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Simplified Space-Heating Distribution using Radiators in Super-Insulated Terraced Houses

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Abstract

The necessity to drastically reduce the space-heating (SH) needs of residential buildings in Europe has pushed the emergence of building concepts based on a super-insulated building envelope, such as the passive house (PH) standard. In these envelopes, the SH distribution system can be simplified because it is theoretically not necessary anymore to place a heat emitter in each room, or in front of each window. There is lack of fundamental knowledge to support this simplification of the SH distribution system. The present contribution focuses on terraced houses heated using a reduced number of radiators. It aims at comparing the balance between energy efficiency, thermal comfort and user satisfaction using simplified SH distribution. For this purpose, two terraced houses built according to the Norwegian PH standard have been investigated using building simulations (using IDA-ICE), field measurements and occupant interviews. With a simplified distribution, one may suspect that occupants experience the thermal environment of rooms without heat emitter as too cold, typically bedrooms. On the contrary, the super-insulation and the high-efficiency heat recovery prevent significant temperature zoning to take place between rooms. Even though the SH distribution is simplified, occupants rather complain about the bedroom temperature which often experienced as too warm if they do not open windows. Unfortunately, this way to control indoor temperature has a strong adverse influence on the SH needs. The trade-off between bedrooms temperature and SH needs is here investigated for different control strategies using calibrated simulations.

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Keywords: Passive House; Space-Heating; Simplified Distribution; Radiator; Terraced House

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1. Introduction

The necessity to drastically reduce the space-heating (SH) needs of residential buildings in Europe has prompted the emergence of building concepts based on a super-insulated building envelope, such as the passive house (PH) standard. While the construction of passive envelopes is more challenging, these envelopes also offer opportunities. Given their level of insulation and the use of high-performance windows, the SH distribution system can be simplified because it is in principle not necessary anymore to place a heat emitter in each room, or in front of each window. A well-known simplification is the so-called centralized air heating [1, 2], but one could also consider a wood stove [3, 4], or a limited number of low-temperature radiators. There is lack of fundamental knowledge to support the SH simplification. It aims to reduce investment costs and thermal losses from pipes, while it may reduce the flexibility for users and increase control losses. Therefore, the present work aims at analyzing the balance between energy efficiency, thermal comfort and user satisfaction using simplified SH distribution. The contribution focuses on low-temperature radiators in terraced houses. The case of apartment buildings has been treated in a previous publication [5].

Two row houses built according to the Norwegian PH standard NS3700 [6] have been investigated. Both buildings are located in Trondheim (in Norway) and equipped with a simplified hydronic system. The temperature differences between rooms have been measured during two weeks during spring 2016. In addition, qualitative interviews have been performed with occupants. Based on these measurements, detailed dynamic simulations using IDA-ICE have been calibrated. These models enabled to investigate the influence of alternative control strategies on the SH needs and thermal comfort in bedrooms.

SH in highly-insulated buildings in Nordic countries was already investigated by previous works, but they essentially focused on other aspects. For example, Wigenstad et al. [7] investigated simplified SH distribution in Norwegian PH but did not perform measurements, or evaluated the temperature differences between rooms.

2. Case description

The two investigated row houses are part of a same construction project located in Trondhiem. They have slightly different floor plans, see Figure 1 for House 1. Each house has a heated area of 142.5 m² and consists of three sleeping rooms. The living room facing south is coupled to the kitchen. In House 1, the entrance is at the ground floor and one radiator is placed in the living room near the open staircase. In House 2, the entrance is in the basement where one radiator is located near the open staircase. Then, the living room has no heat emitter. The hall of the first floor is equipped with a radiator in both cases. The bathroom has floor heating but its influence on the entire building is limited as the door is almost always closed.

Except the basement, the building is constructed in timber and insulated with mineral wool. External and partition walls between houses have a U-value of 0.15 W/m²K. The U-value of the two types of internal partition wall (also insulated with mineral wool) is estimated to be 0.4 and 0.64 W/m²K, and 0.12 W/m²K for internal floors. The normalized thermal bridges are 0.03 W/m²K. Infiltrations have not been measured but the designed value is 0.6 ach at 50 Pa. The balanced mechanical ventilation generates a cascade flow where fresh air is supplied in bedrooms, the basement and the living room, transferred using the corridor and mainly extracted in the bathroom, the technical room and kitchen. The supply air in bedrooms depends on the nominal number of occupants (26 m^3/h per person). The design airflow rate (Vn) is 1.4 m^3/h per m², or 0.52 ach. The air handling unit (AHU) is equipped with a heat recovery wheel with a rated efficiency of 88% (EN308). An electric heating battery is placed after the heat exchanger, where a set-point temperature (Tset,AH) is defined by occupants using a control panel. The ventilation can be operated at three different speeds, where speed two is the nominal one (Vn).

The two houses have not been measured in parallel but sequentially during Spring 2016. Temperature sensors iButton DS1922L-F5 with an accuracy of ±0.5°C registered air temperature every 6 min. One sensor has been placed in each room of the building at a height of ~1m above the floor (see red dots in Figure 1); except for the living room, kitchen, stair case and first floor corridor where 3 sensors have been placed at different heights in order to monitor the temperature stratification. Additional sensors were positioned inside the AHU, at each air terminal device (ATD) (see orange dots in Figure 1) and to measure the outdoor temperature at the north façade. Sensors were also placed on the bulb of the radiators thermostatic valves (TRV), on the radiators surface, as well as water inlet and outlet pipes.

Occupants were able to log in a diary the position of the TRV (Tset,SH), the set-point temperature for the supply air (Tset,AH) and the selected ventilation airflow rate. The opening of all windows and internal doors were monitored using contact sensors. They deliver a binary signal (open/closed) but do not measure the degree of opening.

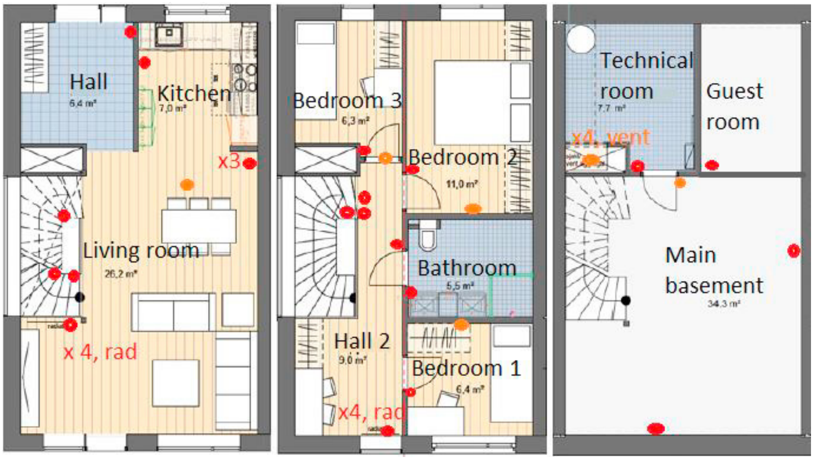

Fig. 1. Floor plan of House 1 for the ground floor (left), first floor (center) and basement (right), with north points upwards.

3. Field-based results

3.1. Interviews

A qualitative interview was performed with the occupant of both houses. Answers regarding the SH season are only reported here. The occupants of the House 1 are satisfied with the living room temperature with a desired value of about 22°C. At first sight, one may believe that a limited number of heat emitters would imply that rooms not equipped with radiators will be experienced as too cold by users, namely bedrooms in the present case. On the contrary, users experienced the bedroom temperature as comfortable, 20°C being the desired temperature. The bedroom windows are almost always closed (also due to the outdoor noise) but are sometimes opened to provide fresh air or control indoor temperature. The bedroom doors are usually left open to keep them warm, but sometimes closed for privacy. The occupants of House 2 are also satisfied with the living room temperature, with a desired value of about 23°C, even though this room is not equipped with a heat emitter. The occupants of House 2 would like to have cold bedrooms, ~15°C being reported as their ideal bedroom temperature. They usually keep the bedroom windows open 6-7 hours per night, except during the coldest periods of winter. The bedroom doors are kept closed to create a temperature difference with the corridor, as well as for privacy. These results are in good agreement with the work of Berge et al. [8]. They performed a questionnaire distributed to the residents of 62 detached and row houses from the Miljøbyen Granåsen in Trondheim. The same SH distribution strategy is applied in these buildings (i.e. air pre-heating battery, simplified hydronic distribution with no radiator in the bedroom, floor heating in the bathroom). Their questionnaire revealed that occupants are mostly satisfied with the thermal comfort in the living room and bathroom. On the contrary, the level of satisfaction is significantly lower in bedrooms where a lower temperature than the rest of the building is preferred. In fact, 50% of occupants experience the bedroom temperature as too warm. About 50% of occupants open the bedroom window in the winter for a least a few hours. The main motive for people to open the bedroom window is the temperature control (not IAQ).

3.2. Measurements

For both houses, measurements confirm that the living room temperature complies with the desired values reported in the interviews. This is also true for House 2 even if the living room has no radiator. The vertical temperature stratification is limited to ~1.5°C in both cases, see e.g. the living room of House 1 in Figure 2.

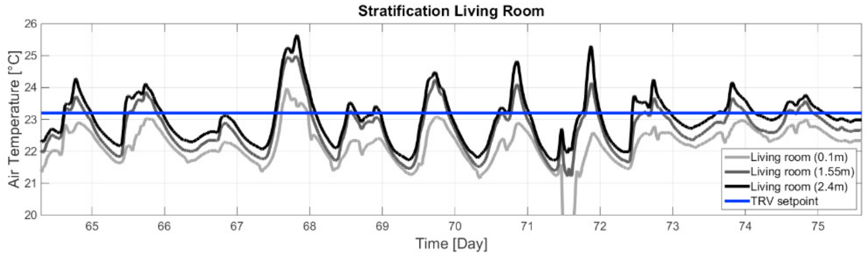

Fig. 2. Measured temperature stratification in the living room for House 1.

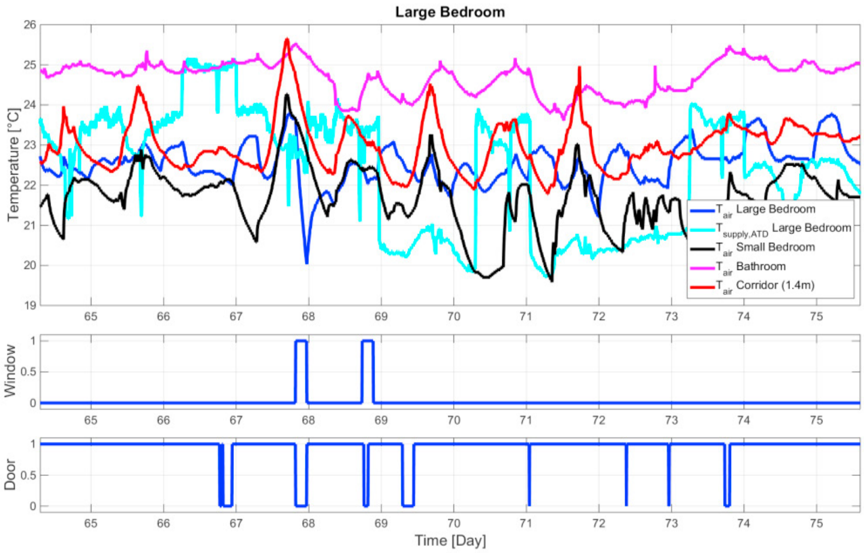

Fig. 3. Temperatures related to the large bedroom for House 1.

Measures also comply with occupants' perception of the thermal environment in bedrooms. For the sake of the concision, results are only shown here for the large bedroom facing north in Figures 3 and 4.

Figure 3 shows that the air temperature of the large bedroom in House 1 oscillates between 22 and 23°C, which is compatible with the temperature desired by occupants. As reported in the interview, the bedroom window is mainly closed and the internal door mainly open. The temperature difference with the corridor is limited. One can notice that the corridor temperature can exceed 23°C, essentially due to solar gains. Accordingly, the medium bedroom facing south shows equivalent peaks during periods of high solar gains (up to 26-28°C). The small bedroom facing north has a lower temperature of ~21°C, with a lower peak at 20°C.

Figure 4 shows that the air temperature of the large bedroom in House 2 oscillates between 16°C and 20°C, which is higher than the desired temperature of 15°C. As reported in the interview, the bedroom window is open several hours during the night and the internal door mostly closed. A rapid drop of the bedroom temperature is clearly visible, each time the window is open. With a corridor temperature of 24-25°C, the temperature difference with the bedroom is then large (4-5°C). Despite the low temperature desired by occupants in bedrooms, they still apply a supply air set-point temperature (Tset,AH) of 22°C. This confirms the findings of Berge et al. [8] showing that "*many occupants do not control the supply air temperature in a manner that provides thermal comfort in bedrooms*".

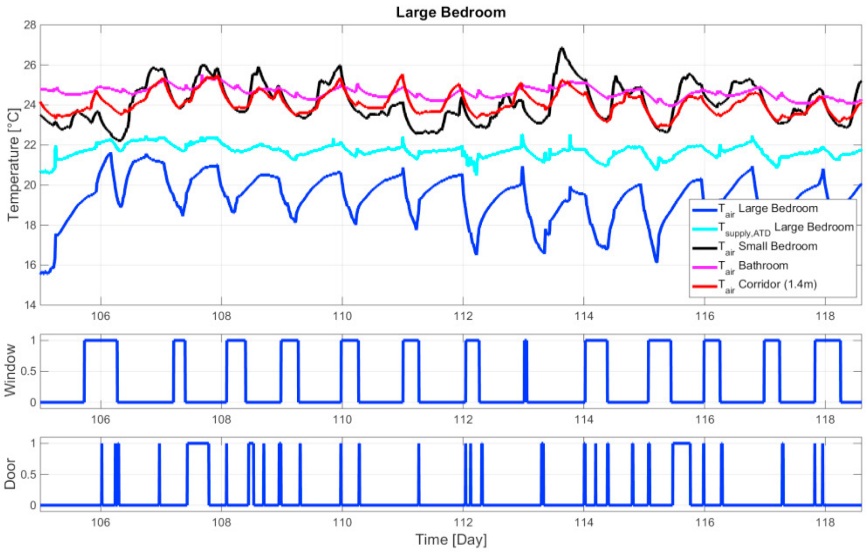

Fig. 4. Temperatures related the large bedroom for House 2.

4. Detailed Dynamic Simulations

Results have been complemented using detailed dynamic simulations, here using IDA-ICE. Alternative control strategies have been investigated in order to determine whether a proper control of the building can generate relatively low temperatures in bedrooms without window opening. Their respective impact on the bedroom temperatures and the SH needs has been analyzed using yearly simulations and standard internal gains from NS3700. A significant work has been done to validate and calibrate the simulation model based on measurement data. Validation results are not reproduced here but the IDA-ICE models proved to fairly reproduce the temperature differences between rooms, even though standard internal gains were used instead of real gains (as they have not been measured).

Table 1. Summary of the investigated control strategies.

Control	Tset,HR	Tset,AH	Tset,SH	Window	Door
0	-	20°C	21°C (or 24°C)	Closed	Closed
0b	-	24°C	21°C (or 24°C)	Closed	Closed
1	-	16°C	21°C (or 24°C)	Closed	Closed
2	16°C	16°C	21°C (or 24°C)	Closed	Closed
3	14°C	14°C	21°C (or 24°C)	Closed	Closed
4	16°C	16°C	21°C (or 24°C)	Open if T>16°C and nighttime	Closed
4b	16°C	16°C	21°C (or 24°C)	Open if T>16°C and nighttime	Open in daytime (window closed)

Tset,HR represents the set-point temperature of the heat recovery unit, as its efficiency can be changed by controlling its rotational speed. In cases 4 and 4b, the window opening in each bedroom is controlled during nighttime using a PI control to keep the temperature at 16°C (with a maximum opening of 10% of the total window area). Results are reproduced in Figure 5 for the case of a constant set-point temperature (Tset,SH) of 24°C.

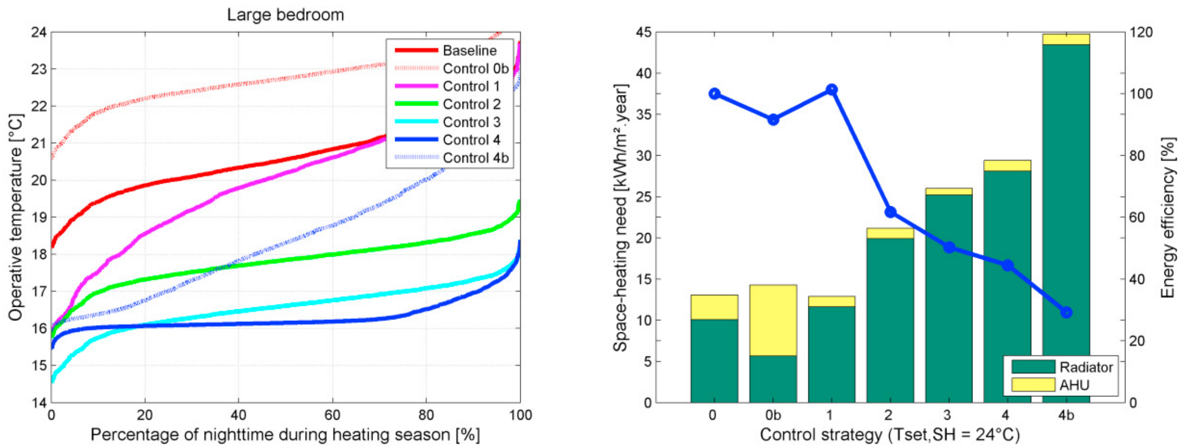

Fig. 5. Duration curve of the bedroom operative temperature (left) and yearly net SH needs for the seven control strategies (right) using a set-point temperature (Tset,SH) of 24°C (the efficiency in "blue" is evaluated by taking case 0 as reference).

Control 0b shows it is possible to reach high bedroom temperatures by increasing the Tset,AH. If desired, a bedroom temperature of 16°C can be generated using window opening (control 4) but it leads to a significant increase of the SH needs. If the bedroom is in addition heated by opening the internal door during daytime (control 4b), the SH needs further increase. A good trade-off is to reduce the efficiency of the heat recovery (control 3) even though this case can generate an uncomfortable draft with a ventilation air temperature of 14°C. In conclusion, the control cannot generate a bedroom temperature in the range of 16°C, without a significant increase of the SH needs.

Conclusions

The present study investigated the indoor thermal environment of super-insulated terraced houses heated using a limited number of radiators. While one could expect the SH simplification to generate cold bedrooms, investigations rather confirmed that bedrooms have a relatively high temperature (~20°C) without opening windows.This is not compatible with the desired temperature of many occupants (~16°C). Simulations showed that the radiator and AHU controls cannot solve the situation: low bedroom temperatures cannot be generated without increasing the SH needs significantly.

Acknowledgments

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