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C. Kral, A. Haumer, M. Plainer
Arsenal Research, Vienna, Austria

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C. Kral, A. Haumer, M. Plainer
Arsenal Research, Faradaygasse 3, 1030 Vienna, Austria

Abstract

SimpleFlow-library was created to model heat and coolant flows of simple thermal equivalent circuits. The main components of this library and their applications are presented in this paper. Furthermore, a thermal model of a surface cooled squirrel cage induction machine is introduced. The simulated temperatures are compared with measuring results which were obtained in the laboratory.

1 Introduction

Typical cooling models consist of a *thermal network model* and a *cooling circuit* of a device (e.g. an electrical machine) which is going to be cooled. The mechanism of coolant flow is different from heat conduction [1], described by the *thermal network model.* Therefore in the second section the *SimpleFlow*-library is introduced. Basic equations and components of the cooling model are presented, as well as the structure of the library. The third section introduces a complete thermal network model of a surface cooled squirrel cage induction machine (totally enclosed fan cooled), using the elements from `Modelica.Thermal.HeatTransfer.` The simulation is presented in the fourth section, whereas the measurement is described in the fifth section. The sixth section compares simulation and measurement results.

2 SimpleFlow Library

The description of coolant flows due to forced convection is difficult. The developed *SimpleFlow*-library was designed to model such coolant flows under the following conditions:

- Splitting of media flows is simple.
- Mixing of media flows obeying mixing rule can be realized easily.
- Reversing the direction of flow is possible.
- No complex media properties are needed.
- The medium is considered to be incompressible.
- Mixtures of different media are not taken into account. Each individual cooling circuit has to have a designated medium.
- Medium properties are considered to be constant.
- Pressure changes are only caused by pressure drops (due to friction of the coolant flow at solid surfaces).

The library design has been restricted to simple media as coolants, only taking basic thermodynamic effects into account, such as the transport of heat by a flowing medium. These prerequisites allow a very easy handling of the library and are sufficient for a wide range of applications, including the cooling of devices. Cooling of electrical machines is an important topic, because the forecast of machine temperature increases allows to improve the machine design as well as to reduce the machine size and mass, which ends up in competitive advantages. In these applications temperature rise of the coolant as well as pressure drop of the coolant flow are rather small, so the abovementioned conditions are fulfilled satisfactorily.

Other applications not fulfilling the abovementioned conditions like complex thermodynamic processes have to be modelled using `Modelica.Media` and `Modelica.Fluid`, which are currently under development. So the *SimpleFlow*-library is not designed to compete with these high sophisticated thermodynamic libraries but to ease the modelling of simpler applications.

2.1 Equations

SimpleFlow-library has to take simple thermodynamic equations in to account. The following quantities have been chosen to describe the state of a coolant flow:

- *pressure* (`p`) and *temperature* (`T`) as potentials
- *mass flow* (`mflow`) and *simple energy flow* (`sEflow`) as flow quantities

The naming of *simple energy flow* is chosen to keep in mind that only the heat transported by the media's thermal capacity is taken into account, avoiding mix-up with thermodynamic energetic quantities like enthalpy.
The basic equations of a flow element are collected in partial models, placed in subpackages named `Partials` and `Friction` [2], [3], [4], [5]:

- Pressure drop is a function of mass flow: linear dependency is assumed to a limit where laminar flow is effective, and quadratic dependency is modelled for higher mass flows approximating turbulent effects.
- Mass flow balance:
  `flowPort_in.mflow +`
  `flowPort_out.mflow = 0;`
- energy flow balance:
  `flowPort_in.sEflow +`
  `flowPort_out.sEflow + Q_flow =`
  `m * cp * der(T);`
  where `Q_flow` is the energy flow exchanged with the environment outside the medium, `m` is the medium's mass, `cp` represents specific heat capacity of the medium and `T` is the medium temperature within the element.
- Energy flow at the port where the mass flow leaves the element:
  `flowPort_out.sEflow =`
  `flowPort_out.mflow * cp * T;`
- Mixing rule at the port where the mass flow enters the element:
  `flowPort_in.sEflow =`
  `flowPort_in.mflow * cp * flowPort.T;`

The actual connectors of any component are `flowPort_a` and `flowPort_b`. If the medium flows from `a` to `b`, `a` is assigned to `in` and `b` is assigned to `out`. For the opposite flow directions `a` is assigned to `out` and `b` is assigned to `in`. This means, that there are two sets of equations used depending on the actual flow direction of the medium. The handling of these two sets of equations is supported by the Modelica statement `semiLinear` [6].
Modelica ensures the correct summation of mass flows and energy flows as well as equity of potentials pressure and temperature of connected ports. Since the mixing rule is applied at the inlet port of an element according to the actual flow direction, the temperature of the port where the mass flow leaves the preceding element does not necessarely show the medium's temperature but the (possible) mixing temperature of the following element. The medium's temperature is represented by the internal state `T`.
Besides the definition of common media (air and water) and appropriate sensors for pressure and pressure drop, temperature and temperature drop, mass flow and energy flow the library puts the following components at the user's disposal.

2.2 Sources

- Infinite ambient with constant or prescribed temperature and pressure which is not influenced by ingoing or outcoming flows.
- An element which allows to define pressure level in a closed circuit, since flow elements only define pressure drops.
- Simple fans (neglecting the media mass within the fan) and pumps (taking the media's thermal capacity into account), allowing to define either pressure drop or mass flow.

2.3 Components

- Isolated pipes with and without consideration of medium mass
- Pipes (with and without medium's mass) with a thermal connector where heat is exchanged with a thermal network.
- A predefined simple cooler, containing a vector of cooler elements, each consisting of a pair of pipes, coupled with a thermal conductor.

The usage of the library is demonstrated with a couple of simple examples. These elements together with `Modelica.Thermal.HeatTransfer` allow the modelling of complex applications like the cooling of an electric machine.

3 Thermal Equivalent Circuit

The components of a thermal equivalent circuit can be imported from `Modelica.Thermal.HeatTransfer`. The thermal networks are designed in the style of electrical components and circuits. The components of such a network are:

- Nodes are regions of constant temperature. The potential of a node represents the absolute temperature of that node. The SI unit of the absolute temperature is K.
- A loss source in the thermal circuit is equivalent to a current source in an electric circuit. There are loss sources where the precalculated losses have to be corrected by the actual temperature of the corresponding node in order to consider copper losses correctly. Other loss sources such as iron losses do not need a temperature dependent correction. The SI unit of the heat flow is W.
- Thermal resistors represent regions of heat conduction. For technical application such as electric machines, heat transfer is mainly heat conduction and convection. Heat radiation is usually not considered. The SI unit of a thermal conductance is K / W. A thermal conductor is the reciprocal of a thermal resistor. Its SI unit is W / K.
- Thermal capacitors represent the ability of storing heat energy in a certain region. The SI unit of a thermal capacitor is Ws / K.

The utilized thermal equivalent circuit is shown in fig. 1. With respect to the thermal heat conduction paths the induction machine is divided into three axial sections. The outer sections are the drive end (A-side) and the non-drive end (B-side). End-rings (`ERA` and `ERB`), end cap air (`AIA` and `AIB`), winding heads (`WHA` and `WHB`), housing (`HOA` and `HOB`) and cooling ribs (`RIA` and `RIB`) refer to either of these sides. The middle section consists of the rotor yoke (`RYO`), rotor slots (`RSL`), rotor teeth (`RTO`), the air gap (`AGP`), stator slots (`SSL`) and stator teeth (`STO`), stator yoke (`SYO`), housing (`HOM`) and cooling ribs (`RIM`).

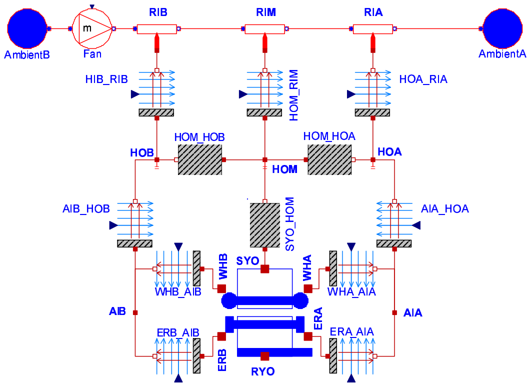

Figure 1: Thermal equivalent circuit of a surface cooled squirrel cage induction machine

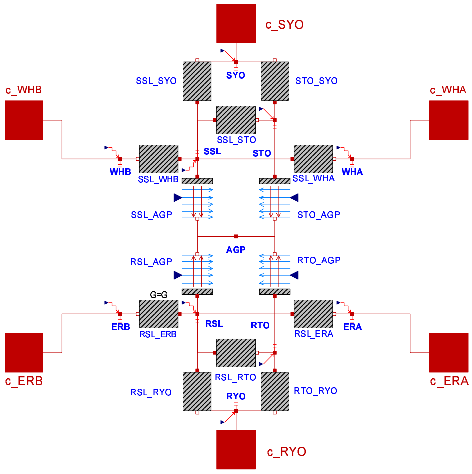

Figure 2: Thermal network of the active part

To achieve reusability, the active part – which is the same for many types of cooling – is modelled as a separate submodel with appropriate connectors (see fig. 2)

The losses of the induction machine have to be separated in accordance to the introduced model. Stator copper losses have to be divided into slot losses (`LSSL`) and the losses with respect to the winding heads (`LWHA` and `LWHB`) of each side. The ratio of these losses is directly proportional to the respective coil length within these sections. Rotor heat losses have to be divided into rotor slot losses (or bar losses; `LRSL`), and the losses with respect to the end rings of each side (`LSRA` and `LEAB`). Stator and rotor iron losses have to be determined with respect to yoke and teeth (`LSYO`, `LSTO`, `LRYO` and `LRTO`). Copper losses are precalculated and have to have temperature correction in order to model the actual losses accurately.

Therefore, there exist four types of nodes:

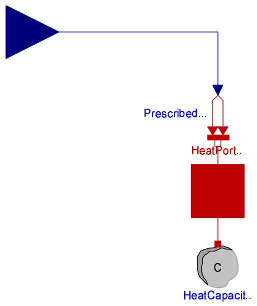

Figure 3: Node with constant losses

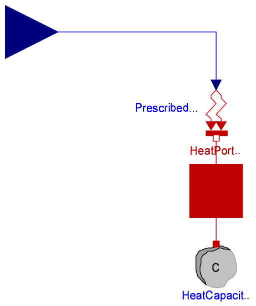

Figure 4: Node with temperature dependent losses

- Node without any properties, such as end cap air (`AIA` and `AIB`)
- Node with thermal capacity, such as the parts of the housing (`HOA`, `HOB`, `HOM`)
- Node with thermal capacity and losses (without temperature dependent correction), such as the stator yoke (`SYO`); see fig. 3
- Node with thermal capacity and losses (with temperature dependent correction), such as the stator slots (`SSL`); see fig. 4

Temperature dependent correction is done by the following formula:

$$\texttt{Losses}\,(T) = \texttt{Losses}\,(T_0)\,[1 + \alpha\,(T - T_0)] \quad (1)$$

where T_0 designates the reference temperature at which the temperature dependent copper losses have been calculated.
Two types of thermal conductances have been used:

- `Modelica.Thermal.HeatTransfer.ThermalConductor` with constant thermal conductance
- `Modelica.Thermal.HeatTransfer.Convection` where the actual thermal conductance is prescribed by a signal input. This allows to define thermal conductance dependent on actual machine speed.

It is advantageous if loss components are directly available from machine design software. Otherwise, these components have to be estimated with respect to the current density or flux density and the mass of these sections.

4 Simulation

The geometric design data of the induction machine were available by courtesy of the machine manufacturer. The electromagnetic quantities such as magnetomotive forces (mmf), flux densities, current densities etc. were determined by motor design software *ASYN*. The output data of the motor design software deal as input parameters for the determination of the relevant thermal parameters of the machine. These parameters are the thermal conductances and capacitances as shown in fig. 1 and have been calculated as follows [2], [3].

- Thermal conductances in a homogenous region:
  $$\frac{1}{R_{th}} = \lambda \frac{A}{l} \quad (2)$$
  where λ designates the material specific thermal conductivity, A is the cross section and l is the length of heat conduction.
- Thermal conductances of heat transfer at a surface between solid and coolant flow:
  $$\frac{1}{R_{th}} = \alpha A \quad (3)$$
  where α designates the heat transfer coefficient which is dependent on coolant properties as well as the velocity of coolant flow and A is the surface area.
- Thermal capacity:
  $$C = mc \quad (4)$$
  where m is the mass of the considered region and c is the material specific heat capacity.

Heat transfer between cooling ribs and air flow was also modelled in three axial sections, using the elements of the *SimpleFlow*-library to describe the air flow. Air flow rate is adjusted proportional to the actual machine speed.

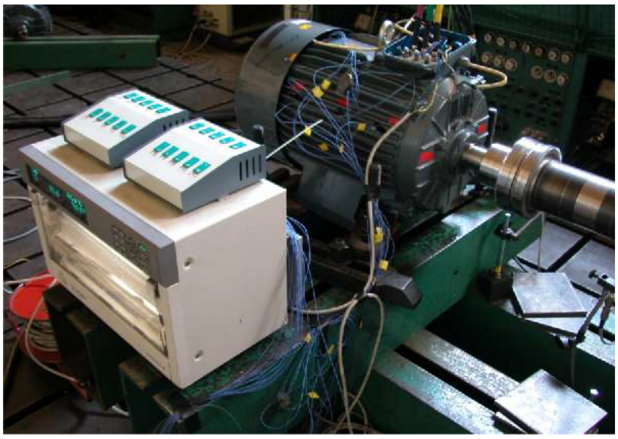

Figure 5: 18.5 kW squirrel cage induction machine with nickel-chromium-nickel temperature sensors and temperature recorder

5 Measurement

Measurements were carried out for a four pole, 18.5 kW squirrel cage induction machine with surface cooling. The machine is shown in fig. 5. The stationary parts of the machine were equipped with nickel-chromium-nickel temperature sensors:

- one sensor in the stator slot (two additional PT-100 sensor were already available in this machine)
- one sensor in a stator tooth
- three sensors in the winding head of each side of the machine in order to average the measured temperature in these areas
- one sensor in the stator yoke
- one sensor on each side of the end cap air (A-side and B-side)
- three sensors in the housing (A-side, middle, B-side)
- one sensor for ambient temperature
- one sensor for the air temperature in the cooling ribs at the B-side (blow-in)
- one sensor for the air temperature in the cooling ribs at the A-side (blow-out)

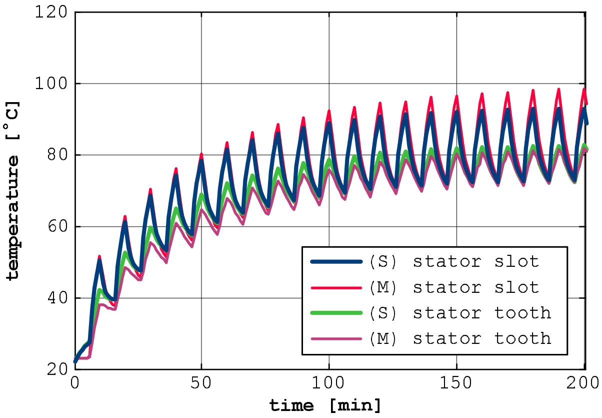

Figure 6: Simulated (S) and measured (M) stator slot (`SSL`) and stator tooth (`STO`) temperature

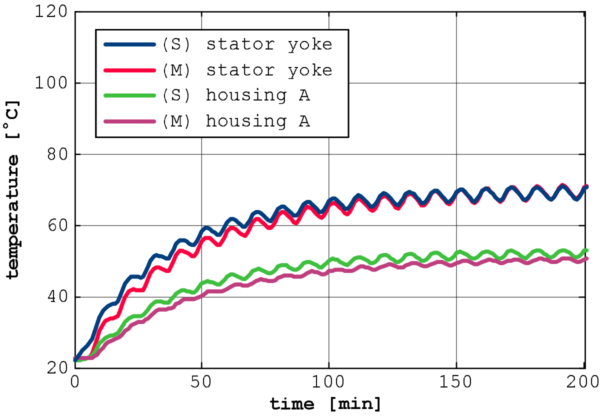

Figure 7: Simulated (S) and measured (M) stator yoke (`SYO`) and stator housing, A-side (`HOA`) temperature

6 Simulation and Measurement Results

Some results of computer simulation (S) and measuring (M) are compared in fig. 6–10. The investigations refer to continuous duty with intermittent periodic loading (duty cycle S6). The motor was loaded with 140% of nominal load for four minutes and no-load for six minutes.
Simulations and measurements match both qualitatively and in quantity.

7 Conclusions

A detailed thermal equivalent circuit of an asynchronous induction machine with squirrel cage was persented. The machine model was built using components from

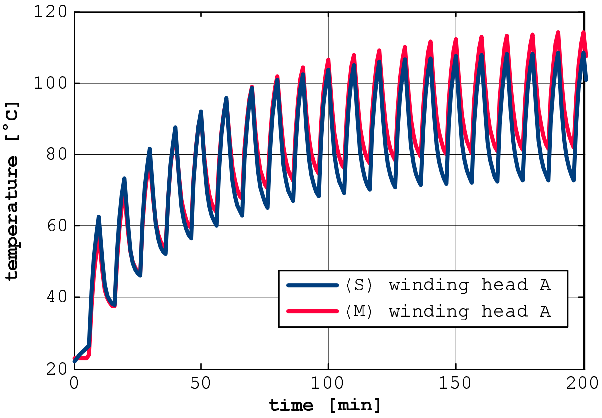

Figure 8: Simulated (S) and measured (M) temperatures of winding head, A-side (`WHA`)

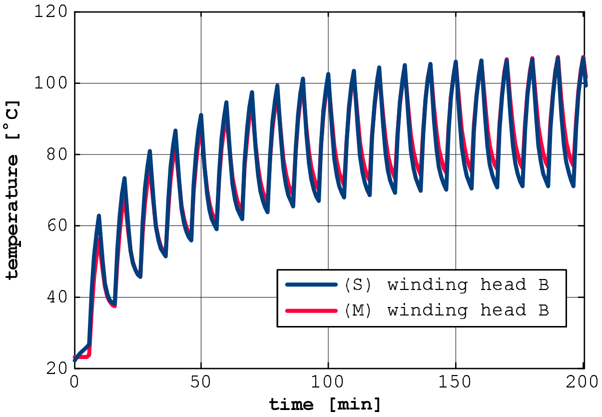

Figure 9: Simulated (S) and measured (M) temperatures of winding head, B-side (`WHB`)

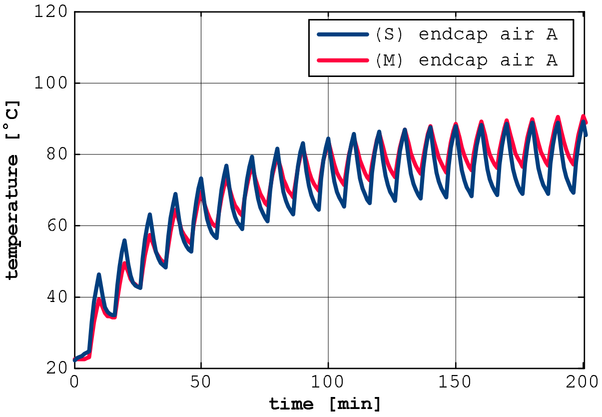

Figure 10: Simulated (S) and measured (M) temperatures of end cap, A-side (`AIA`)

`Modelica.Thermal.HeatTransfer.` This package does not cover the mechanisms of heat transport through a coolant flow, though. Therefore, *SimpleFlow*-library was developed, which is intended to handle applications like cooling of electric machines in a simple way. Other applications which do not fulfill the assumptions of *SimpleFlow*-library have to use the more complex `Modelica.Fluid` and `Modelica.Media` libraries. Since the application presented in the example meets the assumptions of *SimpleFlow*-library very well, the simulation results match with measurements.

The *SimpleFlow*-library is also suitable for other cooling types of electrical machines. Models for such cooling circuits (e.g. open circuit ventilated) are under test. The determination of the relevant parameters is going to be performed with a specific precalculation software which is currently developed.

Models simulating the temperature rise of electrical machines are a very important application because they lead to design optimizations and competitive advantages.

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