Comparing cooling methods for e-motors

A simulation methodology developed by TotalEnergies

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Electrification of light and heavy-duty vehicles can help reduce global emissions by about 1 Gt CO_2-eq. The current automotive market shows a strong acceleration towards electric propulsion (plug-in hybrid and battery), with one million sales in both Europe and China and the global share of electric vehicles exceeding 10% of total sales. The rapid and technically demanding transition poses significant challenges: innovative propulsion systems must be designed quickly, considering complex fluid, electromagnetic and thermal aspects that cannot be easily decoupled or thoroughly analysed with physical prototypes.

As power density increases, standard e-motor cooling methods (based on external air or water-jackets) fail to provide the necessary heat removal performance. Because of all these issues, a direct oil cooling strategy is proposed to directly remove heat from the most critical areas of e-motors, such as the coils and rotor.
In addition, for compact and weight-efficient drive solutions, e-motors are increasingly coupled with transmissions in e-drives, forming a single gearbox, and the same oil used for lubrication is also used in the cooling of the e-motor circuit via pumping systems. Therefore, having a single simulation that can provide information on both e-motor cooling and gear lubrication can be very advantageous.

In this paper, we will present the methodology developed by TotalEnergies and EnginSoft to select, design and improve an e-motor by simulating and predicting electromagnetic losses, fluid flow behaviour and temperature distributions. After establishing the workflow, the main objective of the study is to compare the direct oil-jet strategy with the external water jacket cooling circuit.

This analysis will compare the two approaches by considering various combinations of flow rate and motor speed. In addition, we report on the influence of the oil's physical properties on cooling performance, showing how the established workflow can guide TotalEnergies in the selection and improvement of oil for better e-motor cooling and longer working life.

Mission TotalEnergies: from lubrication to cooling

The thermal properties of electric vehicle fluids are of paramount importance. For decades, the lubricant industry has sought to optimize friction and fuel economy, but today it focuses on improving the thermal properties of the fluids it offers, with thermal management replacing fuel economy as the new leitmotif. Although there are different and sometimes more compact cooling architectures, particularly for the electronic peripherals of the electronic engine, each of these assemblies is subject to different constraints that directly influence the type of fluid required for them. For example, some fluids must provide flawless lubrication, while others do not, but efficient cooling is always crucial and determines the formulation of the different fluids used.

The architecture of next-generation electric vehicles will require the development of a single type of fluid for their electric drive units (EDUs), combining high-performance lubrication of the transmission and efficient motor cooling.

First-generation electric motors were entirely air-cooled, but the low specific heat capacity of air in relation to its volume required a different approach. Thus, water cooling systems began to appear, but these were soon replaced by the use of dielectric cooling fluids, a much-needed step that was also confirmed by the simulation results reported.

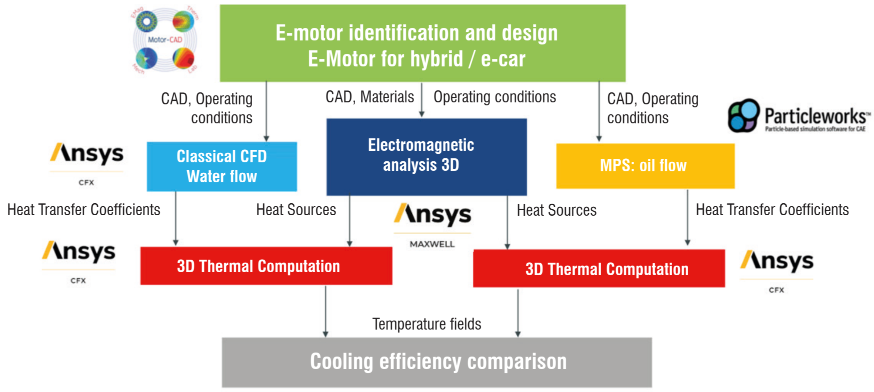


Fig. 1. Overview of the simulation workflow: e-motor identification (Motor-CAD), electromagnetic analysis (Ansys Maxwell), fluid dynamics (Ansys CFX and Particleworks) and thermal model (Ansys CFX). The arrows show the geometry / boundary conditions transferred between the software.

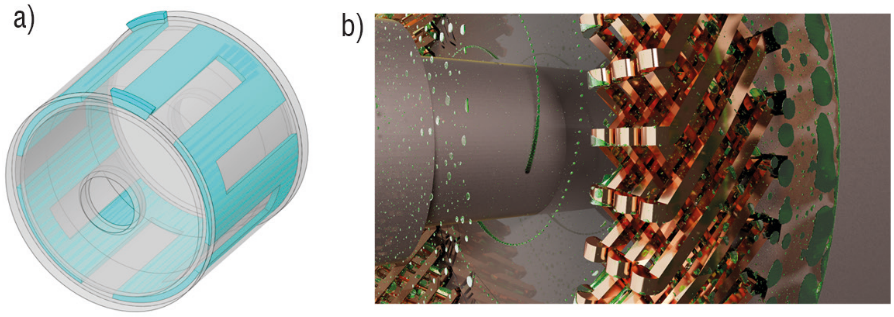


Fig. 2. a) Water jacket for indirect cooling (in blue); b) Oil jets from the rotor shaft and their accumulation on windings and casing (photorealistic rendering of simulation results)

Complete e-motor design and simulation: the advantages of a digital prototype

In collaboration with EnginSoft, TotalEnergies developed a simulation workflow to study the selection, design and improvement of e-motor cooling.

Thanks to the mesh-less nature of the CFD software for oil jet simulation and the Ansys integration between the different simulation tools, the complete simulation (considering geometry preparation and hardware time) took less than two weeks for the first model. Changing operating points or geometric characteristics only resulted in additional simulation time of two to five days.

The reported workflow for the complete e-motor design and analysis includes:

- The selection of electric motors for automotive applications (with Motor-CAD)
- An electromagnetic analysis (with Ansys Maxwell) fluid dynamic analysis (with Particleworks and Ansys CFX, for oil jet and water jacket cooling respectively)
- A thermal analysis (with Ansys CFX)

Articulating the workflow, we first defined a realistic e-motor operating condition (selecting for output torque and rotor speed) and estimated the corresponding efficiency curves with Motor-CAD. Two e-motor operating conditions were identified at 6.000 rpm (representing a car travelling steadily at 70 km/h) and 10.000 rpm (representing temporary acceleration for overtaking). We then exported the e-motor geometry and material properties of the e-motor digital prototype for a 3D electromagnetic analysis in Maxwell. With this analysis, we calculated the electromagnetic losses and heat generation of the two operating points that we then fed to the CFX thermal model.

Direct (vs indirect) oil-jet cooling: the advantages of a mesh-less approach

We compared two cooling strategies for the e-motor: an indirect water jacket embedded in the stator, and direct oil jets hitting the coils and other critical areas (Fig. 2). Focusing on the simulation of direct oil cooling, we used Particleworks, a mesh-less CFD software based on Moving Particle Simulation (MPS) [1].

This method is suitable for the rapid analysis of free-surface flow phenomena such as jets and sprays. Due to its mesh-less nature, it is easy to manage complex geometries (such as windings) or rotating parts (such as the rotor) [2].

For these same reasons, Particleworks is also widely applied in the analysis of lubrication and cooling in transmissions and gearboxes [3], so using this software enables a complete analysis of both gearbox and e-motor systems.

When applied to e-motor analysis, Particleworks allows the following to be investigated (Fig. 3):

- **Flow split within the rotor.** Since part of the cooling circuit is integrated into the rotor shaft, it is important to investigate the flow split between the different branches at different operating speeds.
- **Windage effects.** Air and windage effects can be simulated in Particleworks with the same digital model, further speeding up and simplifying the simulation workflow.

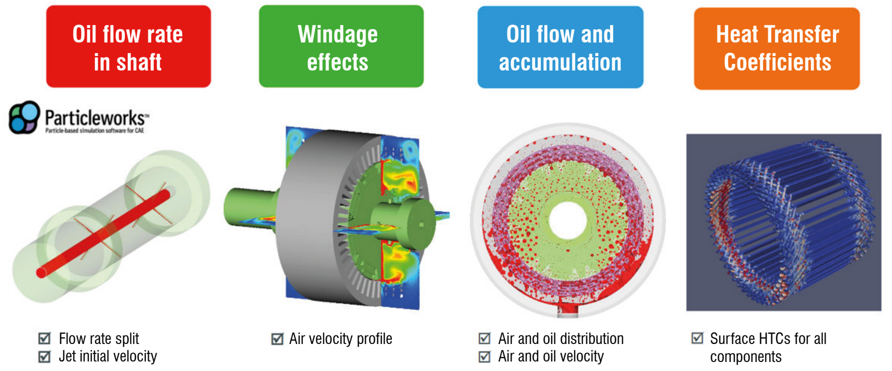


Fig. 3. Simulation steps and observables that can be investigated using Particleworks.

Generally, after the air has been modelled, the airfield is transferred to the oil jet simulation.

- **Oil jet impingement, oil accumulation and wetted surfaces.** The flow of oil jets – influenced by the imported airfield – and its accumulation inside the e-motor is modelled in this final simulation. Wetted surfaces and oil coverage can be also monitored and compared between different configurations.

After the amount of oil had stabilized in the e-motor, we used Particleworks to create maps of the average heat transfer coefficient (HTC) on the most important surfaces. We then transferred the maps to the Ansys thermal solver (Particleworks is also integrated with Ansys Workbench). We then performed a steady-state (6 000 rpm) or transient (10 000 rpm) thermal analysis on the e-motor, also integrating power losses and thermal loads due to the system's electromagnetism (from Ansys Maxwell). Once the steady-state thermal analysis was complete, we used the CFX model to predict the temperature distribution within each component of the e-motor. This methodology for predicting temperature in the e-motor was previously validated with Ricardo, using experimental data from thermocouples placed around the terminal windings [4].

Results

Comparison of direct and indirect cooling strategies

In order to maintain the same cooling capabilities, we normalized the flow rates for direct and indirect cooling accounting for the different physical properties of oil and water.

A cross-section of the e-motor coloured with the temperature profile is shown in Fig. 4 left for the direct oil cooling setup; right for the indirect water cooling configuration. Although the housing and stator are slightly cooler for the latter system, it is clearly seen that the rotor and winding regions reach higher temperatures in the water-based system. Particularly critical is the rotor, which houses the permanent magnets whose performance can be affected by temperature variations. Overall, the average temperature for direct cooling is 10 °C lower.

We tested several flow rate configurations to study the behaviour of the e-motor for the oil jet in the worst case and for indirect cooling in the best case scenarios (2 l/min vs 20 l/min). The average temperature (Fig. 5) of the windings for oil cooling is at least 14 °C lower. This

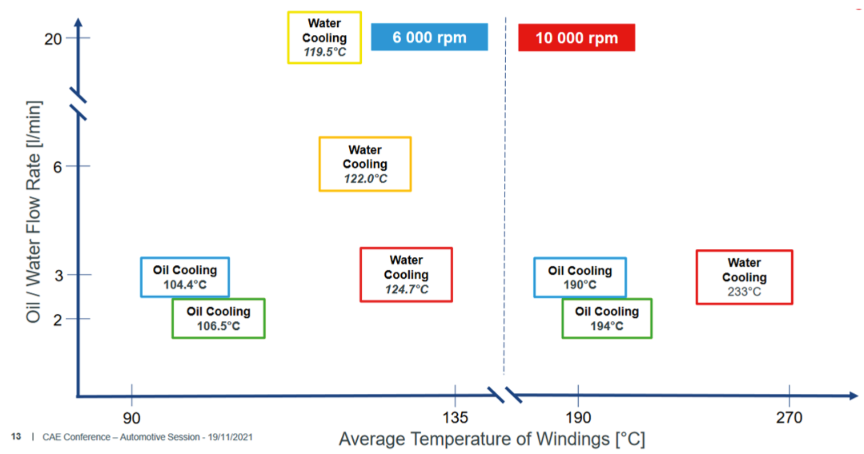
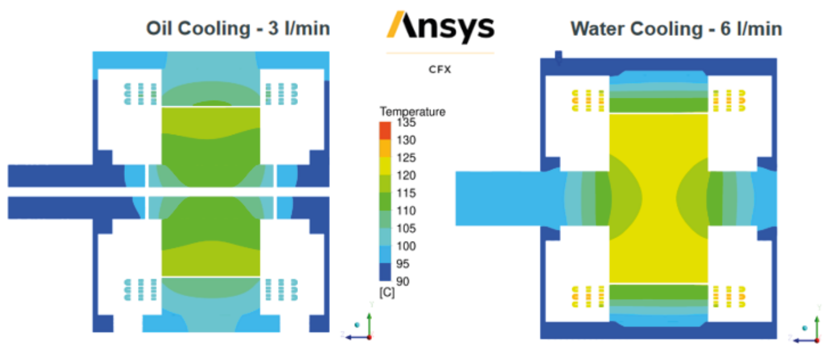


Fig. 5. Average temperature of windings for different flow rate / cooling strategies. Considering different flow rates and rotational speeds, oil cooling proved to be superior to the external water jacket strategy.



	Oil Cooling System 6000 rpm, 3 l/min		Water Cooling System 6000 rpm, 6 l/min	
	Ave. Temp. [°C]	Max. Temp. [°C]	Ave. Temp. [°C]	Max. Temp. [°C]
Housing	97.6	102	-4.3	-4.1
Stator	103.3	110.9	0.7	5.6
Resin	105.6	110.6	8.7	15.6
Windings	104.4	110.2	17.6	18.4
Rotor	115.7	125	7	5.8
Magnets	120.1	124.8	6.6	6
Shaft	98.7	113.6	6.5	7.6

Fig. 4. Temperature distribution inside the e-motor for direct and indirect cooling. In the table on the right, the average temperatures for the different e-motor regions are highlighted. The direct cooling shows lower temperatures for most of the e-motor elements.

trend is also confirmed at the higher speed condition, where the temperature can reach higher values. For this operating point, we report a higher temperature difference (40 °C) for the two cooling strategies.

Influence of physical properties

After demonstrating the superiority of the direct oil cooling strategy TotalEnergies wanted to prove the possibility of screening and selecting the physical properties of the oil to achieve better cooling efficiencies.

To do this, we varied four physical properties compared to the reference oil:

- $1/3\times\mu$, the initial viscosity (fluid 1)
- $2\times\lambda$,the initial conductivity (fluid 2)
- $1.5\times C_p$,the initial heat capacity (fluid 3)
- $1.2\times\rho$, the initial density (fluid 4)

The temperature distribution in the e-motor for the four oil variations is shown in Fig.6. As can be seen, all variations show improved cooling at lower temperatures.

This is in line with the trend between heat transfer and each physical property that can be extracted by explicitly isolating all variables in the Nusselt number:

$$h \propto \frac{(\rho u)^{\frac{1}{2}} (C_p)^{\frac{1}{3}}}{\mu^{\frac{1}{6}}} k^{\frac{2}{3}} \quad \textbf{(Eq. 1)}$$

Looking at the results in more detail, the temperatures decrease strongly for fluid 1 and 2 (reaching a reduction of 4% for the magnets). The average temperature decrease is greater than 2.5 °C for both configurations.

	Viscosity x 1/3		Conductivity x 2		Heat capacity x 1,5		Density x 1,18			
	Oil Cooling System Reference Oil		Oil Cooling System Fluid 1		Oil Cooling System Fluid 2		Oil Cooling System Fluid 3		Oil Cooling System Fluid 4	
	Ave. Temp. [°C]	Max. Temp. [°C]	Ave. Temp. [°C]	Max. Temp. [°C]	Ave. Temp. [°C]	Max. Temp. [°C]	Ave. Temp. [°C]	Max. Temp. [°C]	Ave. Temp. [°C]	Max. Temp. [°C]
Housing	97.6	102	-2.2	-2.8	-2.5	-2.9	-0.9	-1	-0.3	-0.4
Stator	103.3	110.9	-2.2	-2.7	-2.5	-3.2	-0.9	-1.3	-0.3	-0.3
Resin	105.6	110.6	-2.2	-2.5	-2.8	-3.1	-1.1	-1.3	-0.4	-0.3
Windings	104.4	110.2	-1.9	-2.3	-2.7	-3.2	-1	-1.2	-0.3	-0.5
Rotor	115.7	125	-1.5	-3.5	-2.3	-4.5	-0.8	-3.1	-0.3	0.2
Magnets	120.1	124.8	-5.4	-3.5	-6.8	-4.5	-5.4	-3.1	0.9	0.3
Shaft	98.7	113.6	-5.1	-4.3	-6	-5.6	-4.5	-4.3	0.9	0.8

Fig. 6. The average and maximum temperatures of each electric motor component are shown for the reference oil. The temperature differences found for the four different fluids tested are also shown.

This temperature difference can be considered significant, as it is greater than the sensitivity of the digital model.

It is interesting to note that the thermal capacities and temperature differences do not follow the power dependencies shown by the Nusselt correlation in Eq. 1. For instance, viscosity has a greater effect than density, although the exponential factor should be more favourable.

Overall, the results show that simulation and quantitative CFD analysis are crucial and can be more thorough than the theoretical estimates that currently guide most traditional R&D processes. Complex flow patterns and multiphase interactions may arise, resulting in oil accumulations and surface coverage that cannot be estimated without accurate digital models.

Conclusions

The numerical results obtained in this collaborative project between TotalEnergies and EnginSoft consistently demonstrated the superiority of direct oil cooling over indirect water cooling for e-motor systems. With its high dielectric properties, oil can be sprayed or splashed directly wherever heat is generated, resulting in significantly lower average and maximum temperatures of crucial components such as magnets and coils.

Direct oil cooling thus opens the way to higher power densities for the future generations of e-motors and optimized cooling control strategies.

Finally, the digital approach presented in this paper has shown real potential to serve as a versatile complementary tool to optimize the formulation of dielectric cooling fluids and will join other approaches at the core of TotalEnergies' research and development activities for thermal management of electric vehicles.

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About TotalEnergies

TotalEnergies is a broad energy company that produces and markets energies on a global scale: oil and biofuels, natural gas and green gases, renewables and electricity.

Our 100,000 employees are committed to energy that is ever more affordable, cleaner, more reliable and accessible to as many people as possible.

Active in more than 130 countries, TotalEnergies puts sustainable development in all its dimensions at the heart of its projects and operations to contribute to the well-being of people.

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