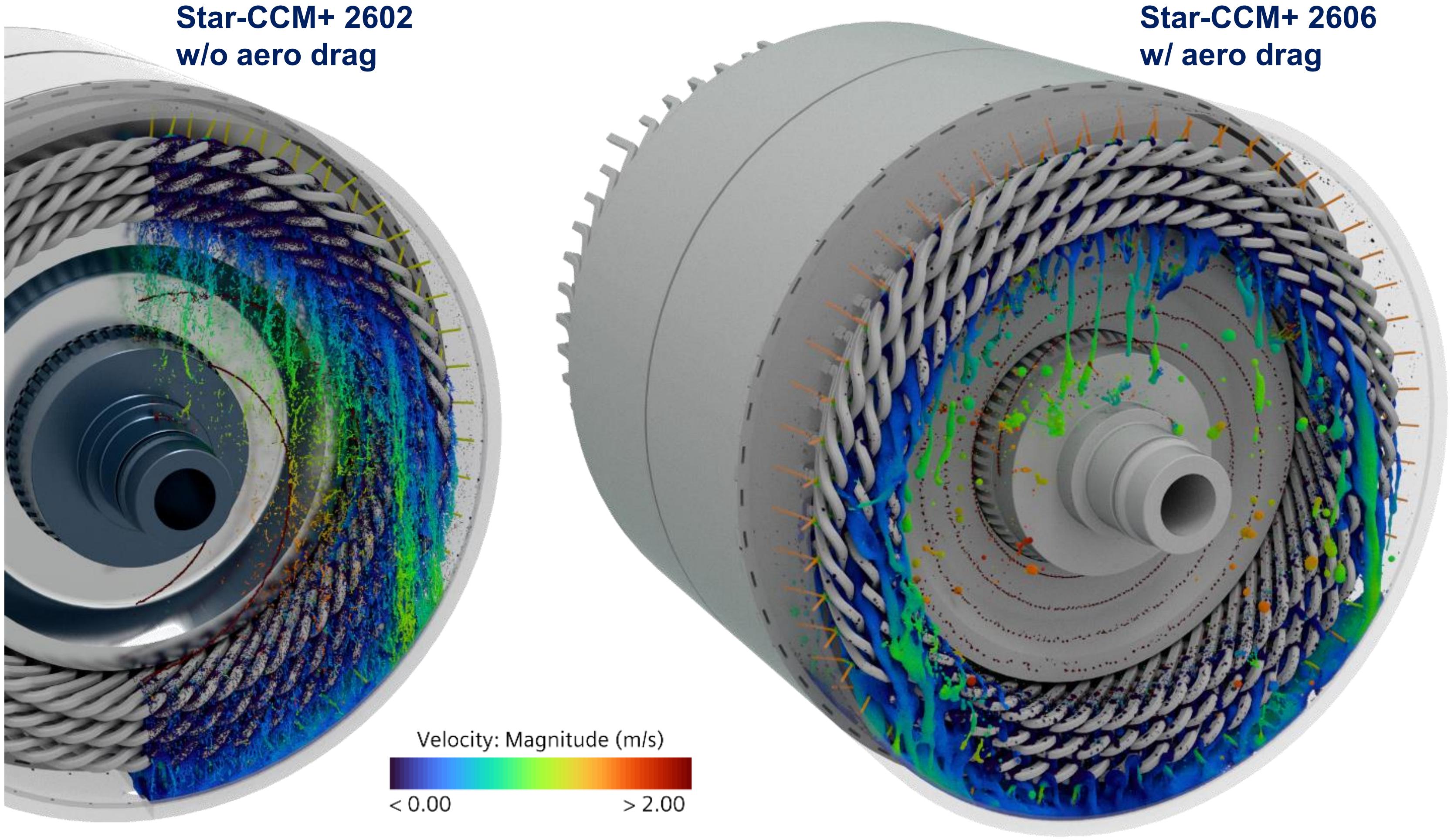
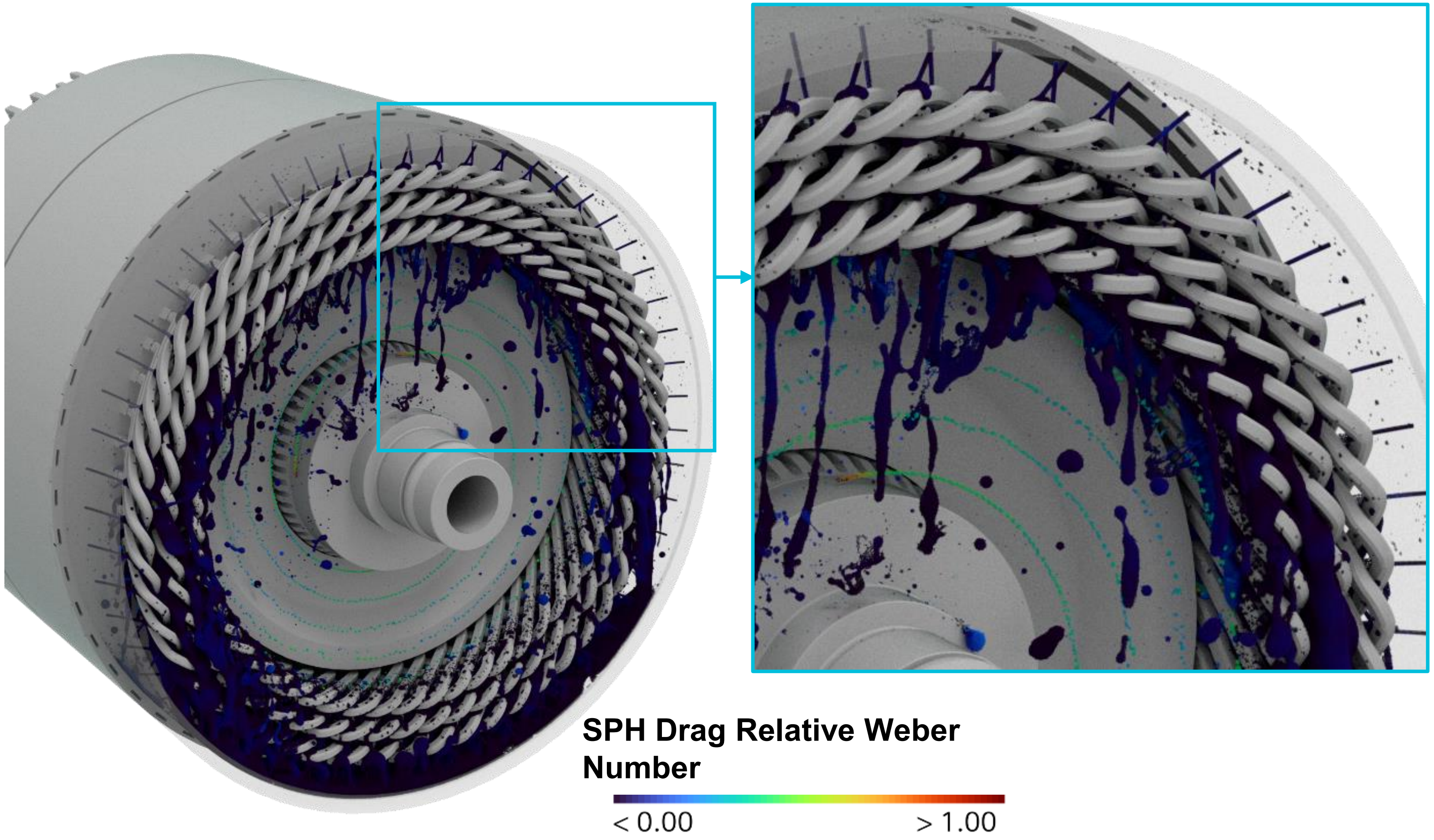


Fig: Velocity Magnitude of SPH particle. left: v2602 without Drag Forces, right: with drag forces and surface tension in v2606

- Strong influence on oil continuum / SPH particles visible with activation of aerodynamic drag forces (comparison left vs. right)
- Surface tension (0.03 N/m) leads to formation of larger oil droplets and filaments
- Asymmetric particle distribution with aerodynamic drag active indicates a measurable influence of rotor air flow on oil particle trajectories, confirming that rotor air velocity needs to be considered in the simulation

PANDORA-E EDU
SPH Analysis: Aerodynamic Drag Forces / Weber Number



- The low Weber number in stator winding region (We < 1) confirms that surface tension dominates, preventing droplet breakup and instead promoting the formation of the elongated oil filaments observed in the simulation.

Fig: Velocity Magnitude of SPH particle. left: v2602 without Drag Forces, right: with drag forces and surface tension in v2606

PANDORA-E EDU
SPH Analysis: Aerodynamic Drag Forces SPH vs VOF

- The simulation of the top quarter segment with VOF shows comparable oil droplet/filament formation to the SPH simulation.

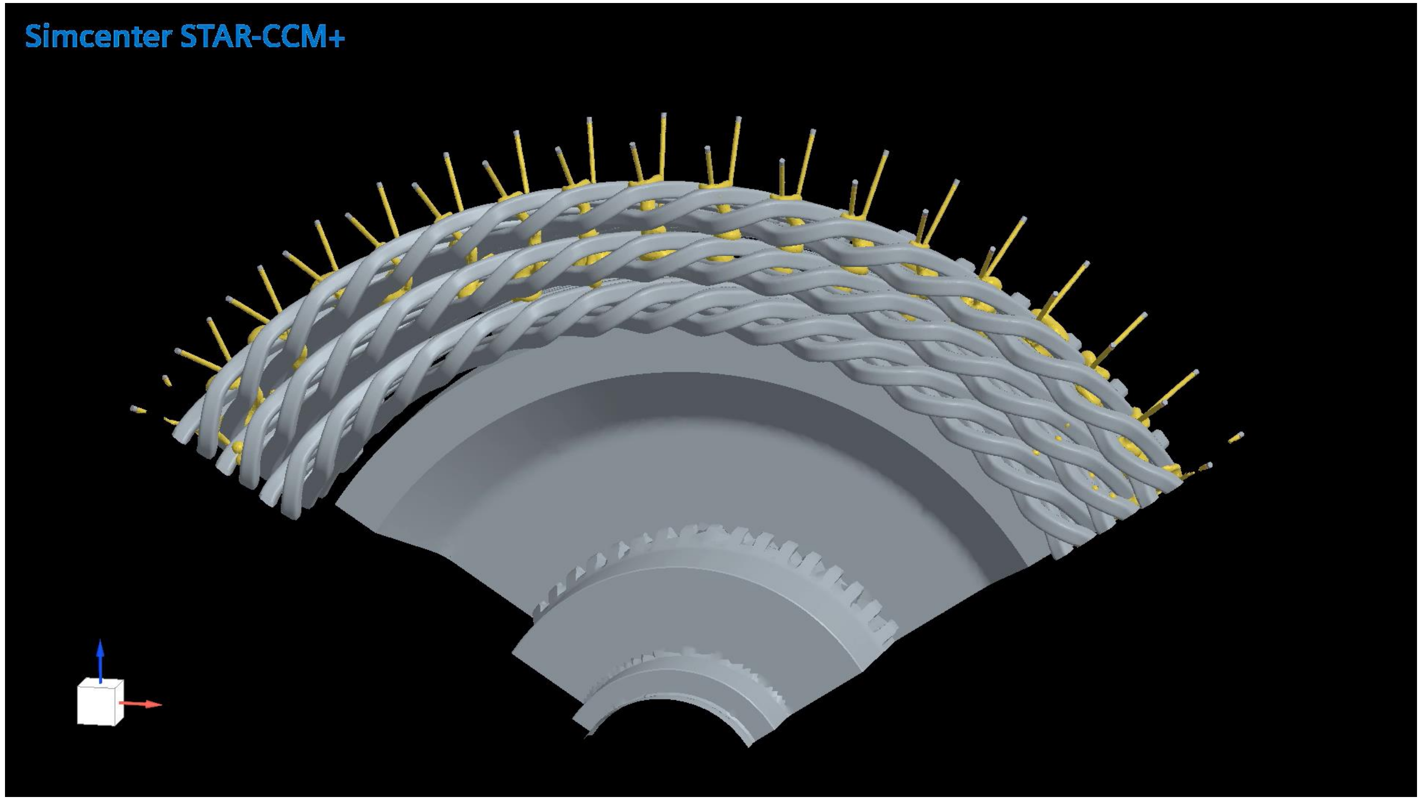


Fig: Comparison of oil filament development with VOF simulation of top quarter segment vs. SPH simulation (right)

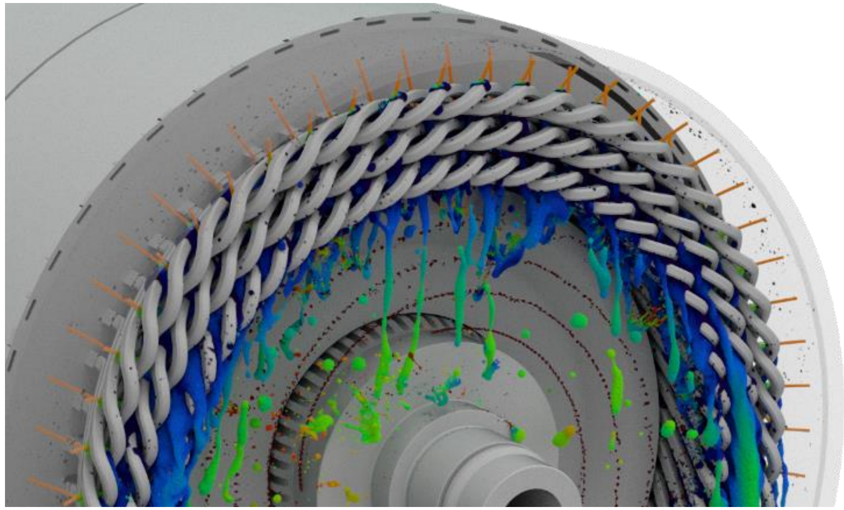


Fig: Velocity Magnitude of SPH particle with aerodynmic drag (@ 0.97 sec)

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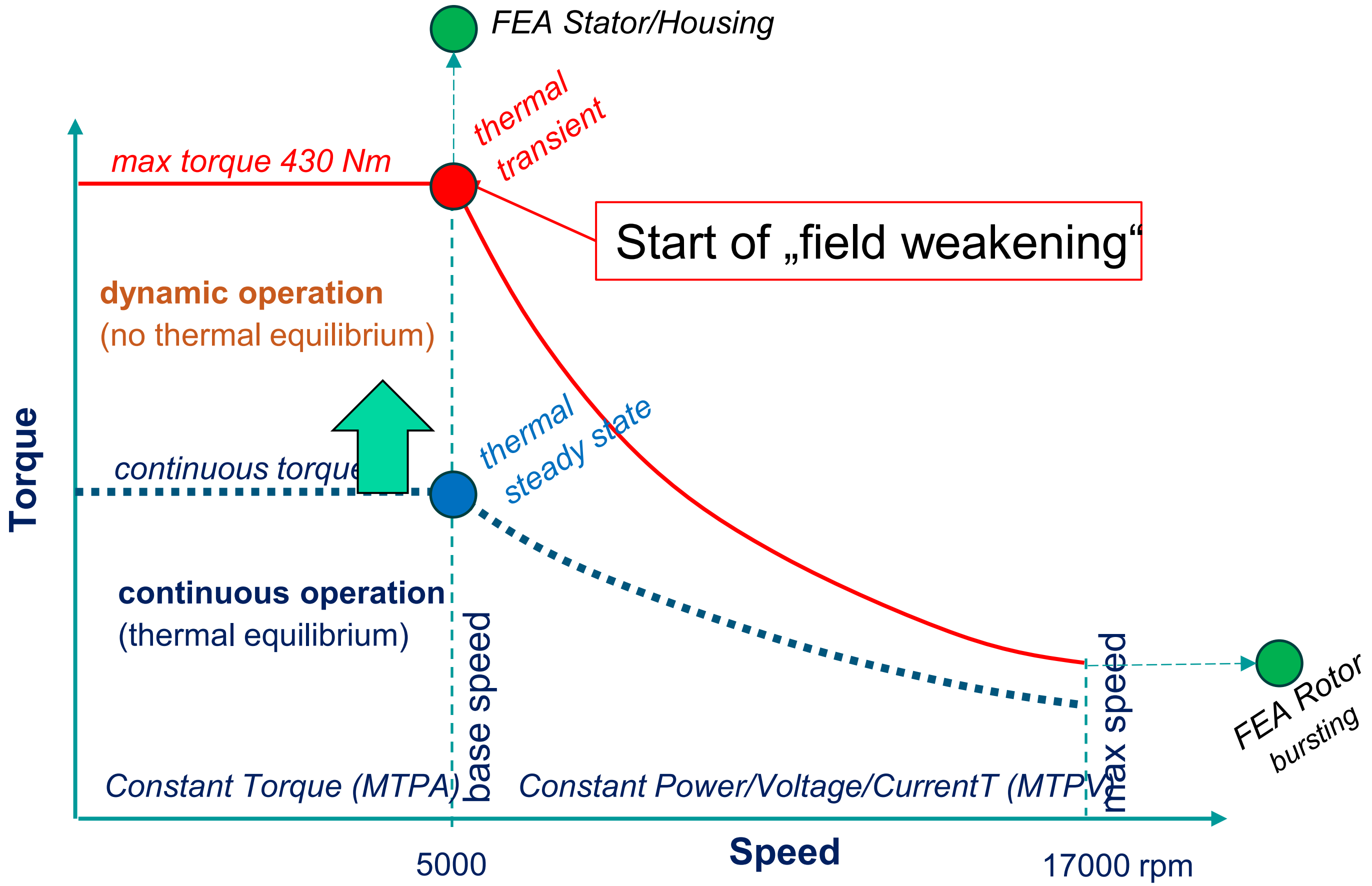
SIEMENS

optimization of an electric motor with combined oil cooling
E-Motor Virtual Development

Targets and Design Verification

Typical torque curves of an e-motor



1. EMAG Simulation
to proof that red characteristic is reached

2. Inverter/Controller Simulation
to control motor operation

3. Structural Simulation
to proof that design is safe

4. Thermal & Flow Simulation
to get the most out of the motor i.e. to push the blue line up

5. Vibro-Acoustics Simulation
to verify vibration and acoustics targets