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Development of a Compartment Model for the Simulation of Thermal Processes in Production Halls

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Abstract—This paper discusses the development of a compartment model for the simulation of thermal processes in a building using the object-oriented programming standard Modelica. The distribution of the temperature within a room is of special interest. One of the main tasks in this work was the successful realization of convection, since the Modelica modelling approach doesn't allow to actually model movement of air packages. Since the walls, roof and floor of the building also have to be part of the building model, this work starts with the description of a solid compartment where heat transfer takes place only via conduction. For the air compartment model, convection formulae for even surfaces and polynomial regression for temperature dependent parameters have been used to calculate the convectional heat transfer coefficient for each compartment surface. A comparison with a real experiment shows the validity of the developed model. To further demonstrate the applicability of the developed room model, an example with the inclusion of a DC motor in the room model is shown.

Keywords - energy optimization; Modelica; buildings simulation

I. Introduction

In times of global warming and shortness of renewable energy sources, energy efficiency of buildings becomes more and more important. Thus, being able to predict the energy consumption is essential for the planning phase of production halls. This can be achieved by a preceding simulation of the building's behaviour with regard to electricity for machines and lightening as well as heating and cooling energy. The simulation of such a production hall requires a detailed model of all machines and energy systems in the hall as well as the building structure itself. This work focuses on the latter by presenting a compartment room model aiming the simulation of the thermal processes.

II. Development of Thermal Compartments

The compartment models for the room are implemented in Modelica [5] using Dymola [4]. Therefore the room has to be divided into cubicles of air as well as solid parts like walls, roof and floor.

A. Thermal Solid Compartment

Each compartment representing a solid part of the building basically consists of a cubicle of certain dimensions and material specific properties. Depending on modifiable parameters like heat capacity, density and conductive heat coefficient of the given material, each compartment has a certain heat capacity and is able to transfer heat via conduction at each surface, which can easily be realised in Modelica via *ThermalConduction* blocks. The conductivity input to the block is calculated from the product of the conductive heat coefficient with the corresponding surface area since thermal conductivity increases with the area as well as with the way to the cubicle's middle due to the related decrease. The remaining way to the other side of the cubicle is considered in the corresponding conductor block at this side. Resultant, one solid compartment consists of a heat capacity in the middle which is connected to six conductor blocks which further lead to a port on each of the six surfaces. The parameters and the block structure of the thermal solid compartment can be seen in Fig. 1.
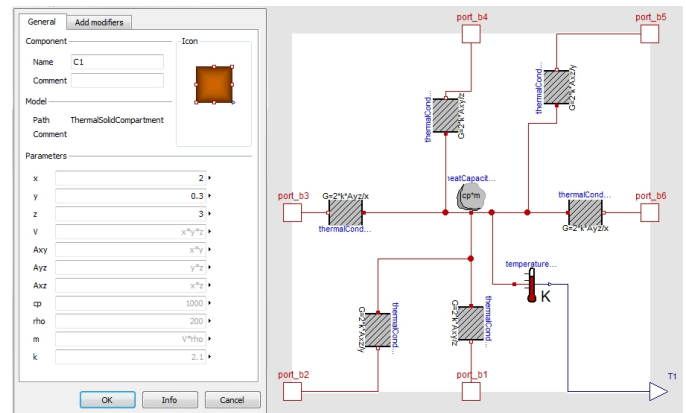

Fig. 1. Thermal Compartment, Developed in the Course of [2]

B. Thermal Air Compartment

Since the compartment model for solid parts does in no way take convection into consideration, it is deficient for air, where most of the thermal exchange takes place due to convection whereas its conduction is almost negligible. Hence, to achieve results comparable to real scenarios, the model described above has been modified to additionally regard convection. Actual particle transport, which would represent convection most specifically, is not possible with the Modelica modelling

T [K]	ρ [kg/m³]	k [mW/(mK)]	ν [$10^{-7}m^2/s$]	Pr	c_v [J/(kgK)]
243.15	1.434	22.023	109.4	0.7161	718.68
253.15	1.3771	22.811	117.7	0.7143	718.58
263.15	1.3245	23.59	126.2	0.7126	718.68
273.15	1.2758	24.36	135	0.711	718.78
283.15	1.2306	25.121	144	0.7095	718.98
293.15	1.1885	25.873	153.2	0.7081	719.28
303.15	1.1492	26.618	162.6	0.7068	719.58
313.15	1.1124	27.354	172.3	0.7056	719.98
323.15	1.0779	28.082	182.2	0.7045	720.58
333.15	1.0455	28.804	192.2	0.7035	721.08
343.15	1.015	29.518	202.5	0.7026	721.78
353.15	0.9862	30.225	213	0.7018	722.58
363.15	0.959	30.925	223.7	0.7011	723.38
373.15	0.9333	31.62	234.6	0.7004	724.38
393.15	0.8858	32.989	257	0.6994	726.48

Fig. 2. Parameter Options for the AirHeatCapacitor Block Implemented in Modelica

Fig. 3. Parameter Options for the ThermalAirConductor Block Implemented in Modelica

approach. An option is given, though, by the Modelica convection block. This block needs the convective heat transfer coefficient as input, which has to be calculated temperature dependently. The development of a Modelica block for this calculation and modified blocks for the heat capacity and temperature dependent conduction have been developed in the course of this work. Since the thermal processes in the room are taken to be isochoric, the heat capacity C for the HeatCapacitor block has to be calculated via $C = c_v \cdot m$ instead of $C = c_p \cdot m$ with the thermal mass m and the isochoric heat capacity c_v instead of the isobaric heat capacity c_p, as would be suggested by Modelica. The isochoric heat capacity depends on the temperature, so the given Modelica block for the *HeatCapacity* has been modified and called *AirHeatCapacity*, wherein the isochoric heat capacity is calculated via a regression polynomial provided by MATLAB using the data given in table I.

The thermal mass is calculated by the product of volume and density, whereas the latter is again gained from a regression polynomial using the initial temperature and keeping it constant for the rest of the simulation. It is necessary to avoid changing the thermal mass during one simulation run to prevent unintended heat loss of the system. The resulting parameter window is shown in Fig. 2.

Since the thermal conductivity k of air also depends significantly on the temperature, the Modelica block *ThermalConductor* has also been modified. The only remaining parameter is the way, consisting of the surface area divided by the length to the middle of the compartment. The resulting parameter window is shown in Fig. 3. To finally be able to calculate the convective heat transfer coefficient, (1) is considered.

$$\alpha = \frac{Nu \cdot k}{l} \quad (1)$$

Nu stands for the Nusselt number, k for the thermal conductivity and l for the straight flow length. To determine the Nusselt number and the flow length, the position where the convection will take place has to be defined. Thus it has to be distinguished between side surfaces, upper surface and lower

surface. In general, the flow length is calculated by the body's surface area divided by the perimeter of its projective area. This results in

$$l = \frac{x \cdot y}{2 \cdot (x + y)} \quad (2)$$

for the upper and lower surface of the cubicle with breadth x and length y. For the side surfaces, their height which equals the height of the cubicle represents the flow length, therefore the formula comes to

$$l = z. \quad (3)$$

The Nusselt number for the upper surface of the cubicle is gained experimently and given in (4). The corresponding equation for the lower surface and the side surfaces are given in (5) and (6) respectively.

$$Nu = 0.766 \cdot \left(Gr \cdot Pr \cdot \left(1 + \left(\frac{0.322}{Pr} \right)^{\frac{11}{20}} \right)^{-\frac{20}{11}} \right)^{\frac{1}{5}} \quad (4)$$

$$Nu = 0.6 \cdot \left(Gr \cdot Pr \cdot \left(1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right)^{-\frac{16}{9}} \right)^{\frac{1}{5}} \quad (5)$$

$$Nu = \left(0.766 \cdot \left(Gr \cdot Pr \cdot \left(1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right)^{-\frac{16}{9}} \right)^{\frac{1}{6}} \right)^{2} \quad (6)$$

To be able to calculate these expressions, the Prandtl number Pr and the Grashof number Gr are required. The Grashof number is defined by

$$Gr = \frac{g \cdot l^3}{\nu^2} \cdot \beta \cdot \Delta T \quad (7)$$

with the acceleration of gravity g, the kinematic viscosity ν, the thermal expansion coefficient β and the temperature difference ΔT. The latter can be calculated by the reciprocal value of β due to the minimal change of pressure. k, ν and Pr have to be calculated again from regression polynomials by the data of table I. By using these formulae and the regression polynomials it is possible to calculate the convective heat transfer coefficient via one formula for each surface depending only on the current compartment temperature and the temperature of the compartment next to the surface. This calculation is realized in the *SISO*-Block *ConvCoeff* (see Fig. 4). The user can choose between the positions *side*, *up* and *down* in a drop-down menu. Additionally, the flow length and the flown area have to be defined. Fig. 5 shows the resulting

Fig. 4. Parameter Options for the Modelica Block for the Calculation of the Convective Heat Transfer

block diagram for the whole *ThermalAirCompartment*. Similar to the structure of the solid compartment, the *AirHeatCapacity* block is connected to six *ThermalAirConductor* blocks which are further connected to the heat ports on each surface. Additionally, a *ThermalConvection* block is connected for all six sides. The input to each *ThermalConvection* block is received from a *convCoeff* block which calculates the convective heat
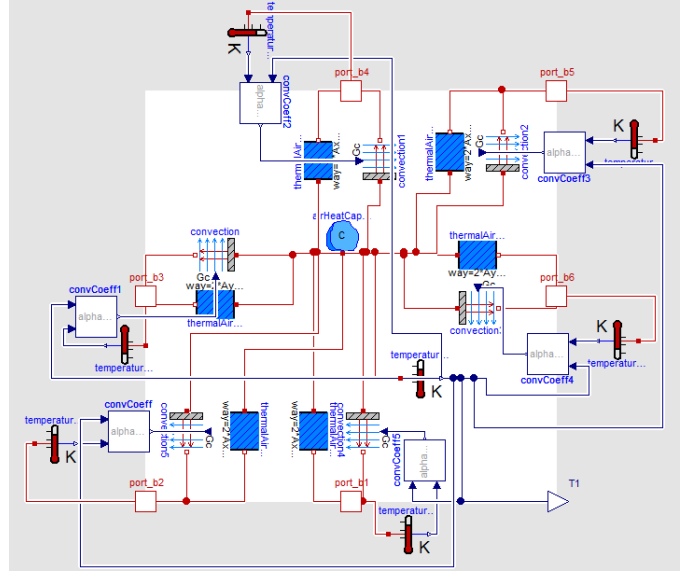

Fig. 5. Block Diagram of the Thermal Air Compartment Implemented in Modelica via Dymola

transfer coefficient at the given position from the compartment temperature at each time step. Fig. 6 shows that the heat capacity, density and thermal conductivity can no longer be set by the user since they are calculated from the compartment temperatures. Apart from the compartment dimensions, the initial compartment temperature can be chosen. Depending on the requirements of the building to be simulated, an arbitrary amount of these compartments is connected to represent the room model.

III. VALIDATION OF THE ROOM MODEL

For the evaluation of the room model described above, a miniature room has been rebuilt with a polystyrene box (see Fig. 7). The box measures $53.5cm \times 34cm \times 24cm$ and can mentally be divided into eight compartments of $26.75cm \times 17cm \times 12cm$. Each of those compartments has been realized as *ThermalAirCompartment* block in Dymola. A soldering iron has been placed in compartment No. 7 to represent a heat source. To be able to determine the progression of the temperature in all compartments, sensors have been inserted through minuscule holes so the temperature is measured in the middle of each compartment. The corresponding Dymola model can be seen in Fig. 8. Due to the small holes for the insertion of the temperature sensors, the room could not be considered completely isolated. Hence, a $9mm^2$ area of every surface representing a hole in the polysterene model has been connected with a *HeatCapacitor* block of high capacity representing the environment in the Dymola model. The temperature of the soldering iron has been realized as a *FixedTemperature* block, whose output is transferred to compartment 7 over a $40mm^2$ area which corresponds to the surface of the iron. The compartment temperature measured over fifty minutes in the polystyrene model is shown in Fig. 9. Fig. 10 shows the results of the simulation of the Dymola
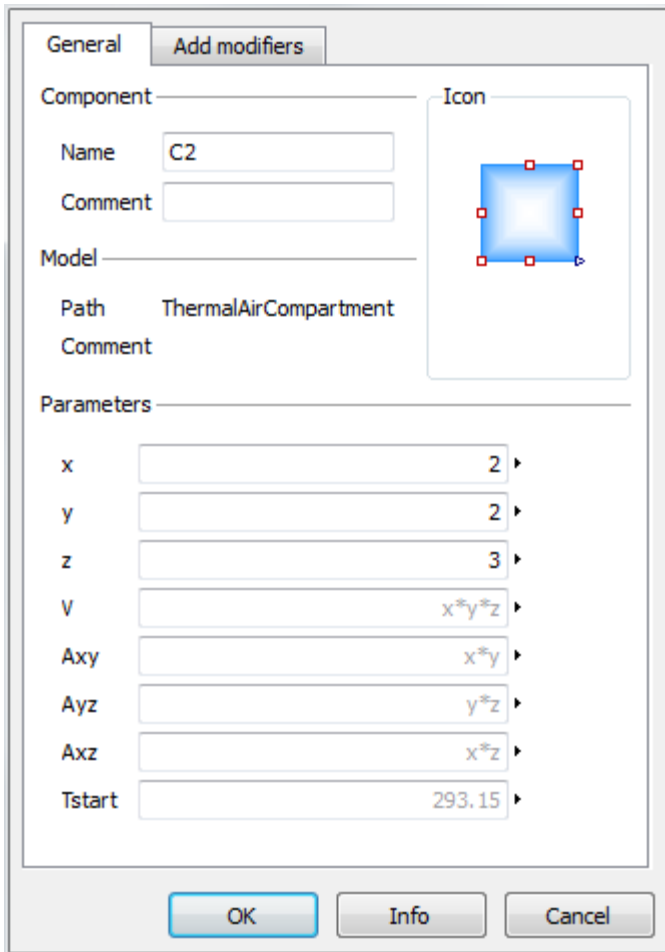
Fig. 6. Input Options for the Thermal Air Compartment Implemented in Modelica via Dymola

Fig. 7. Miniature Room Model Made of Polystyrene

Fig. 8. Miniature Room Model, Implemented in Dymola
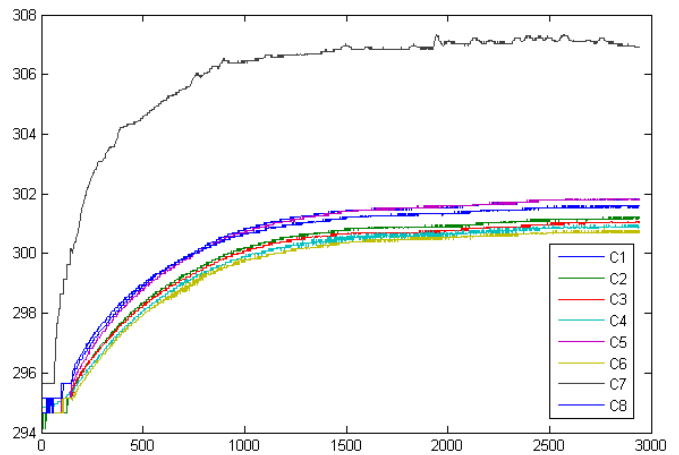
Fig. 9. Measured Compartment Temperature over 50 Minutes

model over fifty minutes. On the first glimpse, the progression of the measured data curve and the temperature resulting from the simulation seem to differ completely. This phenomenon becomes clear if the data are observed for a longer period. As can be seen in the comparison of Figures 9 and 10, the temperature at the end of the fifty minutes largely concurs, especially in the compartments not containing the soldering iron. Since the heat from the soldering iron has to come a c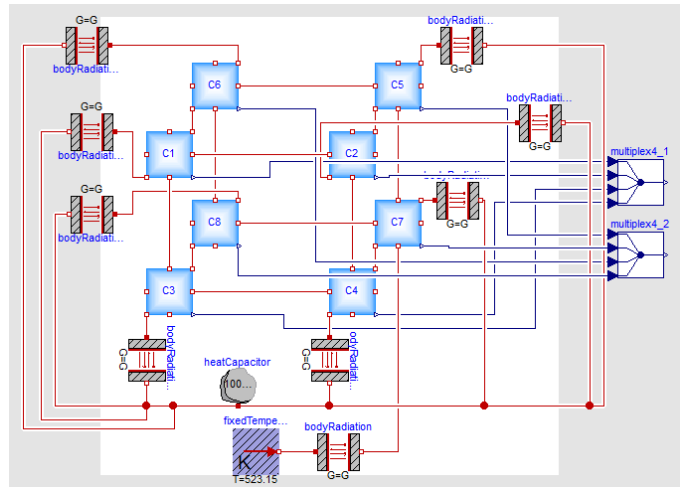ertain way in the real experiment before reaching the next compartments while the heat transfer in the simulation is independent from its position on the compartment surface area itself, the difference between the temperature in the compartment with the heat source to the others is less in the simulation than in the real experiment. In the real experiment, the warm air rises and falls again and again, which leads to a faster intermixture and therefore temperature balance of the system. This causes steps in the progression of the room temperature with an approximate duration of 50 minutes each and resembling the curve in Fig. 9. As this movement cannot be modelled with Modelica, these steps will also not appear in the simulation results. Still, if the model is simulated over a very long time span, the appearance of the compartment temperature's progression is similar to the real experiment, which can be observed in Fig. 11 for the simulation over two days. All in all, the temperature progression shown by the simulation results can be taken as smoothing of the results of the real experiment, as the temperature after the 50 minute period is approximately the same. Finally, the Modelica compartment room model can be found valid.
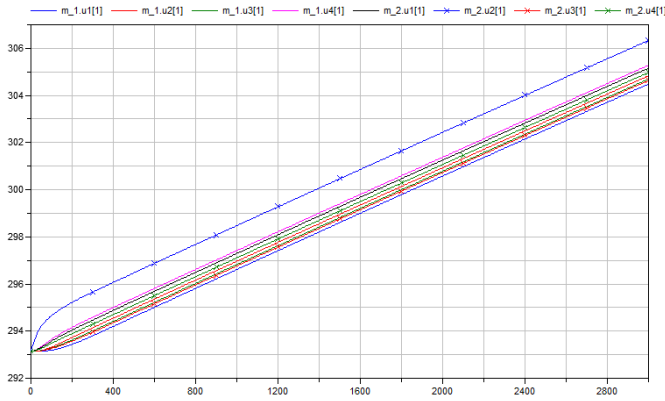
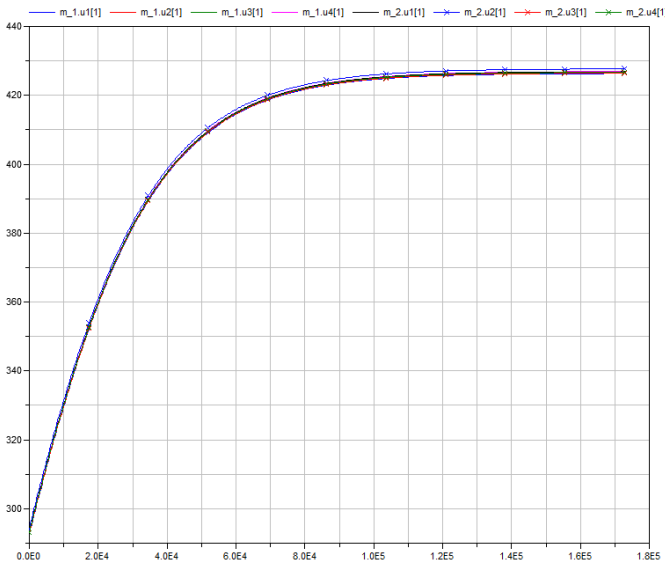Fig. 10. Progression of the Temperature in the Compartments Simulated over 50 Minutes by Dymola

Fig. 11. Compartment Temperature Progression for the Simulation of the Dymola Model over 2 Days

IV. Simple Machine Hall Simulation

As the object-oriented approach of the Modelica language allows intuitive modelling of machines, the developed room model can be used for the simulation of thermal processes in machine halls. To illustrate this, a DC motor model has been added to a room model consisting of six thermal compartments at $2m \times 2m \times 3m$ each. The motor model, which can be viewed in Fig. 12, consists of three circuits of different physical domains.

In the electrical circuit, the voltage drop at the resistor leads to the emission of heat. The electrical energy is further transformed into mechanical energy via an electromotoric force component. The loss of heat due to friction in the mechanical circuit has to be added to the emission at the resistor in a thermal circuit. Since the release of Modelica standard 3.2, optional heat ports are provided for dissipative elements, so the heat emission can easily be obtained without further work.
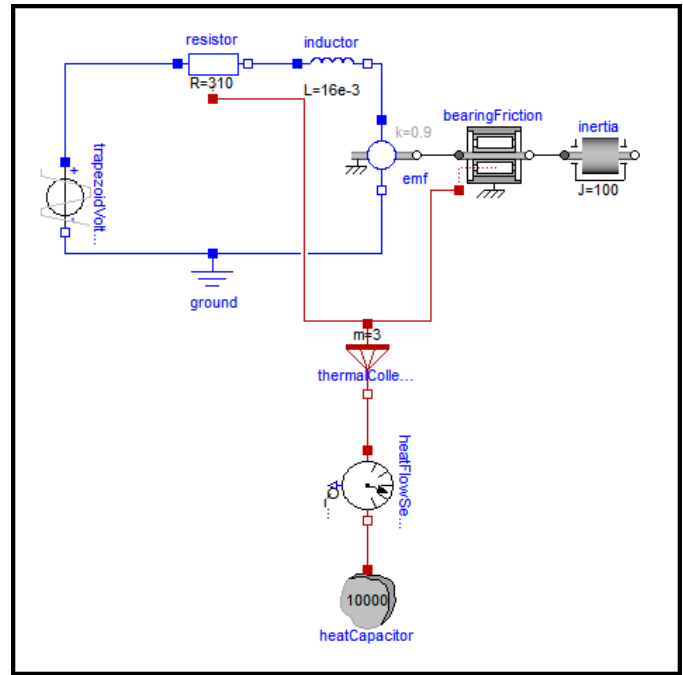

Fig. 12. DC Motor Model, Implemented in Modelica via Dymola

The motor model is connected to the room model, which can be seen in Fig. 13, via a subsystem whose output is the heat emission measured at the motor.
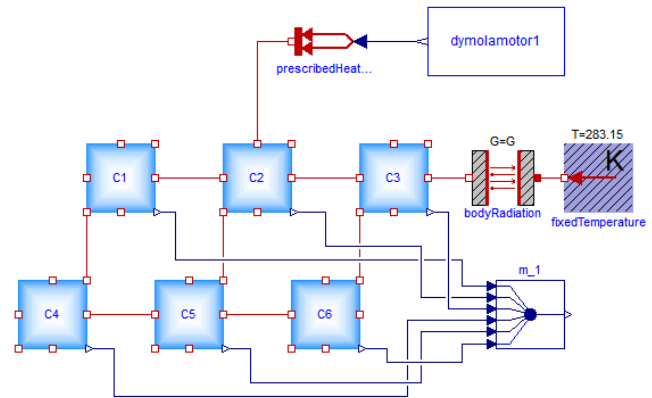

Fig. 13. Model of a Room Containing a DC Motor, Implemented in Modelica via Dymola

The machine is switched on at 08:00 a.m. and runs at a fixed voltage after a warming up phase. At 04:00 p.m. the motor stops, enabling the room to cool down again due to a cold window surface of zero degrees. Fig. 14 shows the heat emission by the motor, Fig. 15 the reaction of the individual room compartments over one day.

Before 8 o'clock in the morning all compartments cool down due to the cold window in compartment C3. As soon as the machine starts to work and emit heat, all compartments warm up until it is switched off again.

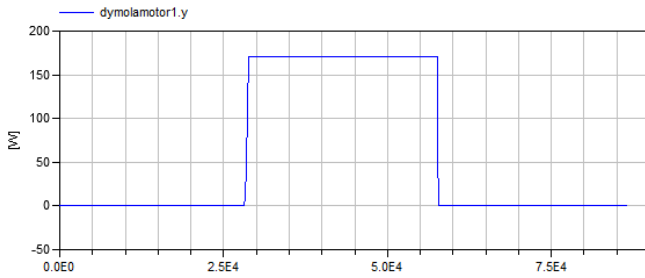The fastest reaction can be seen in compartment C2 (red

Fig. 14. Heat Emitted by the DC Motor and Transferred to the Room, Simulation over One Day
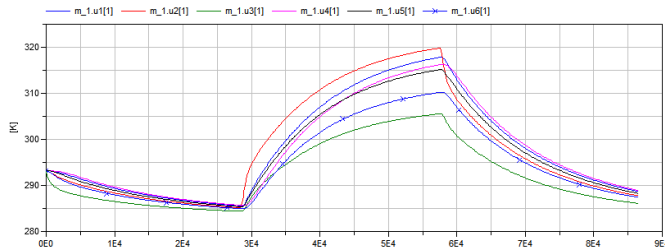

Fig. 15. Reaction of the Individual Compartments' Temperature on the Machine's Heat Emission

line), which receives the heat output from the machine. The temperature in all compartments varies from a minimum of 10 degrees in the compartment with the window to a maximum of 45 degrees near the machine, which is very plausible for a closed machine room.

V. CONCLUSION

This paper has documented the development of a room model in the object-oriented programming standard Modelica. One of the main tasks was the compensation of the inability to let air mass move by using formulae for the convection at cubicle surfaces and considering the temperature dependency of heat transfer coefficients and other parameters needed in the formulae.

The model has been validated by a comparison with an experiment on a miniature model. Still, it will be further evaluated by comparisons with other approaches and special buildings energy software.

The closing example combining the developed compartment model with a machine model shows the applicability of this model for simulations of production halls and similar buildings, as the Modelica approach is especially suitable for the physical modelling of machinery.

VI. OUTLOOK AND RELATED WORK

For further studies on validation and applicability, the behaviour of the room model will be compared to other buildings simulation software, e.g. EnergyPlus [6], which focuses on the temperature progression and exchange between certain zones which are separated by walls and can consist of several rooms in contrast to the model developed in this work, which is designed for additionally dividing one room into several compartments.

[3] presents a Modelica library for thermal simulation of buildings which, similar to EnergyPlus, considers convection only at the change of solid surfaces to air and does not aim the separation of one rooms but provides elements for heating systems and controllers.

To achieve the simulation of a whole complex building using the room model described in this work, the inclusion of heating and cooling systems, detailed machine and temperature control models is required. Since for some of these systems different modelling approaches than the object-oriented approach of Modelica are more suitable, these will be developed in other modelling software and coupled externally.

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