Coupled Simulation of Building Structure and Building Services Installations with Modelica

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Abstract

The Hermann-Rietschel-Institute (HRI) uses the ability of Modelica to aggregate different physical domains inside one simulation model. This approach allows for the coupled simulation of thermal effects in building structures and building services installations applying only one software tool.

We show the capabilities of such coupled simulations, taking a room that is equipped with capillary pipes inside the ceiling and being connected to a chiller as an example.

Keywords: Multi domain simulation; dynamic building simulation; simulation of building installations

1 Introduction

In order to investigate the dynamic thermal behavior of buildings in conjunction with hydraulic networks and new kinds of building heating and cooling systems a number of component models have been developed at the Hermann–Rietschel–Institute (HRI).

The main focus of the HRI is to research thermal building behavior and thermal comfort with different approaches of air–conditioning. Comparing the power consumption and analyzing the employed control strategies are also important topics.

One approach for example is room heating or cooling with large area heat exchangers [1]. Due to the increased heat exchanging surface it is possible to reduce the temperature difference that must be applied to sufficiently heat the room. This in return leads to a lower amount of needed exergy for this heating system minimizing primary energy usage. An appliance is a panel heating system which could be powered by the relatively cool return water of a district heating system. This would further increase the efficiency of the plant providing the heating water and could spare heating costs at the same time since the return water could be bought cheaply. The HRI will focus on this topic in an upcoming study.

Another application is a large area cooling system employing capillary pipe mats. With capillary pipe mats the achievable relative heat flow density is higher than with conventional panel heating and cooling systems. It is possible to even more reduce the surface excess temperature at the same level of cooling power.

This makes it possible to reduce the amount of energy that is needed to cool the room because the efficiency of the chiller increases. This holds true for a heat pump system that is often used for such purposes.

Computer simulations must be carried out to examine the feasibility of new air–conditioning technologies as well as to find ways to optimize standard technologies. The HRI uses Modelica as modeling language to benefit from the possibility to create multi domain simulation models.

To show that multi domain simulation models can be built with the HRI libraries an example simulation setup will be discussed in this paper. The design of several components used in this simulation will be described also.

2 Simulation setup

An exemplary simulation setup is shown in Fig. 1. The graphical representation of the system shows a single room model (1), a panel cooling system (2) that is integrated into the room ceiling, a chiller machine (4) and a heat exchanger (3) that would be used to separate the heat pump circuit from

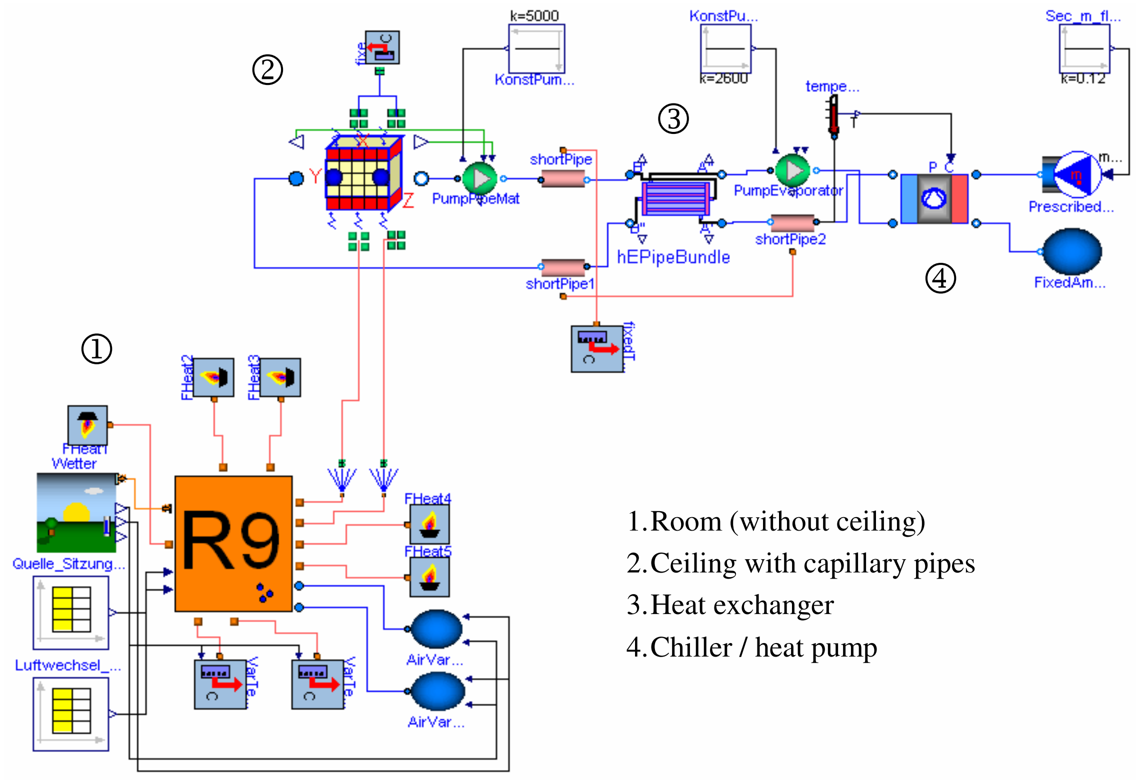

Fig. 1: Graphical representation of the simulation model.

the oxygen enriched capillary pipe mat water system.

Additionally, pipe models connect the mentioned system components and two pumps enforce the necessary fluid flows. The condenser side of the heat pump model is connected to a source with constant medium properties and constant mass flow rate. This would correspond to a supply with ground water.

Room heat loads and air exchange rates are provided by tabulated data. Ambient temperature, air humidity, atmospheric pressure and radiation values are provided by a weather module which uses a test reference year with tabulated values.

Different boundary conditions for the room are applied in this setup. The exterior wall is connected to modules that set the ambient temperature provided by the weather module. Assuming that all adjacent rooms will have the same temperature leads to the boundary condition that no heat flow through inner walls will occur. This is ensured by a second module type.

Temperature and humidity of the outside air will be provided by two reservoirs. The weather module sets the appropriate media properties.

In the following some of the components used in the simulation setup are described in more detail.

3 Simple Room Model

The room model contained in the example represents a cubical room that is enclosed by walls consisting of several layers (see Fig. 2). Three of the four walls are interior walls, the fourth one – an exterior wall – contains a window. Also the floor is modeled with several layers with different material properties.

The model of the ceiling has been deleted from the aggregated room model and was substituted by an external model of a ceiling with embedded capillary pipes (see Fig. 1). These capillary pipes are used to cool the room and act as an interface between the room and the building services installations.

3.1 Radiation Exchange

In addition to basic physical phenomena like heat transport and natural convection, also long wave and short wave radiation interchange are being examined.

Besides the exact approach to calculate long wave radiation exchange between room surfaces basing on angle factors we also implemented a simpler model using an area weighted approach to calculate radiation exchange. This is especially important for assembling rooms that are more complex than a simple "match box" shaped room. In the latter case it would be a challenging and error prone task to determine all necessary angle factors to describe radiative heat exchange.

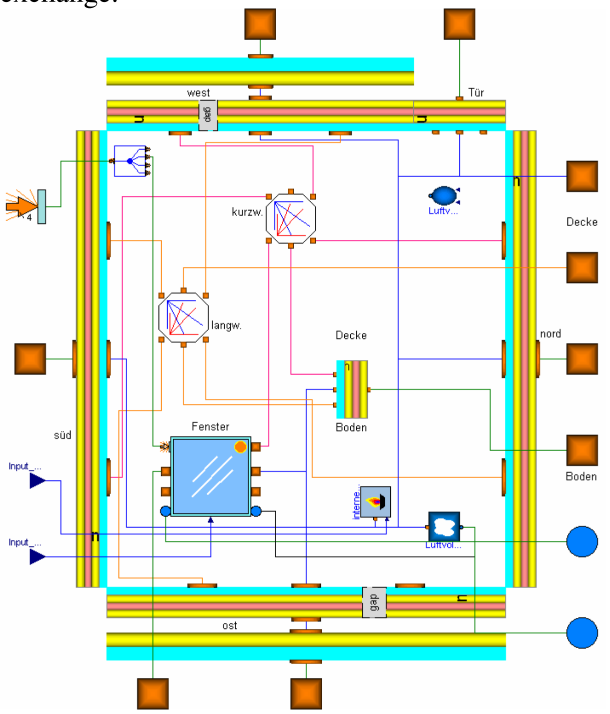

Fig. 2: Graphical representation of the room model.

3.2 Air Volume and Boundary Conditions

The air volume inside the room includes the property of humidity, which is obtained by connecting the model to the *Modelica.Media* library.

In order to observe local condensation on the chilled ceiling surface, we added a sensor that continuously checks the local dew point temperature.

Regarding the interior walls and the floor we assume adiabatic boundary conditions for this simple example – which imply equal temperatures inside the simulated room and the adjacent rooms. So heat transport only takes place through the exterior wall, the window, and the ceiling. A weather model provides the necessary data concerning temperature, humidity, and pressure of the ambient air as well as the solar radiation onto the exterior wall and the window. This is based on measured data called "test reference year", which is provided by the German weather forecast agency *DWD*.

Finally, the control of the inner heat sources inside the room as well as the air exchange through the window are being realised by connecting external files to the simulation model.

4 Building Services Installations

Most of the hydraulic components are black box models. Due to the fact that design specifications are not available from most component manufacturers it is a superior aim for the HRI to model components based on the provided manufacturer data as input parameters and approximately reproduce the components behavior. Trying to model the component as exactly as possible by modeling each concerned physical phenomenon would transcend the needs of the Hermann–Rietschel–Institute. The latter proceeding would be favorable if the behavior of a specific apparatus must be examined or tested. This would normally include to rewrite a considerable amount of code if a different apparatus design shall be examined.

4.1 Panel Heating and Cooling Model

As stated in [1] a model of a panel heating and cooling system was developed at the HRI. Pipes embedded in a wall layer provide heating or cooling. The hydraulic and thermal behavior of the system is modeled in two components:

- the pipe mat model and
- the wall model.

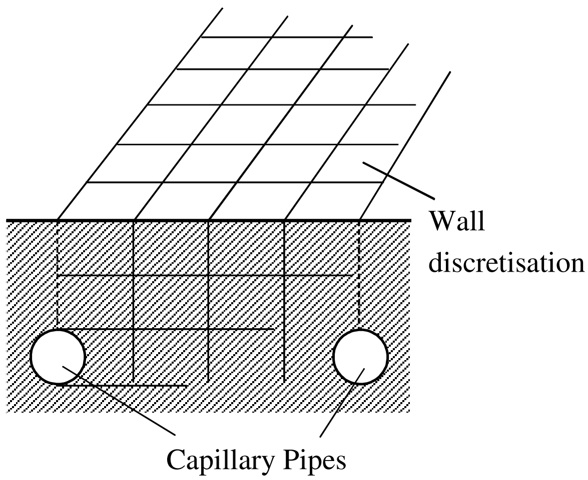

Fig. 3: Illustration of the capillary pipe mat model.

The wall model consists of discrete elements (finite volumes) that conduct and store heat energy allowing for the examination of the temperature distribution in the wall layer. Capillary pipes are built from of a number of small pipe elements connected together to build the large pipe mat model. The pipe model allows heat transfer from the fluid model to the wall model.

The short pipe model contained in the *Modelica_Fluid* library is used to facilitate the pressure loss calculation.

Since the first presentation the panel heating and cooling model has been extended and now provides support for two types of capillary pipe mats (see Fig. 4) and several wall layers to simulate realistic wall designs.

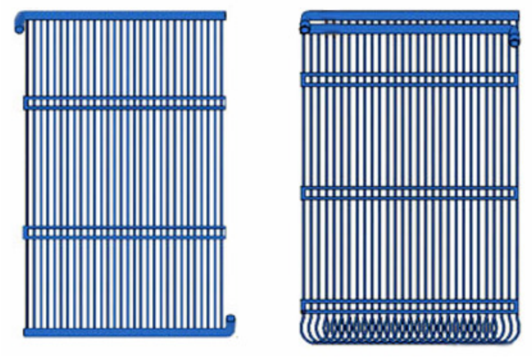

Fig. 4: implemented pipe mat types.

A model of a capillary pipe mat system as described by B. Glück in [3] was replicated and simulation results were compared to the findings of Glück. It could be shown that the replicated model had very small differences in the area–related heat energy storage (Wh/m^2) of below 5% depending on the grid spacing. Some differences between the models remained (unknown material properties of one ceiling layer, modeling of pipes, calculation of heat transfer coefficients at ceiling surface) and will be a reason for the differences.

4.2 Simple Radiator Model

To be able to model a standard European heating system a radiator black box model has been developed. It features radiative and convective heat transfer with the consideration of the influences of ambient air pressure, radiation and air temperature. Parameterization is easy with catalogue data (Mass of steel, water volume, length …) provided by the manufacturer. Correction factors accounting for the situation of installation, coating and other influences can be provided as *parameters*. Fig. 5 shows the graphical representation of this model.

The calculation of current heat flow is based on the ratio of current heater surface excess temperature and its nominal value:

$$\frac{\dot{Q}}{\dot{Q}_{nom}} = \left(\frac{\Delta T_{\log}}{\Delta T_{\log,nom}} \right)^{eh}$$

Since the exponent of the heating surface *eh* is only valid for a small range around nominal conditions an approach applying correction factors is used in order to obtain a reasonable behavior under part load conditions. B. Glück describes the algorithm in [4].

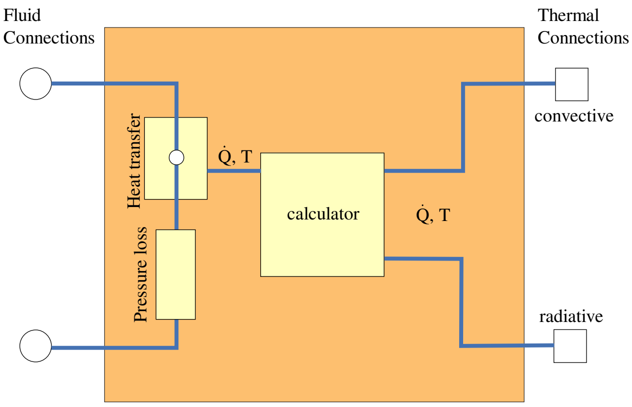

Fig. 5: Illustration of radiator model.

4.3 Simple Heat Exchanger Model

The heat exchanger component used in the described simulation model is a shell and tube heat exchanger with a number of discrete pipe elements to model the heat exchange between shell and tube side fluids.

Compared to the simple pipe model heat convection will now be computed by a variable heat transfer coefficient depending on geometric attributes, fluid velocity and temperature. Algorithms for various kinds of heat convection effects on pipes are based on [2].

Appropriate functions for the heat convection effect can be chosen in the graphical user interface. Because the effect is computed in a separate sub–module it is easy to implement more heat convection effects for other surface geometries.

Currently a one pass heat exchanger with plain tubes is implemented. The structure of the component is depicted in Fig. 6.

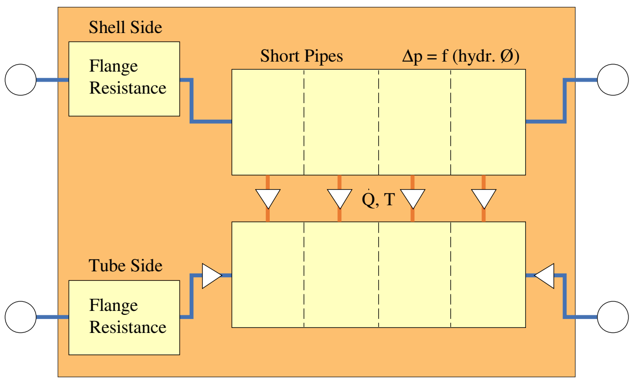

Fig. 6: Illustration of tube and shell heat exchanger.

Thermal effects can be described using an adapted mandrel pipe model [2]. The shell side tube contains a number of inner tubes. Heat transfer between the fluids is influenced by the heat convection coefficients at the tubes – shell side and tube side. The coefficients are calculated using an equation for fluid flow in pipes found by Gnielinksi [2]. For shell and tube side the same equation applies in this case except that the equivalent hydraulic diameter must be provided for the shell side fluid flow.

Instead of modeling all tubes directly, only a single tube will be used to reduce model size and computation time. This is feasible under the assumption of equal temperature distribution normal to the flow direction. Total mass flow rate through the pipe must be reduced to reflect the real flow conditions inside a single tube. Additionally, the transferred heat flow towards the tube side fluid must be adjusted to account for the reduced number of tubes.

The heat exchanger is divided into sections alongside the tube direction to solve for the time and location dependent differential equation.

Hydraulic effects are considered for the flange taps and the heat exchanger's internal fluid flow. Shell side pressure loss for longitudinal flow in tube bundles can be calculated as for fluid flow inside a single tube. In this case the hydraulic diameter of the shell side must be used instead of the pipe diameter.

An option is implemented to regard deposits at the tubes surface with a definable thickness.

Currently a new heat exchanger component is being developed at the HRI. It is based on characteristic values of different types of heat exchangers and various flow types according to the theory in [2]. This generic model will allow covering a broader range of heat exchanger designs in simulations.

4.4 Heat Pump Model

Fig. 7 shows the simplified illustration of the black box heat pump model. There are two heat exchangers (condenser and evaporator) which allow exchanging energy between the medium and the heat pump cycle.

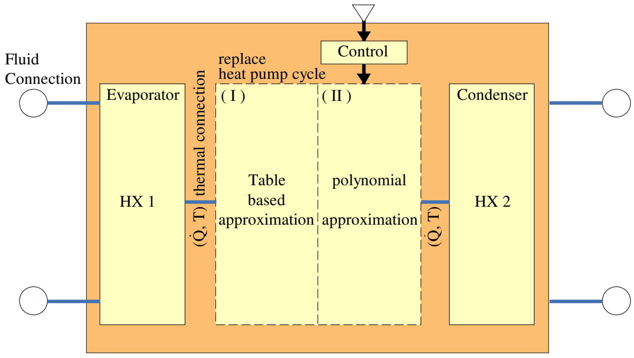

Fig. 7: Illustration of heat pump model.

Two models exist for the inner heat pump cycle. A table based approach offers to easily apply manufacturer data for evaporator power $\dot{Q}_0$, condenser power $\dot{Q}_c$ and engine power consumption P_e. Cooling power and engine power will be interpolated by the *CombiTable2D* module contained in the Modelica Standard Library.

A second model applies polynomial approximations to calculate volumetric cooling power

$$\dot{q}_{0W} = \dot{Q}_{0,nom} / \dot{V}_W$$

of a piston compressor as a function of condenser and evaporator temperature, T_c and T_0 respectively. Volumetric cooling power $\dot{q}_{0W}$ depends on the refrigerant used and the construction of the piston compressor. Approximate values for two refrigerants R404 and R134a used in a variety of piston compressors are known [5]. $\dot{V}_W$ may be calculated using geometric data of the piston which is provided by the manufacturer.

The second approach allows to adjust the cooling power of the generic heat pump very easily by adapting piston size. The first model on the other hand will be more accurate because it employs manufacturer data for a specific heat pump construction.

Power regulation of the heat pump is implemented as continuous speed regulation which is modeled by the ratio of current to nominal speed where the speed range can be chosen freely. Since evaporator power depends on the refrigerants volume flow rate which is directly proportional to the machine speed one can scale nominal cooling power linearly with the speed ratio:

$$\dot{Q}_{0,nom} = \dot{V}_{W,nom} \cdot \dot{q}_{0W}$$

and

$$\frac{\dot{V}_W}{\dot{V}_{W,nom}} = \frac{n}{n_{nom}}$$

Power consumption can roughly be estimated using the affinity law:

$$\frac{P}{P_{nom}} = \left(\frac{n}{n_{nom}}\right)^3$$

To better describe the dynamic behavior of a heat pump in our simulations the model features temperature protection implemented by the use of two boundary temperatures. By default an on–off controller will turn the pump off when the controled temperature T_{target} drops below temperature T_1 and start the machine again when the T_{target} rises above T_2. When the pump turns off it will come to a halt within a definable time period. It will not start again until a minimum amount of time has passed. Besides those implementations there is no modeling of dynamic behavior of the heat pump.

4.5 Other Components

Several additional components are needed to model hydraulic networks. The *HVAC–HRI* library contains most of these components. The models are designed to work with different fluids – mainly water and air in building installations.

An extended short pipe model based on the model of the *Modelica.Fluid* library allows simulating heat transfer from the fluid through the pipe wall, as well as heat storage in the pipe material. The pipe wall consists of two layers to being able to model an insulation layer. An aggregation of a sufficiently high number of these short pipe models allows for the simulation of long pipes.

Single hydraulic resistor elements can be represented by a model applying friction coefficients as is often done when designing hydraulic networks. Based on friction coefficients a three–way pipe model is also available.

Valve models exist for two–way and three–way valves. Additionally, a thermostat head can be combined with the two–way valve to form a heat valve that would normally be used with the radiator model as described in section 4.2.

Two pump models are currently available: one model defines the pump's hydraulic curve (head is a function of mass flow rate) by an nth grade polynomial. Different pump speeds are modeled by employing the affinity law.

The second pump model uses tabulated values for pump head and volume flow rate. Therefore, the pump curves can be modeled very precisely as well as the electrical power consumption of the pump. Several control strategies are available for both pump models. For example constant pump speed, constant pump head and constant volume flow rate.

A generic heater and chiller model allows defining a heat source or heat sink in a hydraulic circuit. A derived model allows defining the outflow temperature depending on an input value. This allows for the employment of heater flow temperatures depending on ambient air temperature. Day and night modes are also possible.

4.6 Exemplary Results

An exemplary result of a simulation with the described model is shown in Fig. 8 and Fig. 9. Two very simple control strategies of the heat pump model have been compared to a simulation without cooling.

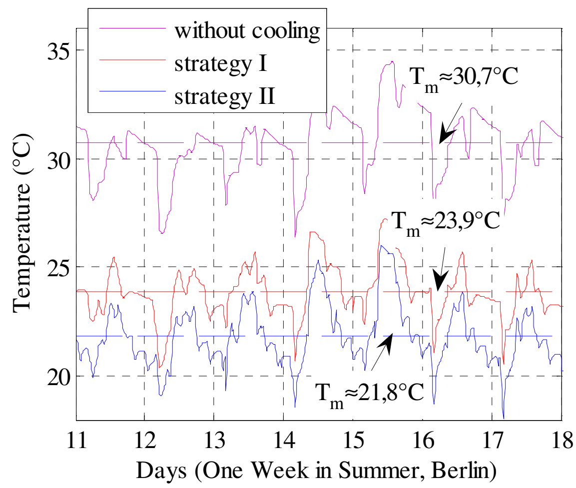

Fig. 8: Room air temperatures of example simulation.

Strategy I uses evaporator outflow temperature to control the heat pump power as displayed in Fig. 1. In strategy II the capillary pipe mat inflow temperature was controlled. The temperatures were lower in this case compared to the values in strategy I.

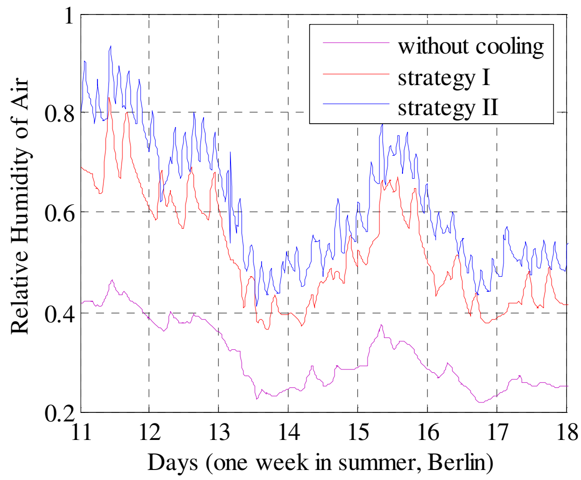

Fig. 9: Humidity of air near room ceiling.

The power control included in the heat pump continuously adapts heat pump power to the input temperature signal. This input signal later can also be provided by a more sophisticated controller algorithm.

One can clearly see the cooling effect of both strategies on room temperature. Because the second strategy yielded lower fluid temperatures in the pipe mat the cooling effect is stronger than with strategy I.

The graphs in Fig. 9 display humidity of air near the cooling panel for both strategies and without cooling. Relative humidity performs as expected according to the mean surface temperature of the ceiling.

The control strategies employed in the described example simulation have not been optimized. Detailed examination of the system behavior considering special requirements (e.g. a maximum humidity level) would allow finding optimized control strategies.

5 Conclusions and Perspectives

The feasibility of thermally and hydraulic coupled dynamic building simulations could be shown. It is possible to test and verify different control strategies of the components. This allows for the research of energetically optimized installations in buildings.

Different approaches to design a model are often useful to account for the specific demands on a model.

Further development will concentrate on the refinement of the models developed at the HRI in combination with larger scale building simulations. New components will also be developed to cover a wider range of building services installations.

Upon completion of new test facilities at the HRI validation of several components and systems will be possible. For example a testing environment with capillary pipe mats for the air–conditioning of two rooms is currently being installed.

List of symbols

eh	exponent of heating surface
n	rotational speed of engine
$\dot{Q}$	heat flow rate
$\dot{q}_{0W}$	volumetric evaporator power (W/(m^3/s))
P	engine Power
T	Temperature
$\dot{V}$	volume flow rate
Indices	
$_{1,\,2}$	minimum, maximum value
$_{target}$	target value
$_{c}$	condenser
$_{0}$	evaporator
$_{W}$	pistion working volume
$_{nom}$	nominal value
$_{log}$	logarithmic value

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