IMPACTS OF CONTROL STRATEGIES ON LIGHT AND HEAVY RADIANT FLOORS IN LOW ENERGY BUILDINGS BY MODELICA SIMULATION

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ABSTRACT

The decrease of heat demand in low energy buildings, very sensitive to solar and internal gains, and the development of new HVAC systems call for a reexamination of the usual modeling approaches in building simulation. A focus is brought on an air-to-water heat pump plugged to a radiant heating floor (RHF) by a hydraulic loop installed in a typical low energy dwelling. Using a RADTEST evaluated Modelica slab model, several floor thermal masses under four different control strategies are compared to determine their impact on HVAC system performances.

Keywords: Low energy building simulation, radiant heating/cooling system, thermal mass, control strategy

INTRODUCTION

The share of floor heating has grown up significantly these last decades and they have already been installed in 50% of the european residential stock and near 90% in Korea (Olesen, 2002). Floor heating systems belong to a larger group of secondary HVAC systems, the **radiant systems** which also includes TABS, radiant ceiling heating and others embedded surface heating/cooling systems. These systems are based on the heating or the cooling of a large building surface (walls, ceiling or more commonly floor) by a water loop associated with a primary HVAC system. However some systems are actively heated with electric heating cables embedded in concrete floors (electric radiant floor) or by using air as a medium instead of water (UFAD: Under-Floor Air Distribution).
This study is focused on hydronic radiant heating floors, but most of the conclusions could be applied to every embedded surface heating/cooling systems.
In addition to being silent and building integrated, the **radiant heating floor (RHF)** has multiple advantages from a thermal point of view:

- The large part of radiative heat, at least 50% (Crocker and Higgins, 2012), and the thermal mass of this system reduce more than 30% of the annual energy consumption and the peak loads of the primary HVAC system, according to theoretical and experimental studies (Stetiu, 1999) (Feustel and Stetiu, 1995). Moreover this system provides a homogeneous heat and a comfortable thermal feeling (Boerstra et al., 2000).
- Operating under low temperatures for heating (supply temperature between 25-35°C) and under high temperature for cooling (between 16-22°C in recent buildings), the radiant systems are low exergy (Hepbasli, 2012) which can be associated with a heat pump providing high performances for these operating temperatures.

However due to their high thermal mass, radiant systems are difficult to be controlled (Sourbron et al., 2009). As heat loads provided by solar gains are mainly received by the floor, and without a predictive controller (Cho and Zaheer-Uddin, 2003), overconsumption and thermal discomfort are frequent. These difficulties of control are even more important when the heat demand of the building decreases, as in **low energy buildings**. As evidenced by Olesen (2001) with standards considerations, the heat emission performance of a RHF in comparison with an ideal emitter is highly influenced by the low heating loads of the building, its thermal mass and its control. Since 2001, the way of installing a RHF has progressed with a better sizing of the different layers (particularly insulation) and with the reduction of thermal bridges. Besides building simulation was considerably refined by introducing **dynamic modeling** that simplifying the entire control closed loop simulation.
This study proposes a precise and dynamic RHF model suitable for low energy buildings simulation, and appropriate to study the impact of four **control strategies** with different **thermal masses** on the RHF performance.
The first part presents an overview of RHF models and determines the most adequate models for low energy building simulation. Then, these models are tested with the RADTEST evaluation method (Achermann and Zweifel, 2003). After the selection of one model, the last part presents the results regarding the effect of thermal mass and control on the RHF behaviour.

RADIANT SYSTEM MODELS OVERVIEW

A radiant heating floor has several contributions in the thermal loads of a building because it represents simultaneously:

- a part of the building envelope contributing to thermal heat losses,
- the main secondary HVAC system that has to maintain the temperature of the room,
- an important component for internal loads calculation, particularly for solar loads that are often considered as directly injected on the floor surface.

Usually, hourly time-step models take into account these three contributions by determining, in two independent steps: firstly the hourly thermal loads (thermal heat losses + internal loads), and secondly the energetic consumption through the performances of the HVAC system. However the solar loads will change the performance of the heat floor and moreover the operation of the RHF will increase the heat losses by the floor. Strand and Pedersen (2002) present the different feedback necessary in EnergyPlus (Crawley et al., 2001) to make the heat demand converge to the heat provided by the RHF by reducing the step-time.

In his 2001 review, Zhang (2001) observed that most of the literature models are dedicated for sizing the RHF and do not consider their thermal masses. This kind of model is not appropriate for this study and are not presented here.

Figure 1 presents the convention and the nomenclature used in the review and the description of the Modelica models subject to the RADTEST evaluation method.

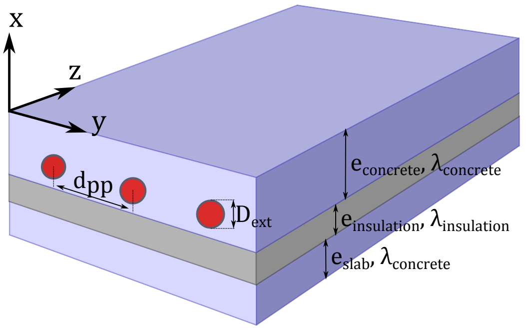

Figure 1: Convention and nomenclature of the radiant heat floor

3D and 2D approaches

The three-dimensions approach makes it possible to represent the RHF without any hypothesis about the geometry: uniformity of temperature between pipes, temperature decrease along the pipe and also impacts of the bending. This approach is extremely detailed and could be made with a Computational Fluid Dynamics (CFD) software. However this method is not adequate for building simulation because it is non generic and, mainly, takes a long time to be parameterized and to be solved.

CFD could be limited to the (x,y) plane to solve in details the heat balance around the pipe and determine the temperature field on the transverse plan of the pipes. As presented below in the 1D approach, a simple and user-friendly tool as THERM (Finlayson et al., 1998) could be used as preprocessor for radiant systems model. Laouadi (2004) proposes to combine a one-dimensional numerical model already used in energy simulation software with a two-dimensional analytic model. This method makes possible, for instance, to determine the minimum and maximum ceiling/floor temperatures required for moisture condensation. In using the symmetries between pipes, some models propose to add parallel thermal nodes on either side of the water loop thermal active node. Finally a coarse 2D approach could be operated as in Flach-Malaspina (2004) or in the energy simulation software TRNSYS from the works on RHF of Fort (1989) or in SIMBAD (Husaunndee et al., 1997).

1D approach

The one-dimensional approach is the most frequently used in building simulation. It determines the evolution of temperatures and of heat losses along the vertical axis. Most of them are based on multilayer models based on an electric analogy. The addition of some contributions corrects some hypothesis of the 1D approach:

z-axis Like any heat exchanger, whereas the temperature along the pipe decreases, the floor is heated up. Zhang (2001) suggests to use the log mean temperature difference (given in Equation 1) to take into account this temperature heterogeneity along the pipe in order to run a three-nodes model.

$$LMTD = \frac{(T_i - T_{conc}) - (T_o - T_{conc})}{\ln(\frac{T_i - T_{conc}}{T_o - T_{conc}})} \quad (1)$$

To also represent the temperature decrease of the layer, it is possible to discretize the RHF as presented in Figure 2.

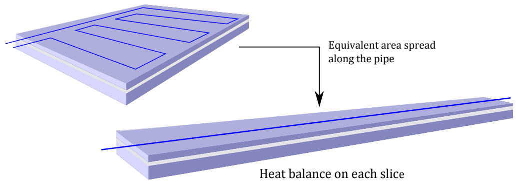

Figure 2: Discretization along z-axis

For each segment, a heat balance is achieved on the water in the pipe and two multilayers elements (resistive and capacitive), representing the upper concrete layer and the lower layers of the floor (insulation and concrete slab). These elements are respectively connected to the inside and outside thermal node.

(x,y) plane To take into account the heterogeneity on the (x,y) plane, Moore (2008) uses THERM (presented above) to determine the equivalent thermal conductivity of the concrete from the pipe to the surface floor. Jin et al. (2010a) suggest two empirical equations depending on the value of the thermal conductivity of the pipe (plastic or metal). For instance, when $\lambda_{pipe} < 2W/m.K$ the equivalent conductivity of the concrete is given by Equation 2:

$$\lambda_{eq} = 8,54 \times \ln(2,0335 + \lambda_{pipe}) \times (1,1596 + \lambda_{concrete})(1,3219 + A_r)^{-1,4264} \quad (2)$$

with $A_r = \frac{4d_{pp}}{\pi D_{ext}}$

Modelica library

Modelica-based modeling and simulation is suitable to support research and development in building energy and control systems (Wetter, 2006). That is the reason why this language was chosen for this study. Two Modelica RHF models are briefly presented.

Modelica EnerBaT library RHF

The EDF R&D Energy in Buildings and Territories Department (EnerBaT) has developed a RHF model based on parametric studies found in the literature. It is a 1D multilayer model taking into account the temperature decrease along z-axis with a discretization along the pipe (see Figure 2). From the study of Sattari and Farhanieh (2006), the temperature heterogeneity on the (x,y) plane could be negligible. Therefore this aspect is not taken into account as for the effect of the water velocity on the pipe heat transfer (Jin et al., 2010b). From the model description on a RHF model in CLIM2000 (Rongere et al., 1989) experimentally validated by Delille et al. (1998), the model is not very sensitive to the representation of the transfer from the water to the concrete. It is considered as one thermal resistance: $\dfrac{e_{pipe} n_{seg}}{2\pi \lambda_{pipe} D_{ext} L_{pipe}}$.

Modelica *Buildings* library slab

Since the version 1.2 Build1 (August 2012), a generic radiant slab is incorporated in the Modelica *Buildings* library developed by LBNL (Wetter, 2009). As the previous presented model, the model is adequate to represent radiant heating/cooling floors, ceilings or walls with a water loop. It is also possible to represent UFAD (Under Floor Air Distribution) in changing the fluid flowing in the pipe. In case of RHF, the model is structurally similar to the previous: 1D multilayer model descretized along the pipe but the thermal resistance between water thermal capacities and the multilayer elements is more precise:

- a first model takes into account the liquid side heat transfer coefficient,
- then conductivity through the pipe is evaluated with $\dfrac{2\pi \lambda_{pipe} L_{pipe}}{n_{seg} \log(D_{ext}/D_{int})}$,
- a last model determines an equivalent resistance, given in Equation 3 to take into account the heterogeneous temperature in the (x,y) plane:

$$R_{eq} = \frac{d_{pp}}{2\pi \lambda_{concrete}} \times \left[\log\left(\frac{d_{pp}}{\pi D_{ext}}\right) + \sum_{i=1}^{100} \left(\frac{\beta - 2\pi i}{\beta + 2\pi i} \times \frac{\exp\left(-4\pi i \frac{d_{pp}}{D_{ext}}\right)}{i} \right) \right] \quad (3)$$

with $\beta = \frac{\lambda_{isolation}}{e_{isolation}} \times \frac{d_{pp}}{\lambda_{concrete}}$.

RADTEST EVALUATION

The RADTEST (Radiant Heating and Cooling Test) evaluation is a numerical benchmark to test software ability to accurately model radiant heating and cooling system (Achermann and Zweifel, 2003). The RADTEST contains 14 runs from the ENVELOPE BESTEST (Judkoff and Neymark, 1995) case 800, to case 2810 modeling a real case with a detailed water loop model.

This benchmark test is used to evaluate the two Modelica models of RHF described above in comparison with provided results from the most common energy building simulation tools.

Solar gains, radiative and convective heat transfers

The modeling of solar gains and radiative and convective heat transfers is significant in the modeling of RHF, following the description of the chosen modeling. Both models received directly all the solar gains on the upper layer of the concrete. The surface heat port (temperature and heat flow connector) is also connected to the room model by two models determining respectively the convective and radiative heat transfers.

RADTEST results

The RADTEST is based on case 800 BESTEST evaluation, that uses a Modelica room model developed at EDF-EnerBaT. Cases 1800 to case 1890 were tested and validated with the Modelica EnerBaT library (room air + RHF models) and the radiative and convective models presented above using Dymola (Dym). The results are presented in Figure 3. The case 800 has different orders of magnitude, this is why the graphs are multiplied or divided by a coefficient indicated between brackets beside the number of the case 800. Due to limitations, certains tools do not permit the simulation of some cases, this is why some zeros are found in the RADTEST chart.

Both Modelica models have a detailed water loop and are able to be tested to 2800 cases (number 2800 and 2810). Figure 3 shows both models are validated for heating and cooling and use in this study.

The discretization method along z-axis needs an infinite number of segments to represent exactly the temperature decrease along the tube. A parametric study is

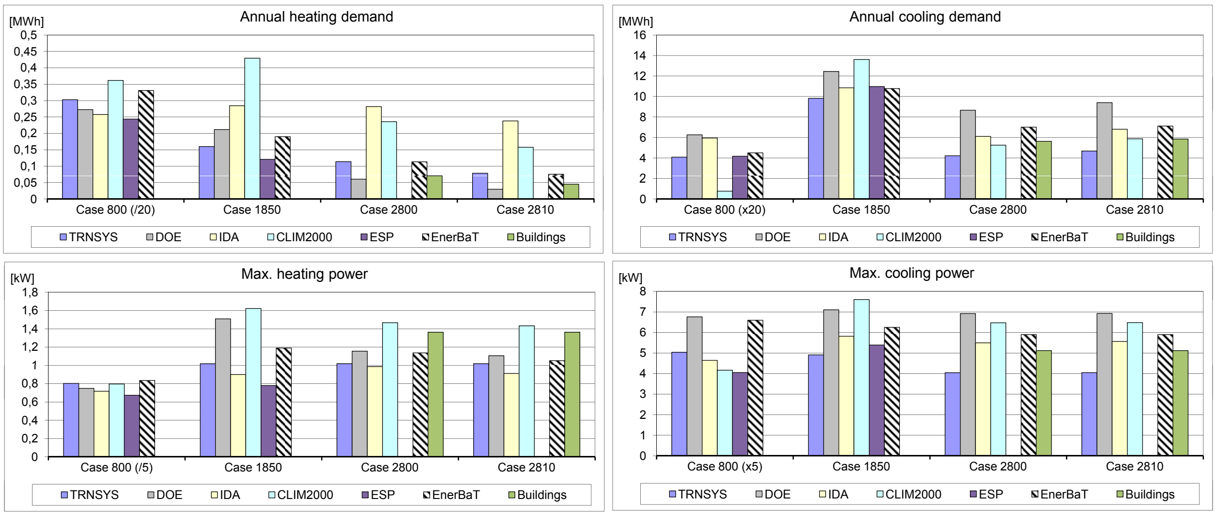

Figure 3: RADTEST evaluation

carried out to determine the value of n_{seg} which leads to the best compromise between reliability and computing time. Figure 4 shows the annual heating and cooling consumption, simulated for a number of segments ranging from 2 to 30. The dotted lines represent the +/-2% interval around $n_{seg} = 30$ case. For $n_{seg} > 10$, the value of the consumption quickly becomes asymptotical, but the graph on the right shows how strongly the computing time increases with the number of segments. For this study, the number of segments is therefore chosen to 10.

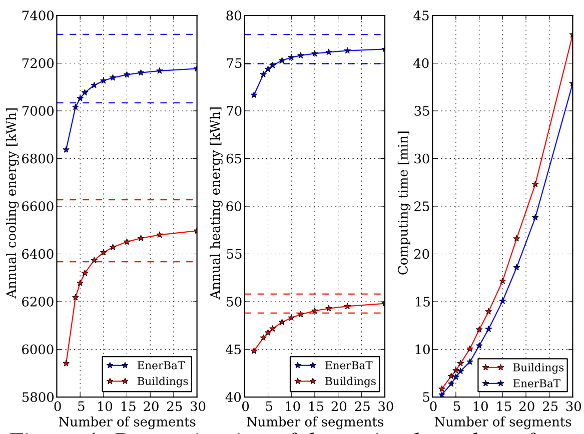

Figure 4: Determination of the optimal number of segments along z-axis

THERMAL MASS / CONTROL EFFECTS

Following the RADTEST evaluation, the Modelica *Buildings* slab model is chosen for the rest of this study as it is considered to be more complete and needs as much computing time as the EnerBaT model. The study uses a complete assembly of a typical low energy dwelling with detailed HVAC system composed of an air-to-water heat pump plugged to a radiant floor heating (RFH) by a hydraulic loop to provide only the heating. A particular attention is given to the implementation of different control strategies.

Building-system description

The building is a 90 m^2 monozone house based on the BESTEST case 800 room air model. Ventilation losses and internal gain scenario (body radiation, specific loads and lighting) are added. The floor is separated from the building in order to simplify its modeling and its connection with the HVAC system. Climatic data comes from Meteonorm (Met) for the town of Trappes near Paris, France. As presented in Figure 5, the HVAC system is composed of three parts:

- ***Primary HVAC system***: A high efficiency air-to-water heat pump (2500 W and COP = 4.2) is connected to a 50 L buffer water tank. The heat pump model is based on the empirical dynamic model presented in (Blervaque et al., 2012). The tank is modeled by two variable volume zones with piston effect between cold and hot water zones. The tank is located in the conditioned room and the heat losses are affected to the monozone building. The heat pump has an on/off operation depending on tank outlet temperature with respect to setpoint that varies with the outdoor temperature. This outdoor temperature control (OTC) is defined in Table 1.

Outdoor (°C)	-20	-7	10	25
Water loop (°C)	35	30	25	25

Table 1: Outdoor temperature control (OTC)

The heat pump is switched off during summer from mid-April to mid-October.

- ***Indoor air temperature control***: A scenario indicates the indoor air temperature setpoint: 20°C if present, 16°C otherwise. The control is achieved with a proportional band from 0 to 1 for +/-0.3°C the temperature setpoint. This value operates a control on the water loop by varying a three way valve to change the mass flow rate or the temperature at the slab inlet. For the flow rate control, the temperature is given by the OTC and the flow rate varies between 0 and 0.12 kg/s. For the temperature control, the flow rate in the slab is fixed at 0.12 kg/s and the temperature is the average between the primary water loop and the slab outlet temperature, weighted by the proportional band. A discomfort model is integrated to quantify the non-respect of the temperature setpoint in terms of °C.h.

- ***Secondary HVAC system***: The secondary HVAC system is the Modelica *Buildings* slab model. The composition of the slab is presented in Table 2 from inside to outside layers as presented in Figure 1.

Layers	e $[m]$	λ $[W/m.K]$	Cp $[J/m^3.K]$	ρ $[kg/m^3]$
Upper	e_{conc}	1.75	920	2300
Insulating	0.15	0.03	1200	35
Lower	0.25	1.75	920	2300

Table 2: Layers of the slab

The value of e_{conc} is modified according to the thermal mass.

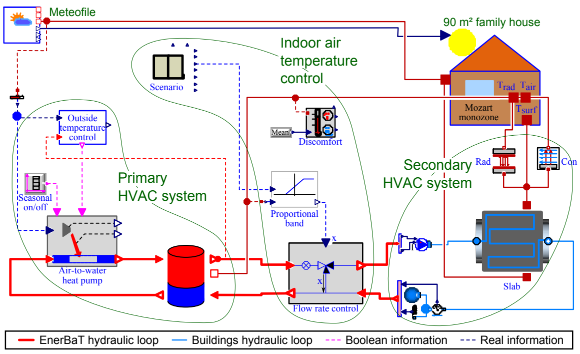

Figure 5: Modelica assembly of the case study

Results

A cross parametric study is carried out by varying slab thermal mass and control strategy: the concrete thickness varies between 0.05 and 0.09 m and the 5 control strategies are described below.

OTC Strategy without indoor air control, the water loop temperature respects the rule fixed at the primary HVAC system (Table 1).

Flow rate The water loop temperature is fixed at 35°C and the indoor air temperature is controlled by varying the water flow rate in the slab.

Temperature The water loop temperature is fixed at 35°C and the indoor air temperature is controlled in varying the water temperature at the slab inlet.

OTC & Flow rate The water loop temperature respects the OTC and the indoor air temperature is controlled by varying the flow rate in the slab.

OTC & Temperature The water loop temperature respects the OTC and the indoor air temperature is controlled by varying the water temperature at the slab inlet.

The OTC is defined to respect the indoor temperature setpoint for the coldest day of the year. For weak isolated houses, the heat demand varies almost linearly with the decrease of temperature. Here, OTC case study presents very bad results: high energy consumption and discomfort. This is due to the fact that low energy buildings are strongly depending on solar and internal gains. Load variation can not be considered as linear. OTC strategy is not adequate and consequently it is not presented in the following of the study.

In a **Reference case**, the RHF and the control strategy are bypassed. The thermal power provided by the heat pump is directly injected to the indoor air (only convective heat flow). The thickness of the upper concrete layer is 7 cm and the heat pump operation is given by on/off control (+/-0.5°C around the indoor air setpoint). The HP inlet water temperature is fixed at 25°C. The annual heat energy provided for this reference case is 884 kWh, for an electric consumption of 249 kWh. The annual results presented on Figure 6 and Figure 7 are normalized depending on this reference case. The continuous lines are for left-side axis and the dotted lines for right-side axis.

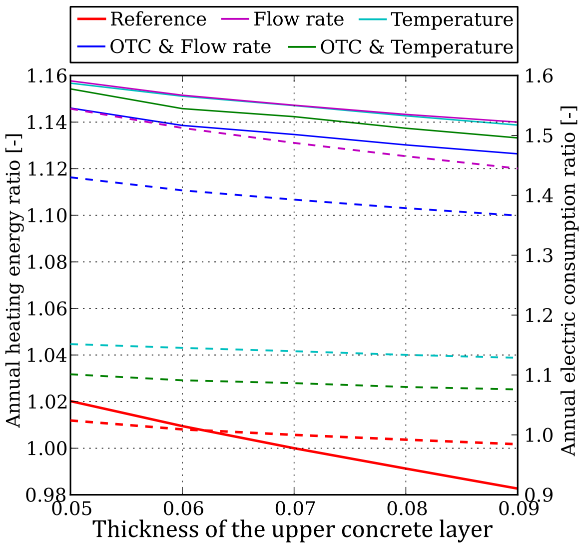

Figure 6: Comparison of the annual heating energy

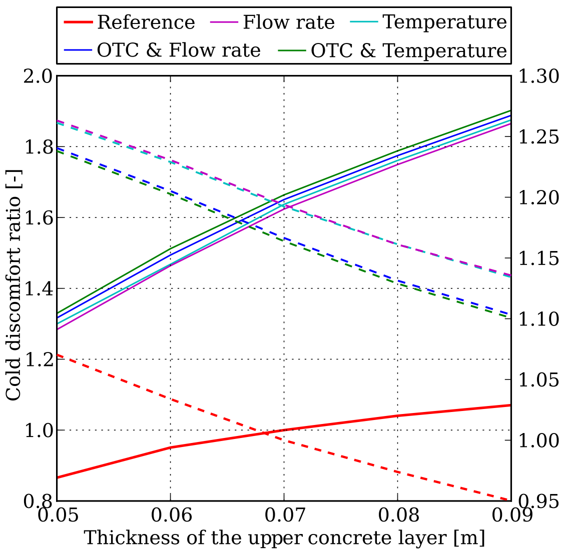

Figure 7: Comparison of the annual discomfort

On Figure 6, the red continuous line shows that in the reference case the annual heating demand slightly decreases with thermal mass increase. Indeed, the rise of the thickness of the upper layer increases the overall insulation of the floor and, mainly, increases the capacity of the upper layer to store heat of solar gains. Normalized annual heating demand varies between 1.13 and 1.16 so the use of a slab increases on average the annual heating demands of 14% compared to the reference case (unreal case, no heat transmitter).
As shown by the dotted lines, the control strategies with the lowest heating loads are not the ones having the lowest annual electric consumption. Indeed, the two OTC strategies (*OTC & Flow rate* and *OTC & Temperature*) and the *Temperature* control strategy reduce the water temperature at the heat pump inlet, which reduces the entropy difference with the outdoor and considerably improves the COP of the heat pump. The *Temperature* control also decreases flow rate at the tank outlet, which divided by 2 the annual number of cycles of the heat pump compared with *Flow rate* strategy. Therefore the performances are better.
To conclude on Figure 6, the choice of the control strategy has more impact than the thermal mass of the HVAC system on annual electric consumption. As a result, we showed that the control modeling can no longer be considered as negligible in the simulation of low energy buildings.

On the Figure 7, the continuous lines show that the use of a RHF multiplies by 1.6 the cold discomfort (when the indoor air temperature is less than 19°C during presence periods). It is a consequence of the delay to heat the floor. This discomfort increases with the thickness of the upper layer. In order to reduce this discomfort, the control has to be modified by shifting the presence scenario to anticipate the delay. In this case, the choice of the control strategy has a limited effect.
The dotted lines show that the warm discomfort decreases with increasing the floor thermal mass because solar gains are spread over time. The OTC control coupled with an indoor air control (*OTC & Flow rate* or *OTC & Temperature*) reduces this discomfort because the water loop temperature is adjusted for the low heat demands in mid-seasons.

The Figure 8 shows the temporal results of a one week simulation during February. The top graph presents the room air temperature between a light (green line) and a heavy (red line) RHF under the same control strategy: *OTC & Flow rate*. The black line is the temperature setpoint: 16°C unoccupancy set-back and 20°C during occupancy.
During cold period the thermal mass of the floor almost maintains the temperature at the setpoint (20°C). Furthermore the heavy RHF ($e = 0.09\ m$) reduces the temperature increase due to solar gains, that explains why the annual warm discomfort is reduced when thermal mass is high. This principle could be reinforced with geo-cooling or free-cooling to decrease the floor temperature during night in order to limit the warm discomfort in summer.
The second graph presents, on the same period, the emitted heat provided by the heat pump to the water loop. The on/off heat pump keeps cycling during

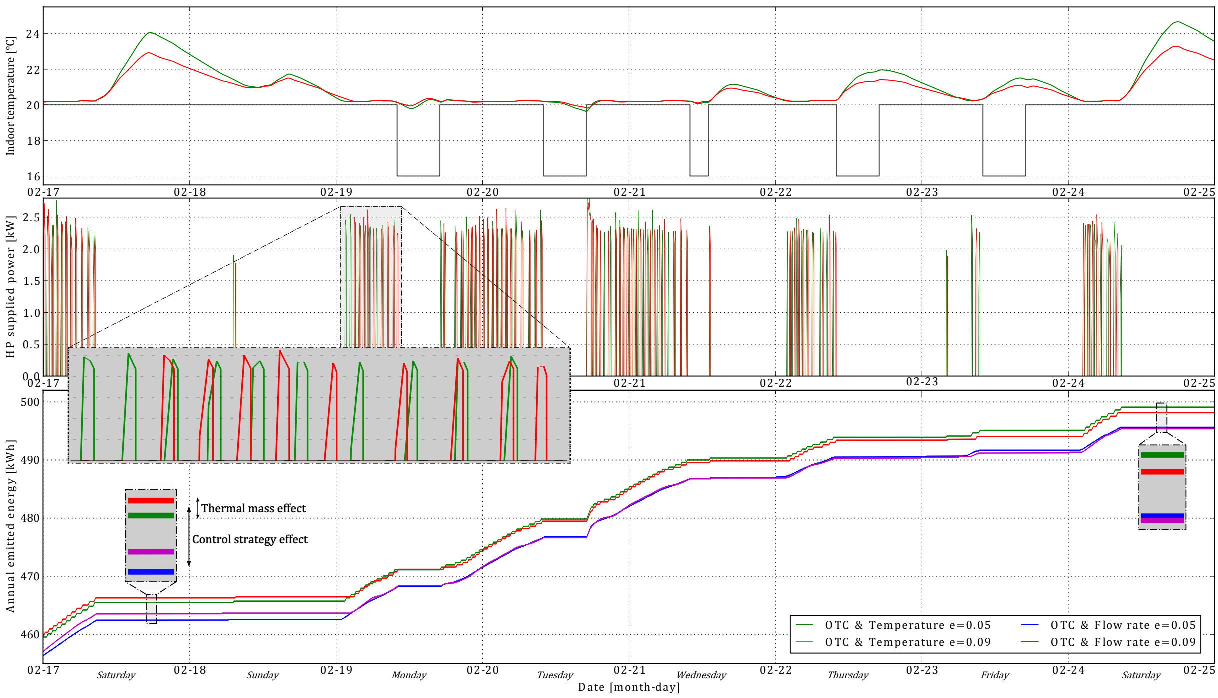

Figure 8: Dynamic simulation results during February

operating periods. Sometimes, the heat pump is in operation while the temperature has already reached the setpoint, it is due to the buffer tank heat losses and the change of the water loop temperature target from the OTC. The thermal mass reduces the power to be provided after sunny days: for instance, at February, 19th (see zoom grey box), there is 9 operating period for $e = 0.09\ m$ case and 10 cycles for $e = 0.05\ m$.
This point is confirmed with the last graph presenting the cumulative emitted energy along the year. Another control strategy for two thermal masses is added on the graph (blue and magenta). More remarkable, at the beginning of the period, systems with light thermal mass (green and blue) seem to be more efficient but finally at the end of the period, the ones with heavy thermal mass (red and magenta) have lower heat demand. Still, this difference between two thermal masses is very low in comparison with the control strategy.

CONCLUSION

The study establishes a certain number of impacts on a radiant heating floor system due to thermal mass and control strategy.
- **Thermal mass**: Light RHF reduces the heating delay of the heat emitter compared to a heavy one. On the other side, the growth of the thermal mass spreads the solar gains over time, which reduces annual heat demand and limits warm discomfort in mid-seasons.
- **Control strategy**: Contrary to the water *Temperature* control, the water *Flow rate* control decreases the heat demand but deteriorates the COP. Adding an outdoor temperature control of the indoor temperature control slightly decreases the heat demand and highly improves the COP. Furthermore, it limits the warm discomfort in mid-seasons.

So the main conclusion concerning thermal mass and control strategy is that the best method is to use a heavy radiant floor with both *OTC* and *Temperature* controls in case of low energy buildings.

The study also established important considerations regarding the modeling of the low energy buildings:
- **Internal and solar gains**: Control strategy without indoor air control shows that the solar gains and in a lower extent the internal gain have a significant effect on the heat demand.
- **RADTEST evaluation benchmark**: It makes it possible to evaluate the model but with a large gap between the reference simulation software results. It is hard to estimate the fidelity of RHF models because dynamic experimental data are difficult to be found.
- **Control modeling**: The main result of this paper is the major effect of the control modeling on the HVAC system consumption and on the thermal discomfort.
- **Dynamic simulation**: Required for the modeling of control strategy, the dynamic simulation and physically-based load models reduce simulation problems with embedded HVAC components. Radiant surface systems or phase change material are simultaneously a part of the building envelope contributing to the heat demand and to the temperature control.

The decrease of heat demand in low energy buildings and the development of new HVAC equipment require a reexamination of the usual modeling approaches in building simulation, in particular by dynamic simulation and control modeling.

This study has identified how to model a HVAC system including a radiant heating floor and what are their advantages (low temperature, radiative warm, etc.) and the drawbacks (slow response, warm discomfort in mid-seasons). Further investigations on radiant heating floor should be undertaken to limit the discomfort problems in low energy buildings by using predictive control solutions for example.

NOTATIONS

λ_x	Thermal capacity of the layer x
ρ_x	Density of the layer x
Cp_x	Heat capacity of the layer x
D_{ext}	Pipe exterior diameter
d_{pp}	Distance between pipes
e_x	Thickness of the layer x
L_{pipe}	Length of the pipe
n_{seg}	Number of segments in discretization
T_i	Water inlet temperature
T_o	Water outlet temperature
T_{conc}	Temperature of the upper concrete layer
COP	Coefficient of performance
HP	Heat pump
HVAC	Heating, Ventilation, and Air Conditioning
OTC	Outdoor temperature control, see Table 1
RHF	Radiant heating floor
TABS	Thermally Activated Building Systems

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