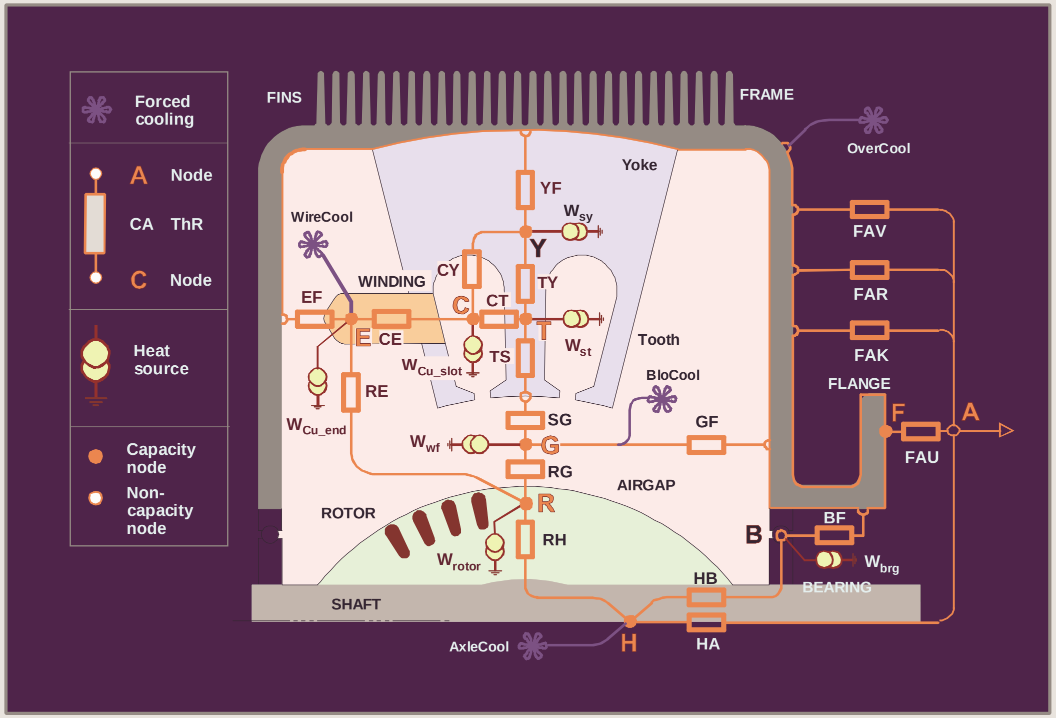
SPEED's Thermal Solver for Electric Motors

...an integral component of SPEED's electric motor CAD



Introduction

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http://www.elec.gla.ac.uk/groups/speed

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1. Introduction

Cooling is one of the most important factors in the performance of electric machines

SPEED's **Hot10 thermal solver is a practical software tool for heat transfer calculations in electric machines.** It is integrated with the SPEED motor design programs . It brings the customary high speed of calculation, friendly interface, and unequalled support that makes SPEED the benchmark for electric machine design software. With a wide use of graphics, an outstanding validation record, and a pedigree that cannot be matched by any other supplier of electric machine software, we are pleased to launch the **Hot10** thermal modell

Traditionally, electric motor designers have relied on simple thermal network models with plenty of calibration. More complex analysis is used only in special cases or for very large machines. *SPEED* provides a range of thermal models to meet the full range of designers' needs, from simple to complex.

Heat transfer calculations often need empirical data to achieve precision. There are two main reasons for this:

(a) The thermal resistance across interfaces is often impossible to calculate from first principles. A good example is the airgap. Another one is the interface between the punchings and the frame.

(b) The convection and flow equations at the frame surface are difficult to solve.

The Hot10 thermal model provides a range of methods for calculating most of the key thermal resistances. It also provides for user-defined values and calibration parameters.

2. Why do we need a thermal model?

We need to know the temperature of the windings, the case, the bearings....indeed all the components of the motor. These temperatures have an important influence on the reliability, efficiency, and ultimately the life of the motor.

We also need to know them if we are to make accurate calculations of the performance.

Since the electromechanical performance depends on these temperatures, and *vice versa* the temperatures depend on the performance, it’s essential **to compute the thermal model at the same time** as the electromechanical model. *SPEED* software does this by integrating the thermal calculations in the heart of the motor design programs.

The first consideration is the required level of complexity. *SPEED*’s thermal model has five levels:

Fixed	The temperatures are fixed at values specified by the user
DegCW	(”degrees C per watt”) uses only a single thermal resistance and capacitance
ThRcct	is a simple thermal resistance equivalent circuit
Hot10	is a comprehensive model with all the main heat flow paths treated individually
Hot10m	is an extension of the Hot10 model with liquid coolant inside the machine.

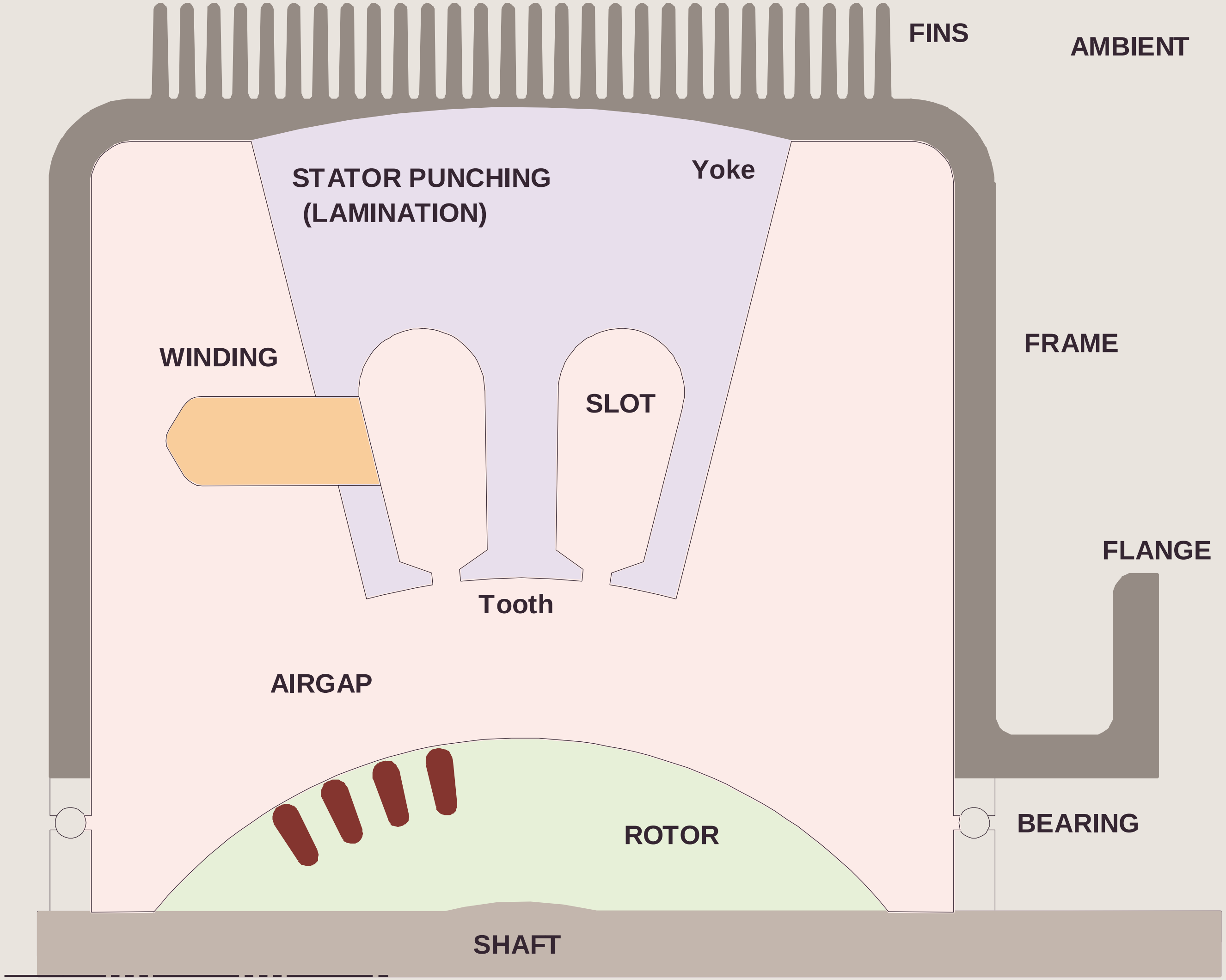
The thermal model comes with many features and options. There is a choice of many different methods for calculating the all-important thermal resistance at the frame surface, with a separate dialog box for this parameter. In addition, the Hot10/m model can calculate most of the key thermal resistances and capacitances from physical geometry and material data.

3. The motor model

The motor model is a hybrid between a transverse and an axial cross-section.

The main components are:

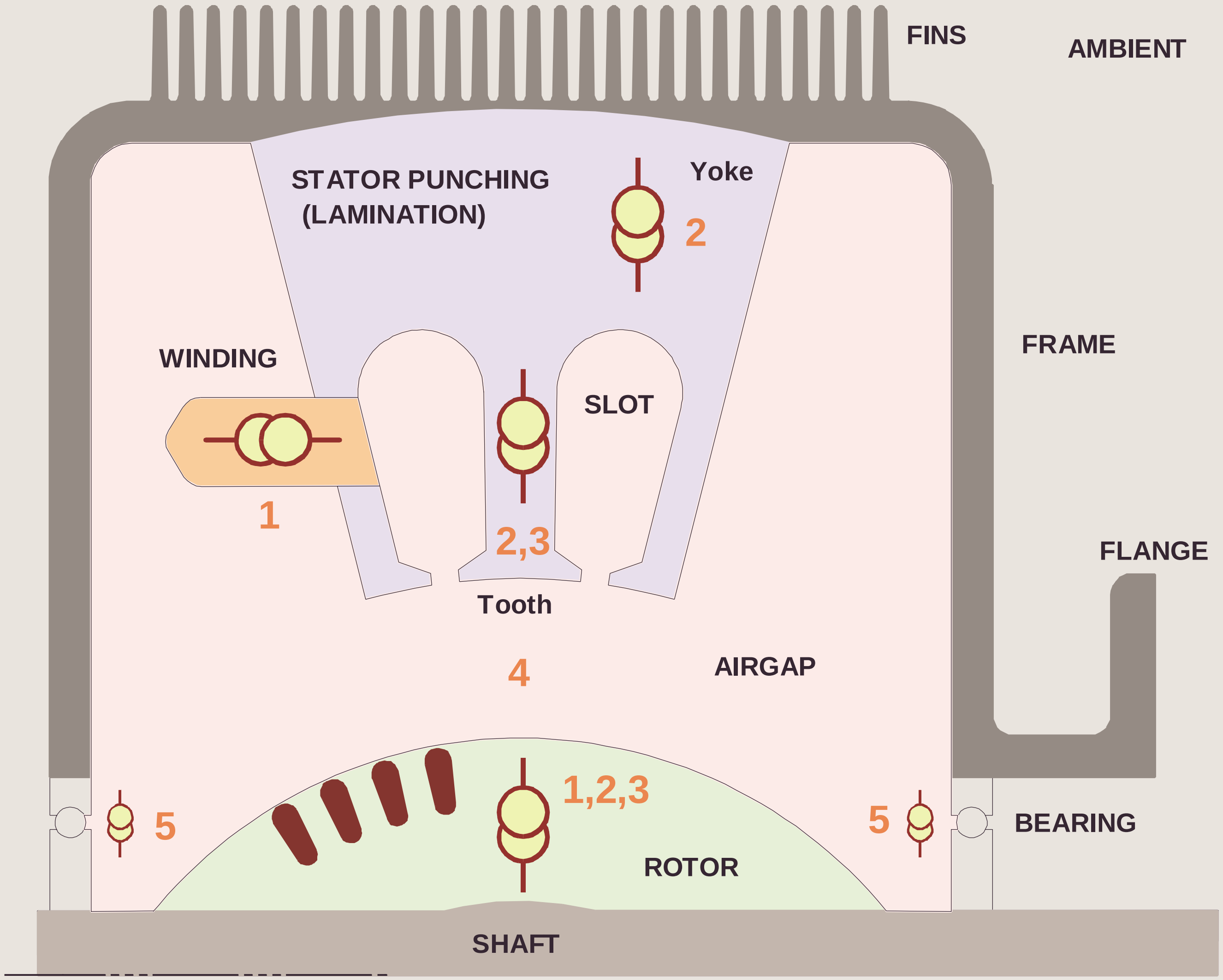
- Frame (with fins)
- Bearings
- Stator punching
- Slots and teeth
- Conductors or "winding"
  (only endwindings shown)
- Rotor
  (with cage bars or magnets)
- Shaft
- Mounting flange



4. Heat sources — where the heat arises

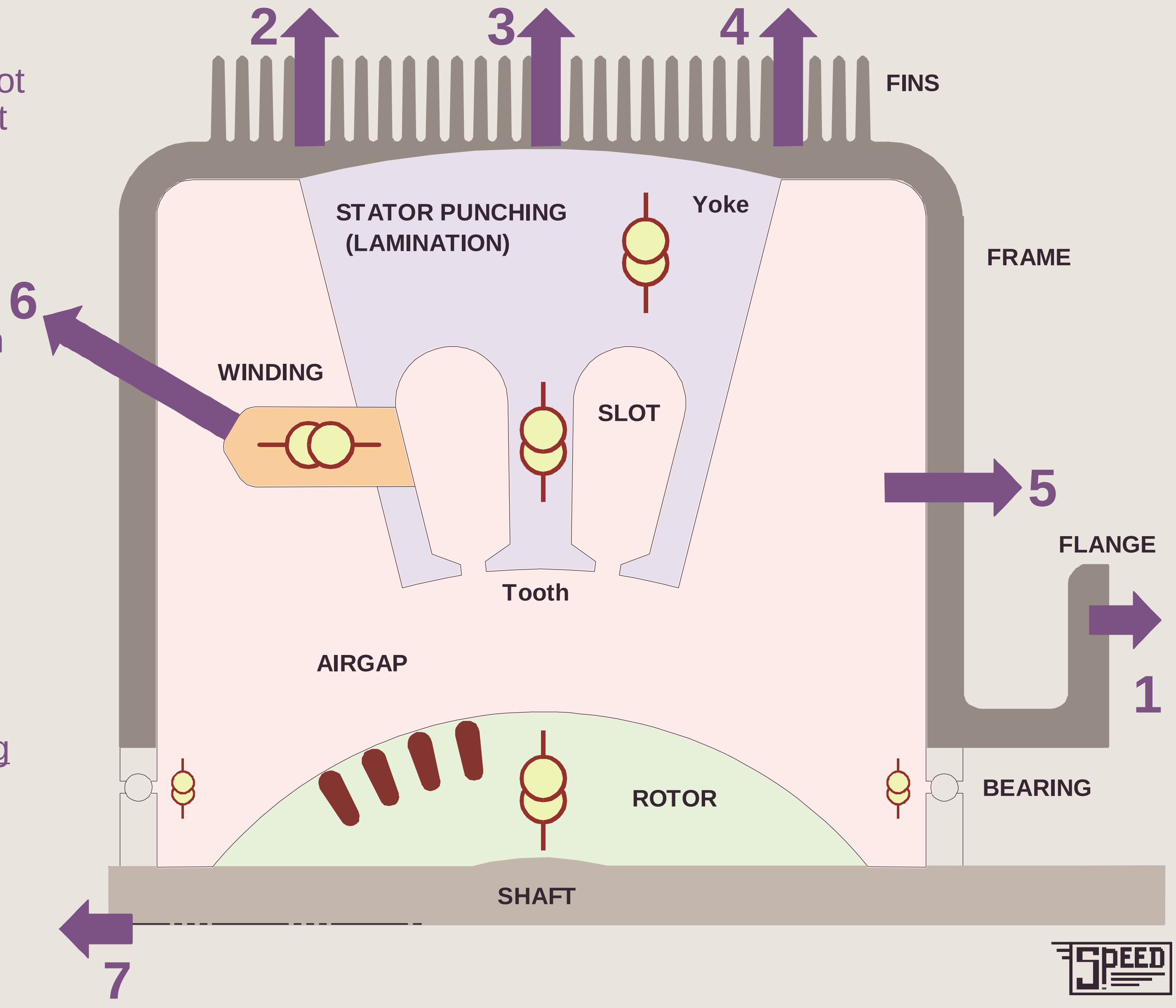
1. **Copper loss W_{Cu}**
2. **Core loss W_{Fe}**
3. **Stray loss W_{SLL}**
4. **Windage loss W_{wf}**
5. **Bearing loss W_{Brg}**

The symbol for a heat source is the same as for a current source in an electrical equivalent circuit



5. Heat sinks — where the heat goes out

1. Conduction
   through the flange or foot mountings and the shaft
2. Convection
   enhanced by finning
3. Radiation
   enhanced by painting in matt black
4. Forced convection
   external fan or water cooling jacket
5. Internal coolant
   "wet" motor with oil or water in the airgap
6. Direct conductor cooling
   oil- or water-filled conductors or cooling tubes in the slots
7. Direct shaft cooling



6. Heat flow — thermal networks

The heat sources and sinks are interconnected by thermal resistances that represent the heat flow paths. The resulting network can be solved like an electric circuit. The result is a set of node temperatures and a set of heat flows between nodes.

The thermal resistances that represent the main heat flow paths have a dominant influence, and for this reason it is often permissible to use only a simple thermal network with a small number of nodes.

Thermal resistances are measured in °C/W. For transient calculations we need to know the thermal capacities of all the components of the motor. These are measured in J/°C.

First we'll consider only the steady-state heat transfer. Later we'll add some transient conditions.

We'll start with the two basic models, **DegCW** and **ThRcct**.

7. The DegCW model

The **DegCW** model has only two temperature nodes:

A ambient (T_A)
F frame (T_F)

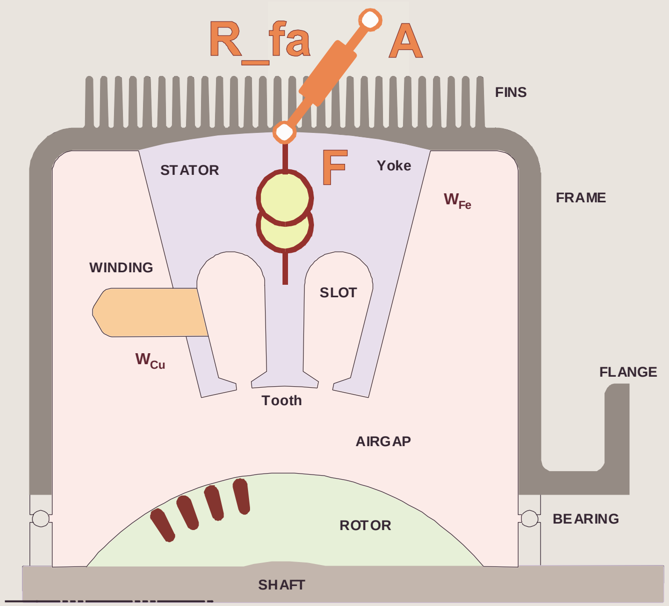
In effect, the model assumes that the whole motor is at a uniform temperature T_F, and ignores any temperature variations within the machine.

The **DegCW** model has just one thermal resistance **R_fa** which usually means the thermal resistance from the frame surface to the surroundings (frame-to-ambient). **R_fa** is specified by means of a single input parameter (also called **DegCW**).

The steady-state temperature rise is then calculated using the equation

$$\Delta T = \mathrm{R\_fa} \times \text{Total Losses}$$

Of course the Total Losses (in watts) are calculated in the electromechanical part of the computation.



This simple model is widely used in the servo motor industry. The thermal resistance **R_fa** is multiplied by the thermal capacity *C* of the motor to give the thermal time constant τ in minutes:

$$\tau = \mathrm{R\_fa} \times C / 60$$

. In some cases R_fa is specified as the thermal resistance by conduction to a cooling plate (heatsink) of standard dimensions.

8. The ThRcct model

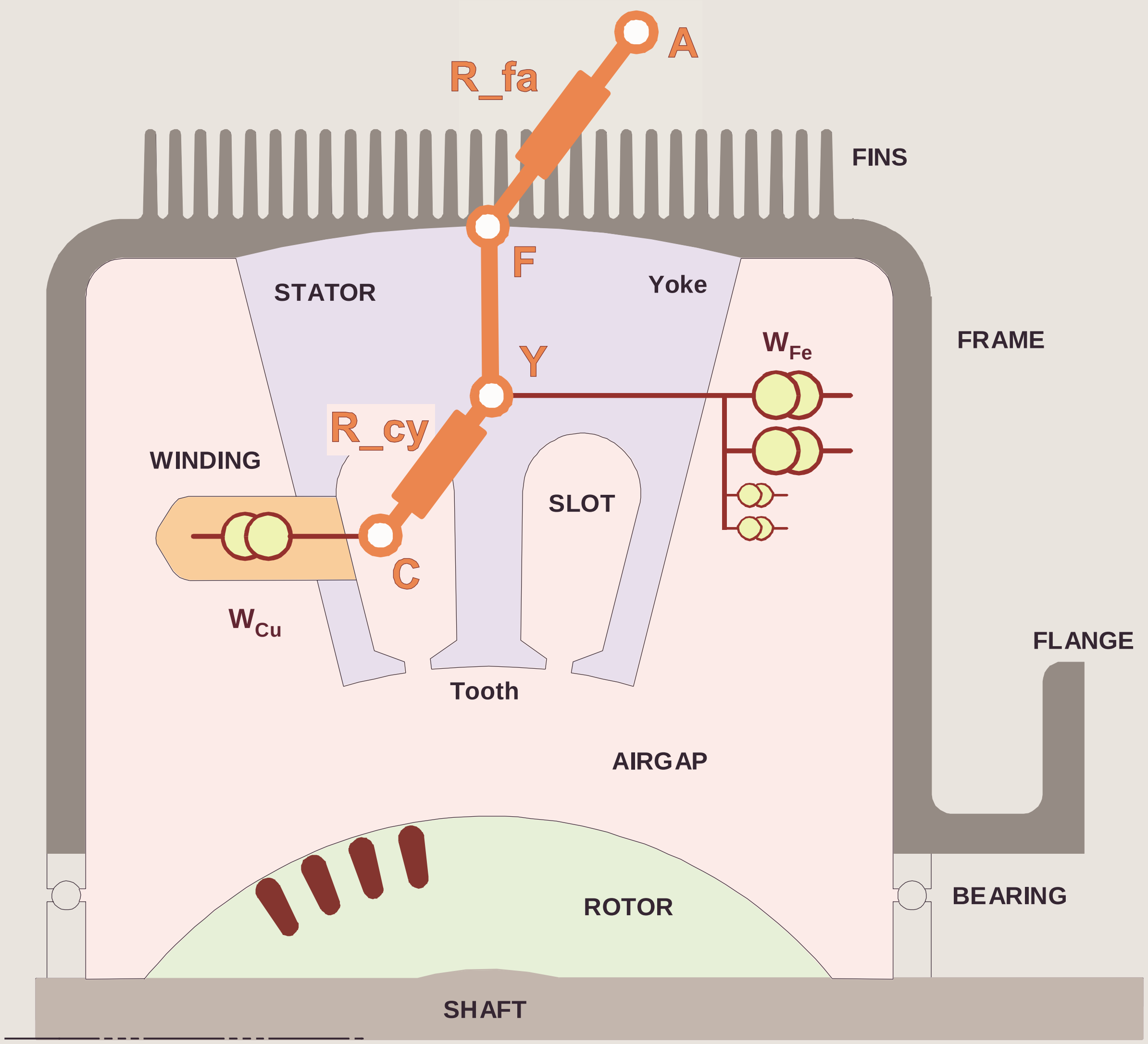
The **ThRcct** model has four temperature nodes:

- **A** ambient (T_A)
- **F** frame (T_F)
- **Y** stator yoke (T_Y)
- **C** conductors (T_C)

The model assumes $T_F = T_Y$, i.e., no temperature drop across the stator punching. *

R_fa is the thermal resistance from the frame surface to the ambient. Click **R_fa** to see how it can be calculated.

R_cy is the thermal resistance from the conductors to the yoke, mainly due to the slot insulation.



* This makes nodes F and Y effectively the same node, but later we'll remove this short-circuit and consider the diffusion resistance through the yoke.

9. Basic thermal network calculations in the ThRcct model

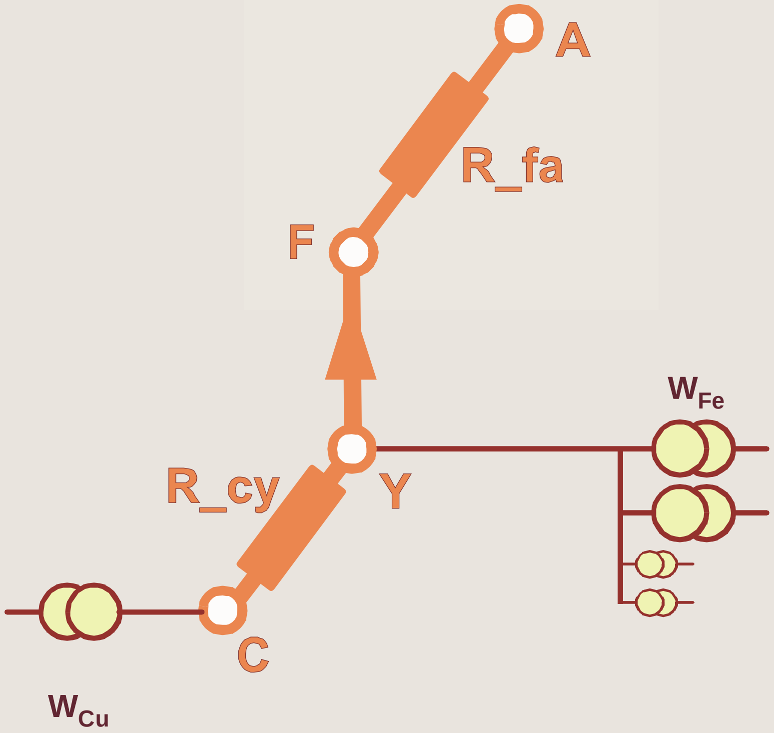
The copper loss W_{Cu} feeds into node C, and all the other losses feed into node Y. In the steady-state all these watts flow out to node A. The temperature rise at node C is

$$T_C - T_A = R\_cy \times W_{Cu} + R\_fa \times W_{Total}$$

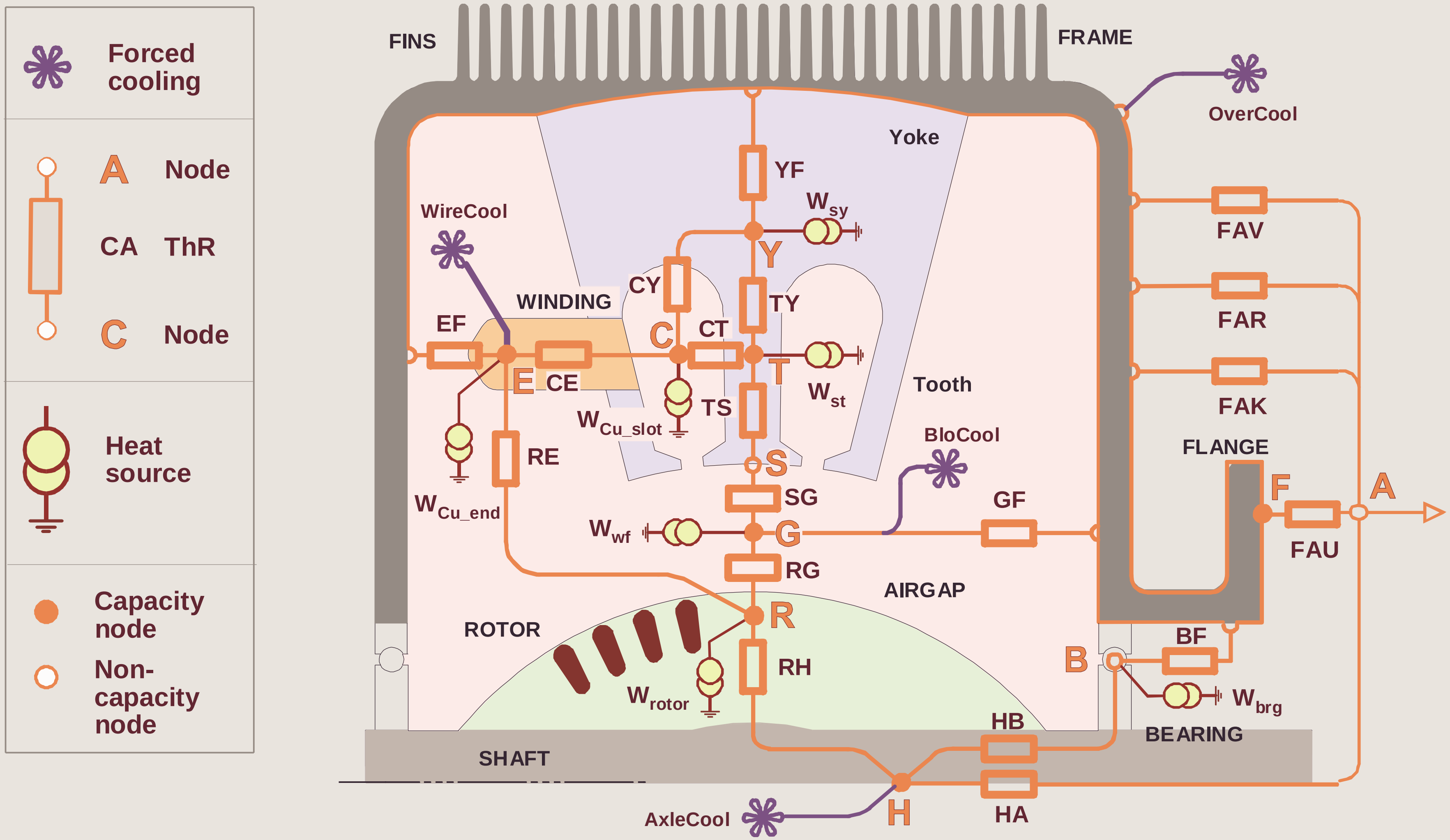
R_fa can be determined by several different methods. Click R_fa to see how it can be determined in *SPEED* software.

R_cy is mainly due to the slot insulation and is calculated from the thermal conductivity of the slot liner, **ct_liner**.

We use the **ThRcct** model for quick calculations, or when we don't have much detail about the construction and materials in the machine. It has more detail than the **DegCW** model, and (importantly) it can distinguish between the conductor temperature and the frame temperature.



10. The Hot10 thermal model



The **Hot10** model is a comprehensive thermal model with 10 temperature nodes (each with its own thermal capacity; 19 thermal resistances; and distributed losses.

11. The Hot10m model with liquid coolant

✻ **Forced cooling**

A Node

CA **ThR**

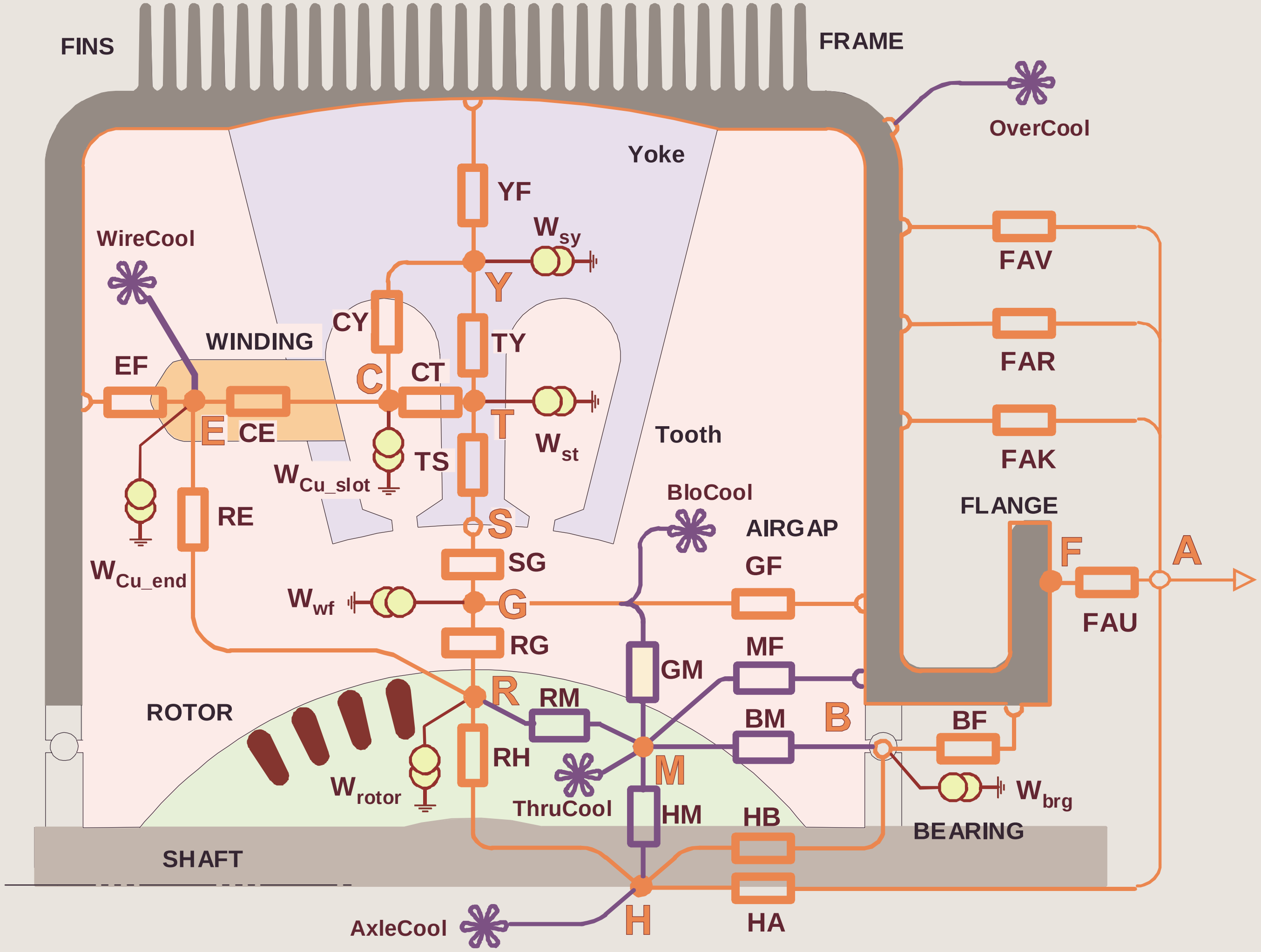
C Node

Heat source

● **Capacity node**

○ **Non-capacity node**

Extra elements for coolant



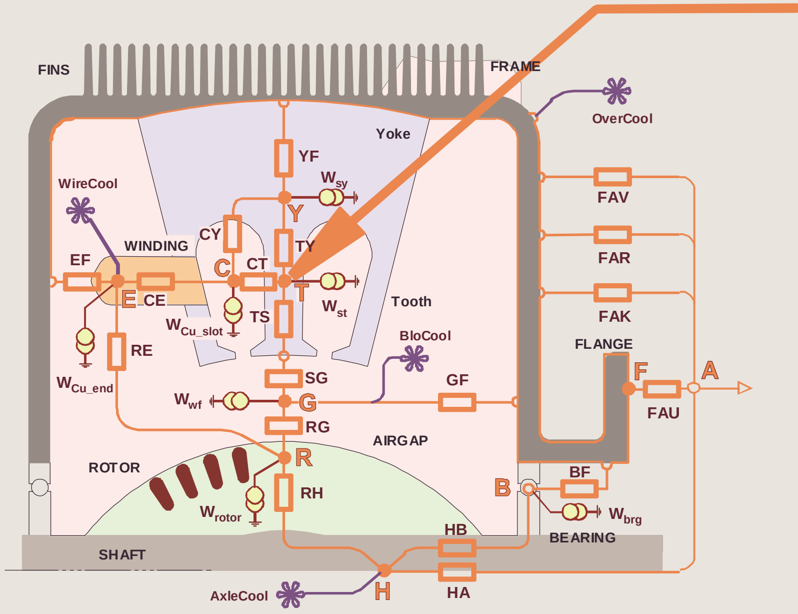
The **Hot10m** model has an additional node M representing liquid cooling in side the machine. There are now 24 thermal resistances.

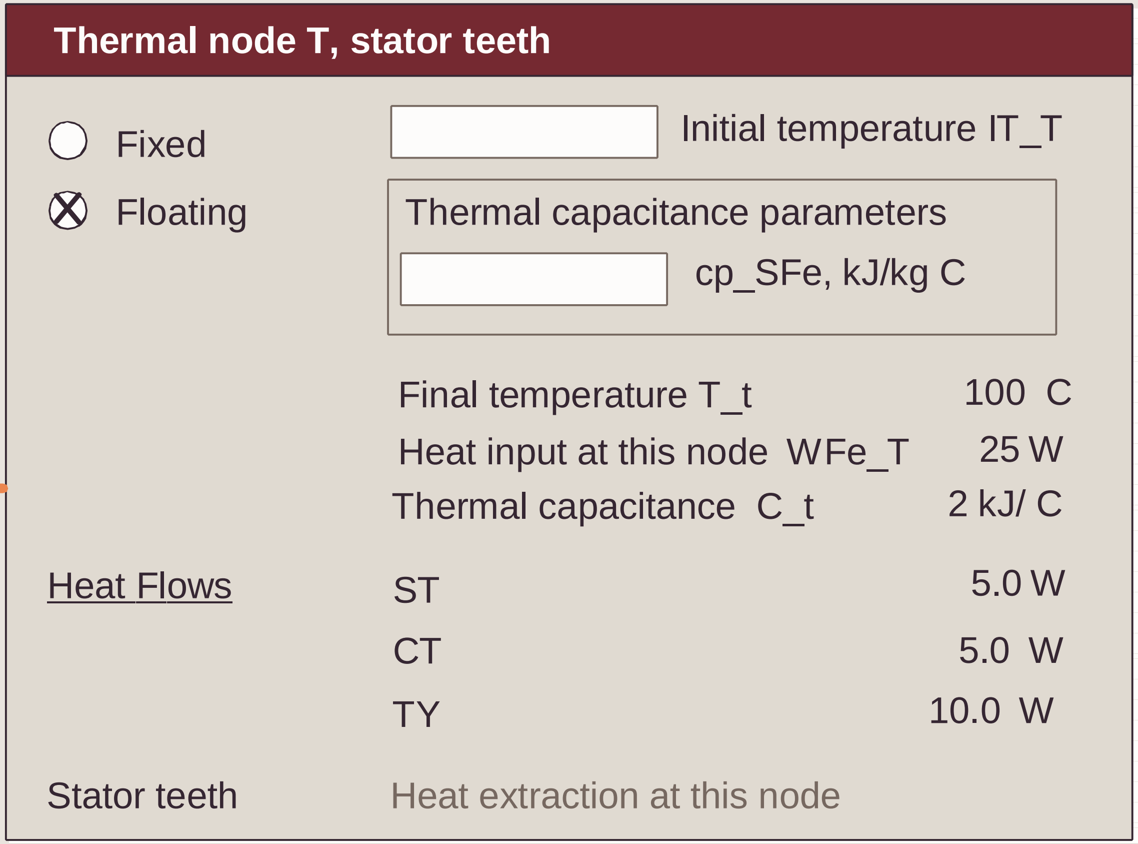
12. Data entry and local results for temperature nodes

Click node T

The dialog box for a thermal node lets you select the type of node (fixed or floating temperature), the initial temperature for transient calculations, and parameters for calculating the thermal capacity at this node.

After the computation, the results include the temperature and the heat flows to and from this node.





Thermal node T, stator teeth

○ Fixed

☒ Floating

Initial temperature IT_T

Thermal capacitance parameters

cp_SFe, kJ/kg C

Final temperature T_t	100 C
Heat input at this node WFe_T	25 W
Thermal capacitance C_t	2 kJ/ C

Heat Flows

ST	5.0 W
CT	5.0 W
TY	10.0 W

Stator teeth

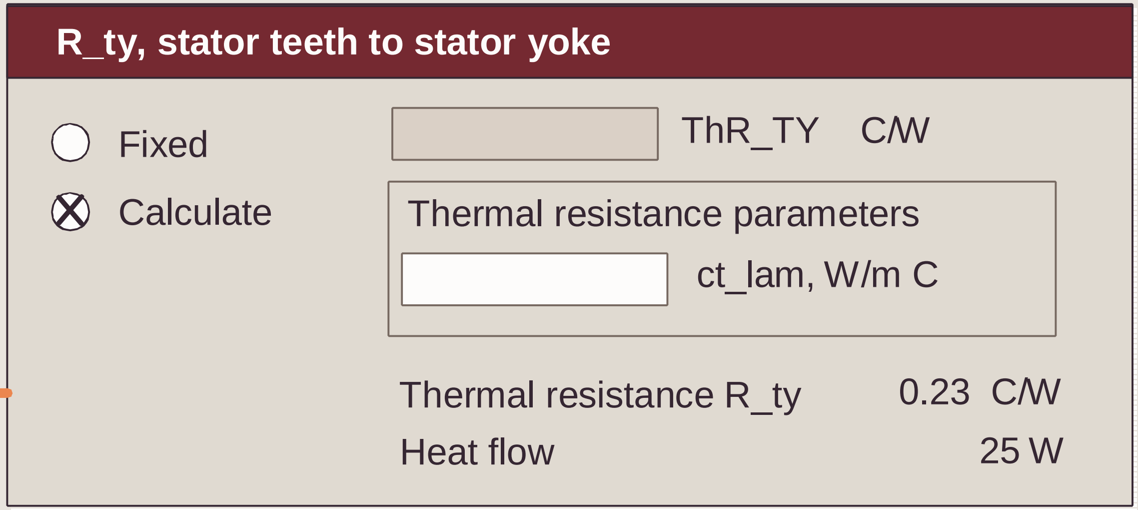
Heat extraction at this node

13. Data entry and local results for thermal resistances

Click thermal resistance **TY**

The dialog box for a thermal resistance lets you decide whether to supply a resistance value, or whether is will be calculated automatically from geometry and material data.

After the computation, the results include the value of the resistance and the heat flow through it.



R_ty, stator teeth to stator yoke

○ Fixed

☒ Calculate

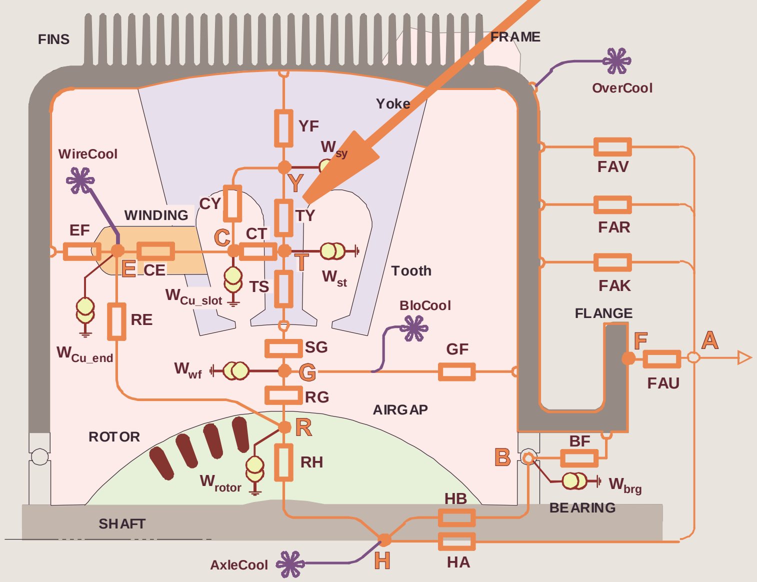
ThR_TY C/W

Thermal resistance parameters

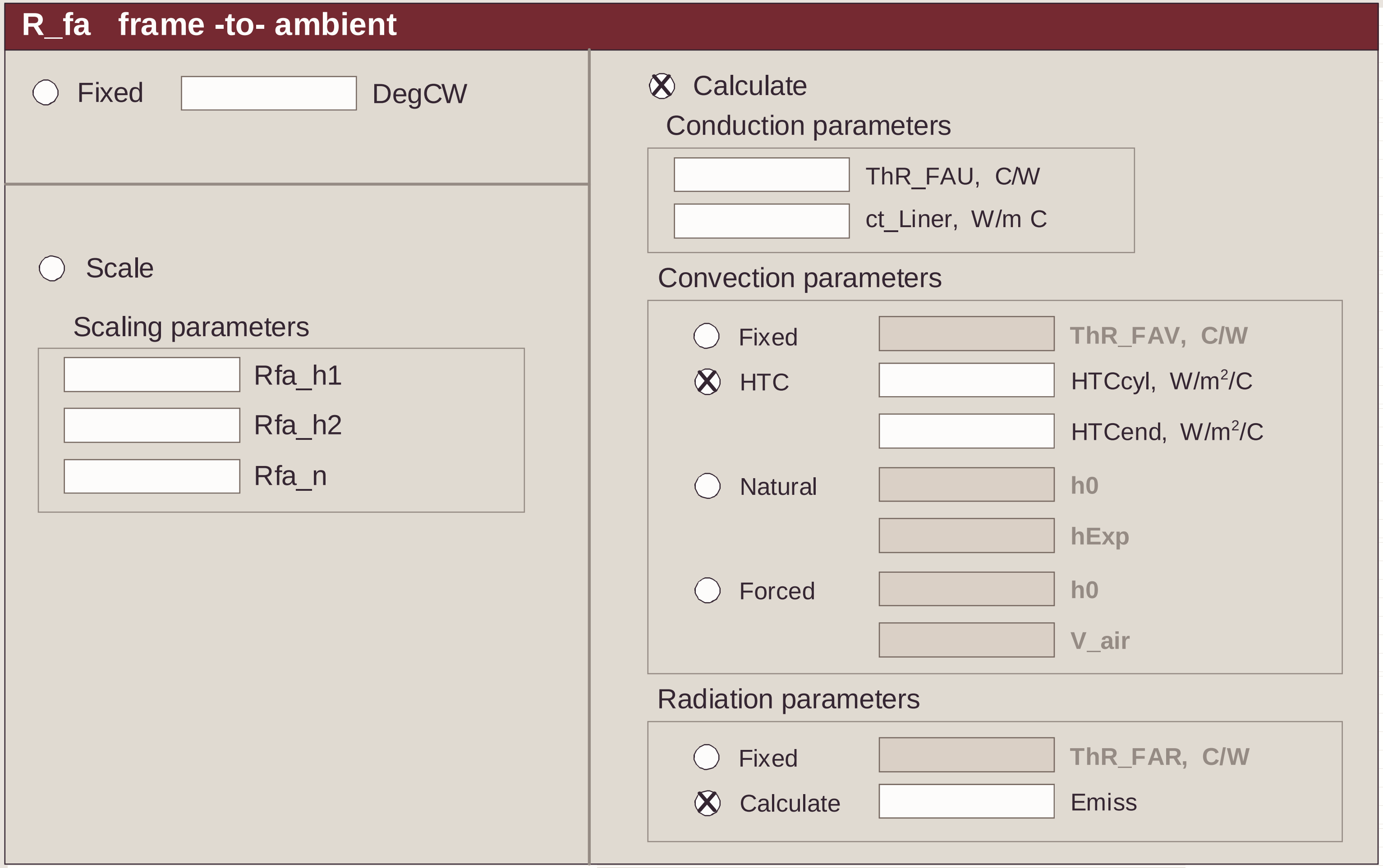
ct_lam, W/m C

Thermal resistance R_ty 0.23 C/W

Heat flow 25 W



14. The R_fa dialog (frame-to-ambient thermal resistance)



R_fa frame -to- ambient

○ Fixed ☐ DegCW

○ Scale

Scaling parameters

☐ Rfa_h1
☐ Rfa_h2
☐ Rfa_n

☒ Calculate

Conduction parameters

☐ ThR_FAU, C/W
☐ ct_Liner, W/m C

Convection parameters

○ Fixed ☐ ThR_FAV, C/W
☒ HTC ☐ HTCcyl, $W/m^2/C$
☐ HTCend, $W/m^2/C$
○ Natural ☐ h0
☐ hExp
○ Forced ☐ h0
☐ V_air

Radiation parameters

○ Fixed ☐ ThR_FAR, C/W
☒ Calculate ☐ Emiss

R_fa receives special attention because it is a very important thermal resistance. There are several different cooling modes (radiation, convection, conduction) and several ways to characterize them. The **R_fa** dialog provides an easy way to organize these methods.

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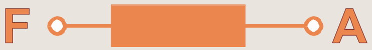
R_fa : more detail...



R_fa is the thermal resistance from frame to ambient, i.e. from node F to node A. It is measured in C/W.

If a **measured value** is available we can enter this in the **R_fa dialog** as a fixed value, **DegCW**.

Otherwise we have two ways to calculate **R_fa**. One is to scale it using three coefficients for the frame-to-ambient heat transfer coefficient. The other way is to calculate it in detail from three components representing conduction, convection and radiation.

The conduction component includes two terms in series. One is **ThR_FAU** (frame-to-ambient by conduction). It is usually the thermal resistance between the motor flange and the mounting plate, and must be specified in C/W. The other is the thermal resistance across the slot liner, whose thermal conductivity is **ct_liner**.

The convection component can be specified as a fixed value **ThR_FAV** (frame-to-ambient by convection), or it can be calculated in one of two ways:

(i) by specifying heat transfer coefficients. The heat transfer coefficients are **HTCcyl** for the cylindrical surface area and **HTCend** for the end-caps, both in $W/m^2/C$.

continued/...

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R_fa continued...

(ii) by using internally calculated heat transfer coefficients. For natural convection the coefficients **h0** and **hExp** must be specified. For forced convection the coefficients **h0** and **V_air** (air velocity) must be specified. These are detailed in the main reference manual.

The radiation component can be specified as a fixed value **ThR_FAR** (frame-to-ambient by radiation), or it can be calculated from the classical radiation formula. For this calculation the emissivity of the frame surface must be specified as **Emiss**.

Note that **R_fa** doesn't include any allowance for internal thermal resistances; they are determined separately.

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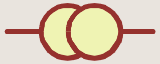
15. Copper losses



W_{Cu}

Copper losses are calculated as I^2R, where I is the r.m.s. current and R is the resistance. Usually R is the resistance of one phase of the winding, and I is the phase current, so the result must be multiplied by the number of phases.

In AC machines (including brushless PM and switched reluctance machines) the phase resistance is increased by the skin effect, which arises not only from the fundamental frequency but also from any harmonic content in the current. This can arise from waveform distortion or from PWM control in the drive. The effect is reduced by using stranded conductors and in some cases even Litz wire.

Because copper is such a good thermal conductor, it is often permissible to treat the whole winding as a single temperature node. SPEED's *Hot10* thermal model has two nodes, one at the slot centre and one at the end-windings, to allow for a small temperature difference between the end-windings and the centre of the windings.

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16. Core losses

Core losses are also known as "iron losses".

Core loss arises from

(a) hysteresis loss caused by the cyclic variation of the magnetic field in the iron and

(b) eddy-current loss induced by the variation of the field in the iron.

Sometimes the iron is attributed with an "anomalous loss" component, because the total iron loss is often greater than predicted by the classical theory of hysteresis loss and eddy-current loss.

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To progress further...

For more detail about the thermal models, please refer to the main SPEED reference manuals.

To see an example of a thermal calculation, run the **Hot10** tutorial.