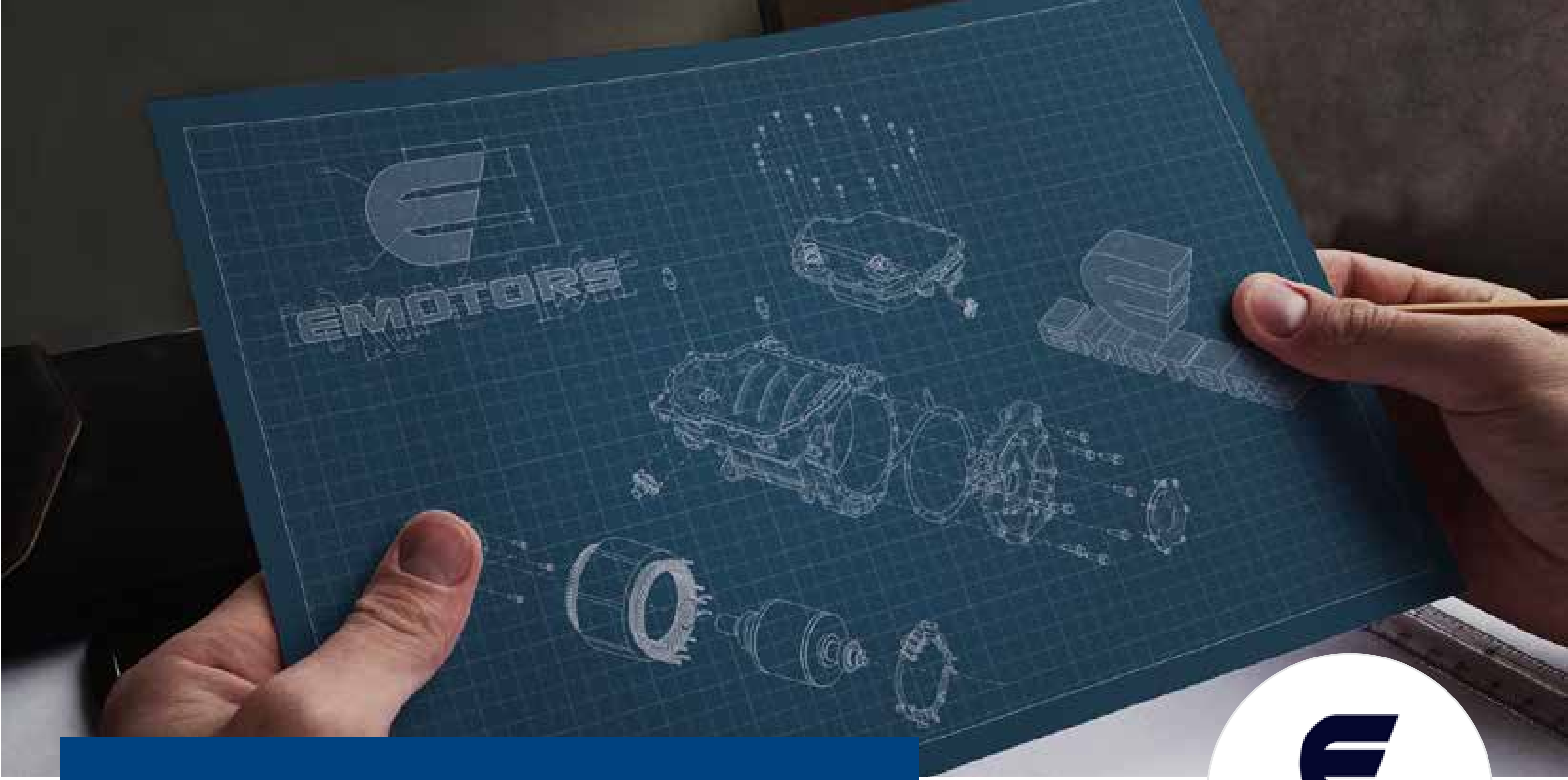

Optimizing the spray cooling of e-drives with moving particle simulation

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Moving particle simulation (MPS)

The advances in simulation methods and computing power have resulted in new simulation methods becoming available over the last three to five years. One of the most interesting for powertrain applications is MPS, a meshless CFD approach.

The MPS method is a deterministic Lagrangian particle method for calculating incompressible free-surface flows and non-Newtonian liquids. MPS was proposed by Koshizuka and Oka in 1996 [1]. While its core concept is similar to smooth particle hydrodynamics (SPH), MPS has evolved from a semi-implicit predictor-corrected formulation to fully explicit formulations that are more efficient for large-scale models, reducing simulating time and computing effort.

The use of MPS has grown in popularity within the automotive sector and it is now a well-established approach to free-surface flow and liquid flow analyses. Applications include oil splash and sloshing in gearboxes and transmissions, forced lubrication by oil jet, piston cooling, crankcase sloshing, and jet or spray cooling of wet electric motors.

The simulation process of e-motor cooling

The simulation of oil-cooled e-motors is difficult mainly due to the geometrical complexity of the system (culminating in the winding region), the multiphase nature of the flow dynamics, and the rotational speeds up to 20,000 rpm.

Traditional, Eulerian mesh-based fluid dynamics solvers are unable to produce models with affordable setup times and computing requirements. These are critical functions to efficiently integrate CFD codes into the industrial R&D workflow.

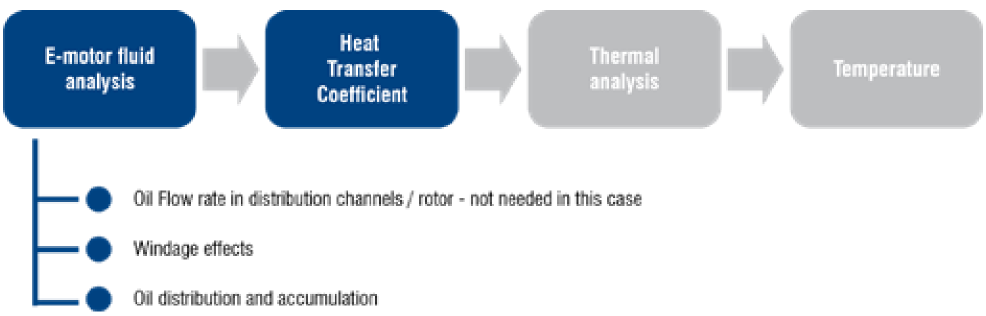

Fig. 1 - Schematic of the simulation methodology for e-motor cooling. The CFD related topics analysed with the MPS method are shown in blue.

Engineers from EMOTORS and EnginSoft have developed virtual e-motor prototypes based on different simulation requirements, rarely considering the subsystems of the unit for further analysis.

However, the main objective of e-motor cooling simulations is to evaluate and improve oil distribution for different cooling branches and to maximize heat transfer between the oil and the e-motor components. The process can be summarized into the following steps (Fig. 1):

1. Evaluation of the oil flow distribution in the rotor shaft channels and at the nozzle outlets;
2. Calculation of the windage effects (aerodynamic drag);
3. Visualization of the oil jets and flow in the e-motor, from nozzle outlet to motor outlet;
4. Mapping the heat transfer coefficient and heat fluxes over the critical geometrical element;
5. Transferring the cooling effects to a thermal model for temperature prediction.

More specifically, given the above-mentioned steps, the entire simulation process (from CAD preparation to the configuration of the different simulations and including the hardware simulation times) takes about two weeks.

As for the numerical parameters and the particle size (a concept comparable to the minimum mesh size of traditional Eulerian methods), these may vary from one sub-simulation to another. In general, MPS simulation times are mainly influenced by:

- Volume of fluid/air to initialize
- Total number of resulting particles (calculation nodes)
- Initial delta time (DT) of the simulation and the Courant-Friedrichs-Lewy condition (usually the Courant Number for MPS is 0.2)
- The type of pressure solver (if implicit or explicit)
- The activation of an additional physics model (turbulence, thermal equation, conjugate heat transfer, etc.)

As shown in Fig. 1, the first step in the simulation process is to analyse the flow distribution inside the e-motor circuit. Fig. 2 summarizes the flow pattern with flow distributed in the rotor, winding and stator regions. It is important to study the distribution of the flow across all sub-circuits and to verify it with respect to different conditions of speed and viscosity to avoid unbalanced configurations. In this step, the pressure distribution of the fluid within the channels can be measured and verified against the design requirements or manufacturing specifications.

Considering that the rotor speed can be up to 20,000 rpm, windage and air drag effects have to be taken into account. For this purpose, an additional simulation is usually included in the presented methodology. In this step, only the air is simulated, with a discretization size capable of providing results within a few hours of simulation. As a result, the same MPS model can be used to extract the internal air flow without creating any additional numerical model and without mesh/geometry cleaning.

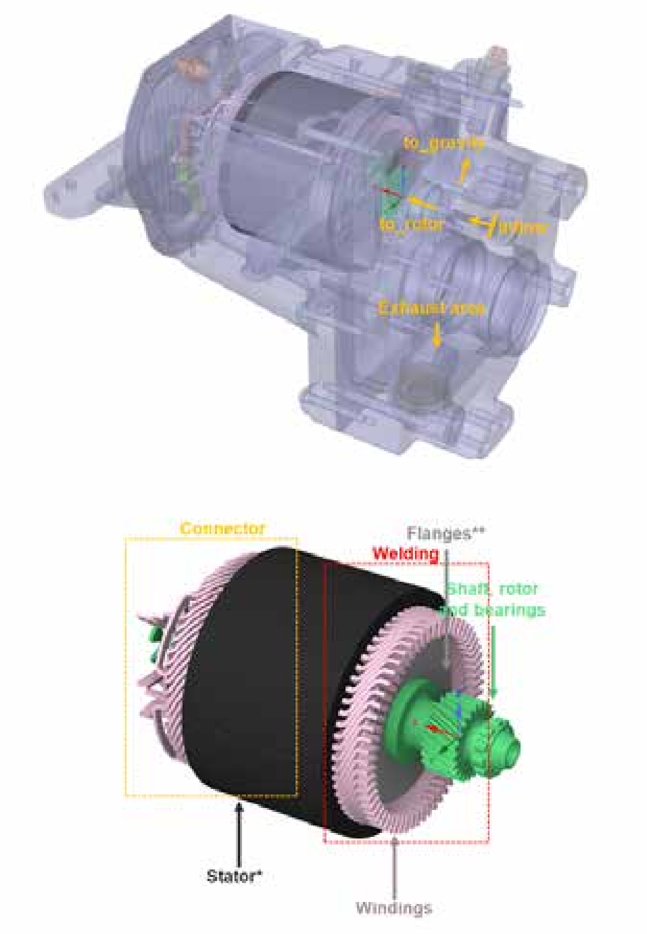

Fig. 2 - Isometric view of the e-motor presented. On the left, the names of the cooling sub-channels. On the right, the names of the most important parts of the e-motor.

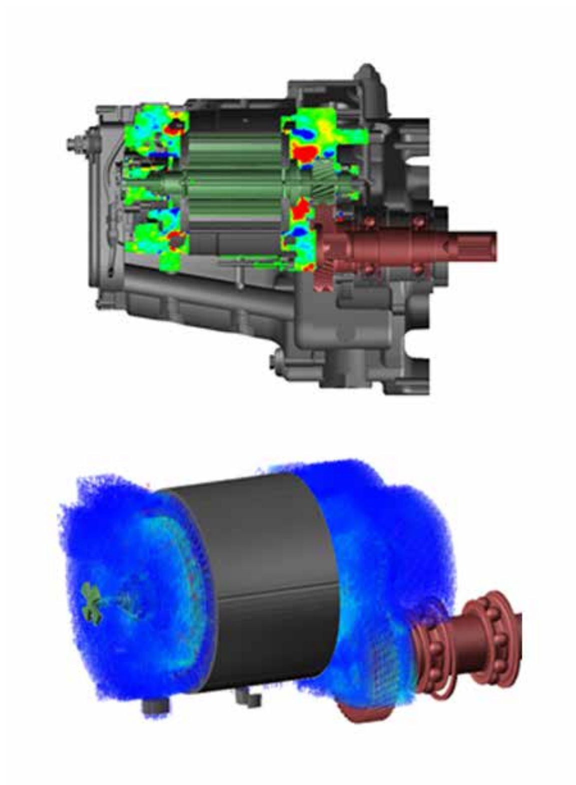

Fig. 3 - Overview of the airfield as calculated by the MPS method (top) and the same airflow as imported into the oil-only simulation (bottom).

Next, the main simulation is performed, focusing on the extraction of the heat transfer coefficient (HTC) maps which are then used to calculate the temperatures inside the e-motor components. The precalculated airfield is transferred to the oil-only simulation, with a one-way coupling (air influencing oil with a specific drag coefficient). The numerical parameters (particle size, simulation time step, thermal modelling) are adjusted to better capture the jet spray effect and for a more correct thermal assessment.

The convergence of the CFD model is checked by monitoring the oil distribution with control volumes in different areas (end-windings, stator, brackets). Subsequently, HTC maps, usually averaged over the last 0.5-1 s of steady-state operation (see Fig. 4) are extracted. In this way, maps as shown in Fig. 4 are obtained for each wetted element inside the e-motor. These maps are also exported as .csv files by the software, ready to be transferred to the finite element analysis (FEA) model for predicting the temperature distribution. For the temperature distribution prediction, the MPS methodology introduced was previously validated by experimental tests [2].

Cooling circuit and validation of the methodology

In the design stage of the prototype, EMOTORS conducted several simulations focusing on different aspects of the e-motor design. The cooling circuit diagram of the analysed prototype is shown in Fig. 5.

method, proved to be troublesome at first. The challenge of modelling this internal flow is mainly related to the multiphase nature of the flow and the high rotational speed. The MPS method has proven to be more reliable for this purpose. In order to validate this first step of the MPS model we used a dedicated prototype designed to test multiple flow configurations and parameters. Different circuit configurations of the prototype were obtained using nozzles and plugs to limit the internal diameter or even to close off certain portions of the circuit.
We also had control over other parameters: oil temperature, inlet flow rate and rotation speed. In addition, we measured the pressures at the inlet and at some intermediate points of the circuit and the flow rate for an outlet branch of the circuit. In addition, we opted for a Design of Experiment (DOE) approach to testing in order to prepare the results for statistical post-processing. The purpose of statistical post-processing of the results is to help us assess the physics and reliability of the measurements and to remove noise from the readings.

We also decided to verify the statistical model we developed with an out-of-sample control configuration that was not used in the post-processing. As can be seen in Fig. 5, the statistical model correctly predicts the flow rate distribution of the out-of-sample dataset.
Fig. 6 compares the results between the experimental data and the MPS calculations, for a single flow operating condition (8 l/min).

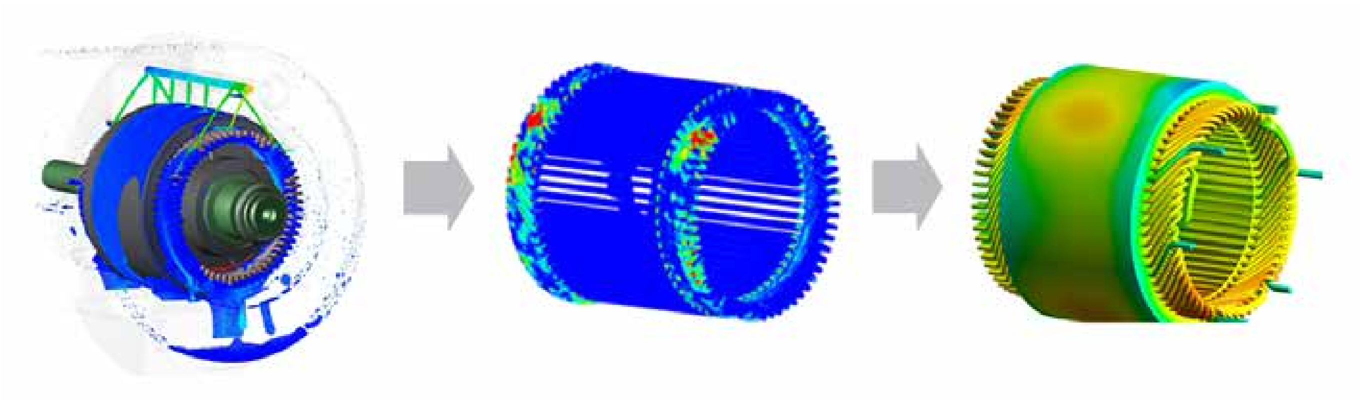

Fig. 4 - From oil distribution to temperature distribution. On the left, the oil can be inspected and, once stabilized, an HTC map is extracted. The maps are transferred to the FEA model to obtain the temperature prediction.

The housing contains two oil cooling circuits: one static (gravity cooling) and one rotating inside the shaft and rotor (rotor cooling).

As shown in Fig. 4, the oil enters the housing from a lateral main circuit which then splits and part of the oil passes into the middle channels of the shaft (rotor cooling) while the remaining oil is directed to an additional upper layer above the windings and stator (gravity cooling). The rotor cooling circuit is designed to cool the inner surfaces of the windings, while gravity cooling sprays the outer surface of the end windings and the outer surface of the stator plate. Volume flow rates are measured by probes placed near the inlet and at the inlet of the rotor cooling and gravity cooling passages.

The simulation of this first step and approaching the problem using the RANS VOF (Reynolds-Averaged Navier-Stokes Volume of Fluid)

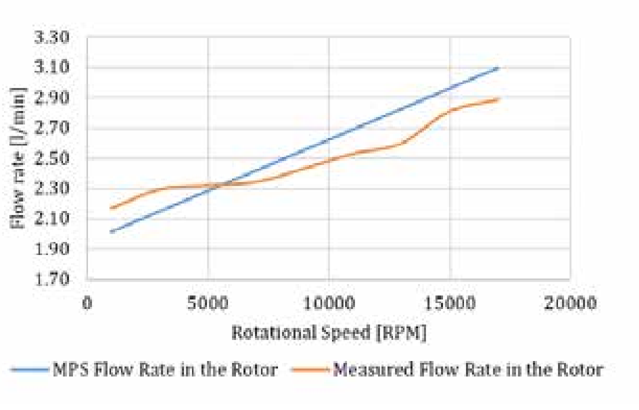

Fig. 5 - Flow rate through the rotor cooling circuit of the out-of-sample dataset (orange) and the predicted trend of the statistical model constructed using the DOE (blue).

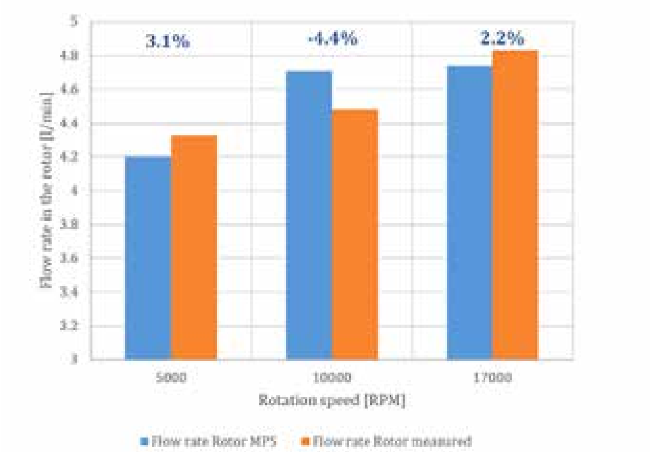

Fig. 6 - Flow rate to the rotor cooling system (rotor circuit) for three rotor speeds. The MPS predictions (blue) are compared to the experimental results (orange).

Fig. 7 - Cross sections of the flanges considered in the single jet HTC analysis.

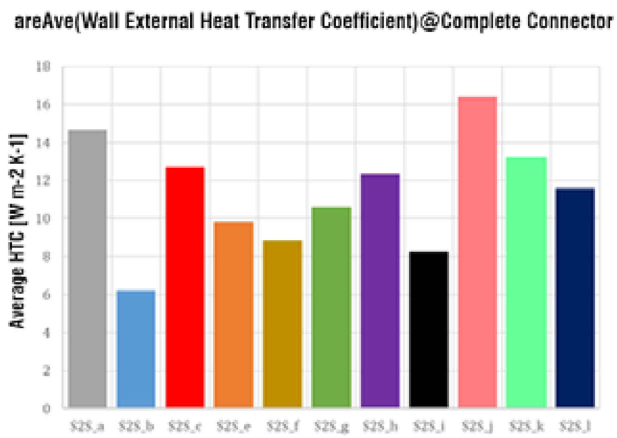

Fig. 8 - Area weighted average HTC across the windings for different flanges (contribution of a single oil jet).

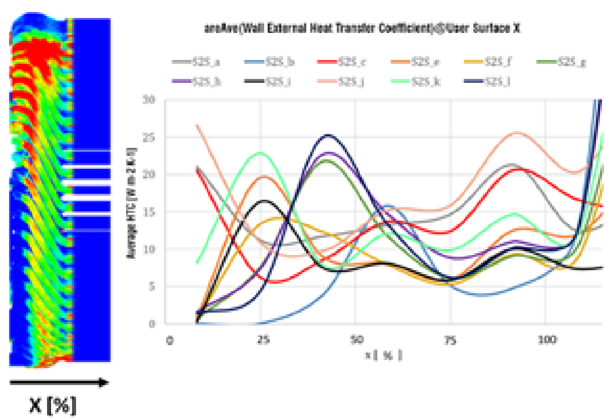

Fig. 9 - AreaAveHTC for different x-slices of the windings. This analysis allows the HTC values to be mapped spatially in a quantitative way.

The flow through the rotor cooling system is reported for three different rotor speeds. We obtained an error of $\pm$5% between the simulation results and the post-processed experimental data.

Design improvements: flanges and brackets

After validating the MPS methodology for internal flow analysis, an important element to analyze in the early design phase are the flanges at each side of the rotor laminations. The size of the oil passage in the flange can change the balance of the oil flow between the rotor and the stator. The shape of the passage was found to have a critical influence on the trajectory of the oil particles and on the size of oil jet before it hits the windings.

To reduce calculation time, only the rear of the windings (the side corresponding to the phase connector element) is simulated. Also, only part of the channel (one of the four jets) is modelled to further reduce the quantity of oil simulated.

Several geometrical modifications to the rotor flanges were considered to improve the cooling efficiency of the e-motor. These geometrical details are shown in Fig. 7.

In order to compare the configurations, we computed the area weighted average of the HTC values (AreaAveHTC) across the exposed windings. The following formula averages the n-th HTC value calculated on the n-th triangular surface of the .stl file, weighted for its surface area:

$$AreaAveHTC = \frac{\sum HTC_n \cdot A_n}{\sum A_n} \quad (Equation\ 1)$$

The results for the designs discussed are shown in the chart below (Fig. 8). As can be seen, careful design and direction of the flow in specific areas of the windings can result in a two- to three-fold improvement in the cooling efficiency, compared to the poorest configuration.

In order to evaluate the flow distribution on the windings in more detail, the average HTC was evaluated for different slices (in the axial direction). The results are shown in Fig. 9. The AreaAveHTC for each slice x is reported against the x % (0 % end of the windings, 100% inner side of windings, rotor side).

It can be observed that:

- Flanges 01_a, c, and j have the best HTC near the 0 and 100% mark of the length of the end winding;
- Flanges 01_g, h, and l have the higher HTC near the 50% mark of the length of the end winding;
- Flange 01_e has a better HTC near the 25% mark of the length of the end winding;
- A small nozzle (01_k) has the effect of focusing the oil near the 25% mark of the length of the end winding (closer to the stator lamination) compared to 01_g and 01_l.

The stator brackets also help to improve heat transfer inside the e-motor. They are situated between the inner surface of the housing and the outer surface of the windings. Without the stator bracket, the oil jet from the rotor will mainly spray the inner surface of the housing. The stator bracket's purpose is to redirect the oil from the rotor injection towards the windings. We decided to test the possibility of improving the performance of the baseline bracket design. The geometrical features of the two variations (labelled as Small and Axial) are shown in Fig. 10 below.

One way to monitor the efficiency of a specific design is to measure the amount of oil in the region of the windings by means of a control volume. Fig. 11 shows the oil accumulation trend for the first two seconds. A clear difference can be seen between the proposed designs and the baseline. To examine the efficiency of the system more closely, we focused on the AreaAveHTC on the windings, comparing the two bracket designs with the baseline. The AreaAveHTC result trends follow the oil accumulation, with the baseline design showing better cooling performance.

These simulations enabled us to test and exclude two proposed bracket designs that proved to be less efficient at keeping more oil in the area of the windings.

Conclusions

This paper described the simulation of e-motor cooling using MPS, a mesh-less approach well-suited to impinging jet and free-surface flow analyses. We reported the methodology of the MPS e-motor simulation, the internal flow rate split, the windage effects, the HTC distribution, and the temperature distribution.

At the internal flow distribution step, we validated the MPS methodology using a dedicated prototype and a statistical technique. This validation also demonstrated the range of reliability and confidence of the simulation results, significantly reducing the number of prototypes necessary to move from the initial design to the final product.

Moreover, we showed how MPS simulation can provide insightful design indications for key components of the e-motor, like the rotor flanges and the stator brackets. The EMOTOR engineers were thus able to propose further improvements to the cooling of their e-motors, achieving competitive power densities for the motor while reducing the use of materials and increasing the reliability of key components.

References

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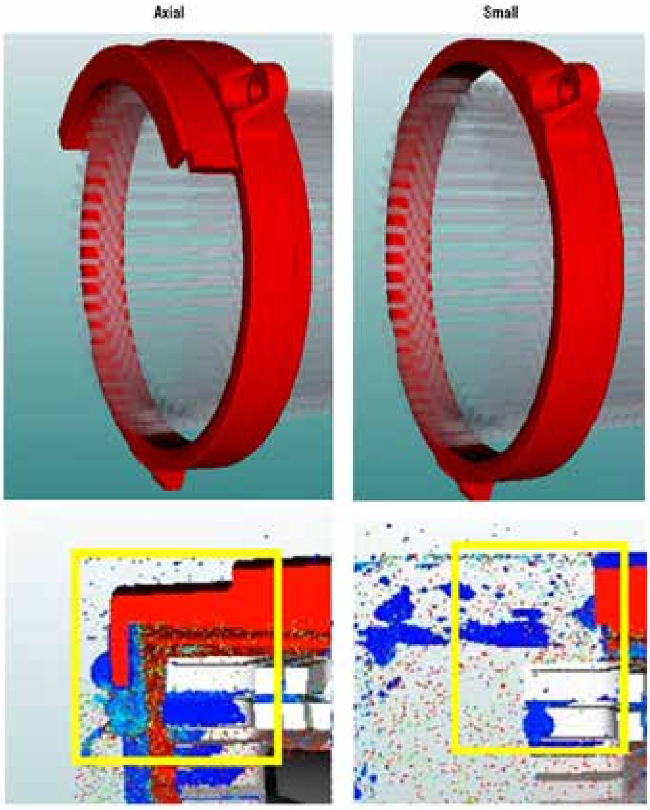

Fig. 10 - Overview of the bracket design (top, isometric view) and detail of the modification near the windings (bottom). As can be seen, the Axial bracket design collects the oil (blue) so it does not splash onto the external housing as seen on the bottom right.

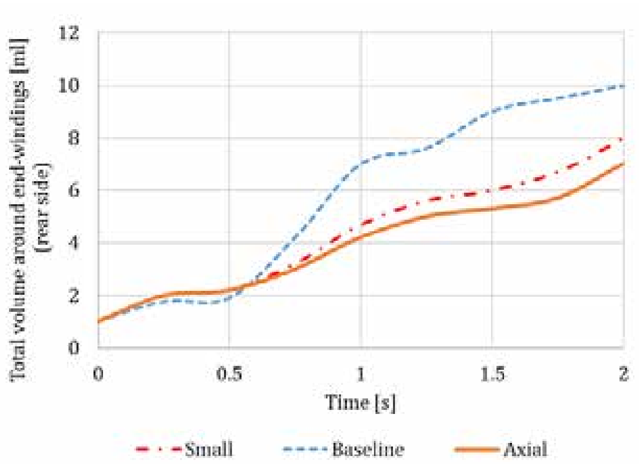

Fig. 11 - Total amount of oil in millilitres around the windings (at the rear of the e-motor). Two proposed bracket designs (Small, Axial) are considered as possible improvements of the baseline.

	Area Weighted Average HTC
Small	68
Baseline	84
Axial	63

Fig. 12 - AreaAveHTC for the two proposed brackets (Small, Axial) compared to the baseline design.