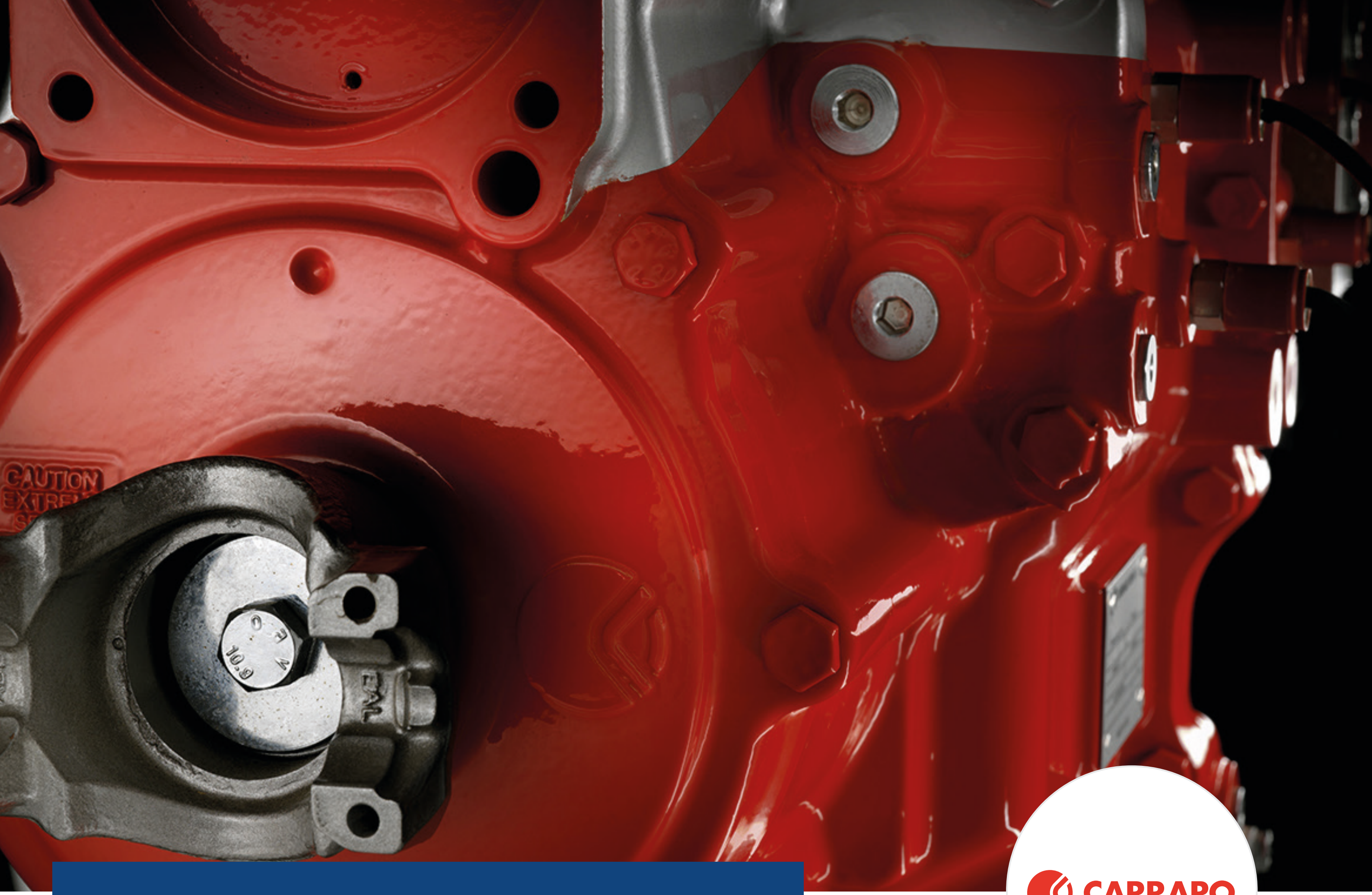

The importance of numerical simulation in optimizing electrified power transmission systems

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Off-road vehicles are evolving towards full sustainability, driving the need for solutions that maximize fuel efficiency while reducing atmospheric emissions. To meet the growing interest in electrification, the significant challenge of power loss management in electric engines must be addressed.

Power losses affect drivetrain components, specifically from friction between gears, shafts, and seals, as well as gear churning and bearing losses due to the oil in the transmission. These factors, which are directly related to operating speeds, can cause the internal components and the oil to overheat.

To minimize power loss and maximize transmission system efficiency while ensuring proper lubrication and heat dissipation, oil flows within the transmission and their interactions with dissipation sources must be verified. This verification usually takes place during bench tests using physical prototypes with specific openings to check oil flow, pump suction zones, and proper gear and bearing lubrication. Simultaneously, temperatures and power losses are checked under all operating conditions, including critical ones.

The rise of simulation-aided engineering

Identifying and addressing potential issues early in the development phase is crucial to minimize the need for experimental testing, which can cause delays with substantial economic consequences.

Detailed digital prototypes that use mesh-free CFD modelling, like Particleworks, support engineering R&D for the lubrication and cooling of critical components like gears, transmissions, bearings, and electric engines, in various industries including automotive.

Carraro, a leading manufacturer of transmission systems for off-road vehicles, uses such software and analysis to optimize product development, reduce the risk of reworking prototypes and improve the efficiency of transmissions for electrical applications.

eCarraro – Carraro's integrated proposal

In response to increasingly strict emission regulations and efficiency concerns, Carraro has developed transmissions that integrate electric engines. These transmissions meet the regulatory constraints while reducing emissions and maintaining current levels of performance and productivity.

eTB220C transmission

Developed for all-electric applications, this drivetrain minimizes power loss even at high speeds and ensures flexibility by integrating compact electric engines for multi-stage solutions. This family of scalable electric motors offers low- and high-voltage power sizes and functions.

THE solution: plug-and-play hydrostatic and electric solution

Designed for a wide range of light construction machinery, "THE solution" allows vehicles to switch between hydrostatic and electric applications without altering the chassis or transmission layout. It is suitable for telescopic handlers, backhoe loaders, skid steer loaders, and wheeled excavators.

Hardware and software

In this era of digital transformation, Carraro also offers innovative solutions for the electronic control of transmission systems and vehicles catering to e-mobility. Customized software development supported by Carraro hardware platforms ensures vehicle functions from user interfaces to traction management and the entire electrified powertrain.

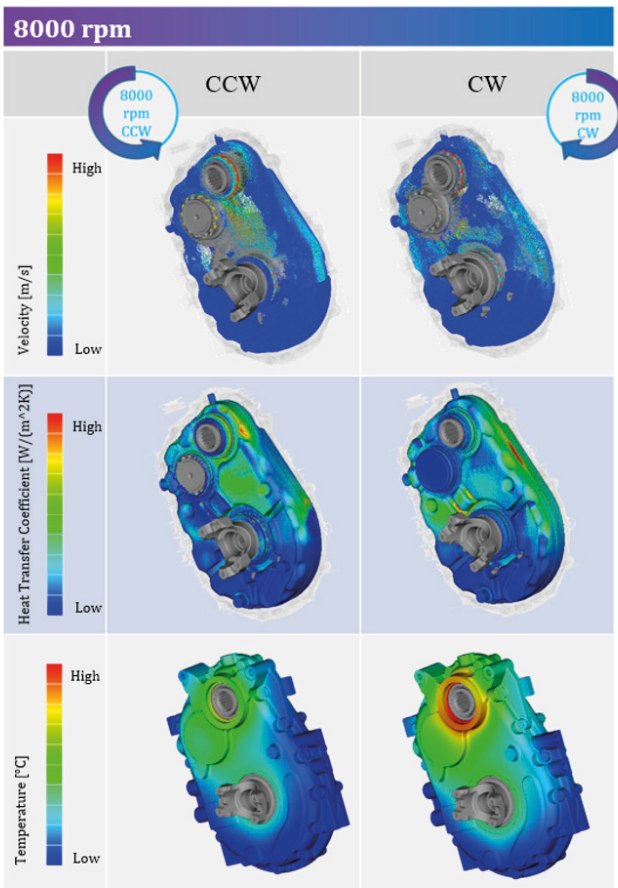

Fig. 1. Comparison of oil distribution, heat transfer coefficient, and temperature maps between two opposite directions of rotation with the same speed at transfer box inlet.

Expanding lubrication analysis and churning loss estimations to temperature estimates

An in-depth analysis of power loss and operating temperatures in electric applications was performed using the specific case study of a compact wheel loader's transfer box, consisting of three shafts and two total gear pairs, for a total input-output ratio of 4,861.

The study aimed to extend the company's simulation workflow by incorporating temperature evaluations at critical points of the transmission and considering heat exchanges and the estimated power losses due to regulations.

Particleworks was used for the fluid dynamic simulations and subsequent conjugate heat transfer (CHT) thermal analyses, which were compared with Ansys Mechanical thermal solvers in a first simulation. The Particleworks simulations were performed on a workstation equipped with an RTX A5000 GPU.

Particleworks thermal model and comparison with Ansys Mechanical

The initial fluid-dynamic simulations assessed the correct lubrication of the bearings and gears and obtained the heat transfer coefficient (HTC) map dependent on the specific oil flow rate of each case study while also extracting the estimated losses due to the interaction of the gears with the oil - part of the total power losses of the system.

The various contributions to the dissipated power were then analysed theoretically with reference to the ISO-TR 14179/2 standard, and compared to the software's estimates and the experimentally measured losses.

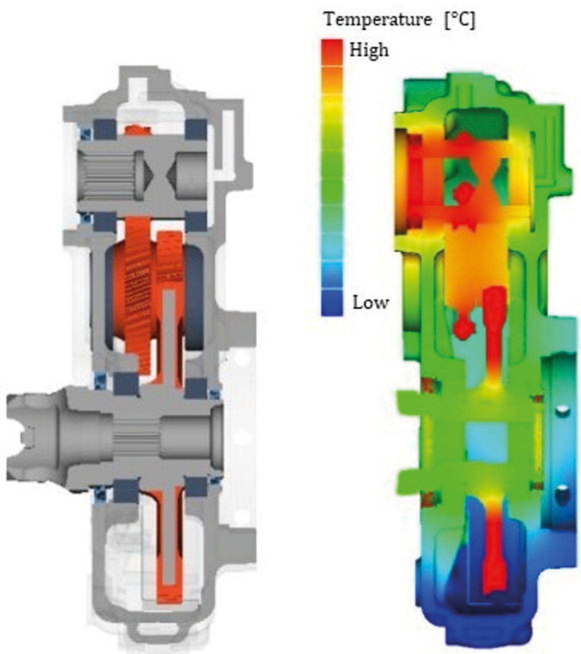

Fig. 2. From the temperature map section of the transfer box, you can see the contribution of each power source: seals, bearings and outer portions of the gears.

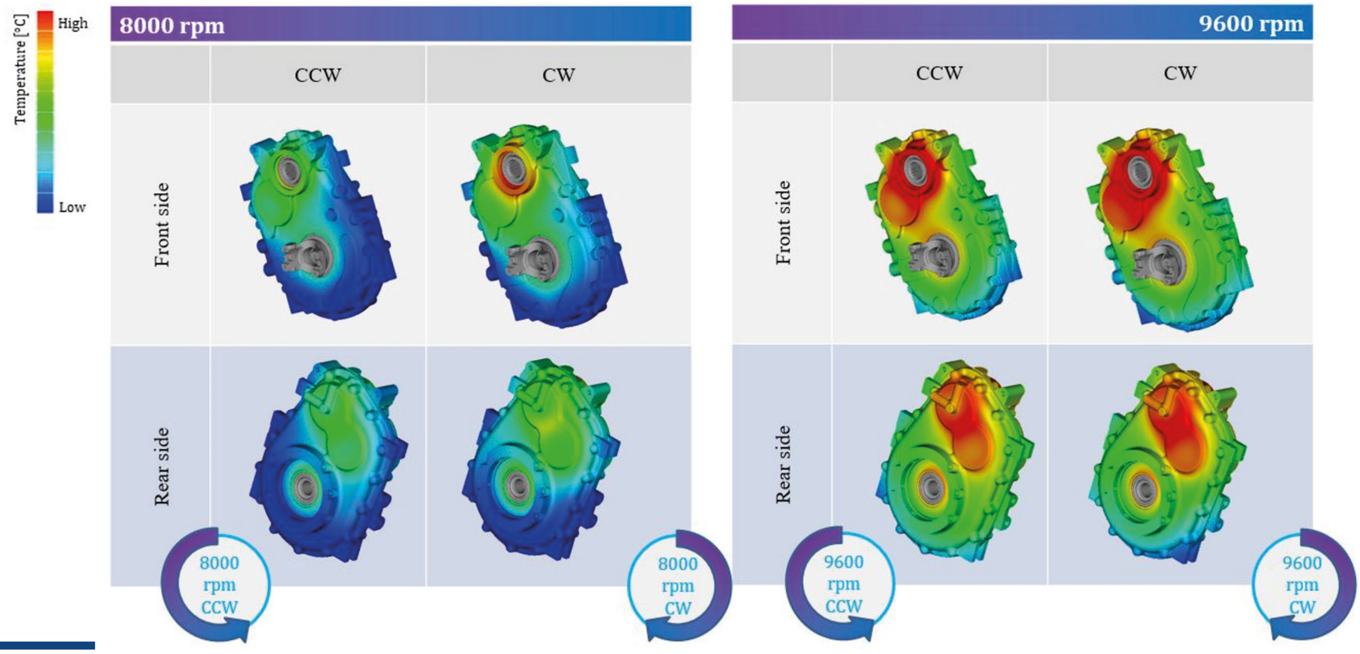

Fig. 4. At higher input speeds transfer box temperatures are superior to the ones at lower input speeds, due to the higher power losses, especially near bearings and seals.

Thereafter they were used as input as heat sources to the subsequent steady-state thermal simulations. In other words, the sealing losses, the bearing churning losses, and gear churning losses were applied to the respective thermal energy source according to the calculations for each single contribution. Only the outer portion of the gears was considered as a power source, since this is the part which has most contact with the oil thereby generating the churning losses.

Firstly, in an analysis undertaken in collaboration with the University of Padua's Department of Mechanical Engineering, two thermal simulations were conducted using the same input data and including the thermal conduction coefficient between the components and the natural convective heat transfer coefficient (HTC) for the external surfaces. The only difference between the two simulations was the inclusion/exclusion of the convective HTC map on the internal surface of the gear box derived from the internal oil flow.

Validation of Particleworks' thermal solver with experimental thermocouples

The results show that the HTC map was a non-negligible variable in this type of thermal analysis since the temperature errors in the simulation without the HTC

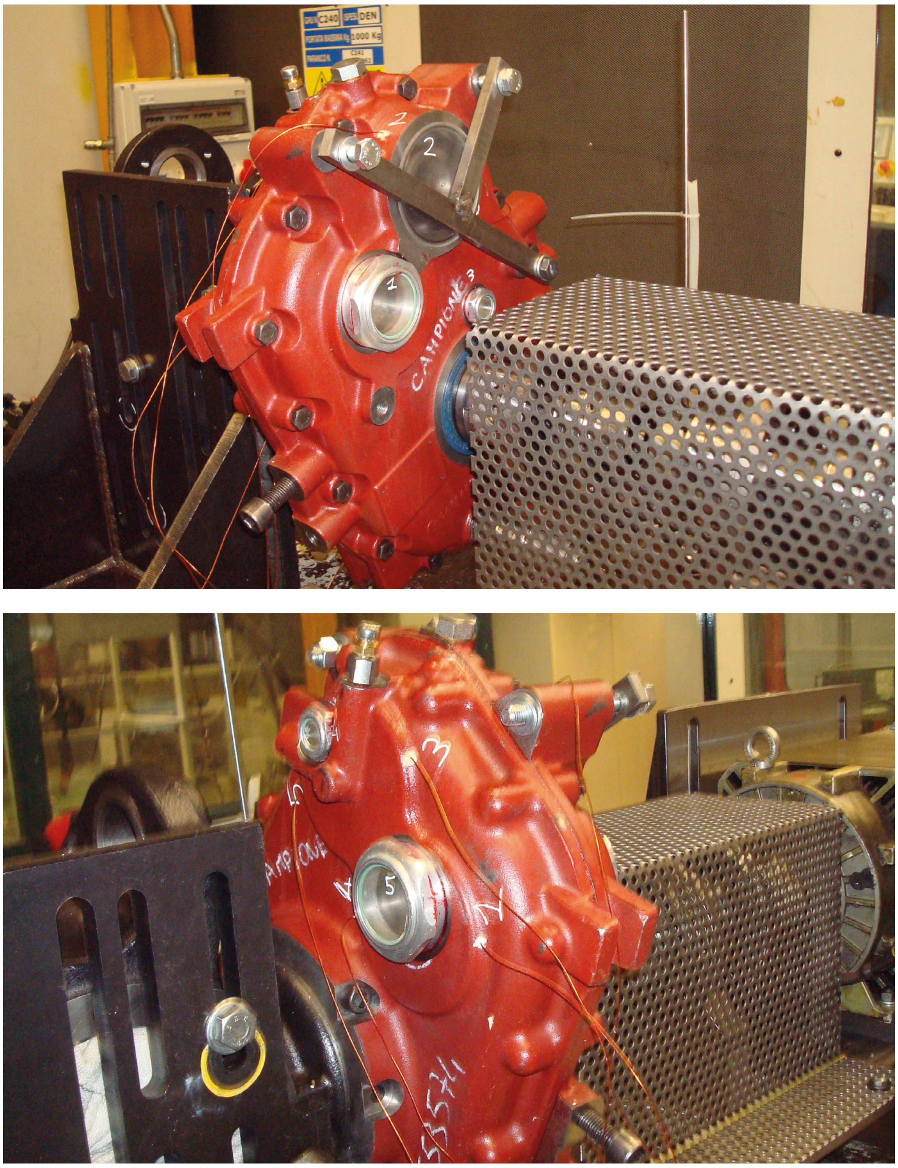

Fig. 3. Experimental setup of the transfer box.

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Thermal gaps [°C] with experimental measurements - Process 2							
Input speed [rpm]	Input sense of rotation	T_1 [°C]	T_2 [°C]	T_3 [°C]	T_4 [°C]	T_5 [°C]	T_5 [°C]
8000	CCW	-4,6	6,4	9,7	-5,4	1,6	3,6
8000	CW	-2,0	9,6	7,3	-2,1	4,5	5,5
9600	CCW	-7,8	1,8	4,5	-8,7	-5,2	-3,4
9600	CW	-8,6	9,1	7,8	-4,4	3,2	3,6
$T_i = T_{sim\_i} - T_{exp\_i}$						gap < 5°C; 5°C < gap < 10°C; gap > 10°C	

Fig. 5. Differences between temperatures estimated by Particleworks simulation and the experimental values at the 6 thermocouples of the transfer box bearings under analysis: the maximum temperature gap was 10°C.

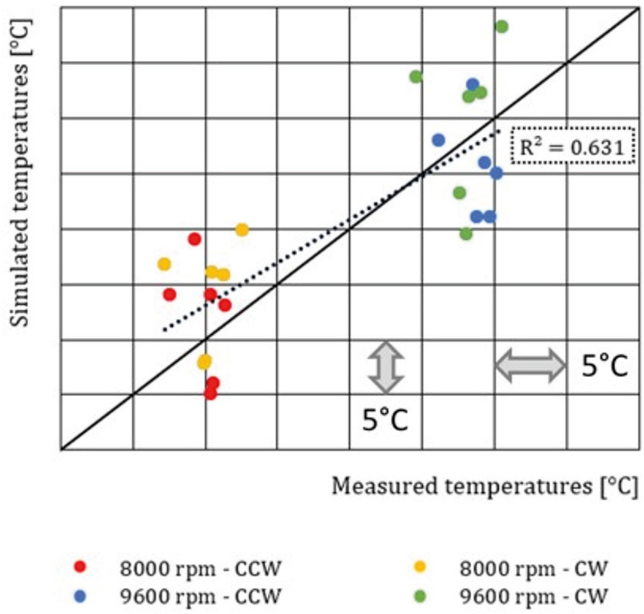

Fig. 6. The values of the second CHT Particleworks iteration were plotted in a graph showing the correlation between the measured and simulated temperatures. The solid line represents the ideal correlation while the dotted line links the trend of all points for which the R2 values were calculated.

About Carraro Group

Carraro (carraro.com) is an international leader in transmission systems for off-road vehicles and specialized tractors. The group has two business areas:

- Transmission systems (axles and transmissions) and components mainly for agricultural and construction equipment; and gears for diverse sectors, from the automotive industry to material handling, agricultural applications, and construction equipment.
- Specialized tractors (for vineyards and orchards, between 60 and 100 horsepower) for third-party brands; and engineering services for the design of innovative tractor ranges.

The group's headquarters is in Campodarsego in Padua in Italy. At the end of 2023, Carraro had 3,859 employees, 1,800 of which were based in Italy, and four manufacturing facilities in Italy, with others in India, China and Argentina.

map reached 35% when using the experimental measurements as a baseline. In any case these values are in line with the experimental expectations because the exclusion of the HTC map on the internal surfaces of the transfer box causes higher temperatures due to the lack of contribution to the heat exchange and the dissipation of power loss.

Thereafter we compared the results from two thermal analyses with the same input data performed in Particleworks and Ansys Mechanical and, considering the temperature values of the bearings, a maximum difference of less than 10°C was found between the two simulations.

We then compared experimental bearing temperatures to Particleworks' thermal CHT simulations for four operating conditions, considering two different speeds (8,000 and 9,600rpm) with two input rotation directions (clockwise and anticlockwise).

Conclusions

In conclusion, this validated study shows the uses of a digital modelling tool for fluid dynamics and thermal analysis. The easily implemented workflow was used to analyse Carraro off-road transmissions, providing the engineering team with detailed information on temperatures and power loss in the early product development stage.

By using the Particleworks thermal solver to compare four different case studies, we verified that the different speeds of the gears and the different oil distribution within the transmission as a result of the different rotation directions creates a different interaction with the heat sources. Quantitatively, using an HTC map that included the inner surfaces of the gearbox, the seals, and the bearing raceways, the temperature values obtained from the CHT simulations showed a maximum deviation of 9°C compared to the experimental data detected with the thermocouples.

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