Felgner F., Agustina S., Cladera Bohigas R., Merz R., Litz L.:
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2nd International Modelica Conference, Proceedings, pp. 147-154

Paper presented at the 2nd International Modelica Conference, March 18-19, 2002,
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Oberpfaffenhofen, Germany.

Simulation of Thermal Building Behaviour in Modelica

F. Felgner, S. Agustina, R. Cladera Bohigas, R. Merz, L. Litz (felgner@eit.uni-kl.de)
Fachbereich Elektrotechnik und Informationstechnik, Universität Kaiserslautern,
Erwin-Schrödinger-Straße, D 67663 Kaiserslautern,
March 2002

1. Abstract

During the past decades heating and air conditioning systems were usually designed and consequently oversized according to simplified, mostly static calculating procedures. The increase in primary energy costs, rising cost pressure felt by private and public clients as well as increased demands on comfort forced engineers to change the customary procedure. Thus the dynamic simulation of building and system behaviour plays an increasingly important role in planning and dimensioning heating and air conditioning systems. This change is supported by the growing performance of personal computers in use. This means that calculating methods which used to be too expensive and time-consuming became practicable and could even be improved.

Building and system simulation aims at emulating the thermal and energetic behaviour of an existing or a fictitious building and of its HVAC system as well as their interaction. For this purpose the external influences through the outdoor climate, user behaviour and internal loads are to be taken into account. The comprehensive building design requires the adequate description of real processes within a broad spectrum of mathematical, physical and engineering disciplines. The model of just an uncomplicated heating system includes various components from thermodynamics, fluid dynamics, mechanics, electrical and control engineering.

It is true there is a great variety of simulation tools - mostly conceived for architects and building engineers - varying according to the methods they use, the effects they consider as well as to their objectives. Such simulation tools pretend to offer a high transparency and flexibility through their menu-guided modelling but can often not be completely overlooked by the user as to their numeric methods, the effects considered and approximations applied. Operations going beyond what is provided by the menu are either not possible or can only be realized at great expense.

Therefore we intended to take another way. Using an open simulation system, which provides the mathematical formalism, the model specification is done by the description of basic physical laws describing the relevant properties [Fel-01], [Mer-01], [Sit-01]. An object-oriented, non calculation-causal simulation language like *Modelica* offers perfect conditions for this concept.

In the context of our work a model library for the simulation of thermal building behaviour has been developed in *Modelica*. Due to the interdisciplinary character of building simulation this domain is an ideal application of *Dymola/Modelica*. We used *Dymola 4.1a* from *Dynasim (http://www.dynasim.se)*.

The new model library is divided into four sublibraries:

- *Building* (chapter 2),
- *Weather* (chapter 3),
- *Heating* (chapter 4),
- *controller* (chapter 5).

The building models have been validated in exemplary configurations with the building simulation system *TRNSYS* [Trn-02], [Kle-00], [Kie-01].

In the following chapters the most interesting components or those sublibraries will be presented.

2.1 Basic Building Elements

The characteristic thermal behaviour of a building structure is determined by the storage and the conduction of heat within walls, ceilings, floors and the air inside and outside the building as well as the heat transmission between those components [VDI-01]. The processes of heat storage and transmission are described by basic building elements, which are the primary components of a thermal building model.

Heat storing elements (fig. 2.1a, b) correspond to electrical capacitors, where electrical current is replaced by heat flow j and the place of the electrical potential is taken by the temperature T:

$$m \cdot c \cdot \dot{T} = j \qquad (2.1)$$

(m: mass of heat storing body, c: specific heat capacity).

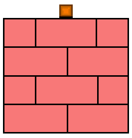
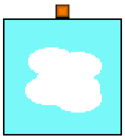
a stone  **b** air 

Fig. 2.1: Heat storing components of a building

Heat conducting elements (fig. 2.2) correspond to electrical conductors:

$$j_{1\to 2} = \frac{\lambda \cdot A}{d}\Delta T = \underbrace{\frac{\lambda \cdot A}{x_2 - x_1}}_{\text{conductance } G}(T_1 - T_2) \quad (2.2)$$

(λ: heat conductivity, A: area perpendicular to heat flow j, d: distance between two heat storing elements with the temperatures T_1 and T_2).

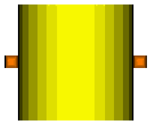


Fig. 2.2: Heat conductor

Convection (fig. 2.3) is described with the same mathematical structure if the convective heat transfer coefficient α is supposed to be a constant:

$$j_{1\to 2} = \alpha \cdot A \cdot (T_1 - T_2)\,. \quad (2.3)$$

Convection takes place between the air and walls, floors and ceilings inside the building as well as outside.

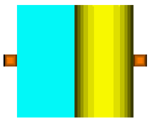


Fig. 2.3: Convection with constant α

Radiation – the third way of heat transfer – plays an important role, too, especially as far as solar radiation, the emission from radiators and the heat exchange between walls are concerned. The power $P_{\text{rad}} = j_{\text{rad}} = \left|\vec{j}_{\text{rad}}\right|$, emitted from a surface with the temperature T, is given by Stefan-Boltzmann's Law,

$$j_{\text{rad}} = \sigma \cdot \varepsilon \cdot A \cdot T^4 \quad (2.4)$$

(σ: Stefan Boltzmann constant, ε: emission coefficient of surface),

which is implemented in a model class (fig. 2.4) describing the exchange of radiation between a surfaces A with the temperature T_1 (e.g. the surface of a wall) and a fictive black body with the same surface and the temperature T_2:

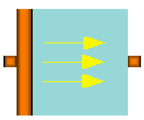


Fig. 2.4: Radiation to a black body

$$j_{1\to 2} = \sigma \cdot \varepsilon_1 \cdot \underbrace{\varepsilon_2}_{=1} \cdot A \cdot (T_1^4 - T_2^4)\,. \quad (2.5)$$

Those components will be used for the so-called *two-star room model* (see ch. 2.2).

The library also contains components simulating the radiation between two parallel or two perpendicular surfaces (fig. 2.5a, b). For this purpose the equation (2.5) has to modified by an additional factor taking

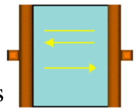
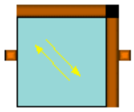
a parallel surfaces  **b** perpendicular surfaces 

Fig. 2.5: Radiation between two surfaces

into account the surfaces' dimensions and relative site.

2.2 Composed Building Model Classes (walls, windows, doors, rooms)

The basic building elements presented in ch. 2.1 serve to compose models of more complex parts of a building. As a first instance the model of a *wall* be considered:

Within solid matter heat transport is provided by conduction. This means that in case of one-dimensional heat flow in x-direction the temperature $T(x)$ is given by the well-known partial differential equation

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial x^2}\,, \quad (2.6)$$

which cannot be implemented directly in *Modelica* as there is only one independent variable (`time`) provided. But the derivation in x can be approximated by discretizing the coordinate x into x_i (i = 1, 2, 3, ...) with $\Delta x := x_i - x_{i-1} = const.\ \forall\, i$:

$$\frac{\partial^2 T}{\partial x^2} \approx \frac{T(x_{i+1}) - 2T(x_i) + T(x_{i-1})}{(\Delta x)^2} := \frac{T_{i+1} - 2T_i + T_{i-1}}{(\Delta x)^2} \quad (2.7)$$

Thus the equation (2.6) can be approximated by

$$c\rho \dot{T} = \lambda \frac{T_{i+1} - 2T_i + T_{i-1}}{(\Delta x)^2} \quad \Leftrightarrow$$

$$c \cdot \underbrace{\rho A \Delta x}_{m} \cdot \dot{T} = \underbrace{\frac{\lambda A}{\Delta x}}_{G}(T_{i-1} - T_i) - \underbrace{\frac{\lambda A}{\Delta x}}_{G}(T_i - T_{i+1})\,. \quad (2.6')$$

Using the components for heat storage and conductance introduced in ch. 2.1 the equation (2.6') can be implemented by the *Modelica* model in fig. 2.6, which is a simple thermal model of a wall with mass m, specific heat capacity c, surface A and thickness $2\Delta x$.

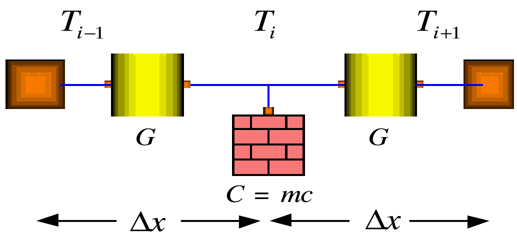


Fig. 2.6: Model of conduction within a wall

A more precise model of a wall is achieved by dividing the wall into several layers – at least two – and adding the convection model from fig. 2.4:

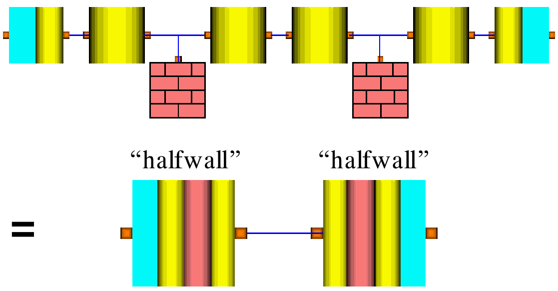


Fig. 2.7: Two-layer model of a wall (or floor / ceiling) with convective heat transmission to air

The model in fig. 2.7 is of course suitable for floors and ceilings, too.

Before constructing the thermal model of a room the radiative heat transmission between its walls, floor, ceiling and other radiating surfaces (e.g. radiator surface) shall be considered first. Using the models from fig. 2.5 would lead to a complicated network of connections between each surface and all the others. A room of a simple rectangular geometry would demand three instances of the parallel surfaces model (fig. 2.5a) and 12 instances of the perpendicular surfaces model (fig. 2.5b). A non-rectangular room geometry and the radiation from a radiator surface would demand very special additional model classes which are much more complex or even do not exist in a parameterised form, respectively.

For this reason the building library presented here makes use of a certain approximation – the so-called *two-star model* (see for example [Fei94]). In this model all radiating surfaces are connected to a fictive massless black body, which has an infinite heat conductivity and fills in the whole volume of the room. In the model diagram this body is simply a nodal point. Each long wave radiation emitting surface is connected to that nodal point via a radiation junction component from fig. 2.4 (ch. 2.1). A second nodal point provides the convective connection of the surfaces to the air via convective junction components (fig. 2.3). Fig. 2.8 shows the two-star model of a room with four walls (plus floor and ceiling). Only one half of each wall is represented in the model of a room, the second half is part of a neighbouring room.

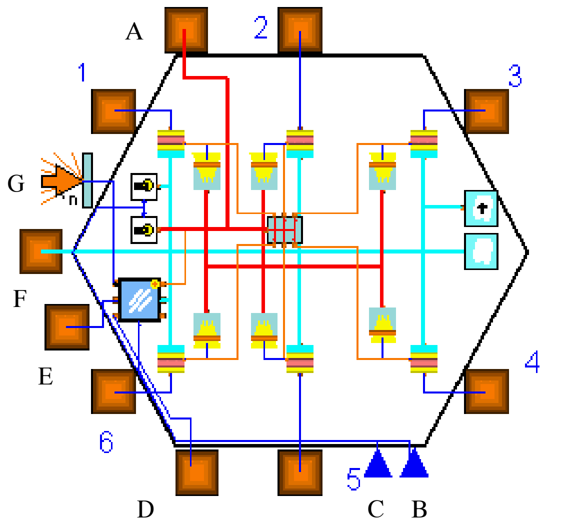


Fig. 2.8: Two-star model of room with four walls.
External cuts: 1 – 6 walls, floor, ceiling;
A radiation from external model (radiator);
B signal for air exchange through window;
C signal for internal gains;
D Radiation to sky through window;
E convection on the outside of the window;
F convection from or to external model;
G connection to solar radiation model.

Additionally models for internal gains (with a light bulb in the icon) as well as the model of a window (fig. 2.8) describing air exchange and heat transmission by conduction, convection and radiation. There is a special cut in the window model and in the room model ("G" in fig. 2.8) providing a connection between the window and a model from the solar radiation library (see ch. 4). A radiator (as an external model) can be connected to the room via two cuts: Cut "A" provides the connection to the radiation nodal point, cut "F" transmits convective heat transport from the radiator to the air.

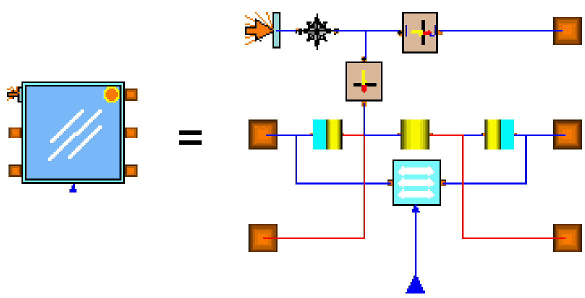


Fig. 2.9: Model of a window with controlled air exchange and heat transmission by conduction, convection and radiation (including solar radiation)

3. Solar Radiation Models

3.1 Introduction

Comprehensive modelling of thermal building dynamics requires considering the influence of nature. In order to simulate the impact solar radiation has on energy consumption and controller behaviour in a realistic manner a highly refined solar radiation library has been developed. With its models it is possible to calculate the solar radiation on a tilted surface at any location [Duf-74]. The models are very user-friendly since simulation periods can be defined by entering date and local clock time. Moreover, real weather data can be integrated in the simulation model by reading external ASCII files and interpolating the data in different ways. The models reproduce the broad spectrum offered by modern building simulation tools (e.g. *TRNSYS* [Trn-02], [Kle-00], [Spr-01]).

3.2 The Models

The solar radiation models contain a large number of algorithms, which cannot be explained within the limitations of this article.
In the following a brief overview of some important components will be described.

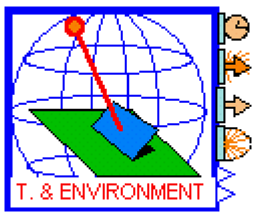


Fig. 3.1: calculation of solar radiation on tilted surfaces

The encapsulated model in fig. 3.1 calculates the solar radiation on surfaces of any orientation. Two versions of that model will be presented now:

The diagram layer of version I is shown in fig. 3.2 (without the cuts on the highest hierarchy level). There are eight important components performing the calculation:

(1) distributes the information about location (*longitude* and *latitude*) and *time zone* to all components that need this data.

(2) calculates the time variables that are needed in addition to the (physical) simulation time: *solar time* and *standard meridian time*. (Switching to daylight time is possible, too.)

(3) produces the *declination angle*.

(4) calculates the position of the sun determined by *zenith angle* and *azimuth angle*.

(5) calculates the solar *radiation on an extraterrestrial horizontal surface*.

(6) determines the *atmospheric attenuated solar radiation*. For this a so-called *clearness index* k_T is used. The calculation with a constant k_T is an approximation, which should be used only for clear days. (And even in that case k_T is not exactly constant.) In a further model (version II) this component is replaced by importing real or fictive weather data from an external file.

(7) divides the total radiation on a horizontal terrestrial surface into *beam radiation* and *diffuse radiation*.

(8) transforms the results of component (7) into total radiation on a tilted surface.

In version II (fig. 3.3) the disadvantage of component 6 (only suitable for clear days) has been removed by importing radiation data from an external file. The radiation data may be based on measurements of a weather station or a typical climatic conditions of the location. The radiation data (total radiation on a horizontal surface) is imported by a new *ASCII table reader* (component 6A). Table readers from the Modelica standard libraries could not be used for they perform a linear interpolation using a C function. The new table reader makes use of a special C function without linear interpolation. As tables contain sampled values – official weather data for a German test reference year are available at hourly intervals (DIN 4710) – a linear interpolation would produce big mistakes during the hours of sunrise and sunset. To avoid such mistakes the table data has to be read in

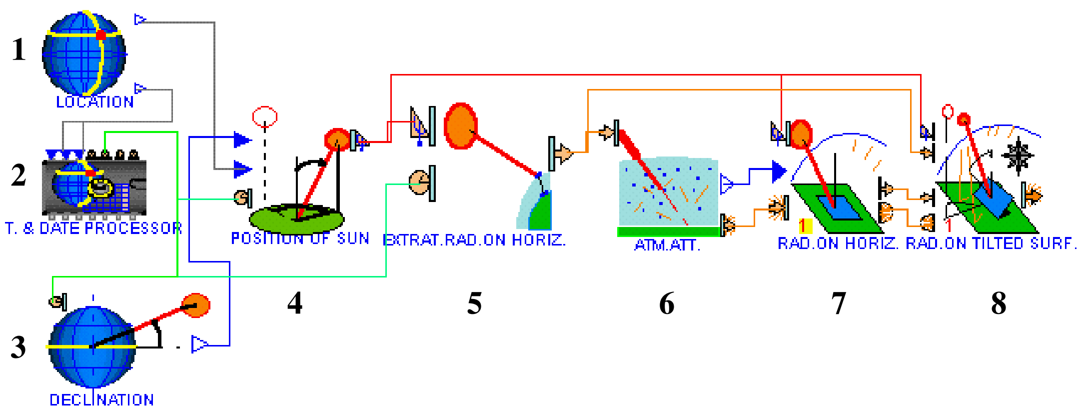


Fig. 3.2: Aggregation pattern of solar radiation model (Version I)

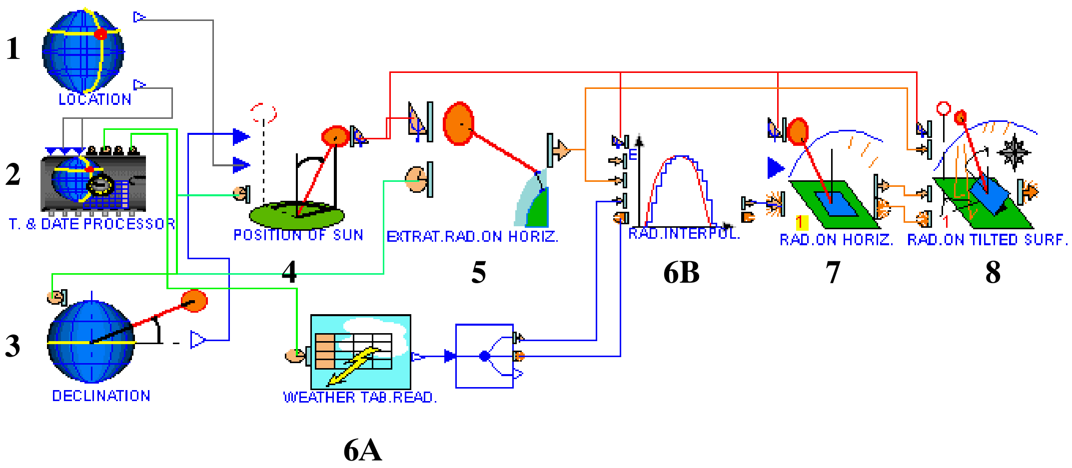


Fig. 3.3: Aggregation pattern of solar radiation model with table reader and interpolator (Version II)

advance. In this way sunrise and sunset are detected in time. Afterwards an appropriate interpolation is performed (component 6B). The library offers a selection of different interpolation methods.

4. Models of Heating Systems

4.1 Introduction

The heating library allows composing models of electrical heating systems as well as hot-water heating systems. In view of physical modelling hot-water heating systems (HWH) are more interesting than the electrical ones, which produce almost immediately a certain heat flow prescribed by the controller. Yet the dynamics of an HWH is determined by transient processes caused by the thermal inertia of various components. Those are the water, the pipes, the radiators and – especially in case of floor heating systems – the stone of the floor. In addition slow transport of water through long pipe systems in large buildings bring about dead time. All those characteristics complicate controlling an HWH for its delayed reactions may have a negative influence on stability.

In the following chapter a dynamic pipe model will be presented.

4.2 Pipes and Radiators

A universal model of a water pipe must combine mechanical and thermal aspects of flowing water. Both aspects are interdependent: The temperature profile depends on the mass flow rate, whereas the mass flow rate is influenced by the viscosity, which is rather strongly depending on temperature. The impact viscosity has on a pipe's flow resistance is determined by the form of flow.

In case of steady laminar flow *Hagen-Poiseuille's Law* is valid for cylindrical pipes:

$$\dot{m} = \frac{\rho \pi D^4}{128 \eta L}(p_1 - p_2) \tag{4.1}$$

($\dot{m}$: mass flow rate, D: diameter, L: length of pipe, η: dynamic viscosity, $p_1 - p_2$: pressure drop).

If the Reynolds Number $Re = \rho v D/\eta$ is greater than $Re_{\text{crit.}} \approx 2300$ the flow becomes turbulent, and pressure drop is usually approximated by

$$|p_1 - p_2| = \lambda \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2} \tag{4.2}$$

(v: average speed, λ: pipe friction coefficient).

If $Re < 100\,000$, the factor λ is given by

$$\lambda = \frac{0.3164}{\sqrt[4]{Re}} \quad \text{(formula of Blasius).} \tag{4.3}$$

In the pipe model developed here λ is approximated by pieces of straight lines – as well as the viscosity $\eta(T)$.

The thermal dynamic of a fluid within a cylindrical pipe can be described by the partial differential equation (PDG)

$$\underbrace{-c\dot{m}\cdot\left(\frac{\partial T}{\partial x}\right)_t}_{\substack{\text{steady release of}\\ \text{heat (per meter)}}} \underbrace{-c\rho\pi\frac{D^2}{4}\left(\frac{\partial T}{\partial t}\right)_x}_{\substack{\text{unsteady release of}\\ \text{heat (per meter)}}} = \underbrace{\alpha\cdot\pi D\cdot(T - T_{\text{wall}})}_{\substack{\text{heat transmitted by convection}\\ \text{to pipe wall (per meter)}}} \tag{4.4}$$

(c: specific heat capacity of water, ρ: density of water, α: convective heat transfer coefficient), where heat conduction in x-direction within the water has been neglected. To solve this problem the PDG has to be transformed to a system of ordinary differential equations by a discrete coordinate x: A long pipe is composed out of short pipe elements, each of the length $L := \Delta x$:

$$-c\dot{m}\cdot\frac{T_{\text{out}}-T_{\text{in}}}{L}-c\rho\pi\frac{D^2}{4}\frac{\mathrm{d}T_{\text{out}}}{\mathrm{d}t}=\alpha\cdot\pi D\cdot(T_{\text{out}}-T_{\text{wall}}). \tag{4.4'}$$

As an approximation of α one might take for instance *Schack's formula* [Rec-97]:

$$\alpha = 3370\cdot\left(1+0.014\frac{T_{\text{out}}}{°\text{C}}\right)\left(\frac{v}{\text{m/s}}\right)^{0.85}\frac{\text{W}}{\text{m}^2\text{K}} \tag{4.5}$$

$$(D = 15 \ldots 100 \text{ mm}).$$

That formula is, however, not suitable for v = 0 as water being at standstill would release no heat at all in such a model.

The equations (4.1) to (4.5) are implemented in model class describing a cylindrical water element (of Length L) flowing through a pipe (fig. 4.1). The cut variables are pressure, temperature and mass flow rate (blue cuts) or temperature and heat flow rate (red cut), respectively.

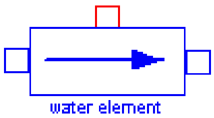


Fig. 4.1: Water element within a pipe

A model describing the conductance and storage of heat within the pipe's wall and heat insulation material is composed out of heat capacitors and cylindrical special heat conductors (fig. 4.2).

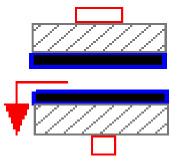


Fig. 4.2: Pipe wall and insulation

With the help of a `for`-loop a series connection of n water elements, each connected to a wall and insulation component, is generated. The complete pipe model (fig. 4.3) can be connected to a temperature source or another (big) heat capacitor (e.g. a wall or a floor in which the pipe is embedded), which absorbs steady heat loss.

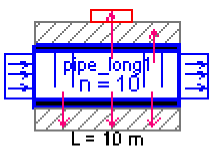


Fig. 4.3: Long water pipe with insulation

Fig. 4.4 shows a circuit with a 20 m-pipe (consisting of 20 pipe elements, i.e. n = 20), a pump producing a constant pressure and a boiler switched on at t = 600s. At t = 0 all components have the temperature T_0 = 10°C. The boiler has a two-state controller with a hysteresis between 90°C and 95°C. The results of the *DYMOLA* simulation are shown in diagram 4.1.

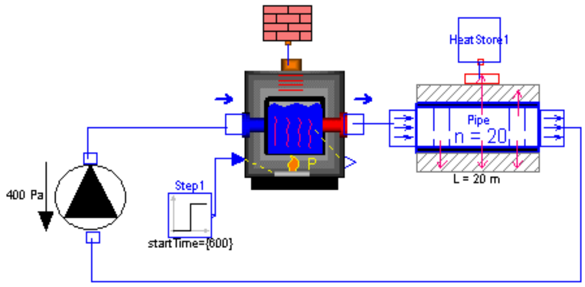


Fig. 4.4: Circuit with long pipe, boiler and pump

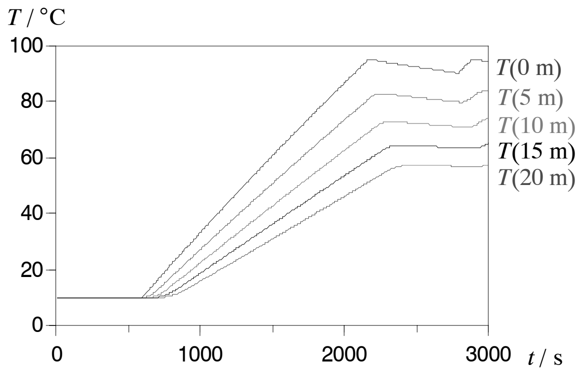


Diagram 4.1: Results of *DYMOLA* simulation of model in fig. 4.4: water temperatures at different positions in the pipe

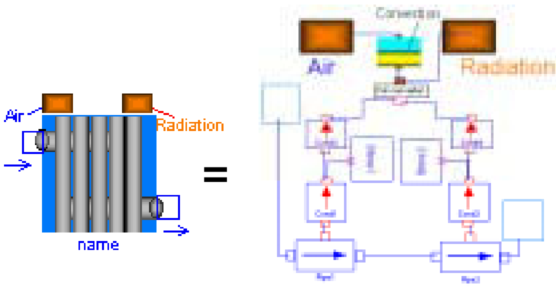


Fig. 4.5: Hot-water radiator

By analogy with the pipe model a *radiator model* can be designed by leaving out the heat insulation (fig. 4.5). The radiator can be connected to the *two-star room* presented in ch. 2 via two cuts: one cut for convective heat transmission to air and another cut for a connection to the room's radiation nodal point.

5.1 Standard Controllers

The first part of the controller library contains several components simulating standard control algorithms. Some components, however, have extended functions. There are two sublibraries, one with continuous and one with discrete controllers.

The *continuous controller sublibrary* contains PI and PID controllers with an anti-wind-up reset function and a pulse width modulator.

The *discrete controller sublibrary* contains special PI and PI controllers emulating the signal processing of digital controllers. In this way the influence of important quantities such as the number of bits or the sampling period can be included in the simulation.

5.2 Fuzzy Control

The Heating, air-conditioning and ventilation of a building requires the control of many interdependent quantities belonging to rather complex physical processes. Therefore, Fuzzy Control is an appropriate alternative to standard control strategies. With the new *Modelica Fuzzy Control library* to design a Fuzzy Controller and to test different rule bases,

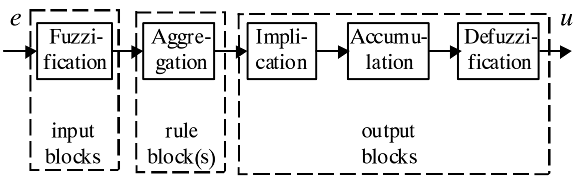


Fig. 5.1: The five steps of FC processing and their assignment to input, output and rule blocks

methods etc. on a Modelica model.

The Fuzzy Control library has a modular structure. A Modelica Fuzzy Controller (FC) has to be composed by the user out of special blocks for the linguistic input and output variables and for the rules. Due to

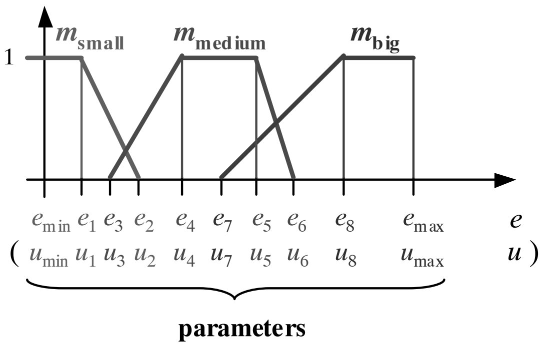


Fig. 5.2: Predefined fuzzy sets for input or output variable (e / u) with parameters of corresponding input or output block

the large variety of settings defining an FC (numbers of inputs and outputs, fuzzy sets, rules, methods of inference and defuzzification) a modular structure supports the clarity of the FC model. Fig. 5.1 shows the assignment of the FC-processing steps to instances of different model classes: input blocks, output blocks and rule blocks.

The fuzzy sets for each input variable and each output variable are defined by choosing an input or output block, respectively, and entering the blip abscissas of the predefined membership functions (fig. 5.2). Currently there are input and output blocks with three or five membership functions. The linguistic values have predefined names.

As fuzzy implication, accumulation and defuzzification are performed in the output block of each linguistic output variable, the library contains different output blocks according to the methods used for implication, accumulation and defuzzification and according to the number of fuzzy sets.

Two different versions of the FC library have been developed so far. In the first place the two version vary in the way the rules are formulated. Fig. 5.3 shows the *Modelica* diagram layer of an FC accord-

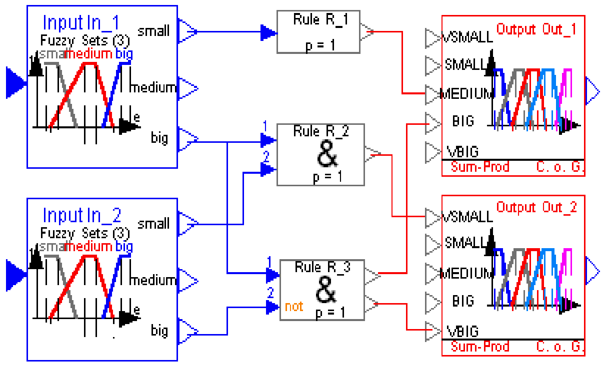


Fig. 5.3: FC according to Version I with the rules:
1. If In_1 small, then Out_1 medium.
2. If In_1 big and In_2 small, then Out_2 very small.
3. If In_1 big and In_2 not big, then Out_1 big and Out_2 very big.

ing to Version I of the library. The methods of implication, accumulation and defuzzification are *sum/product/centre of gravity*. The diagram is similar to a circuit diagram of Boolean logic: There is a rule block for each rule that has to be connected to the input and output blocks. This means that the rules are visualised by the connections the user must draw. There are various types of rule blocks in the library according to the numbers of input values and output values appearing in a rule. Each input value can be negated by entering a certain parameter into the rule block concerned.

Fig. 5.4 is the diagram layer of the same FC composed in Version II: In this case, only one central rule block is needed. The rules are entered into its parameter table as text using a special syntax. The rule block is prepared for up to ten input variables, five output variables and fifty rules. It interprets the aggregation by comparing the components of each rule vector with the predefined linguistic values “vsmall”, “small”, “medium”, “big”, “vbig” and “nvsmall”, “nsmall”, “nmedium”, “nbig”, “nvbig” (v = “very”, n = “not”, output values in capital letters for better readability).

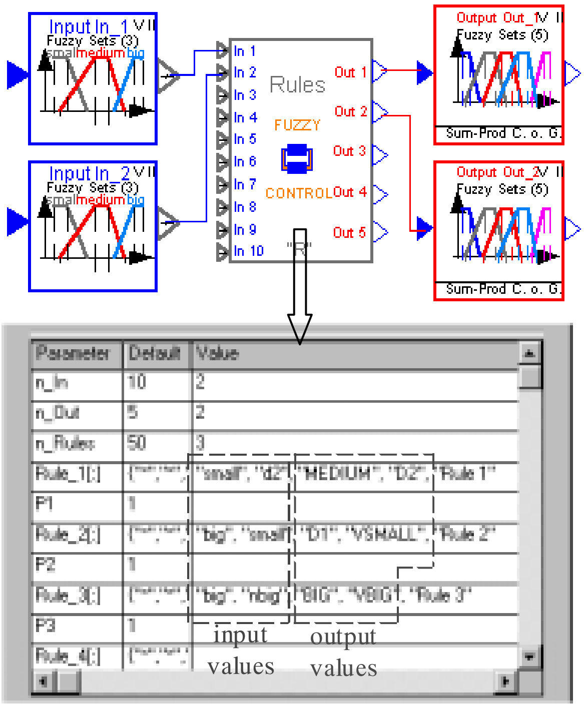


Fig. 5.4: FC in Version II
(corresponding to FC in fig. 5.3)

6. References

[Duf-74]
Duffie J.A., Beckman W.A.: Solar Energy thermal process, Wiley, New York (1974)

[Fei-94]
Feist W.: Thermische Gebäudesimulation Kritische Prüfung unterschiedlicher Modellansätze, Verlag C.F. Müller, Heidelberg (1994) pp.135

[Fel-01]
Felgner F.; Merz R.: Thermohydraulische Simulationsmodelle für Heizungsanlagen ASIM 2001, 15.Sym. Sim.tech. Paderborn 2001

[Kie-01]
Kienzlen K. und da Silva P.: Das Haus im Entwicklungslabor, TAB (Technik am Bau), Bertelsmann Fachzeitschriften GmbH, Gütersloh, 10 (2001) p. 35-39

[Kle-00]
Klein, S.A., Duffie, J.A., Mitchell, J.C., Kummer, J.P., Thornton, J.W., Beckman W.A., Duffie, N.A., Braun J.E., Urban, R.R., Blair, N.J., Mitchell, J.W., Freeman T.L., Evans B.L., Fiksel A.: TRNSYS, a transient system simulation program, Solar Energy Laboratory University of Wisconsin, Madison 1996

[Mer-01b]
Merz R., Litz, L.: Objektorientierte mathematische Modellbildung zur Simulation thermischen Gebäudeverhaltens, ASIM 2001, 15.Sym. Sim.tech. Paderborn 2001

[Rec-97]
Recknagel, Sprenger, Schramek: Taschenbuch für Heizungs- und Klimatechnik. 68.Auflage. Oldenbourg Verlag. München, Wien, 1997.

[Sit-01]
Sitompul E., Merz R.: Anwendung objektorientierter Entwurfsmethoden zur generischen Entwicklung von Regelungsalgorithmen in der Anwendungsdomäne Gebäudeautomation ASIM 2001, 15.Sym. Sim.tech. Paderborn 2001

[Spr-01]
Sprengard C. Merz R.: Simulation des energetischen und thermischen Verhaltens eines Niedrigenergiehauses mit dem Gebäudesimulationsprogramm TRNSYS ASIM 2001, 15.Sym. Sim.tech. Paderborn 2001

[Trn-02]
TRNSYS, www.transsolar.de, Homepage der Fa. Transsolar Energietechnik GmbH. Stuttgart 2001

[VDI-01]
VDI Richtlinie 6020: Anforderung an Rechenverfahren zur Gebäude- und Anlagensimulation, VDI, Düsseldorf, Beuth Verlag GmbH, Berlin (2001)