Underfloor heating system model for building performance simulations

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Abstract

The efficiency of heat pump systems is highly dependent on the temperature gap between the sink and the source side. Therefore, it is necessary to accurately model the sink side to enable the most accurate and holistic analysis of building energy systems. In both residential and non-residential buildings, underfloor heating systems are becoming more and more widely used. The use of underfloor heating lowers the flow temperature of the heating system compared to a radiator, which increases the efficiency of a heat pump system. This paper provides an underfloor heating system model including automatic parametrization according to the European standard for surface embedded heating and cooling systems EN 1264. Since the model represents a whole underfloor system, it consists at the system level of the distributor and several heating circuits and takes the heat transfer at the smallest level from a pipe element through different floor layers into account. The model is verified for the system requirements according to European standard EN 1264. A parameter study with a variety of different underfloor heating parameters and floor layers shows that reductions in heat transfer in the underfloor heating system are compensated by an increase in the flow temperature. The highest influence on the temperature level of the system is exerted by the pipe spacing T, which raises the flow temperature by up to 10.9 K, from 36.6 °C ($T = 100$ mm) to 47.5 °C ($T = 400$ mm). The model is freely available on GitHub:
https://github.com/RWTH-EBC/AixLib/tree/issue890_HOMProject_FloorHeating
Keywords: Building performance simulation, EN 1264, automatic parametrization

1 Introduction

The accurate modelling of underfloor systems is important since the combination with heat pumps is on the rise and their efficiency is very sensitive to the temperature gap between the source and the sink side. While the source temperature is largely determined by the environment, the sink temperature is significantly influenced by the heat transfer system. Thus, the heat transfer system influences the efficiency of the heat pump and the efficiency of the entire building energy system. In a holistic analysis of a building energy system, accurate modelling of the heat sink is therefore always of great importance. Underfloor heating systems as an already widespread type of heat transfer systems offer several advantages over conventional radiator systems.

A great advantage is a uniform temperature distribution in the room due to a large transfer surface. Thus, underfloor heating systems transfer about two-thirds of the heat flow to the room by radiation and one-third by convection (*Taschenbuch für Heizung + Klimatechnik 13/14* 2012). Due to the high amount of thermal radiation, there is an increase in the temperature of the surrounding room surfaces, which leads to higher comfort in the room. From an energy perspective, underfloor heating systems require lower flow temperatures compared to conventional radiators which increases the potential of heat pumps. Furthermore, the possibility of passive cooling in combination with geothermal energy or even active cooling are promising methods in times of increasing cooling demand.

Hot water underfloor heating sytems according to EN 1264-1 (2021) are widely used. In this type of heating systems, water-flowing pipes (or other hollow sections) are laid in the floor (Hestermann et al. 2010). The European standard EN 1264 provides guidelines for surface embedded heating and cooling systems for residential and non-residential buildings and focusses on systems for thermal comfort. The standard also specifies standardized product characteristics by testing and calculation the thermal output of heating for technical specifications and certification. Additionally, the standard only describes systems that are attached directly or by means of fasteners to the structural base of the perimeter surfaces of the building. The EN 1264 series is devided in five parts:

- Part 1: Definitions and symbols
- Part 2: Floor heating: Methods for the determination of the thermal output using calculations and experimental tests
- Part 3: Dimensioning
- Part 4: Installation
- Part 5: Determination of the thermal output

To the best of the authors' knowledge, there are no models for underfloor heating in the known Modelica libraries that allow a quick and easy parameterization according to EN 1264 and fit the modelling approach of the AixLib library. Borrajo Bastero et al. (2019) indicates a model and validation of a specific building. The focus of his work is the modeling of a specific building energy system. The design of the underfloor heating is not the main focus. Thus, the length of each heating circuit of the system and the associated pressure drop are not explicitly calculated. The underfloor heating system model of Weitzmann et al. (2005) uses the finite volume method where the heat flow is considered only. Also in this work, the system is modeled for a specific building. The key advantage of this model is the validation against measured data. The model considers the floor construction in detail. A quick transferability to other buildings does not seem to be possible. Within this paper, a simulation model for an underfloor heating system is presented. The model represents a wet system and contains all components of an underfloor heating system. It consists of several heating circuits for the heating of the individual rooms and a heating circuit distributor. In addition, the floor layers below and above the heating pipes are implemented. The highlight of this work is the automatic parameterization according to EN 1264-3 (2020), which ensures a fast application of the developed model. To connect the model to a building, only the building parameters, such as the number of rooms, room size, specific heat load of each room, and wall construction have to be transferred to the model. Standard values such as the pipe diameter or the pipe spacing can optionally be overwritten. Afterward, the system is dimensioned using the design equations of the implemented standard.

In the following, we will describe the underfloor heating system model and its submodels for the discretized pipe element, the heating circuit, the room level and the heating circuit distributor in detail. Afterwards, we discuss the results and demonstrate the validity of the model. We also show the influence of different parameters, such as the pipe spacing or the floor layers on the return temperature. At the end of this paper, we summarize the work and give an outlook for further improvements.

2 Underfloor heating system model

The model represents a wet system and contains all components of an underfloor heating system. It consists of the distributor and several heating circuits to warm up individual rooms. For that, the floor layers that are located above and below the heating pipes which transfer the heat to the rooms, are implemented in detail. The design according to EN 1264-3 (2020) is part of the model and can thus calculate its design parameters.

The floor heating model has the title *UnderfloorHeatingSystem* and follows a hierarchical structure. This allows the parameters to be passed to the respective submodels and makes parameterisation necessary only at the top level. The submodels of the overall system can also be used individually and are not only executable in the overall model.

The focus is set on the comprehensibility of the model. In each level, therefore, only the equations are implemented, which are crucial for this level. As can be seen in Figure 1, the smallest element of the undefloor heating system model represents a discretized pipe element. This pipe element is connected several times in series on the next higher level to form a heating circuit. In order to realize several heating circuits within a room, a model with parallel heating circuits exists on the next level.

The overall system at the top level connects the individual heating circuits from the rooms in a heating circuit distributor to distribute the total mass flow to the individual circuits. The system level is also used to connect the building model and the energy system with the underfloor heating. Furthermore, it provides the design parameters for mass flow and supply temperature. The individual model setups are explained in more detail in the following chapters.

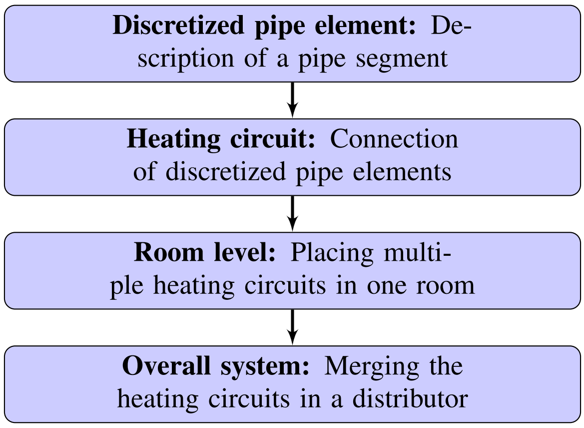

Figure 1. Hierarchical model structure of the developed underfloor heating system from the smallest pipe element to the complete system

2.1 Discretized Pipe Element

The discretized pipe element as the basic model of the underfloor heating system describes the thermal heat flow. Figure 2 offers an overview about the pipe element model. The aim of this model, called *UnderfloorHeatingElement*, is to divide a heating circuit into short pipe sections so that the decreasing fluid temperature within the pipe can be calculated in arbitrarily small steps.

Each pipe element is interpreted by a volume model with uniform fluid temperature, which represents the water volume in that discrete pipe section. The discretized pipe element model can calculate the water volume in two different ways. On the one hand it can use the inner diameter of the pipe, and the other it can use a time constant τ. In the model for the pipe element, the maximum value for the fluid velocity in the heating pipe is set to $0.5\,\mathrm{m\,s^{-1}}$. The user can decide whether exceeding this value will cause a warning or an error. If the water volume is calculated by means of time constant and the fluid velocity in the pipe

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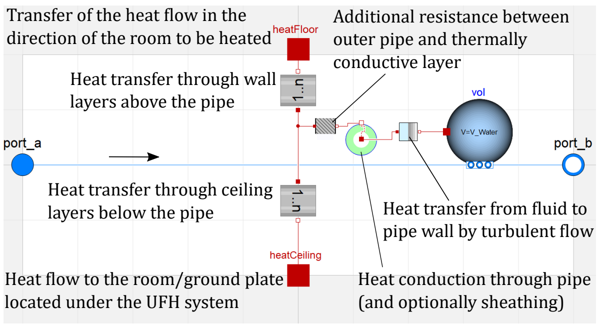

Figure 2. Model view of the discretized pipe element in Dymola: The volume element "vol" contains the volume of water that is in heat exchange with the pipe walls and floor/ceiling layers; fluid and thermal quantities are calculated at the ports for connection to other quantities are calculated for the connection with other models

exceeds the maximum value of 0.5 m s^{-1}, the model gives the user a default value for the inner diameter for which the limit value is observed. If the parameter determination for the inner diameter is not intuitive for the user, this gives the possibility to determine a reasonable value.

The heat transfer through the floor layers is represented in the model *UnderfloorHeatingElement*, which means that it is also discretized in the overall model. This is necessary in order to generate the correct surface temperatures of the floor and ceiling and, consequently, the actual heat transfer into the rooms. Above a pipe section, there is thus exactly the floor surface that is heated by this pipe element.

Heat transfer through the discretized pipe element is divided into heat transfer through the pipe and heat conduction through the floor layers involved. From the inner pipe wall, heat is transferred by convection from the fluid onto the pipe wall and heat conduction through the pipe wall. For the interpretation of the heat conduction, the simplified model of the *AixLib CylindricHeatConduction* (Müller et al. 2016) was chosen, which calculates the steady-state heat conduction in the hollow cylinder. This keeps the parameterization simple for the user. Since the inertia of the system is primarily caused by the floor layers and the thermal conductivity for different pipe and sheathing materials is given in EN 1264-2 (2021) Annex D, this simplified way was chosen.

An additional resistance is implemented between the outer wall of the pipe and the floor layers. This can be interpreted primarily as the heat transfer between the pipe outer wall and the heat-conducting layer. This thermal resistance is indispensable because it is used to calculate the average temperature of the heat-conducting layer, which is transferred to the floor layers.

The heat conduction from the heat-conducting layer through the floor layers is divided into the layers above and below the floor heating. Therefore, there are two components which use the model *SimpleNLayer* from the *AixLib*. Those describe the transient heat conduction through these layers. The model *SimpleNLayer* is based on the consideration of two resistances and one capacitance per layer. The parameterization of the floor and ceiling layers is done by *Records*, analog to the High Order Model of *AixLib* (Constantin, Streblow, and Müller 2014). In these records, the material properties of the floor layers are stored, namely the density, thermal conductivity, heat capacity and the thickness. Since the floor and ceiling layers are already implemented in the underfloor heating model, it is necessary that they are bypassed or not included in the building model it is used within.

2.2 Heating Circuit

The model for a heating circuit in the floor heating system establishes the connection of several pipe elements. Different properties of the heating circuits in the system essentially determine the heat transfer to the heated room. Important parameters for determining the heating circuit structure are summarized in this model, called *UnderfloorHeatingCircuit*. The most important component of the heating circuit model is the arrangement of pipe elements connected in series, which are described by the model *UnderfloorHeatingElement* from chapter 2.1. Apart from that, the pressure losses and the average floor surface temperature in the room are determined at this level. Figure 3 shows the model's structure.

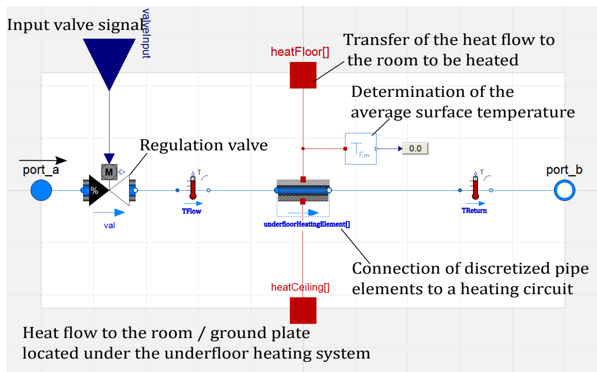

Figure 3. Model view of a heating circuit in Dymola: The discretized pipe elements are connected to form a heating circuit and can be controlled via the regulating valve

The number of pipe elements within a heating circuit is specified by the user through the parameter *dis*. Temperature sensors are placed directly in front of the first and behind the last element to determine the flow and return temperature in each heating circuit. Furthermore, each heating circuit in the underfloor heating system is equipped with a control device. For that, a valve is placed in front of the first pipe element. The valve is designed as an equal-percentage two-way valve, which can regulate volume flows.

The nominal pressure loss is divided into the pressure loss caused by the pipe resistance and the valve. The pressure loss of the heating pipe *dp_Pipe* has a reference value of 100 Pa m^{-1}, but can also be adjusted by the user. The pressure loss through the control device *dp_Valve* is based on the data for a heating circuit distributor from Schütz Energy Systems (2017). The model verifies that the limit value of 250 mbar according to EN 1264-3 (2020) is not exceeded.

To maintain comfort in rooms, the floor surface temperature T_F should not go beyond certain limits. The limits for the average floor surface temperature $T_{F,m}$ are given in EN 1264-2 (2021). However, the user can also specify his limit value as a parameter. That the maximum value for the average surface temperature is not exceeded is also checked by the heating circuit model. With the mean surface temperature, the user keeps control over an important limit value in underfloor heating systems.

2.3 Room Level

The model *UnderfloorHeatingRoom* bundles the results of one heated room in the underfloor heating system. The main tasks of the model are the parallel connection of several heating circuit models that belong to one room and the calculation of the nominal mass flows of these heating circuits according to EN 1264-3 (2020). An overview of the model is shown in the Figure 4.

The maximum pipe length of heating circuits is between 80 m and 120 m depending on the manufacturer. To meet this requirement, the user can specify a maximum pipe length for the room level model. If the max-

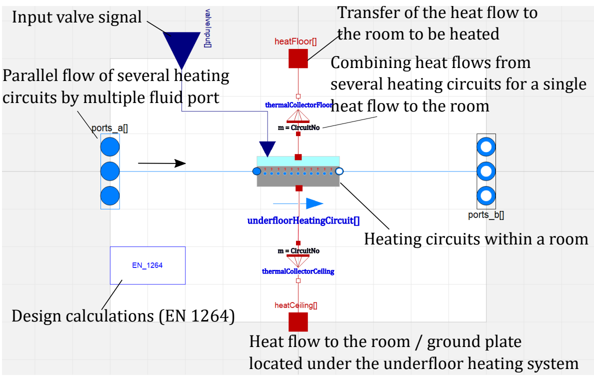

Figure 4. Model view of the room level in Dymola for the underfloor heating system: Several heating circuits located in parallel in one room; According to EN 1264, the required system-dependent coefficients for the design are calculated

imum specified pipe length is exceeded, another heating circuit is provided in the room whereas all existing circuits within a room are identically parameterized and designed. Accordingly, several identical heating circuits can be controlled individually via the vectorized valve presetting.

The system-dependent coefficients are calculated according to EN 1264-3 (2020). To determine these values, a submodel *EN_1264* is inserted into the room level model. In this submodel, the system-dependent coefficient K_H and the limit of specific thermal output q_G are calculated for further use at the room level. To determine these values, the necessary tables from EN 1264-2 (2021) are deposited.

The limit of specific thermal output q_G is used in particular to check the plausibility of the input parameters. If the value for q_G exceeds the maximum limit of specific thermal output $q_{G,max}$, the model will report this with an error and the user needs to adjust his input parameters. Besides, the limit of specific thermal output is used to find out whether the underfloor heating is sufficient to cover the present heat load. If the calculated limit of specific thermal output is below the specific heat load q_{des}, further heat flow needs to be generated by other heating devices. The model *UnderfloorHeatingRoom* informs about this as well.

The *Records* for the floor and ceiling layers must be constructed correctly for the model to define screed and flooring as the layers above the heating pipe. The lower floor layers must consist of insulation, load-bearing substrate and plaster. If the ground plate is below the underfloor heating, there must be four layers below the underfloor heating. The top layer must then still be the insulation layer. The assignment of the values in the *Records* to the model is illustrated in Table 1. A correct definition of the layers in the data set is a prerequisite for a correct design of the underfloor heating system in the model.

In addition, compliance with the thermal resistance specifications for insulation according to EN 1264-4 (2021) Table 1 is checked at the room level. For rooms located above other heated rooms, the minimum for the insulation's thermal resistance is set at $R_{\lambda,\mathrm{Ins,min}} = 0.75\,\mathrm{m^2\,K\,W^{-1}}$, for adjoining unheated areas at $R_{\lambda,\mathrm{Ins,min}} = 1.25\,\mathrm{m^2\,K\,W^{-1}}$. In order to ensure a proper comparison between the actual and minimal values, the assignment of the floor layers from Table 1 must be observed.

2.4 Distributor

The top level of the model for an underfloor heating system includes the consolidation of all heating circuits in the distributor and is called *UnderfloorHeatingSystem*. The room level, which was represented in chapter 2.3, is inserted as a sub-model in the respective number of rooms to be heated. The overall model can be used to connect to the building and the energy system for detailed thermal building simulation.

A heating circuit distributor divides the total mass flow to the individual heating circuits and recombines them after passing through the room level in return. The flow and return temperatures are recorded by sensors. With the valve settings passed through from the individual heating circuit to the overall system, each heating circuit in the underfloor heating system can be controlled separately. The heat flows of the heated rooms are transferred from the underfloor heating to the rooms by means of discretized *heatports*. The thermal connections via the *heatports* represent the interface to the building model. Due to the discretization of the pipe element and, consequently, the floor, each room needs to have the same number of *heatports* corresponding to the discretization number *dis*. Care should be taken to assign the ports in such a way that the floor

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Table 1. Assignment of the thermal resistances from the records of the floor layers to the model on room level

Floor Layer	Position in Record	Thermal Resistance
Flooring	wallTypeFloor[2]	$R_{\lambda,\text{B}}$
Screed	wallTypeFloor[1]	$s_\text{u}/\lambda_\text{E}$
Insulation	wallTypeCeiling[1]	$R_{\lambda,\text{Ins}}$
Load-bearing substrate	wallTypeCeiling[2]	$R_{\lambda,\text{Ceiling}}$
Plaster	wallTypeCeiling[3]	$R_{\lambda,\text{Plaster}}$
Foam glas in floor plate	wallTypeCeiling[3]	$R_{\lambda,\text{Ceiling}}$
Gravel under floor plate	wallTypeCeiling[4]	$R_{\lambda,\text{Ceiling}}$

heating is located between the wall models for floor and ceiling.

The design according to EN 1264-3 (2020) is done in the model with the room that is connected to the building model first. Since the design is done with the room that has the highest specific heating load, care must be taken to ensure that this room is first in the vectorial setup. If this is not the case, the model will show an error. It is therefore essential that the building model is subjected to a heat load calculation before being used with the model for the underfloor heating system. The final design of the entire underfloor heating system according to EN 1264-3 (2020) determines a general flow temperature for the system and the nominal mass flow rate for each room.

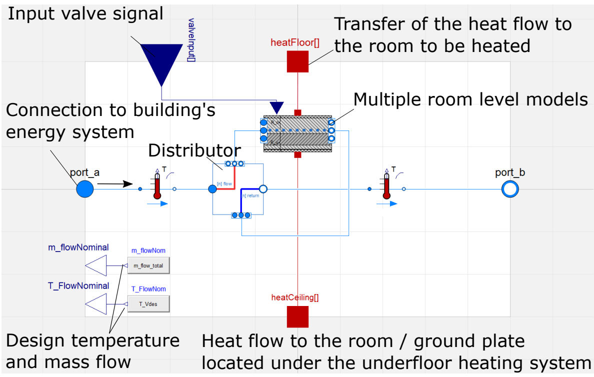

Figure 5. Model *UnderfloorHeatingSystem* in which the needed underfloor heating circuits are generated and designed for each heated room

Figure 5 depicts a schematic of the *UnderfloorHeatingSystem* which unifies the heating circuits of the individual heated rooms. It includes the previously presented models of chapters 2.1-2.3 in a hierarchical structure. It contains an automated design according to EN 1264-3 (2020) and the nominal pressure loss calculation of the heating circuit valves. Additional heating circuit parameters can be assigned to each room via the vector parameterization.

3 Results and Discussion

The following chapter is divided into two parts. Firstly, the model will be verified in a simplified test scenario. This is followed by a parameter study to investigate the influences of various system parameters such as the flooring or the pipe spacing.

3.1 Model verification

The verification of the model is performed with two in a simplified way designed room models. The first room has a specific heat load of $q''_{\text{des},1} = 50\,\text{W}\,\text{m}^{-2}$ while the second room's heat load is $q''_{\text{des},2} = 33\,\text{W}\,\text{m}^{-2}$. The heat transfer from the floor surface to the room is mapped according to EN 1264-3 (2020) with a purely convective heat transfer coefficient of $\alpha_\text{floor} = 10.8\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$. The verification is carried out based on the room and return temperatures that occur. The expected values must be achieved for various floor heating parameters within the standard limits. For this reason, the simulation is performed with different parameters for pipe spacing, inner diameter and pipe material. The model is verified using the target room temperature of 20 °C and the calculated return temperature from the standard. In summary, the model was verified under the following aspects:

- Room parameters (room size, specific heat load, floor/ceiling wall parameters) of design room transferred into the underfloor system model
- Flow temperature and mass flow are equal to design temperature and design mass flow, which are calculated by the model itself (Using EN 1264-3 (2020))
- There is no further control of mass flow or temperature
- All boundary conditions are steady-state
- $\Delta T_\text{Room} = T_\text{design} (= 20\,°\text{C}) - T_\text{Room}$
- $\Delta T_\text{r} = \vartheta_\text{design} - \vartheta_\text{r}$

Table 2 shows the results of the room ΔT_Room and return temperatures $\vartheta_\text{r}, \Delta T_\text{r}$ from the simulations for verification as absolute values with deviation.

The results show that the designed room with the higher heating load has room temperatures between ϑ_room1 = 19.9892...19.9935 °C which is slightly below the target room temperature of 20 °C The return temperature

Table 2. Results of the verification of the overall model: Consideration of two rooms with different heating loads at different underfloor heating parameters

Room 1: $q''_{\mathrm{des},1} = 50\,\mathrm{W\,m^{-2}}$

	ΔT_{Room}[K]	ϑ_{r}[°C]	ΔT_{r}[K]
T = 100 mm	-0.0108	31.7458	-0.0011
T = 200 mm	-0.0065	34.7029	-0.0010
T = 350 mm	-0.0075	40.2079	-0.0010
d_{i} = 21 mm	-0.0071	38.2973	-0.0010
PP-pipe	-0.0069	41.5902	-0.0010

Room 2: $q''_{\mathrm{des},2} = 33\,\mathrm{W\,m^{-2}}$

	ΔT_{Room}[K]	ϑ_{r}[°C]	ΔT_{r}[K]
T = 100 mm	+0.0105	24.6451	-0.0024
T = 200 mm	+0.0168	25.8692	-0.0027
T = 350 mm	+0.0177	28.1566	-0.0032
d_{i} = 21 mm	+0.0132	27.3619	-0.0030
PP-pipe	+0.0125	28.7318	-0.0033

is achieved to two digits after the decimal point. For the designed room with the lower heating load, the underfloor heating system calculates room temperatures between $\vartheta_{\mathrm{room2}}$ = 20.0105...20.0132 °C which are thus slightly above the set temperature. The mean absolute percentage error (MAPE) for the return temperature of the underfloor heating system is less than 0.011 %. The room temperature is achieved with a MAPE of 0.0388 % for the designed room 1 and 0.0706 % for the designed room 2.

Thus, the model can be seen as verified for the system requirements according to EN 1264-2 (2021). The small deviations are due to the division of heat transfer at the floor surface into radiation and convection. While the design according to the standard assumes constant heat transfer coefficients, the model considers the dependence of radiation on the room's surface temperature. This justifies small deviations in the heat transfer.

3.2 Influence of system parameters

A parameter study is performed to investigate the influence of the variable parameters on the the underfloor heating system. The influences of pipe spacing T, pipe materials with different thermal conductivities $\lambda_{\mathrm{material}}$, pipe diameter d_{i} and pipe coating s_{C} are considered. Besides, the changes due to a variation of floor layers with different thermal resistances $R_{\lambda,\mathrm{F}}$, screed thicknesses s_{u} and insulation thicknesses s_{ins} are investigated. The results for supply and return temperatures are examined since these are of greatest importance for a building energy system. For this purpose, all simulations are performed with a discretization of 50 pipe elements. The floors of all rooms are discretized as well. The parameter study is performed in conjunction with the single-family house of the High Order Model from the AixLib library (Constantin, Streblow, and Müller 2014). Table 3 shows the range of variation of the parameters and the reference parameters.

Table 3. Reference and range of variation of different system parameters

parameter		reference	min.	max.
T	[mm]	200	100	400
d_{i}	[mm]	13	10	20
$\lambda_{\mathrm{material}}$	$[\mathrm{W\,m^{-1}\,K^{-1}}]$	PE-RT	0.22	390
s_{C}	[mm]	0	0	4
$R_{\lambda,\mathrm{F}}$	$[\mathrm{m\,K\,W^{-1}}]$	0.1	0.0118	0.188
s_{u}	[mm]	60	40	80
s_{ins}	[mm]	35	35	75

Generally, decreases in the total heat transfer within the system are compensated by an increase in the flow temperature. If the heat transfer to the room is not directly affected, changes are compensated by increasing the mass flow. This is to ensure the required heat flow at all times.

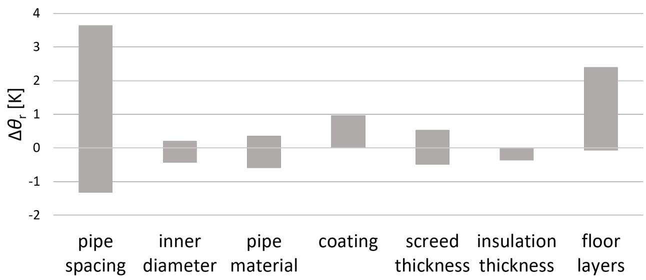

Figure 6. Influence of different system parameters on the return temperature

Figure 6 summarizes the changes in return temperature due to various system adjustments. The pipe spacing has the greatest influence on the temperature level of the system. The return temperature can increase up to 3.5 K due to the necessary increase in the supply temperature. Also, the floor layer has a non-negligible influence. Thus, the return temperature varies by about 2.5 K for the used floor layers (elastomer, laminate, wood parquet, carpet, linoleum). The variation of the pipe material, the pipe sheathing and the thickness of the screed layer are of little significance concerning the return temperature. The return temperature changes by less than 1 K. The thickness of the insulation layer also has the least effect on the return temperature. Primarily, the changes in heat transfer due to the insulation are compensated with an adjustment of the mass flow.

4 Conclusion and Outlook

In this work, we present an underfloor heating system model, which is built on four submodels. The model is freely available on GitHub:
https://github.com/RWTH-EBC/AixLib/tree/issue890_HOMProject_FloorHeating.
The smallest unit is a pipe element, which is connected

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in a row for several times to form an axial discretized heating circuit.

Based on this, the next level model forms a connection for a room, which may consist of several heating circuits. The overall model connects several rooms to form an underfloor heating system, whose heating circuits converge in a distributor and enable connection for a building energy system.

The specifications of EN 1264-3 (2020) are included in the model to allow direct use of the calculated supply temperature and design mass flow. The model is verified for the system requirements of EN 1264-2 (2021) and shows an accuracy of less than 0.01 % (MAPE) concerning the room temperature. In a parameter study, the influence of different system parameters is investigated. The pipe spacing has the greatest influence and can cause an increase in the flow temperature by up to 10.9 K.

All in all, we show an underfloor heating model in Modelica which is automatically parameterized by the integrated variables of the standard. In future work, the model will be integrated into building energy systems to allow a holistic analysis of those.

Acknowledgements

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