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A combined thermo-hydraulic approach to simulation of active building components applying Modelica

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Abstract

Optimization of building climatisation systems often leads to usage of large-area heat exchangers: Economical and environmental advantages result from the low temperature differences needed for heating and cooling. Simulation models containing such heat exchangers embedded in wall layers demand for a coupled consideration of hydraulic and thermodynamic phenomena. For that reason the Hermann-Rietschel-Institut developed new tools for building simulation with combined thermo-hydraulic capabilities, based on the free Modelica library "ATplus".

Keywords: active building components; climatisation; heat shift; building simulation

1 Introduction

Increasing operating costs, proceeding depletion of fossil fuels and new national guidelines for consumption of primary energy demand for new technologies in the field of building climatisation.

Up to now the main focus of research and development activities has been the optimization of the efficiency of system components. This energetic perspective does not take into account, that the needed amount of primary energy can also be reduced by constraining the exergy rates in energy flows: Reducing exergy rates leads to an equivalent increase of anergy rates which can be taken from the ambiance.

Exergy-optimized technologies – so called LowExergy technologies – offer a new approach to indoor climate control. By using phase change materials (PCM) in combination with large-area heat exchangers embedded in wall layers, several applications may be considered:

- heat shift to the ambiance,
- heat shift from one room to another and
- heat shift from day to night (heating/cooling load equalization).

Due to the physical properties of PCM these systems can transfer heat at very low differences in temperature, causing low exergy losses due to heat transfer processes. To examine the practicability of these systems, in-depth simulations must be conducted.

The first part of the paper describes the basics of our room simulator. The second part investigates the simulation of embedded heat exchangers in detail.

2 Simulating basic building behavior

Thermal building behavior is modeled at Hermann-Rietschel-Institut using Dymola by Dynasim. The simulation model is based on the "ATplus" library, which was implemented at Universität Kaiserslautern [1]. To accomplish our special requirements, a variety of newly composed and modified elements have been designed.

Up to now, heat transfer phenomena are modeled one-dimensionally. This leads to short computing time combined with a sufficient accuracy.

2.1 Walls, ceiling and floor

In order to reproduce the dynamic behavior of a room, walls, ceiling and floor are designed as aggregations of several layers with different material properties [2]. An element called "n-layer" (Fig. 1) allows defining the number of layers by a parameter and stores all property data in tables.

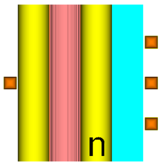

Fig. 1 "n-layer"

Combining geometrical information, density, heat capacity and thermal conductivity of every layer leads to a mathematical representation of heat conduction within the wall. Furthermore "n-layer" elements have been extended by adding a surface heat convection process, so they can be linked directly to the element representing the room's air mass.

2.2 Radiation exchange

Due to deviating absorption coefficients, short wave (solar) and long wave radiation exchange between the enclosing surfaces of the room have to be modeled autonomously (Fig. 2).

For that reason, n-layer elements have been equipped with two connectors allowing a separate treatment of the two radiation instances.

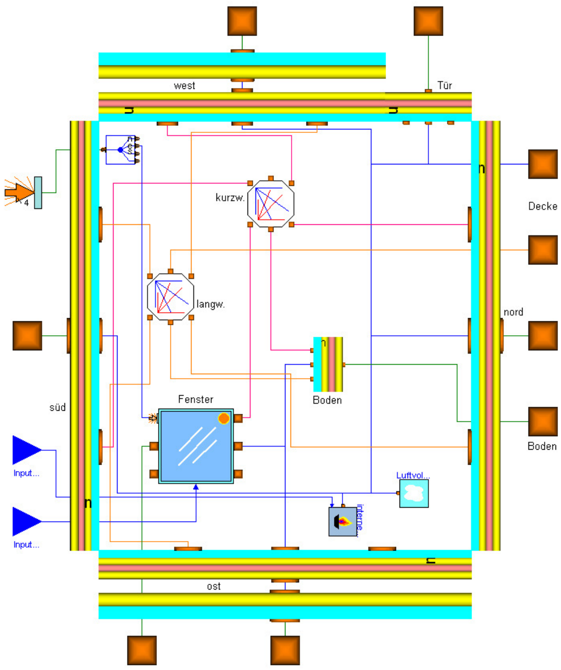

Fig. 2 Model of sample room

2.3 Internal gains

Internal gains representing thermal power of persons, electric lights and further electrical equipment are modeled as convective heat sources, which can be leveled by a timetable provided in an external file.

By this means daily load profiles up to whole year specifications are possible.

2.4 Solar gains

Solar gains due to solar radiation through windows are simulated depending on their orientation with high accuracy. Time depending values for solar radiation on a horizontal surface are taken from an external file containing test reference year data provided by the German weather forecast agency *Deutscher Wetterdienst* (DWD). By processing this data through a self implemented solar radiation calculator, emissions on vertical surfaces facing north, west, south and east are determined and provided via connectors. The orientation of the window is defined by connecting the window element to one of the four radiation connectors.

The intensity of solar radiation is finally being adjusted by considering sun blinds and absorbance/reflection at the window surface. The resulting specific power is linked to the short wave radiation exchange element of the room. By absorbing incident light, the enclosing surfaces convert solar short wave radiation to heat.

2.5 Air exchange

The effect of direct air exchange from within the room to the ambiance is modeled as a part of the window element. Time depended air exchange rates are provided in an external file.

3 Thermally active building elements (hydraulic panel heating/cooling)

Panel heating and cooling uses controlled temperature surfaces on the floor, walls or ceiling. The defined temperature of the panel can be obtained by circulating water.

The considered active building elements are pipes embedded in the walls of a room (Fig. 3). To simulate such systems it is necessary to regard the hydraulic and thermal behavior.

The model for thermal active building elements is divided into two parts:

- **pipe** model and
- **wall** model.

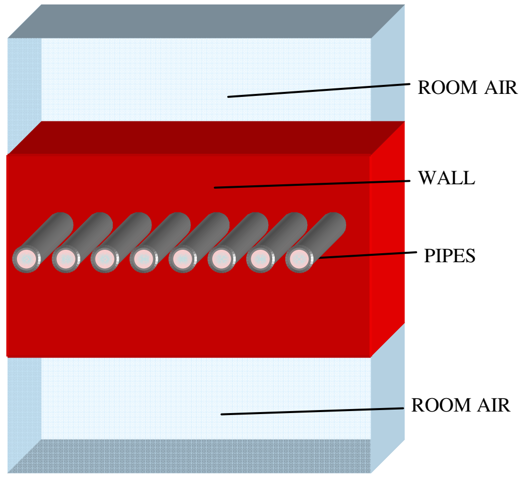

Fig. 3 Cross section of a wall with embedded pipes

The connection between both sub models is realized by the variables of temperature and heat power (Fig. 4).

The model of active building elements represents the interface between the thermal room model and the thermal and hydraulic system model.

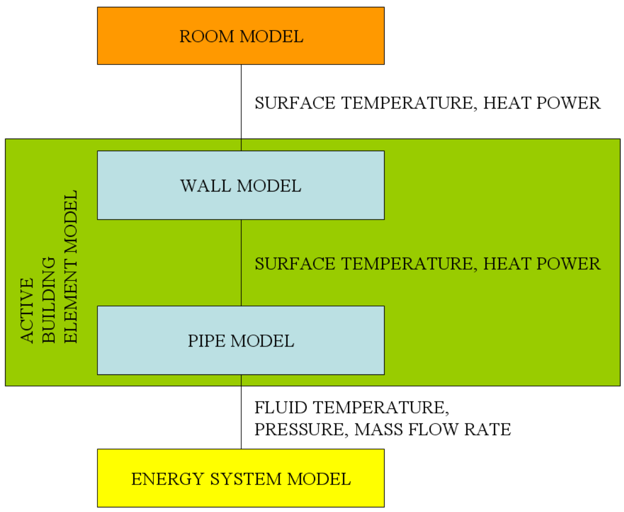

Fig. 4 Connections between the parts of the model

4 Pipe model

4.1 Thermal behavior

The description of thermal behavior proceeds from a partial differential equation, which comes of to the balance of the energy flows in an infinitesimally small element of the tubing volume (Fig. 5):

$$-\dot{m}_F \cdot c_F \cdot \frac{\partial \vartheta_F}{\partial y} \cdot dy = dm_F \cdot c_F \cdot \frac{\partial \vartheta_F}{\partial t} + U(\vartheta_F - \vartheta_W) \cdot dA$$

Partial differential equations cannot be implemented in Modelica directly. Since the heat storage capacity of the heating water in the pipes is relatively small in comparison to the wall, frequently a stationary approximation can be used. It applies thus:

$$\frac{\partial \vartheta_F}{\partial t} = 0$$

The partial differential equation goes over into a pure temporal differential equation:

$$-\dot{m}_F \cdot c_F \cdot \frac{\partial \vartheta_F}{\partial y} \cdot dy = U \cdot (\vartheta_F - \vartheta_W) \cdot dA$$

This equation can be solved analytically and describes an exponential temperature profile consisting of wall, input and output temperature (Fig. 5):

$$-\dot{m}_F \cdot c_F \cdot \ln \frac{\vartheta_O - \vartheta_W}{\vartheta_I - \vartheta_W} = U \cdot A$$

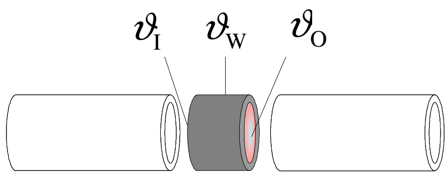

Fig. 5 Temperature-variables of a tubing element

The heat transfer coefficient is included in the u-value, which is accepted in the available model as constant.

4.2 Hydraulic behavior

The hydraulic part of the pipe depends strongly on the flow characteristics in the pipe. The Reynolds Number can be used as criterion for **laminar or turbulent** flow situation:

$$Re = \frac{\rho \cdot v \cdot L}{\eta}$$

The dynamic viscosity results from a temperature-dependent approximation.

If the flow is laminar the pressure drop is computed by the following equation (Hagen-Poiseuille equation):

$$\Delta p = \frac{8 \cdot \eta \cdot L}{\pi \cdot r^4} \cdot \dot{V}$$

In the turbulent regime the algorithm changes to:

$$\Delta p = \lambda \cdot \frac{1}{2 \cdot r} \cdot \frac{1}{2} \rho \cdot v^2$$

5 Wall model

The connection between room and active building element model takes place by models for **radiation and convection**. Two approximations are used:

A) Natural convection and radiation from or to the panel surface is recreated by a combined heat transfer coefficient. Convection in a panel system is a function of the panel surface temperature and the temperature of the air stream layer directly below the panel. The combined heat transfer from a panel surface can be determined by adding the radiant heat transfer to the convective heat transfer.

B) Convection and radiation are treated separately. The convective part results from the equation:

$$\dot{Q} = \alpha \cdot A \cdot \Delta\vartheta$$

The heat transmission coefficient α can be computed temperature-dependent or accepted as a constant. The heat transfer by radiation is computed on the basis of the surface temperatures by the radiation model of the room.

Two other important effects are **thermal conduction and storage** within the wall. Active building elements are strongly shaped by a different temperature distribution within the construction unit. These temperature differences are reflected depending upon pipes distance and wall thickness also in different surfaces temperatures again. The effect of the inhomogeneous heat flows in the wall causes an uneven temperature profile at the wall distribution. To model these effects a two-dimensional modeling has to be applied.

The two-dimensional intermittent temperature distribution in homogeneous bodies is defined by the following partial differential equation:

$$\frac{\partial\vartheta}{\partial t} = \frac{\lambda}{\rho \cdot c}\left(\frac{\partial^2\vartheta}{\partial x^2} + \frac{\partial^2\vartheta}{\partial y^2}\right)$$

Since this equation type is not implemented in Modelica, two other approaches for the computations of the temperature distribution were used (ribbed pipe and finite volume model).

5.1 Finite volumes model

The effects of heat storage and conduction inside the panel can also be described by a partial differential equation. To transform this equation into to a system of ordinary differential equations a discrete volume method can be used. By applying a 2D-discretization it is possible to calculate the heat flux and temperature drop in two dimensions (Fig. 6).

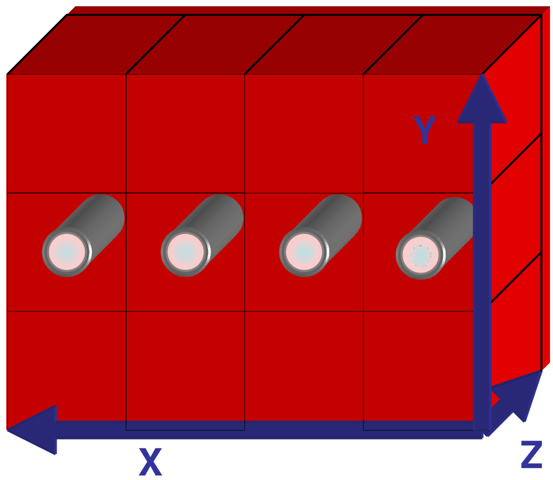

Fig. 6 Finite volumes of a wall

The discretization of the wall takes place in x- and y-direction. The finite volumes are arranged to the pipe axle lengthwise.

For each dimension the energy conservation law has to be solved. For an individual volume element (Fig. 7) the following equation results:

$$\begin{aligned} 0 = & m_{element} \cdot c_{element} \cdot \frac{\partial\vartheta_{element}}{\partial t} \\ & + U_x(\vartheta_{element} - \vartheta_{x+1}) \cdot A_x \\ & + U_x(\vartheta_{element} - \vartheta_{x-1}) \cdot A_x \\ & + U_y(\vartheta_{element} - \vartheta_{y+1}) \cdot A_y \\ & + U_y(\vartheta_{element} - \vartheta_{y-1}) \cdot A_y \end{aligned}$$

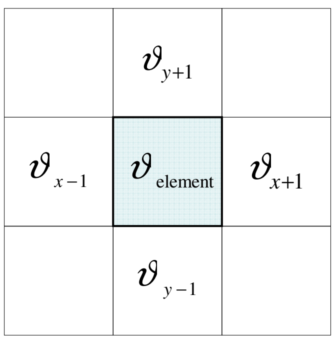

Fig. 7 Individual volume element

5.2 Ribbed pipe model

Apart from the numeric calculation of the finite volumes method also approximation methods can be applied to estimate the heat flux through the wall.

A possible simplification is a ribbed pipe model. Analytic solutions for ripped pipes are known for different conditions. A two-dimensional computation is possible for this approach. For pipe rows in walls a special algorithm has already been presented admits [3]. Its suitability for the computation of thermally active elements is proven.

The implementation of this algorithm in Modelica permits the two-dimensional computation of the thermal behavior in x- and y- direction (Fig. 8).

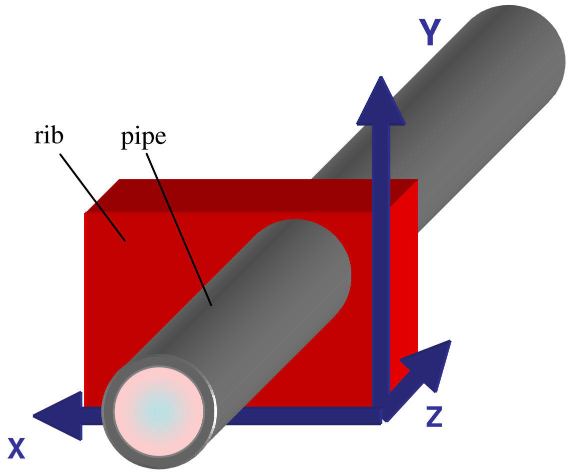

Fig. 8 Ribbed pipe

In difference to the finite volume method, no discretization is necessary. The computing time shortens.

6 Validation experiments

Different publications contain characteristic values of active building elements [4], [5]. For steady and dynamic state the models are compared with the known values of these investigations.

Validating the models must consider both the dynamic and the static behavior. In order to reach this, a transient condition of the wall when rapid change the fluid temperature was selected. The case of reference represents an investigation in [4].

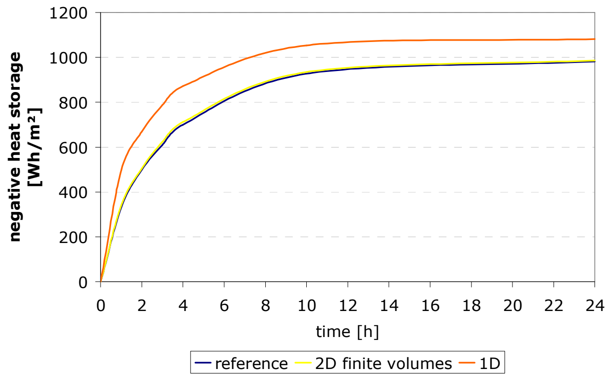

Fig. 9 Dynamic behavior of different models

Figure 9 shows the result of the experiment with a pipe distance of 15 mm. Criterion for the accuracy is the area specific stored heat in the wall. This variable represents a suitable value to illustrate dynamic conditions in the wall.

$$Q = c \cdot th \cdot \left(\vartheta_{\text{element}} - \vartheta_{\text{room air}}\right)$$

The reference temperature represents the room air temperature.

The results of reference and finite volumes agree very well. Both during the transient and in the stationary condition deviations are hardly to be determined. The good agreement indicates the same dynamic and static behavior.

In addition to the comparison a 1D-model is specified. This exhibits both stronger deviations. Besides, this tendency strengthened with increasing pipe distance (Fig. 10). The 2D-modelling, like the finite volume method, is more exact.

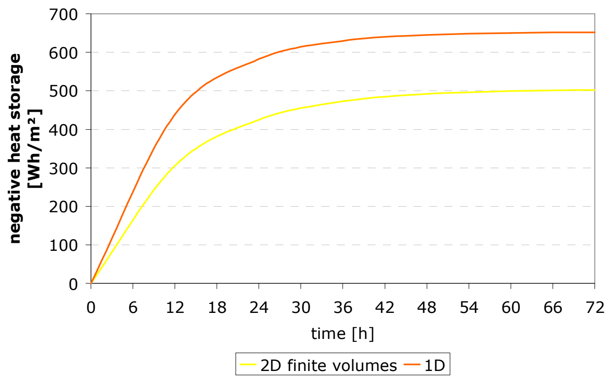

Fig. 10 Dynamic behavior of different models with larger pipe distance

6.1 Interaction with the room model

The function of the active building component model within a room simulation has been tested on the basis of an average office room, as it is described in [6]. The east-oriented room is equipped with a relatively large window (7 m²) and has a base area of 17.5 m². As an active building component, the ceiling has been modeled with embedded capillary tubes. They are flown through by water in order to cool the room.

Figure 11 shows the results of the coupling of room model, active building elements model and energy system model. The clear influence of the active building elements on the room air temperature shows up. High summer temperatures in the room, caused by high ambiance temperatures and large solar gains, can be leveled by the use of the thermally active ceiling.

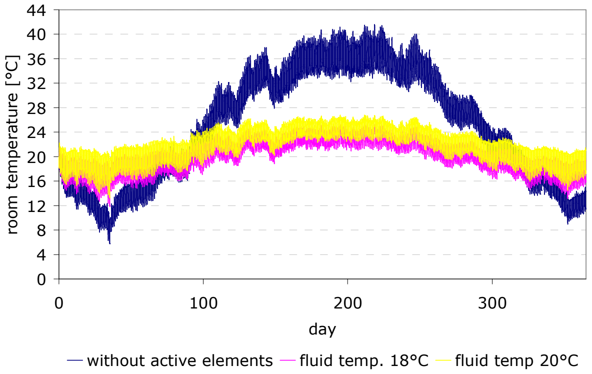

Fig. 11 Change of the room air temperature with employment of active building elements

7 Conclusions

The performed development work expanded the components of the ATplus library by such elements, which now also allow thermally activated components to be simulated. The next step is the development of a model for heat storage with phase-change materials.

In addition to that, further validations must be carried out in order to confirm the correctness of the simulation results. For this reason not only comparison calculations will be undertaken, but also experiments. The derived data will be used to improve the represented dynamic behavior of the simulation models.

Finally, it remains to be examined whether if it is reasonable to increase the amount of observed dimensions in the room simulation. In this context the question appears whether a CFD-model for the calculation of air currents in the room could contribute to better predication of inner-room comfort. A restriction to those expansions of the room model will be – as always – the necessary computing time of the simulation.

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List of symbols

A	area
c	specific heat capacity
L	length
m	mass
$\dot{m}$	mass flow
p	pressure
$\dot{Q}$	heat flow
r	radius
t	time
th	thickness in y-direction
U	resistor of thermal conductivity
v	velocity
$\dot{V}$	volume flow
x	coordinate
y	coordinate

Greek symbols

α	coefficient of convective heat transfer
η	viscosity
λ	coefficient of thermal conductivity
ϑ	temperature in °C
ρ	density

Indices

F	fluid
I	input
O	output
W	wall

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