Proposal for standardization of Heat Transfer Modelling in NewThermal Library

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Abstract

This article presents the `NewThermal` library that extends the capacities of `Thermal` library from the Modelica Standard Library (MSL) including a proposal for standardizing the use of `Material` models. The new library is intended to decouple the models that collect the equations of heat transfer phenomena from the thermo-physical properties of the matters (fluids and solids).

The `NewThermal` library, in the same way that the current `Thermal` library from MSL, is composed of thermal system components to model heat transfer and simple thermo-fluid pipe flow. Nevertheless, the models from the package proposed inherit the thermal properties from `Media` and `Material` models of the fluids and solids involved (either temperature dependent or constant). In this way, the user has three aspects to define; the heat transfer phenomena to be modelled, the geometrical characteristics of the bodies, and the matters involved.

Components inside `HeatTransfer` package are implemented such they can be used for any material model in `Materials` package, in the same way that components from `Modelica.Fluid` were carried out for their use with media models from `Modelica.Media`.

The `NewThermal` library, in addition, provides some general base models for the modelling of 2D and 3D heat conduction in basic solid geometries.

Two examples of use for different domains are presented to illustrate the features of the new libraries.

Keywords: Modelica; heat transfer; thermal properties; thermal conduction, three dimensional heat flow

1 Introduction

In a general view, any heat transfer phenomena can be described with three different aspects:

- Heat transfer mechanism: conduction, convection or radiation or a combination of them.
- Geometrical characteristics of the phenomena: dimensions of the bodies, relative position between bodies and/or fluids.
- Properties of the substances involved, fluids and solids.

On one hand, in the modelling of any detailed thermal behaviour, the thermal properties of the solids and fluids involved (density, thermal conductivity, specific heat,…) acquire a relevant importance and in many cases it is essential to take into account their dependence on the temperature.

On the other hand, the geometry of real bodies usually can be constructed by the addition of basic geometries, that is, from a macroscopic point of view almost all bodies can be discretized in parallelepipedic, cylindrical and annular nodes (lumped elements) or a combination of them.

Considering this ideas and following the philosophy of replaceable media models in fluid models from MSL[1][2], IK4-TEKNIKER has created the libraries `NewThermal` and `Materials`. This first version provides mainly models for the modelling of conductive heat transfer. But there are described also some guidelines to extend the library to other mechanisms such as convective and radiative heat transfer modelling.

The goal of the `NewThermal` library is to provide standard components for heat transfer modelling dependent on geometry but independent of material properties.

2 `Materials` Library

It is defined as the library of solid material property models. The models from `Materials` Library are based on the `partialMaterial` partial model. This partial model has declared, as replaceable models, all models required in the modelling of any heat conduction phenomenon. In the figure 1 is shown the replaceable models mentioned above. On one hand, there is the inertia model, required if the heat capacity of the material is taken into account, and on the other hand the models needed for the modelling of heat transport inside the material are available. The latter are chosen depending on the geometries involved, illustrated in the figure 2.

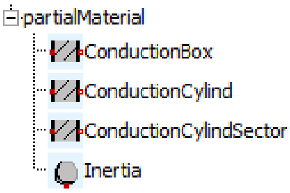

Figure 1: Components of `partialMaterial` class

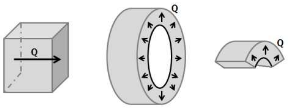

Figure 2: Box, cylindrical and cylindrical sector geometries

Hence, material models extend from this partial model and add in each case the thermal properties of the substances to be modelled.

That is, in the same way that models from `Modelica.Fluid` library with models from `Media` library, any thermal model can include a replaceable instance of `partialMaterial` which allows selecting models from `Materials` library choosing between a large list of materials to inherit their thermal properties, as it is shown in the figure 3.

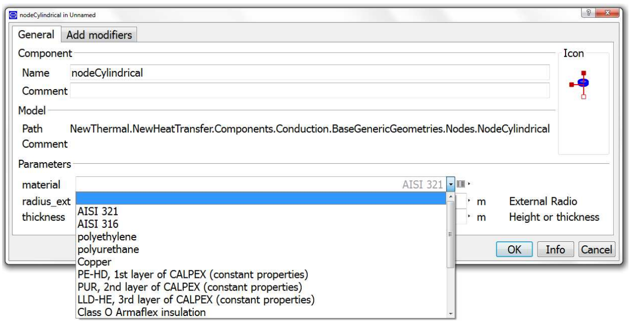

Figure 3: Component for the modelling of the thermal behaviour of a body with cylindrical geometry.

In this case, the external radius and the height of the cylinder are parameters and the specific heat capacity, density as well as conductivity of the material extends from the replaceable material model.

Current `partialMaterial` model includes only replaceable models for the modelling of conductive heat transfer but it is possible to extend it in the future adding replaceable models relative to radiative heat transfer.

3 `NewThermal` Library

3.1 General Library Structure

The `NewThermal` library has the same structure as `Thermal` library from MSL, as it is shown in the figure 4. All new models are built with connections on existing `Interfaces` package, so they are compatible with any model inside `Modelica.Thermal`.

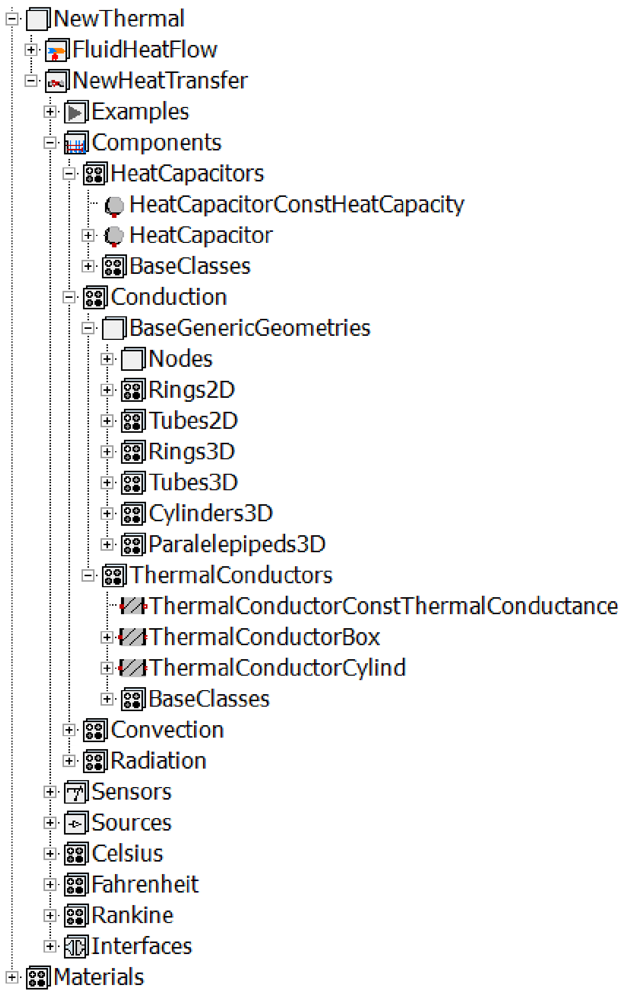

Figure 4: `NewThermal` library structure

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Most of new models are based on the use of replaceable material models and for this reason it is essential to open it together with `Materials` library.

Following sections are focused on `HeatCapacitors` and `Conduction` packages that support simulation of heat conduction through any solid.

3.2 `HeatCapacitor` Library

As shown in the library structure, `HeatCapacitor` subpackage is included in `Components` package. In this subpackage, a collection of generic models for the heat capacity of a material can be found. In these components, no specific geometry is assumed beyond a total volume with uniform temperature for the entire volume. Furthermore, only one parameter it is required, precisely the volume of the body to be modelled, in such a way that the heat capacity value is inherited from the replaceable material model. The figure 5 shows the information expected from the user when the heat capacitor model is used.

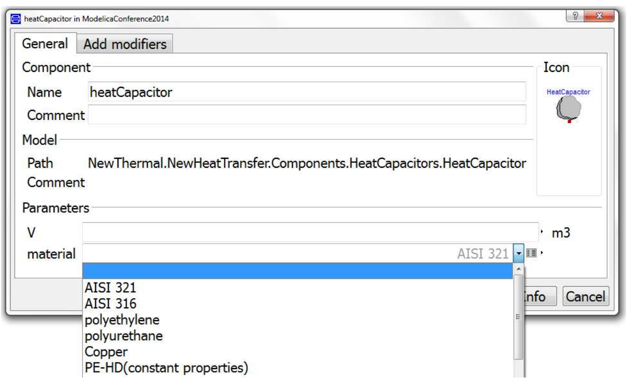


Figure 5: `heatCapacitor` class

3.3 `Conduction` Library

The `Conduction` subpackage from `NewHeatTransfer` package is composed of two groups of models.

In the first one, named `ThermalConductors`, a collection of thermal conductor models can be found, for 1D conductive heat transport. It contains a sort of models for different geometries with the option to choose the material of the body to be modelled.

The second library, called `BasicGenericGeometries`, collects a large list of models for the simulation of conduction heat transfer in any 2D or 3D geometry (parallelepipeds, cylinders, rings or tubes) and again all of them have the option to choose the material to be modelled.

3.3.1 Heat Conduction Base Classes

The base classes of the `ThermalConductors` package are partial models that define the interface and the equation of the heat conduction phenomena. Models of `ThermalConductors` have only geometry values as parameters, inheriting the value of conductivity from the replaceable material model. The figure 6 shows the information to be defined by the user to model heat conduction in box type geometry.

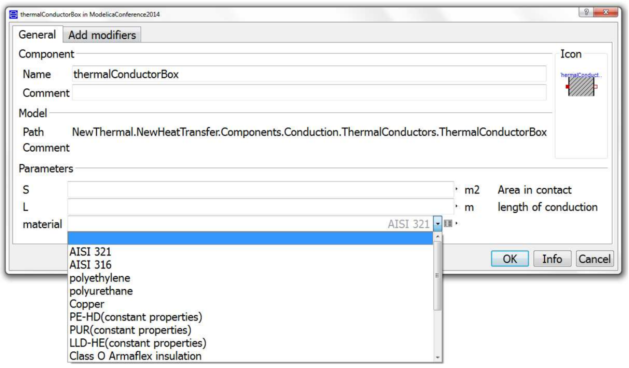


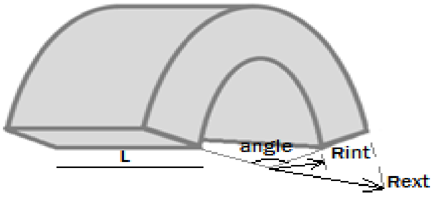
Figure 6: `thermalConductorBox` model for the transport of heat through box geometry in any material

`partialThermalConductor` provides the thermal conduction equation `Q_flow = G*dT`, where `G` is defined as thermal conductance of material and its calculation depends on the geometry through which the heat flows. The partial model extends from existing `Element1D` which provides two thermal ports `port_a` and `port_b` which are common in all components for modelling heat transfer, such as heat convection or heat radiation.

`ThermalConductors` package offers a set of models which extend from `partialThermalConductor` partial model adding the equation characteristic of `G` depending on geometry:

- $G = \frac{k*A}{L}$ for a box geometry under the assumption that heat flows along the box length.
- $G = \frac{2*\pi*k*L}{log\left(\frac{R_{ext}}{R_{int}}\right)}$ for a cylindrical geometry, under the assumption that heat flows from the inside to the outside radius of the cylinder.

- $G = \frac{angle*k*L}{log\left(\frac{R_{ext}}{R_{int}}\right)}$ for a sector for any cylindrical geometry, under the assumption that heat flows from the inside to the outside radius of the cylinder.



In all the equations k is the thermal conductivity of the material.

3.3.2 Nodes Base Classes for different 2D and 3D geometries

BaseGenericGeometries package in Components.Conduction contains a set of components for the modelling of 2D and 3D heat conduction through bodies with different geometries. These models are built on arrays of components from Nodes package, a collection of models of basic units (lumped elements) for the construction of geometries above mentioned. This approach has been suggested in previous works such as [3].

Thereby, in Nodes package, it can be found annular nodes, parallelepipeds nodes and cylindrical nodes. In the figure 7 the model and icon for parallelepiped node in 3D are shown.

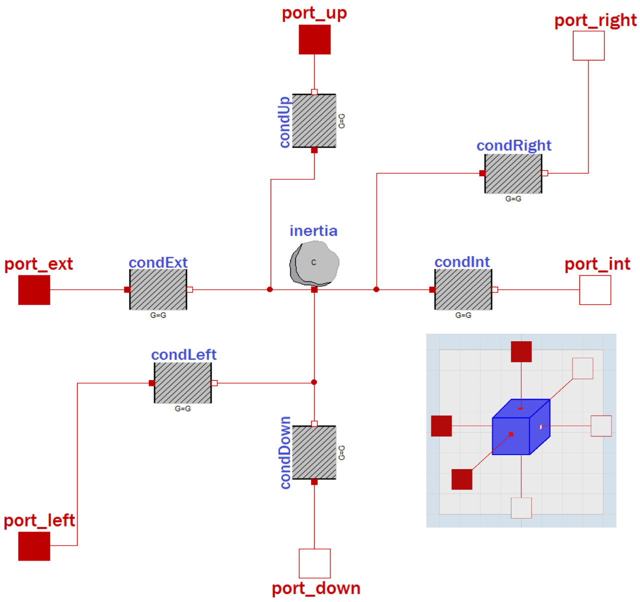


Figure 7: Basic 3D node class

All these components are composed of:

- A heatCapacitor model, from HeatCapacitor library, for the thermal storage capacity of the node and it is assumed a uniform temperature in it.
- Four/six thermalConductor models, from ThermalConductors library, for modelling the transport of heat. Each couple of thermalConductor models describes the heat transport along the two/three dimensions.

3.4 Convection and Radiation Libraries

The models from Convection library, with two heat ports as it is common in all components for modelling heat transfer, are prepared for connecting one of the heat ports to the solid and the other heat port to the fluid, in such a way that the component itself, has as internal variables the temperature at solid and fluid and the heat flow rate from/to solid and fluid. Following the same philosophy used for the creation of HeatCapacitor and Conduction libraries and taking advance of the accessible fluid and solid temperatures involved, all components in Convection library have been provided by a replaceable medium model and correlations for natural and external forced convection [4][5] (forced convection problem inside conduits is already solved in Modelica.Fluid). Thereby, the user only has to provide the geometry information of the body involved in the convective heat transfer and to select the media.

Models in Radiation library respond to the Q_flow=Gr*sigma*port_a.T^4-port_b.T^4) radiation formula, where Gr is function of the emittance of material surfaces involved in the thermal radiation and its calculation depends on the geometry and arrangement of surfaces. The emittance of surfaces tends to vary its value with the temperature and this effect is more relevant as the temperature increases [6]. The emittance is considered to be included in material models because it is an intrinsic property of material surface. Therefore, the same as in Conduction library, the Radiation package would offer models for the modelling of thermal radiation depending on the geometry and the arrangement of objects involved but independent on materials.

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4 Examples

4.1 Insulated Pipe

Based on the `dynamicPipe` class from `Modelica.Fluid` and `NewThermal` features, a model of an insulated pipe has been created. Although the model has been named `insulatedPipe`, it describes the hydraulic and thermal behaviour of any pipe with one or more solid layer(s) assuming radial symmetry in all phenomena. Hence, with this model the user can model from a simple copper tube of any home heating system to a more sophisticated plastic tube with some insulation layers.

The cover of the dynamic pipe is compounded at most of five layers of any material from `Materials` library. The first layer is the closest to the fluid, that is, the layer with the smallest radius.

The user has to indicate how many layers the pipe has and the thickness of each layer, as well as the layers materials and the internal radius of the first layer.

If the number of layers is less than five, the user can disable the layers no required, switching to false the corresponding boolean `useLayer`. On the left side of the figure 8, it is shown the two systems of the insulated pipe:

- the hydraulic system defined by the `dynamicPipe` model from MSL
- the thermal system for the cover of the pipe, defined by the `multipleCylinder` model

The right side of the same figure shows the five layers of the cover, each one can be disabled if it is not required for the modelling of the insulated pipe.

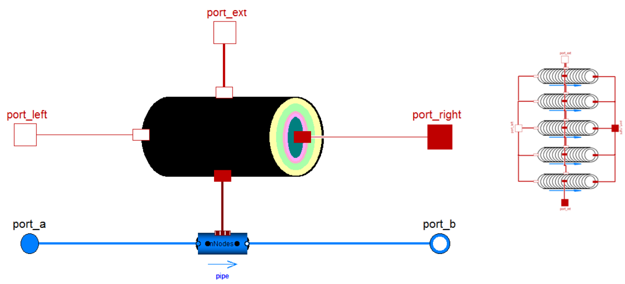

Figure 8: `insulatedPipe` (left) and its `multipleCylinder2D` base clase (right)

The `insulatedPipe` model has been built easily with several instances of the 2D tube class from `BaseGenericGeometries` package in `NewThermal.HeatTransfer.Conduction`

(right side of the figure 8). It is prepared to be divided into `nNodes` equally spaced segments along the flow path, therefore, the same number of lumped elements are in all matter layers, as much to fluid line as to cover layers.

The model, in addition, has the option of neglecting the axial conductive heat transfer (parallel to the fluid path) throughout the solid materials of the pipe. This assumption is quite reasonable in some cases, depending on the thermal properties of constituent materials, and it can significantly speed up simulations.

The `insulatedPipe` model has been used for the modelling of pre-insulated pipes in a small District Heating system [7] with good results, error of roughly 5%, in comparison with technical report of heat losses provided by the pipe manufacturer.

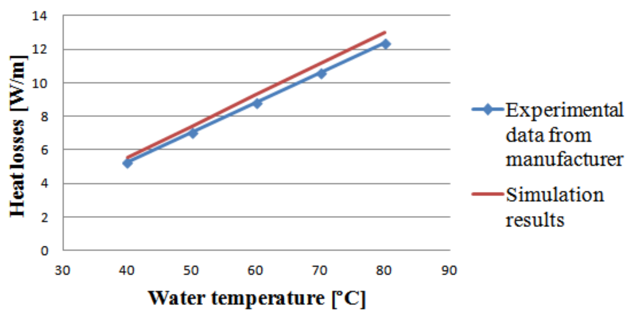

Figure 9: Experimental data and simulation results for `insulatedPipe` model adapted for commercial pipe simulation.

4.2 Heat transfer in 3D cylinder

Based on models from `Tubes3D` library a discretized cylinder was built. The model was used for simulating laser surface hardening process of a crankshaft. In this case, a 3D model was absolutely indispensable because there was a relative movement between the crankshaft and the punctual heat source (punctual laser).

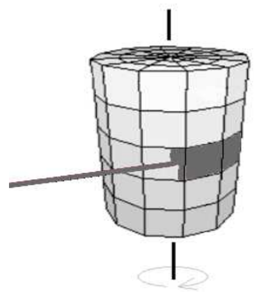

Figure 10: Simplified sketch of the interaction between the punctual heat source and the crankshaft

In this case, Modelica model was especially interesting in order to define and also simulate the control strategy of the process.

Before using it for this purpose, 3D tube model was validated with a FEM model (MSC NASTRAN®). Both models were discretized in the same way and exposed to the same external conditions to compare the evolution of the temperature in some nodes.

The tube was discretized in:

- Number of rings (radial direction): 20
- Number of sectors: 16
- Number of slices (axial direction): 5

The following external conditions were assumed:

- Convection in internal and external lateral surfaces:
    - $h_{internal}$ wall: 10 W/m^2K
    - $h_{external}$ wall: 100 W/m^2K
- Constant temperature in the upper and lower external surfaces:
    - Upper surface: 500 ºC
    - Lower surface: 100 ºC
- Temperature of nodes at t=0s, 20ºC

The good agreement between stationary simulation results of both models can be appreciated in the figure 11.

The discrepancy on transient behaviour is due to different initial conditions in some nodes. All the nodes in the FEM model could not be initialized at 20°C due principally to the way of imposing external conditions. In this case, the nodes from the upper slice and the lower slice were in contact with an imaginary plate at 100°C and 500°C, so that, this nodes inherited directly the temperature of them at t=0. In Modelica model, nevertheless, all nodes started the simulation at 20°C.

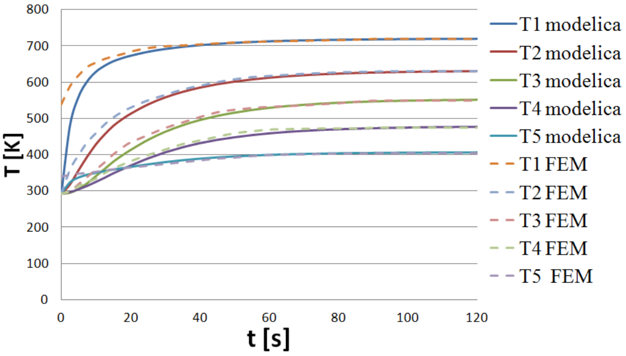

Figure 11. Temperatures of five nodes of the FEM and Modelica models

5 Conclusions

`NewThermal` together with `Materials` libraries have been created by IK4-TEKNIKER in order to extend MSL capabilities for heat transfer modelling. The new libraries decouple material properties from heat transfer phenomena modelling and allow taking into account the influence of temperature on material properties such as thermal conductivity, specific heat capacity, etc.

`NewThermal` library provides also basic models to simulate 2D and 3D heat conduction problems in bodies with simple geometries.

Two practical examples from different application domains have been shown to demonstrate the use of the libraries.

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