Thermal Analysis of Electrical Equipment
A review and comparison of different methods

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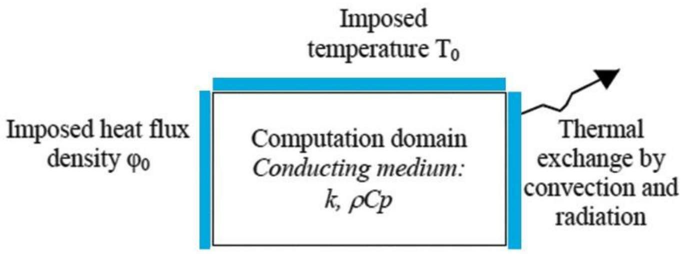
Nowadays, it is more and more difficult to design electro-technique devices without having a look at thermal stress. In more and more applications (more electric vehicles, more electric aircrafts, …) designers need to reduce weight, cost, increase efficiency, and keep the same security factor. One possibility is to increase current for the same device, needing to check how to draw away the heat. This is why the classical approximations need to be cross checked with complementary analysis. These new tools have to be rapid and accurate in order to run parametric and even optimization analysis. There is also a need for fast model in order to check robustness versus driving cycles. The goal in this article is to review rapidly the different methods available, depending on the accuracy required and the solving speed.

The method includes equivalent thermal circuits, Finite elements methods and CFD analysis.

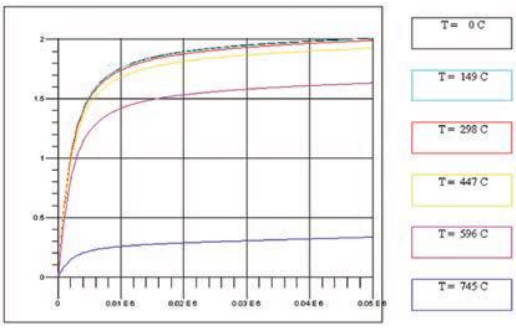
What is thermal analysis?

Thermal analysis reveals the impact of power supply on the heat of the different components of a device. A conventional project will include: one or more power supplies, conducting bodies, convection and radiation between a surface and a fluid. In the fluid you may have laminar flow or turbulent flow.

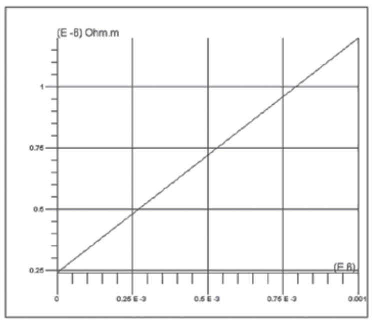


Typical thermal application.

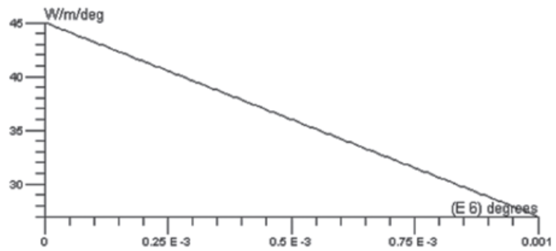
One benefit of this type of computation is the temperature dependency of all material properties: magnetic materials lose their magnetic property at Curie temperature, resistivity increases with temperature.



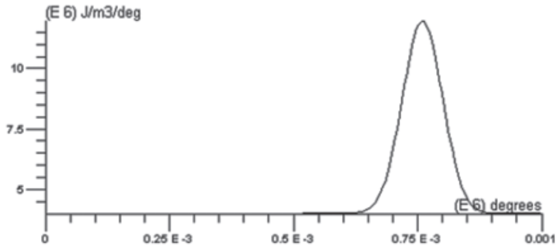
Magnetic property versus temperature.



Electrical resistivity.



Example of thermal conductivity.



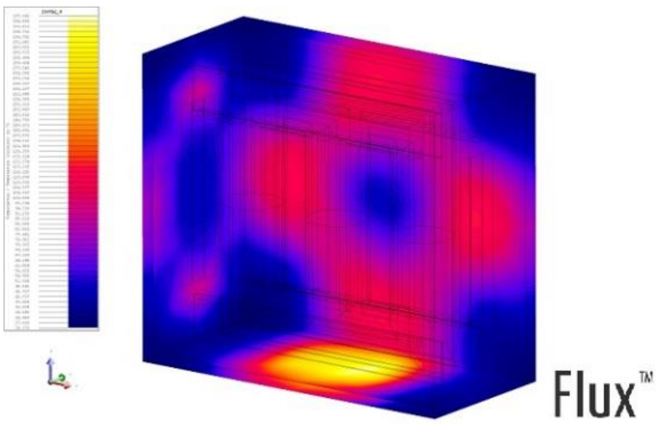
Thermal capacitance around Curie point.

Thermal conductivity and the thermal capacitance also vary versus temperature (especially around the Curie temperature).

Conventional thermal analysis tools

Traditionally, different methods are available for thermal analysis.

- The first is based on **equivalent circuit parameters** for thermal flow. This means identifying the circuit followed by the heat flow, and determining each component. This **produces very quick solutions but needs calibration to be efficient**. The corresponding tools are system simulation solvers like **solidThinking Activate™** or Matlab®/Simulink solvers, or analytical solutions like Motor-CAD.



Isovalues of current density on the tank surface.

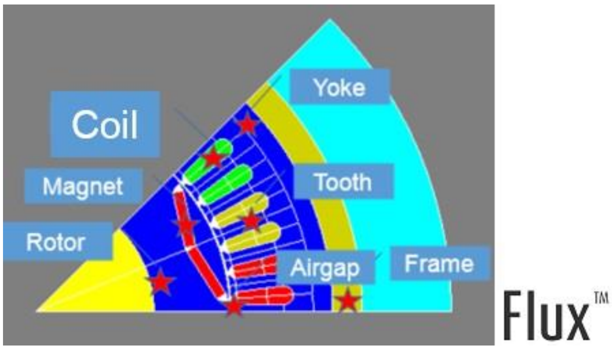
- When **considering only conduction in solid bodies** (and not in fluids, such as air), **Finite Element tools such as Flux™ are appropriate**. This produces **accurate computation**; convection and radiation coefficients must be known.

- To take into account the **whole thermal flow including fluids with turbulent or laminated flow**, **CFD code, such HyperWorks AcuSolve®** (or CD-adapco/ STAR-CCM+ or ANSYS/Fluent) is a good tool. Hot spots can be determined, but it takes time to produce results.

A table at the end of the document summarizes each methods advantages and typical applications.

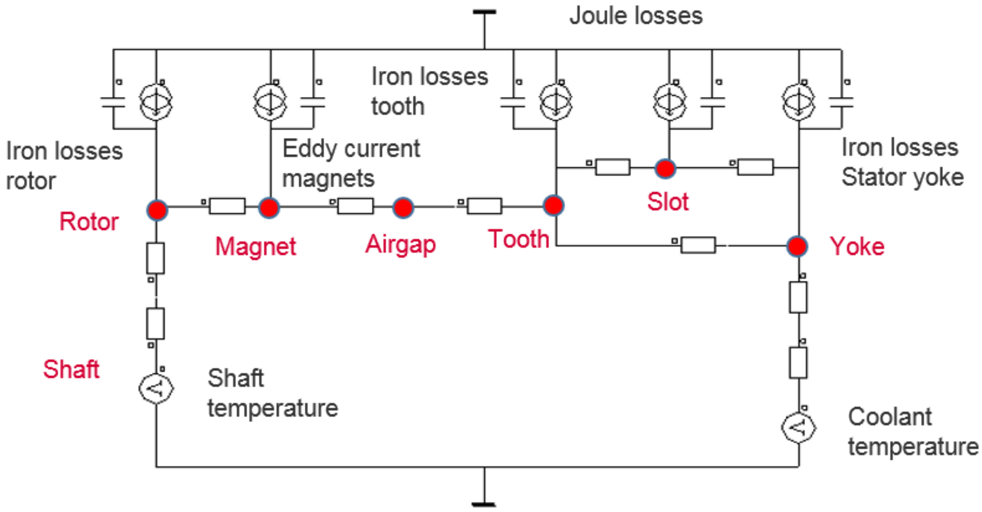
Equivalent Thermal Circuit

The goal of the equivalent thermal circuit is to split the motor in different areas where the temperature is assumed to be constant. With a reduced number of nodes you can already have a good estimation of what is going on thermally in your motor. The power transmitted from one point to another is then simulated by a thermal resistance. The losses are represented by current supplies. The current in each resistance corresponds to the heat power transferred from one node to another node. The convection and radiation is taken into account through dedicated resistances. You can deduce the temperatures in each node corresponding to steady states. You also have the possibility to add capacitances in order to take into account transient thermal.



Temperature nodes for thermal analysis

Just to give an example, you will see below the circuit corresponding to a Prius like motor.



Equivalent thermal circuit

What is interesting is that, to compute the equivalent thermal resistance, you can use analytic formula, or thermal FEA analysis.

The benefit of this method is the quite ease of use, and the solving time which is very fast. The counter part is that it requires good knowledge of exchange coefficients, especially convection and radiation. You often need to calibrate the model with measurements or a more precise method explained below. But once the model is calibrated, even for another motor, you can benefit from your acquired knowledge to predict what will happen.

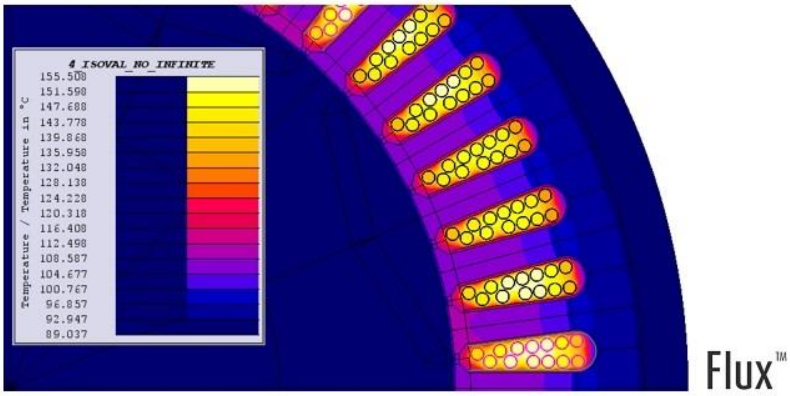
Thermal Finite Element Analysis

Another way of analysing the thermal behaviour of your motor is the use of FEA. The main benefit is a better understanding of the exchange of temperature inside the motor itself. Again, you will need to have knowledge about quite the same information as for the equivalent thermal circuit method: exchange coefficients on the boundaries. The key points are the following:

- Modelling of the airgap
- Exchange coefficient for external part of motor, and also for holes
- Sometime the increase of temperature along water coolant
- Modelling of the coil

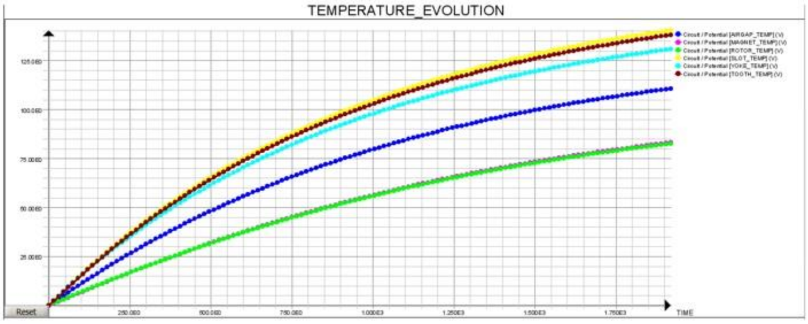
The airgap is often modelled with an equivalent thermal conductivity depending on various parameters: the velocity of rotor, the speed of airflow (fan or not on the shaft), liquid, … The modelling of the coil depends on the accuracy you want to get at this level. If you want full accuracy, then you can represent each turn, with each insulation. And if it leads to too complex modelling, you often simplify model it by using an equivalent region, keeping the ratio between copper faces, and insulation faces.

An example of the temperature color shade is given below after reaching steady state for Prius like motor.



Temperature color shade results in Flux™ 2D

With Flux™ FEA analysis, you can also study the thermal transient behaviour. You only need to know all the losses for each step of the cycle. An example of the temperature increase before reaching steady state is given in figure below.



Rising temperature before reaching steady state computed in Flux 2D

It is possible to compare the temperature for the same working condition using the equivalent circuit method and Flux 2D for instance. We can see there is a good correlation between both methods.

Node	Equivalent thermal circuit (C°)	Flux (C°)
Rotor	101,54	98,62
Magnets	101,77	99,24
Air gap	147,2	151
Tooth	148	148,81
Coil	174,9	175,77
Stator Yoke	89,29	90

Table of temperature

Latest improvements in Flux™:

New possibilities have arisen with new macros to reveal current supply required to follow a specific thermal profile. Flux can do one computation, carry out a test and then decide to keep going or redo the current step with a new power value. A power supply limitation can also be added.

What are the Flux™ advantages?

Since the beginning, Flux has offered numerous benefits:

- Good **material properties** (taking into account all temperature dependencies)
- **Specific dedicated regions** (line regions, thin regions, non meshed coils)
- **Meshing** precision (especially to model skin effect, penetrating slowly inside the body)
- **Parametric analysis** (any dimension can be parameterized including the mesh versus the frequency)
- **Circuit coupling** (ability to represent any type of circuit, using formula with voltage depending on point temperature)
- **Accuracy**
- **Complementary software and methods available**, offering **different computation speed vs accuracy compromises**, from pre-design to validation design needs

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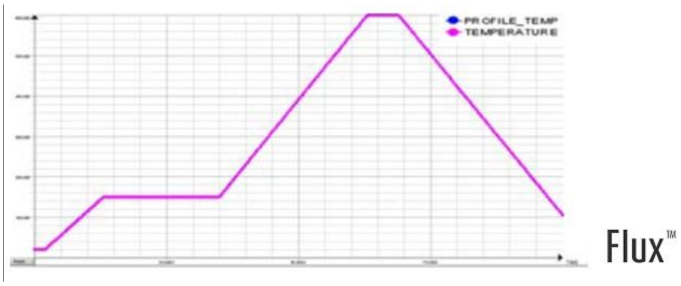
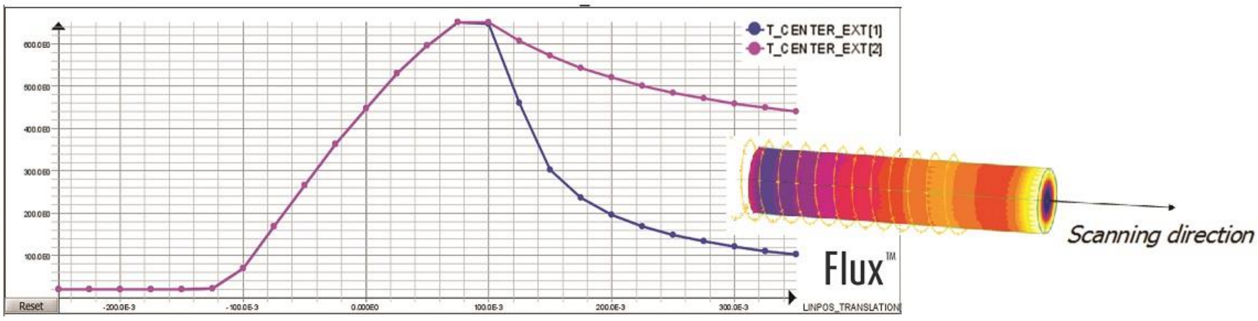
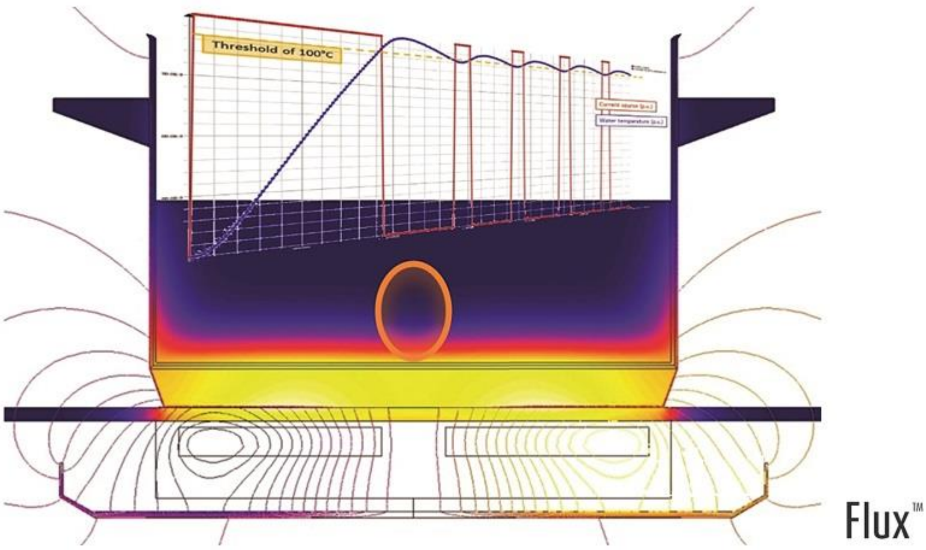


Targeted temperature & temperature obtained (curves are surimposed).

Another interesting feature is the ability to easily represent a cooling system with a shower, using formulae, including when the shower will appear. The graph shows the temperature fall with air or with a shower (for hardening purposes).



Temperature with air cooling or with shower cooling

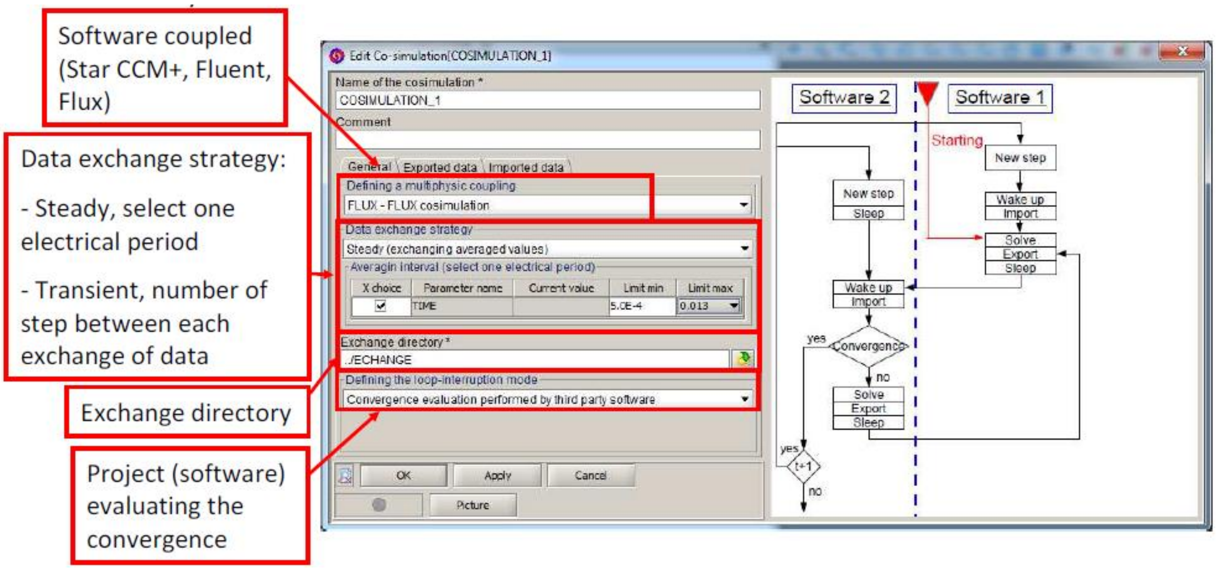


Displaying of the magnetic flux isolines superimposed with the resulting temperature map.

Flux environment embeds an electrical circuit editor, including different type of sensors that can be positioned in the application in order to easily and precisely control the heating of the application.

Multi-physics analysis with magnetic FEA and other tools

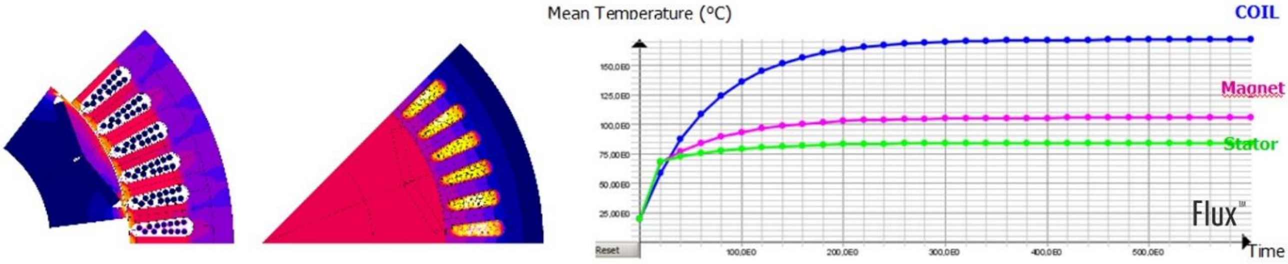
In order to improve the accuracy of results, it is possible to link the magnetic computation to the thermal computation. And this is important as remnant flux density of magnet is depending on temperature as well as resistance of coils. Therefore, when the temperature is increased, the current has also to be increased in order to compensate for the drop in remnant flux density of magnet for keeping a constant torque. One key point here is that the time constants are quite different: a few milliseconds in magnetic analysis, minutes or hours on thermal part. What we propose is to allow a full coupling at each time steps (when thermal transient is fast), and also allow analysing one magnetic project and extract from the last electrical period average losses. With Flux software, you can couple a 2D or 3D project to another thermal project which can be a Flux computation or another CFD tool.



Defining the co-simulation project in Flux

We have applied this new coupling on the analysis of PRIUS II motor for a specific working point. The project has been defined in magnetic and also in thermal application. After computing one electric period, the average value of power is computed in coil winding, in magnets and in sheet as iron losses. The average power losses are automatically transferred to thermal analysis. In each project we have to define the input and output values, the type of coupling project and so on, as described in the attached figure.

As regard losses and temperature, the result is the following:

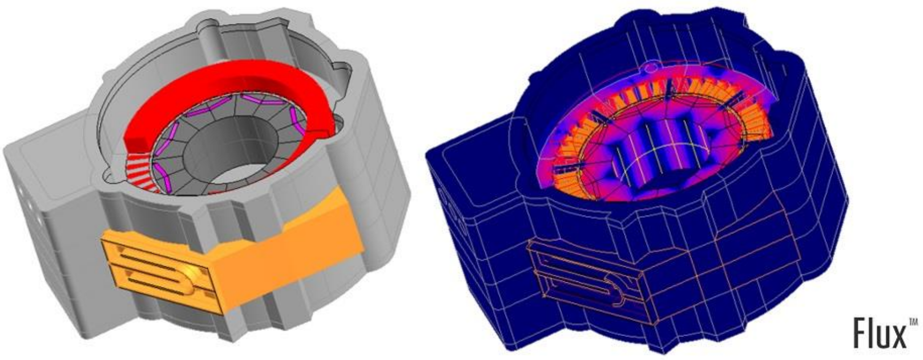


Losses, temperature and rising temperature

Focus on coupling magnetic FEA to CFD code

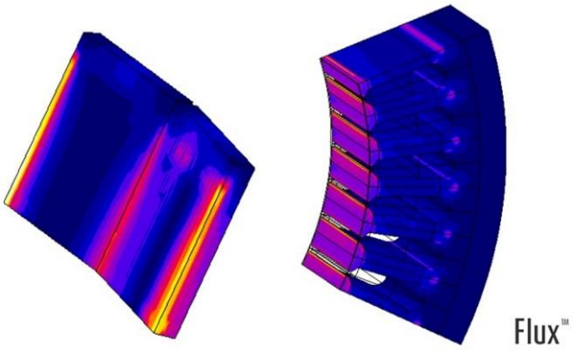
If you want to have more accurate results, the use of CFD analysis is the solution. With CFD code, the main benefit is that there is no more assumption on the exchange coefficients, you just represent the different elements of your motor, with for instance a fan on the shaft, a cooler with a velocity for the liquid, … It helps a lot in order to understand where is the flow, and to better understand critical areas where focus should be on to improve thermal exchange.

The method has been applied on the Prius like motor using Flux 3D and AcuSolve®. The model includes not only the rotor and the stator, but also the casing.



Motor with the casing and B color shade in Flux 3D

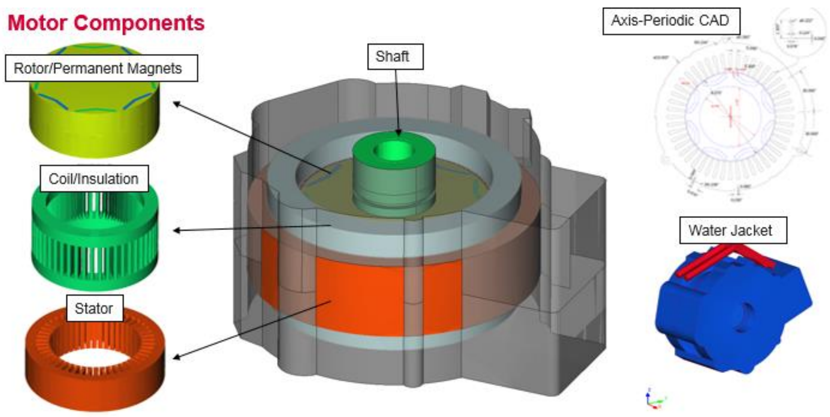
From Flux computation, for the chosen working condition at 900 rpm, we will extract average losses for **magnet** (due to eddy current), in **coils** (Joule losses), **iron losses** in stator and rotor. These values are nodal values corresponding to average losses over one electrical period. Dedicated menus have been developed in order to compute directly these values.



Eddy current losses in magnet and iron losses in stator

Once the losses are computed in Flux, we can export directly a file in a format that can be read by AcuSolve in Nastran format.

In AcuSolve, the geometry of the motor has to be described as well. In the specific case of this motor, the cooling is done with an external coolant, plus the use of oil in part of the casing. The different solid components are described.



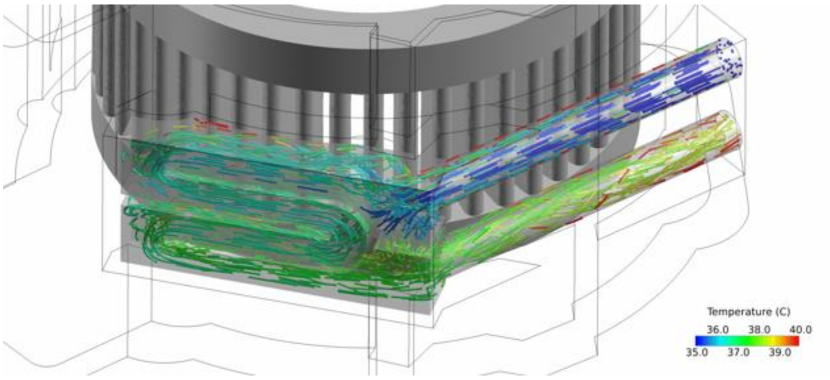
Solid components of the motor

AcuSolve can then be used in order to determine the behaviour of the fluid surrounding the solid components. Rotational effects are considered. Convection on outer surface can be determined. The losses imported from Flux can be read directly, with the possibility to scale, shift or rotate if periodicity is present. The total heat load in watts can also be applied (on coils for instance). A coolant liquid enters and exit with an external water jacket to help cool the motor at 35°C and 2.4 Gal/min. The rotation of the rotor is also taken into account by modifying fluid region adjacent to it.

Coolant Temp (°C)	35
Coolant $\dot{V}$ (m^3/s)	1.50e-04
Stator Losses (W)	951
Windings Losses (W)	1015
Rotor Losses (W)	237
PM Losses (W)	40

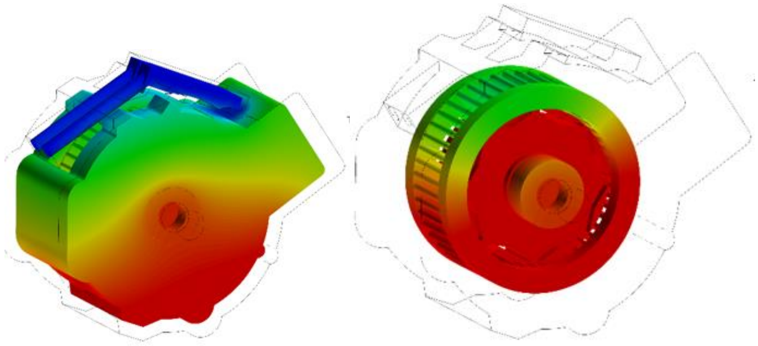
Losses computation

The results allow to understand the flow in the water jacket, and also the temperature distribution in the different elements. There is an increase of 5 degrees between the input and the exit of the water jacket.



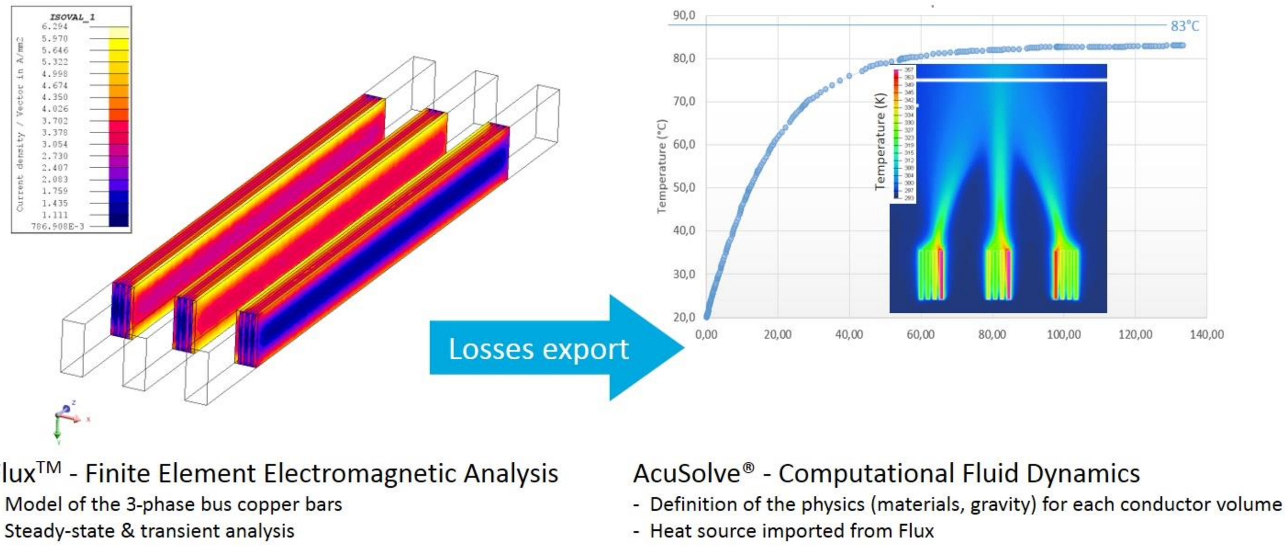
Flow in the external water jacket computed in AcuSolve

The temperature on the casing is shown on the next figure:



Temperature distribution analysis in AcuSolve®

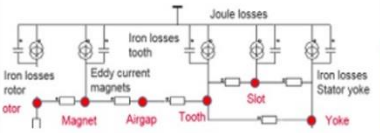
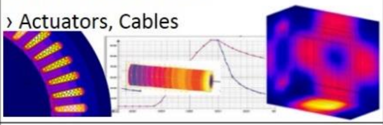
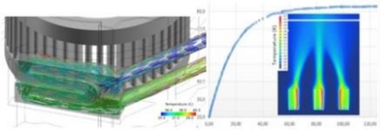
The main benefit is a better understanding of the flow inside and around the motor.



Heating of bus bars coupling both Flux 3D with AcuSolve

Conclusion

Thus we have seen that different methods are available in order to estimate the thermal behavior of electric motors. Each method can be used at different level of the motor design. The equivalent model is interesting at the early design stage in order to check basic working points, or duty cycles. The solving time is fast, allowing parametric design. When more accuracy is required, using finite elements is a good idea, in order to have a better knowledge of losses (iron losses , eddy current losses), and their impact on thermal analysis. The rise of temperature in different areas is also easier to understand and to follow with animation for instance. Then if designers want more accuracy, or to better understand the flow, they can combine FEA magnetics with CFD code. It takes more time to create projects and for the solving time. The use of distribution of computation allow decreasing dramatically the solving time.

	Flux – lumped thermal model coupling with Activate	Flux magneto-thermal coupling	Flux – CFD coupling with AcuSolve
Positioning	**Pre-design** › Global estimation of temperature & variations	**Design** › Study of temperature distribution in the parts	**Validation** › Study of thermal flow › Calibration for Flux & lumped models
Accuracy	› Good global with calibration	› Good global	› Best accuracy › Determination of hotspots
Model set-up	› From Flux thermal model, easy extraction of lumped thermal resistor, or › From analytical solution, requires more knowledge	› Only Flus is used › Flux user with thermal knowledge › Generic method for any application	› 2 software to be run and coupled › Thermal simulation expert required
Solving time	› Very fast: seconds to minutes	› Reduced compared to CFD calculations (minutes to hour)	› Several hours required
Typical application	› Electric motors (calibration, pre-design) › Power transformer 	› Induction heating › Electric motors (incl. convection estimation) › Power transformers › Actuators, Cables 	› Electric motors (validation) › Power transformer (convection) › Power bars, power connections 
Solvers required	› Activate system solver accessible with HyperWorks Units to Flux users	› Flux electromagnetic & thermal modules (static & transient) are included in Flux 2D & 3D with HyperWorks Units	› AcuSolve CFD solver accessible with HyperWorks Units to Flux users

Nowadays more and more possibilities are available in order to improve accuracy of results. New couplings are developped in order to help the designer to be more efficient and more accurate. Do not hesitate to adapth your methodology in order to benefit from the latest developments!

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