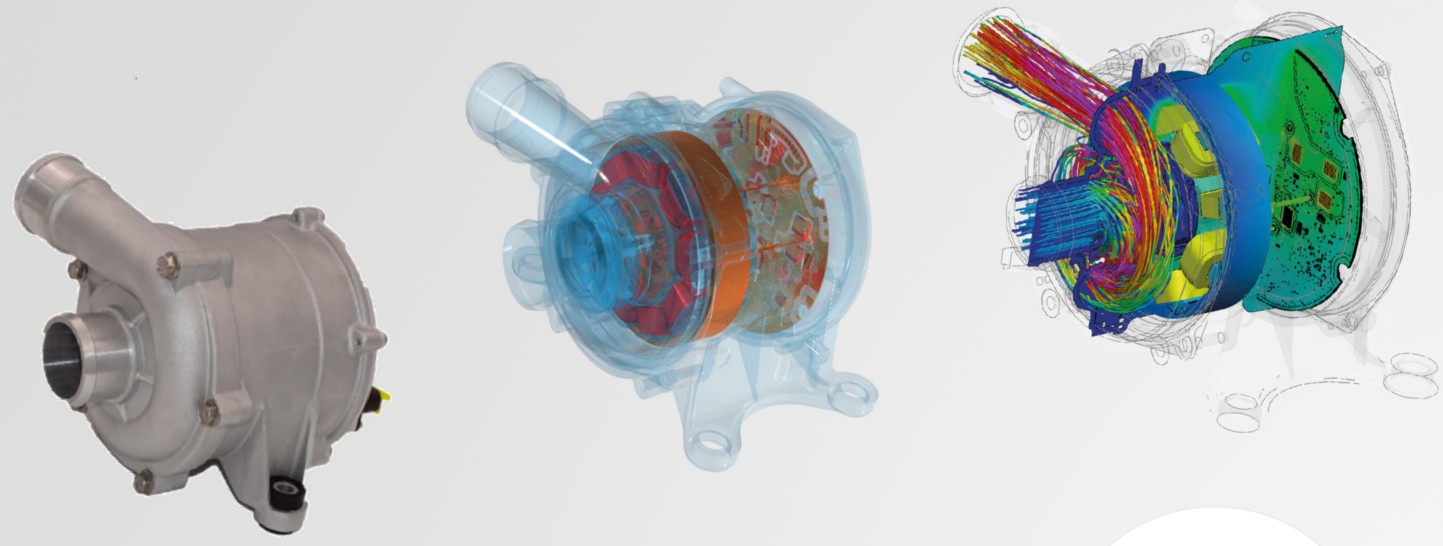

Thermal management: challenges in and strategies for developing electrified products

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The constant demand to make products more efficient, compact, and reliable while reducing costs typically drives the activities of R&D departments in the automotive industry and beyond. Thermal management (TM) is one of the key challenges to be addressed and needs to be considered from the earliest stages of defining the design, especially when dealing with electrified products. So, what is it?

Thermal management refers to all the strategies, technologies and tools that keep a system within its optimal range of operating temperature, thus ensuring that all its parts operate safely, reliably, and efficiently.

This general definition can be applied to daily work as a pragmatic mixture of thermal assessments with different levels of complexity and a "system view". These two key elements can support all phases of product development with the right effort and provide opportunities to:

- avoid multiple design loops and prototypes,
- avoid compartmentalized design,
- optimize reliability and efficiency.

The result is faster time to market, cost savings and the best system solution.

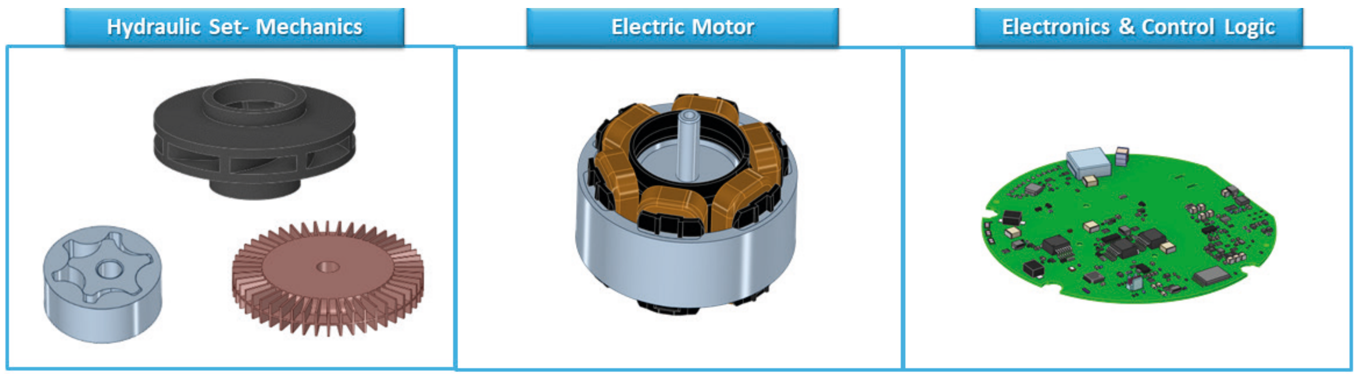

Fig.1. Main subsystems of a typical electrified product.

After briefly introducing electrified products and their requirements in the initial design phase, this paper focuses on some characteristics of 3D thermal analysis, typically reserved for advanced phases of development when designs are verified and improved.

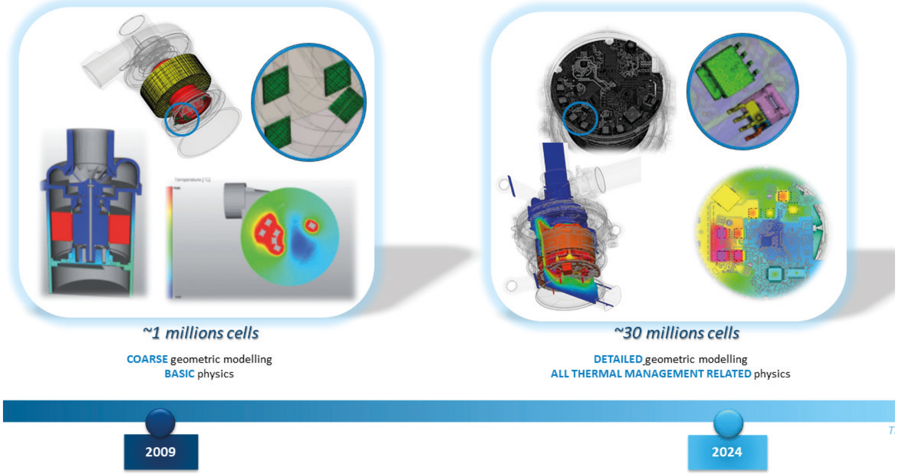

Fig.2. Capability evolution in model development.

Electrified products

The authors work for the Rheinmetall group in the Thermal Management Business Unit (BU-TM). The company has several divisions, one of which – Power Systems – deals with automotive/civil applications. In its turn, the Power Systems Division also has several business units including Thermal Management, which focuses on developing components, modules and systems for e-mobility and industrial applications. BU-TM's electrified product portfolio includes:

- electric water pumps (eWP) mainly used for TM,
- electric oil pumps for both lubrication and TM,
- electrified valves for system management,
- high voltage components such as hydrogen recirculation blowers (HRB) for fuel cells,
- thermal modules for automotive and non-automotive applications,
- components for home heating and other industrial applications.

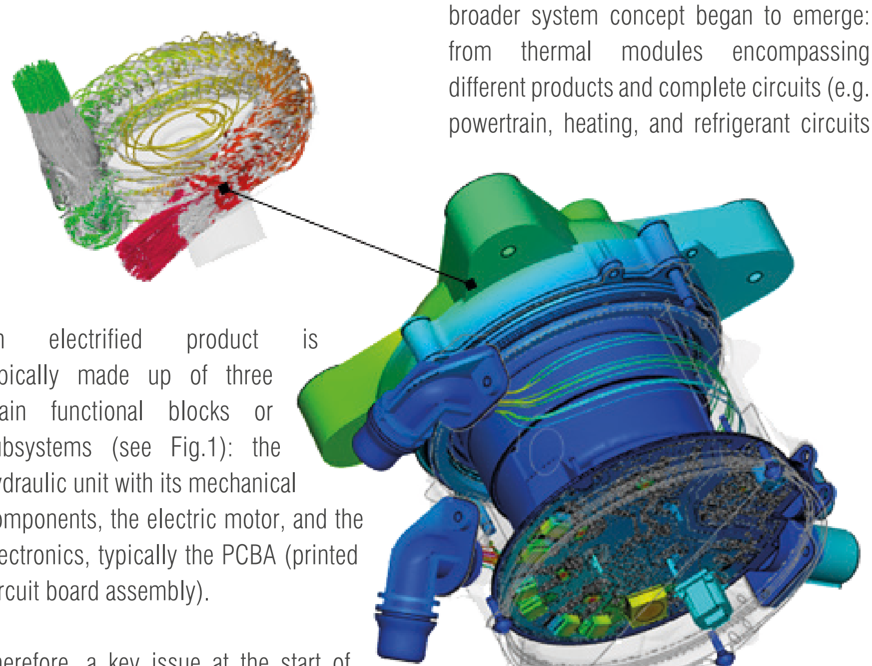

Fig.3. Examples of a fully coupled model complexity.

An electrified product is typically made up of three main functional blocks or subsystems (see Fig.1): the hydraulic unit with its mechanical components, the electric motor, and the electronics, typically the PCBA (printed circuit board assembly).

Therefore, a key issue at the start of the product concept is the choice of the assembly layout. This refers to the relative positioning of the aforementioned subsystems and their interfaces, which constrain each other and strongly influence the thermal paths used to dissipate heat. As a result, preliminary thermal assessments are made in the pre-design phase, usually through analytical or 1D approaches. Note that high overall product efficiency and lean design are only possible with an advanced view: products are systems, no longer single-level physics.

Against this background, the company's Modelling and Simulation (M&S) department started working on a new way of thinking. With this new mentality, and considering the evolution of the automotive market, an even broader system concept began to emerge: from thermal modules encompassing different products and complete circuits (e.g. powertrain, heating, and refrigerant circuits of a passenger car) up to an entire vehicle, supporting a general cultural evolution within the company. In parallel, dedicated know-how and a complete set of tools have been developed, from 1D model-based system engineering to 3D thermo-fluid dynamic simulations, the objective of this paper.

Thermal modelling: focus on 3D thermo-fluid dynamic analysis

The first 3D thermo-fluid dynamics research and simulations started around 2009 as a structured and systematic approach in the M&S department of the BU-TM, with the first publication of its results in 2011 [1].

The evolution of skills in terms of increased know-how, improved networking between people responsible for different sub-systems, and improvements in CAE tools now make it possible to build very complex models that take into account all the physics involved in TM.

As an example, in 2009, a typical 3D model of an electrified product in a commercial CFD tool could contain about one million cells, whereas in 2024 it is feasible to build models with around 30 million cells in a reasonable amount of time (see Fig.2). This increase in detail and physics increases the resolution of the thermal results as well as their accuracy.

As mentioned, this type of analysis usually takes place when designs are verified and improved. At that point, the most pressing question is whether the electric motor and electronics are properly cooled. To answer

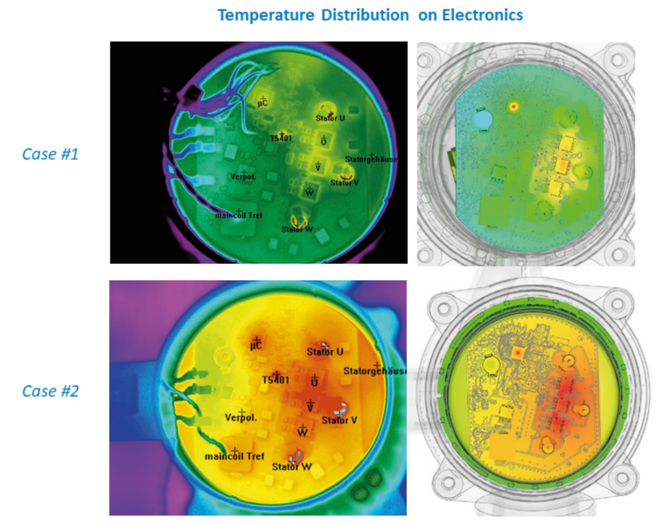

Fig.4. Comparison between experimental and virtual thermography of a PCBA.

this question, a standard analysis must provide the following key results: the temperature distribution within the product, a virtual thermography of the PCBA, and the distribution of the heat flows to highlight the thermal paths for heat dissipation.

Two main model options are available during configuration, depending on the coupling method between fluid and solid domains:

- an all-in-one model with matched interfaces (conjugated heat transfer, CHT method) [2],
- co-simulation between a solid and a fluid model (coupled heat transfer method) [3].

Both of these methods have their advantages and disadvantages, and the choice is made on a case-by-case basis, depending on the goal of the analysis and the physics involved. Simplified approaches can also be used, keeping the computational effort to a minimum. Fig.3, which shows the results of a CHT method from a high-voltage HRB, gives an idea of the complexity that can be achieved. The model consists of a pneumatic set providing the required recirculation of hot gas, an externally fed cooling jacket, and the complete 3D assembly including air gaps and cavities.

In terms of geometry, these models can easily contain up to forty parts for the pump assembly and thousands of parts for the PCBA alone. Such a remarkable number of components allows reliable results to be obtained with incredibly detailed resolution. Fig.4, which shows an example of virtual versus experimental thermography for two case studies of an eWP, gives an idea of the quality achieved.

Thermal verification loop: behind the scenes of full 3D analysis

Of particular note is the information required to feed a fully coupled 3D simulation. The diagram in Fig.5, which highlights all the necessary steps of the thermal loop, illustrates the complexity of this topic.

Starting with the design of the hydraulic unit and assembly, fluid dynamics and mechanical analysis are performed to obtain torque at the shaft. This output plus the rotational speed and electrical constraints are the main inputs for the e-motor experts and, subsequently, the electronics experts to provide predicted thermal losses. Once all the information is available, thermo-fluid dynamic analysis can provide temperature fields and thermal paths. These outputs can be used to iterate the loop and eventually, once convergence is achieved, to guide design verification and improvement.

It is becoming increasingly clear that the loop involves the contribution of several disciplines and departments. All these actors must be in constant dialogue to manage the exchange of information and coordinate activities (see Fig.6), always guided by the "system view". In this sense, thermal management is also a matter of human relations between people, cultures, and professional specializations.

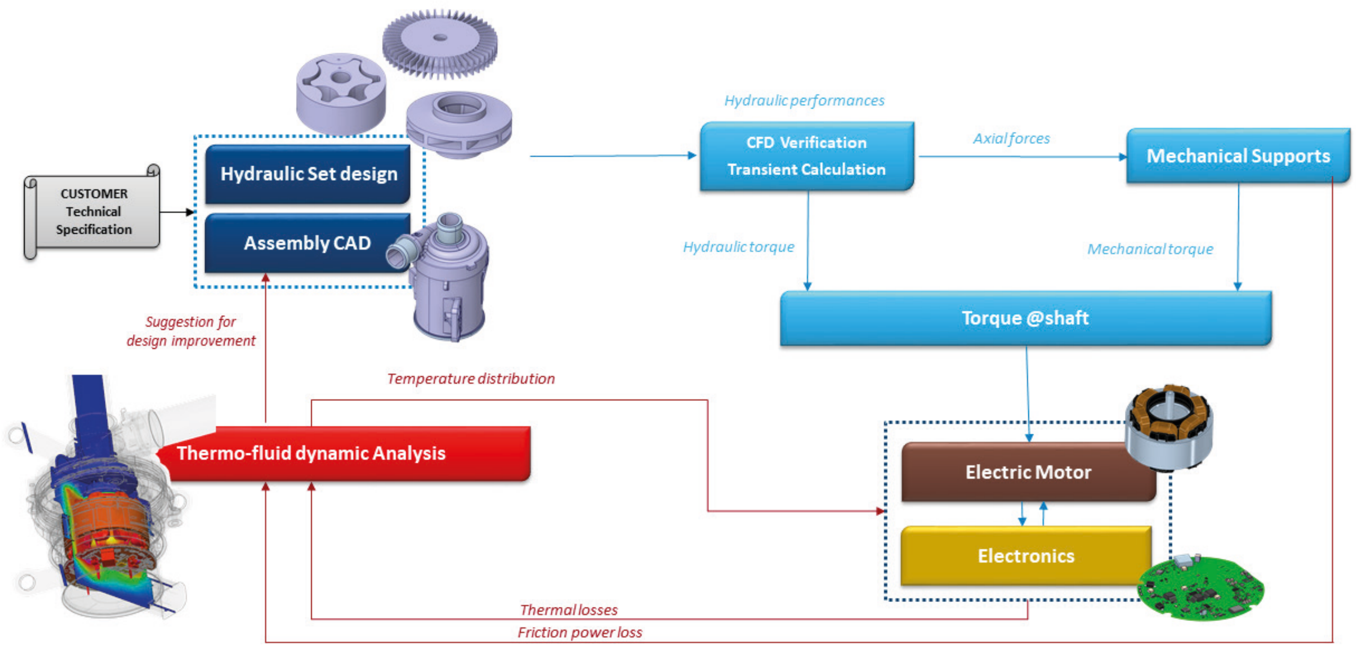

Fig.5. Thermal verification loop for an electrified product.

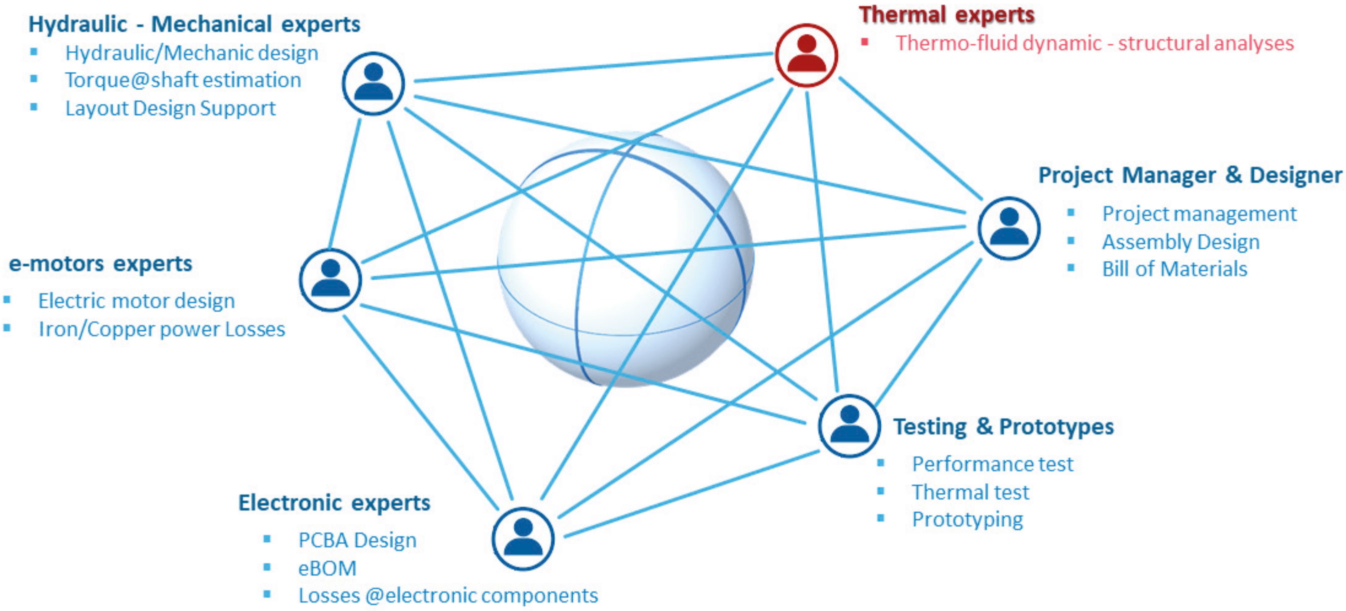

Fig.6. Relations for thermal management.

Conclusions

Thermal management is a growing trend in the automotive industry and beyond.

It is now a standard part of the overall design process and is typically addressed by the M&S department through different levels of analysis and modelling strategies, ranging from analytical estimates to fully coupled 3D thermo-fluid dynamic analysis. The latter approach can ensure reliable and accurate results that can be used to verify and improve the design. Underlying this is an inherent complexity in terms of the relationships and information exchange required between different complementary skills.

Above all, thermal management represents a cultural evolution and a change of perspective capable of recognizing a product as a system and extending interest and know-how beyond the product itself.

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About Rheinmetall

As an integrated technology group, the listed company Rheinmetall AG, headquartered in Düsseldorf in Germany, represents a group that is as strong in substance as it is successful internationally. The organization is active in various markets and offers an innovative range of products and services. Rheinmetall is a leading international systems supplier in the defence industry as well as a driver of forward-looking technological and industrial innovations in civilian markets. The company employs 30,000+ employees in 167 sites.

Pierburg Pump Technology Italy and Pierburg Pump Technology France, which belong to Rheinmetall, specialize in the manufacture of various types of pumps, such as mechanical and electrical oil pumps, vacuum pumps and water pumps. All products are continuously developed by the R&D team, so that the companies can offer their customers a wide range of customized solutions for all engine applications and requirements.