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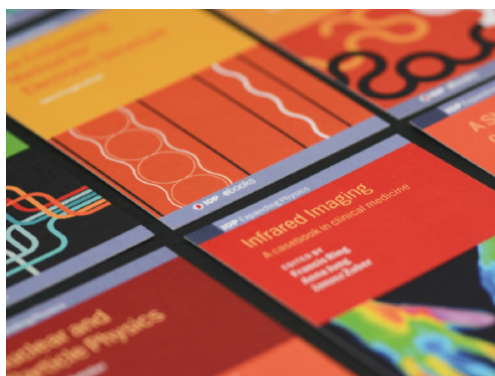
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A novel concept for energy-efficient floor heating systems with minimal hot water return temperatures

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Abstract. The study proposed and investigated a new concept for hydronic floor heating in dwellings with the aim of reducing hot water temperatures toward a more robust and energy efficient operation. Modern heating systems often rely on low return temperatures to improve operation efficiencies through reduced heat losses from return pipes, greater utilisation of condensation heat from boiler flue gases or from the increased COP of heat pumps. Our study investigated the potential of using an apartment heating substation (or ‘flat station’) to supply space heating through two mixing loops using hot water supply temperatures of 30°C to bathrooms and 24°C to all non-bathrooms. The concept sought to minimise hot water supply temperatures to utilise a self-regulating effect while ensuring low return temperatures. In the first iteration of the concept, the high-temperature return water from the bathrooms was cascaded to the non-bathrooms to heat these rooms and provide further cooling of the hot water. The calculated energy-weighted return temperature under this original concept was 25.6 °C for the example case of a new energy-efficient apartment building. However, there was limited potential to utilise the cascaded coupling, so considering the complexity of its configuration and controls, the authors simplified the proposed concept to two mixing loops without a cascaded coupling. The calculated return temperature with the updated concept was 25.7 °C. The control of the floor heating included some aspect of self-regulation because the heat transfer strongly depended on the indoor temperature. Based on the results of this preliminary investigation, the concept may provide a robust and energy-efficient option for configuring floor-heating systems in situations that rely on low hot-water return temperatures.

1. Introduction

Radiant floor heating is commonly used in both new and existing constructions. In Denmark, Germany and Austria, between 30-50% of new residential buildings use radiant floor heating systems [1]. Radiant floor heating systems are popular for several reasons: they provide greater comfort due to warm floor surface temperatures and even heat distribution; they can improve the air quality in the occupied zone due to enhanced thermal stratification [2]; and they are minimally obtrusive to living spaces. Furthermore, radiant floor heating systems consume less energy for heating because they can provide similar perceived temperatures (also known as operative temperatures) with lower air temperatures because the large warm surface is located near to the occupants. Lastly, while radiator-based heating systems typically use hot water supply temperatures up to 85°C, floor heating systems often use temperatures below 35°C [3]. Thus, radiant floor heating systems can permit lower heat losses from the supply and return pipes in buildings or in district heating networks due to lower operation temperatures. Furthermore, many modern heating systems include condensing boilers, which require low return temperatures to maximise the heat output from condensing flue gases. Thus, radiant floor heating



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systems can improve the efficiencies of heating systems by guaranteeing low hot water return temperatures from space heating when using low supply temperatures [4].

Control strategies for floor heating systems use intermittent flow, continuous flow or a combination of both. To ensure sufficient flow while heating, many controllers use intermittent flows where the valve has two positions: fully open or fully closed. In its most basic form, the valve fully opens when the indoor air temperature decreases below the desired setpoint and turns off again when the indoor temperatures surpasses the setpoint plus perhaps the addition of a dead-band. This can result in significant overshoot due to the thermal inertia of heavy floor heating, so a more advanced approach modulates the heat output using pulse-width modulation (PWM) of the open-close valve. In such cases, a PI controller may determine the duty cycle (i.e. opening time for the valve in each period) based on the measured and desired indoor temperatures. In one such system, Hu and Smith [5] observed that a building inspector increased the hot water supply temperature centrally in response to complaints from occupants. As these faults turned out to be local issues with the floor heating in each apartment, the increase in supply temperature masked the faults and exacerbated issues related to excessive heating and high return temperatures. In this case, supply temperatures less than 35°C should have been sufficient to meet the demand for heating at all times, but the operator centrally raised the supply temperature to 40°. With a dimensioned cooling of 5°C, it should have been possible to realize return temperatures of 30°C or less, especially when reducing the supply temperatures at part load, but it was difficult to realise this potential in practice due to the ease with which the building operator could increase supply temperatures in a system based on intermittent flows. Olesen et al. performed a parametric study of different control strategies, including intermittent flow operation, and posed that the operation time period has a great influence on the system energy efficiency when applying intermittent flows [6]. They further stated that the most important task is to establish theoretical guidelines for intermittent flow schemes that are sensitive to climatic characteristics, building load and thermal characteristics and building regulations.

Most continuous flow systems aim to minimise the supply temperature through floor heating circuits to realise high flows and a more even distribution of heating from the floors. Often the central heat source has a higher supply temperature than is necessary for space heating because domestic hot water systems (DHW) require high temperatures to minimise the risk of harmful Legionella growth. To realise a more suitable supply temperature for radiant floor heating, systems typically employ a mixing loop that recirculates a share of return water into the supply water, thereby adjusting the flowrate of hot water from the heating system. This type of controller may not account for variations in pressure and temperature in the distribution network, so there have been efforts to propose improved control strategies. Nielsen et al. proposed a closed-loop control strategy with feedback from the heating distribution network, which integrated two sub-controllers to monitor local attainment of supply temperatures and flowrates within acceptable limits. The operation costs decreased by 5% during 9 months of testing [7].

A supply temperature controller often uses a weather compensation curve to adjust the supply temperature according to outdoor temperatures as a form of open-loop control. While the implementation is simple, the drawback is that it does not take into account internal heat gains due to appliances, occupants or solar radiation. In newer buildings with lower space heating consumption, these variations become increasingly impactful. Fortunately, in such systems, there is a self-regulating effect, whereby the heat flux decreases with increasing indoor temperatures due to the large heat transfer surface area of the floor and a reliance on small temperature differences between the floor surface and the indoor air. Thus, as internal heat gains rise, the heat flux decreases. Karlsson verified the self-regulating effect when setting a constant low supply water temperature in a radiant floor heating system [8]. Similarly, Weitzmann conducted a numerical investigation for an office building with an integrated heating and cooling system and found that water supply temperatures close to room temperature were sufficient for both heating and cooling [9]. As the demand for heating decreases in new low-energy buildings, self-regulating heating systems become increasingly feasible, with the benefits of simpler, more-robust control and a reduced risk of excessive heating. Karlsson presented a self-regulation

utilisation factor and stated it as high (i.e. more favourable) in low-energy buildings, which implies a high degree of self-control. Thus, floor heating systems in low-energy buildings may improve through the use of a self-regulating feedforward control instead of intermittent flow control, as the investment cost could decrease significantly without the need for room sensors and thermostats.

The challenge with a self-regulating floor heating system with minimal supply temperatures is that the demands for heating are highly dissimilar for different room types. Bathrooms typically require higher floor temperatures to maintain thermal comfort due to the higher conductivity of ceramic tiles compared to other floor coverings such as wood. According to DS/EN ISO 11855-1:2015 [10], the comfortable surface temperature range for marble or tile flooring is 27.5-29°C. As summarised by Berge et al., residents in low-energy housing also often prefer higher air temperatures in bathrooms (e.g. ~25°C) and living rooms (e.g. ~23°C) than in bedrooms (e.g. as low as 12-18°C) [11]. Thus, the requirements for supply temperatures in a self-regulating floor heating system would vary from room to room, and it may not make financial sense to design a system with a mixing circuit for each zone. Thus, an appropriate design could optimise the number of mixing circuits while minimising the supply and return temperatures of the system. There are few investigations into novel systems that target these aims, so the present work seeks to fill this gap by investigating the potential of novel floor heating systems that combine mixing circuits, self-regulation, minimally-intermittent flows and potentially cascaded flows to minimise return temperatures.

2. Case study building

The case study uses construction data from a low-energy apartment building in Copenhagen, Denmark. Figure 1 shows the floorplan and IDA-ICE model of the apartment. The case study considers an apartment building with a heating substation in each dwelling. The hot water in the main riser is assumed to be 55°C, as required to safely heat DHW up to 50°C using a heat exchanger. The case study assumes the desired room temperatures based on the typical comfort criteria outlined above for low-energy buildings in Northern Europe, such that the minimum room temperatures are 25°C in bathrooms, 22°C in living rooms and 20°C in bedrooms.

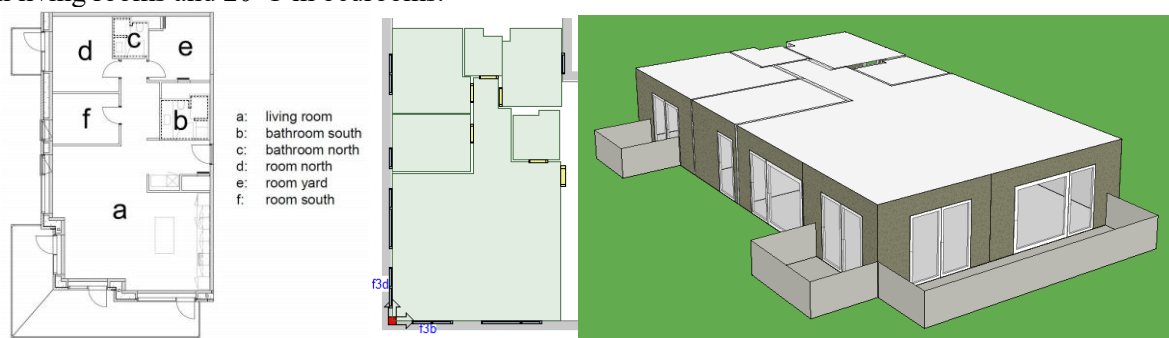


Figure 1. The floorplan in the case study apartment.

3. Proposed concept

To obtain the required floor surface temperatures for comfort in bathrooms of 27.5-29°C, the required hot water supply temperature needs to be 30°C. The bathrooms in the case study building do not have any wall elements in the external façade. The ventilation system extracts airflows from the bathroom and the makeup air comes from the corridor, so the primary heat loss in the bathroom is due to the temperature difference between the intake air from the corridor and the extract air from the bathroom. As this remains constant throughout the heating season, the supply temperature to the floor heating of the bathroom remains constant at 30°C. In low-energy dwellings, the other room (i.e. non-bathrooms) do not require as high supply temperatures, so this investigation proposes a separate mixing circuit for all non-bathrooms in each dwelling. In the present case study, the maximum required supply temperature for all non-bathrooms is 24°C and is reduced to 23°C at outdoor temperatures above 0°C as a form of weather compensation.

3.1. Cascade system

As the return temperatures from bathrooms are likely to be sufficient to supply all other rooms, this investigation first considers a cascade arrangement, where the return water from the bathrooms is supplied to the mixing circuit for all non-bathrooms to assess whether this significantly reduces the aggregated return temperature for the whole system. Figure 1 depicts such a system without going into details about how these flows are achieved, but as a basis, the system controls the ratio of recirculated flow in each circuit by thermostatically regulating a return valve based on the mixed supply temperature. Designing a well-controlled system with cascading flows requires complex hydraulic arrangements, so this analysis first estimates the potential for such a system using dynamic simulations and simple energy conservation equations. In such a system, the return flow from the bathrooms circuit (i.e. flow B in the figure) is prioritised as a supply source for the non-bathrooms. If there is no demand from the non-bathrooms, the flow is returned to the central heating system.

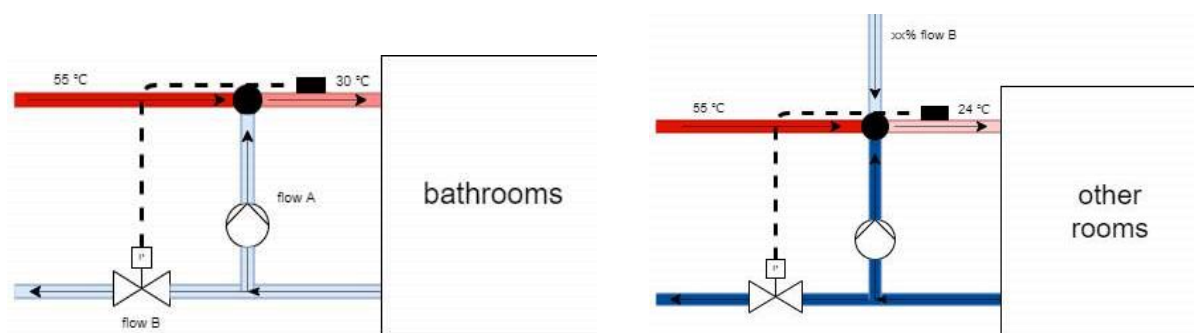


Figure 2. A schematic diagram of the bathrooms circuit (left) and the non-bathrooms (right). Note: xx represents a value from 0 to 100 and depends on the heat demand of the non-bathrooms.

The investigation applied dynamic simulations in the software IDA-ICE to determine the required hot water flows to the floor heating circuits for the bathrooms and non-bathrooms and observe the resulting temperatures of the air, floor surface and water. By default, IDA-ICE allows one hot water supply temperature, so the authors simulated hydronic floor heating in the bathrooms and ideal heaters in the other zones. This was repeated where the living room instead used hydronic floor heating. Due to the high heat retention of the building envelope and the lower air temperature setpoint of the bedrooms, the bedrooms demanded nearly negligible heating in the yearlong simulation and were not included in the investigation of the effect of cascading flows. Danish residences do not use active cooling and instead use passive cooling by means of natural ventilation, which can be difficult to simulate realistically. The cooling period was not the focus of this investigation, so the simulations used an ideal cooler in the living rooms and bedrooms to maintain indoor temperatures below 28°C.

As the mixed supply water temperatures to the bathrooms and living room are close to the desired indoor temperatures in the proposed concept, the floor heating system relies heavily on the self-regulating effect using continuous flows rather than open-close valves for supplying intermittent flows. The simulated flow rates were based on the design heat demand for each zone and a cooling of 1°C in floor heating circuits of the living room and 1.5°C in the bathroom. The final flowrates were 0.2739 kg/s in the living room and 0.0466 kg/s in the bathroom.

3.2. Non-cascading system

If the results indicate that the cascading system does not reduce return temperatures enough to justify the added hydraulic complexity, a simpler system with separate mixing circuits for the bathrooms and non-bathrooms may be the most cost effective options. Figure 3 shows a schematic of the proposed apartment substation without a cascade, which uses minimal supply temperatures in each circuit and where the space heating is operated by manual on-off control for each room loop. It is proposed that the occupant would close the heating to the bedrooms if they preferred cooler temperatures while sleeping

and close the heating to the living room outside the heating season while likely leaving the bathroom heating active throughout the year and simply adjust the supply temperature on a comfort basis.

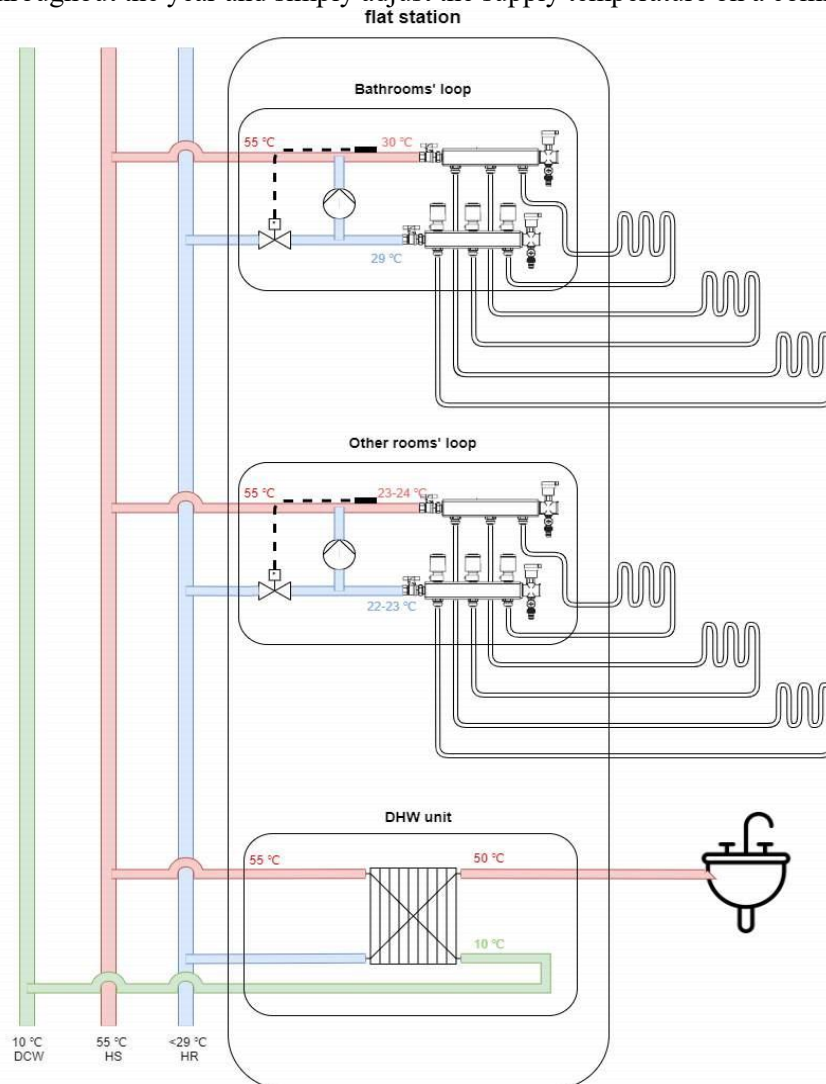


Figure 3. The apartment heating substation for the proposed floor heating system.

In this concept, each apartment has a heating substation with one DHW unit and two mixing loops for space heating. The outdoor temperatures have a rather small, indirect influence on the heat demand in the bathrooms as the temperatures rise seasonally in the surrounding rooms, but generally, the bathrooms have relatively stable heat demand throughout the year due to the requirements for high floor temperatures when using tiled surfaces. Thus, the bathrooms employ a steady flow of heating. This provides the additional benefit of maintaining warm risers and pipes leading to the apartment substation, which is necessary to rapidly heat DHW. This helps to avoid the need for a bypass to maintain warm pipes, which otherwise increases the return temperatures in the heating system and carries the risk of excessive flows if not properly commissioned. Brand et al. investigated the potential of redirecting bypass flow to the bathroom floor heating, and it appeared that a small flow rate could maintain sufficiently warm temperatures at the DHW unit [12]. However, the investigation was not directly comparable since it applied twin pipes with state-of-the-art insulation properties to supply a single-family dwelling in a low temperature district heating network. Therefore, the heat loss of the circulation pipe in each case should be modelled to assess whether the constant flow in the bathroom is sufficient

to avoid the need for a bypass in each design situation. For the DHW unit, 55°C hot water is directly supplied to the heat exchanger and 10°C domestic cold water is heated up to 50°C for use. The return water on the network side of the DHW unit can be cooled down to nearly the cold water temperature because there is no bypass circuit in this newly proposed heating system, which ensures low return temperatures.

4. Results and discussion

4.1. Simulation results

The apartment contains two bathrooms with similar heating systems and requirements for thermal comfort, so this analysis combines the bathrooms and uses their average temperatures and the sum of their flows. This simplification is merely for convenience and visualisation. Figure 4 shows the simulation results for the floor heating circuits of the bathrooms and the other rooms.

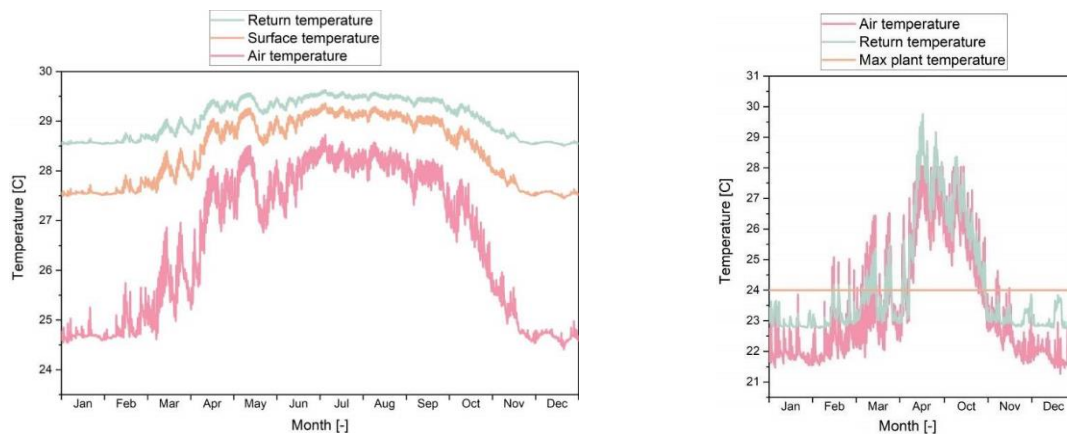


Figure 4. The relevant temperatures for the bathroom (left) and the non-bathroom circuit (right).

The return temperature from the bathroom circuit was 28.5° during the heating season (from November to February) and roughly 29.5°C outside the heating season. The floor surface temperature and air temperature of the bathrooms were within comfort bounds, which implies that a constant self-regulating flow to the bathrooms could be effective. The air temperature in the living room is roughly 22° during the heating season and the return temperature is often 23°C during the same period. From early April to late October, the return temperature exceeds the supply temperature, which implies that the heating circuit becomes a cooling circuit. While it may be effective to combine self-regulating heating and cooling, this was not investigated in the present work, and the flow through this circuit was considered to be stopped from March to October. As such, there was no cascading flow during these months.

4.2. Return temperature with cascade and non-cascade systems

This analysis focuses on the period from November to February, as these are the only months where the return flow from the bathroom can be cascaded to supply the other rooms in the case apartment. The supply flow to the mixing circuit of the bathrooms is 55°C, so the flow discharged from the bathroom circuits is determined by Equation 1.

$$M_{bath} = \frac{\text{floor heating power}}{c_{water} \cdot (55 - T_{return\ water})} \quad (1)$$

The heat demand in the bathrooms is very stable from November to February. The average floor heating power and return temperature within this four-month period are 136 W and 28.6°C respectively. Based on these average values, the discharge flow from the bathrooms is 0.0012 kg/s, which is the maximum flow that can be cascaded to the non-bathroom circuit.

The heat demand in the other rooms is not as stable due to the influence of outdoor temperatures, so the potential to utilise the cascaded flow must be assessed using dynamic simulations. As the return temperature from the bathroom circuit is 28.6°C, Equation 2 expresses the maximum cascaded flow that can be utilised by the non-bathrooms.

$$M_{other} = \frac{\text{floor heating power}}{c_{water} \cdot (28.6 - T_{return\ water})} \quad (2)$$

If M_{other} is less than M_{bath} , the surplus bathroom flow needs is returned to the heating network. And if M_{other} is greater than M_{bath} , the bathroom flow is insufficient to meet the needs of the non-bathrooms and additional hot water supply at 55°C is needed.

Figure 5 shows the comparison between the two mass flow rates. M_{other} is larger than M_{bath} for more than 80% of the heating season, which indicates that the bathroom return flow can be highly utilised during these months. This cascading flow decreases the return temperature of the bathroom circuit from 29°C to roughly 23°C. Figure 5 also shows the comparison of the floor heating power for the non-bathrooms and the maximum power supplied by the return water from the bathroom to the non-bathrooms. This figure implies that the heat supplied by the cascaded flow is relatively small compared to the heat demand of the non-bathrooms. Table 1 shows the significant parameters and results regarding the operation of the cascade floor heating system during the heating season. The average return temperature of the cascade system is 25.6°C during the heating season and 29.5°C outside of the heating season.

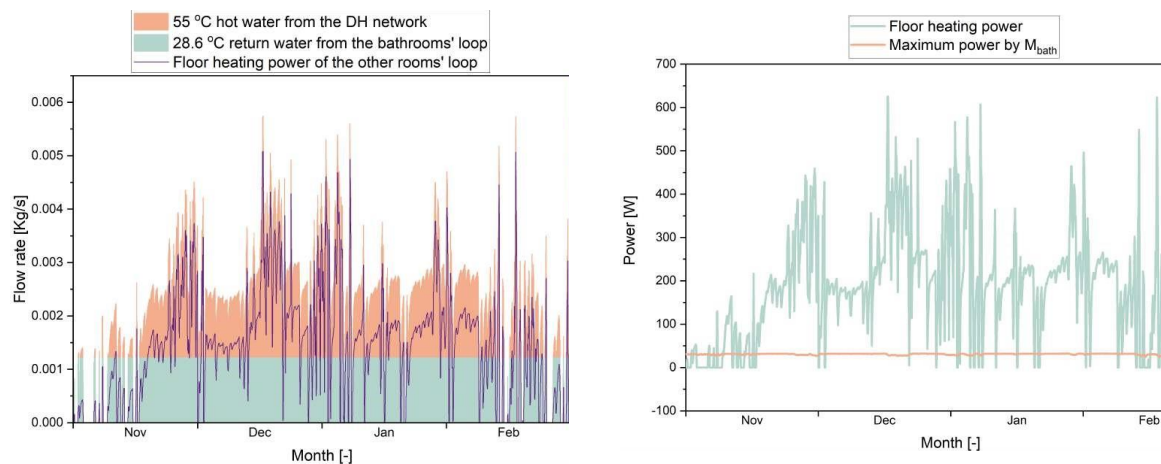


Figure 5. The flow supplied to the non-bathrooms before mixing with the recirculating flow (left), and the heat required by the non-bathrooms and the maximum heating from the cascaded flow (right).

The cascading flow rate is relatively small, which limits its influence on return temperatures from the heating system. When the cascade is removed, the average total return temperature only increases by 0.1°C. Furthermore, such cascade systems often required complicated hydraulics and controls, so it seem very impractical to implement the proposed cascade from the bathroom circuit to the non-bathroom circuit when the non-cascade system has a reasonably strong potential for low return temperatures and robust operation.

Table 1. Operation of the proposed floor heating system during the heating season.

Cascade system		Non-cascaded system	
Bathrooms	Non-bathrooms	Bathrooms	Non-bathrooms

Average heat consumption [W]	136	178	136	178
Constant circulating flow [kg/s]	0.0464	0.2739	0.0464	0.2739
Non-recirculated flow [kg/s]	0.0012	0.0022	0.0012	0.0013
Average return temperature [°C]	28.6	23.0	28.6	23.0
Total average return temperature [°C]		25.6		25.7

5. Conclusion

The paper proposed a novel hydronic heating substation for apartments that aimed to simplify controls and minimise water return temperatures. It further analysed the potential of a cascade coupling from one circuit to another in a case apartment, but this only provided only slightly lower return temperatures, which would not offset the increased cost and complexity of a cascade system. The proposed system without the cascade coupling provides a simple and robust solution with self-regulating heating and nearly minimal return temperatures. In the case apartment without a cascade, the resulting return temperatures were 25.7°C during the heating season and 29.5°C outside the heating season. The bathroom uses heating throughout the year, which helps to avoid the need for a bypass to rapidly heat domestic hot water, and this may further reduce return temperatures.

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