Setback efficiency of limited-power heating systems in cold climate

Tuule Mall Kull[1], Raimo Simson[1] and Jarek Kurnitski[1]

[1] Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
tuule.kull@ttu.ee

Abstract. The main aim of this work is to analyze the energy saving potential and peak power impact resulting from the temperature setback approach. This paper analyses low energy buildings incorporating high-efficiency heating systems with limited power, as additional power for district heating and heat pump systems will need costly investments. The setback efficiency is estimated for different types of heating systems. Underfloor heating is compared to radiators both for limited and excess power. Based on estimated time constants, suitable heat-up time is calculated to minimize the time when temperatures stay below setpoint during occupancy. The energy saving potential of night-time and weekend setback periods in an office are analyzed. It is found that the energy saving potential of setback is low under given constraints. Therefore, for modern buildings the cost-optimality has to be assessed separately for specific cases.

Keywords: Temperature setback efficiency, low-energy buildings, limited power, cold climate.

1 Introduction

The method of periodically decreasing the set temperature of heating systems in buildings when the rooms are vacant, often called intermittent heating or the setback approach is a widely used method for energy saving. In several studies [1–3] energy saving potentials of up to 20 % were identified. In single cases, the observed reductions are much higher [4] or much lower [5]. In the mentioned studies, mostly moderately insulated buildings are considered, with simple setback control mechanisms based on pre-defined set-temperature schedules. However, such an approach generates discomfort during the times when people arrive and the temperature has not achieved its set value. In recent years, most intermittent heating control systems for low energy buildings include advanced control methods to solve this problem [6]. However, these are not simple to apply. Applying setback temperatures requires over-dimensioned heating systems to enable fast heat up times[7]. However, a typical advantage of modern low energy buildings is the utilization of low peak-power heating systems, which reduces the building's investment cost.

Our assumption is, that only very low energy savings can be achieved by temperature setback in modern well insulated buildings, and therefore the required investment in over-sized heating systems is not profitable. Therefore, the efficiency of intermittent heating in modern and old buildings is compared in this work.

2 Approach

2.1 The building description

Envelope. The room model used for the simulations is a 13.3 m^2 office with a 3-m^2 window facing north. We have previously described this model with all construction specifications for modern and old buildings as well as heavy and light construction types in [8]. The room has one external wall and an external floor over outdoor air, therefore its heating demand is larger than for an average office building. This case is defined as ‘modern-high-loss’ office and will be the standard configuration in this work. For comparison, a similar office room with less insulation is defined as ‘old’ office. The third configuration is referred to as ‘modern’ as it has modern constructions but its floor is adiabatic and a the window is south-facing. The total heat loss coefficient (without ventilation system) is 7, 9 or 18 W/K for modern, modern-high-loss, and old buildings respectively.

Ventilation and internal gains. We have redefined the internal loads and ventilation control according to the Estonian norms for office simulations [9], meaning that the ventilation airflow is 2 l/s/m^2 during the occupancy hours (7 a.m. to 6 p.m. at workdays) and 1 hour before and after this timeframe. The usage profile is depicted in **Fig. 1**. These usage factors are multiplied with 5.8 W/m^2 for occupant heat gain, and 9.5 W/m^2 for heat gains from lighting and electrical appliances. During the weekends and holidays, the building is not in use. The supply air temperature of the ventilation is 18 °C. For the modern offices, 80% heat recovery from the exhaust air is assumed, whereas the old building has no heat recovery at all. The infiltration in modern buildings is 1.3 l/s; in the old buildings, it is included in the ventilation.

Heating systems. Two types of limited power heating systems are simulated: ideal heaters and electric floor heaters. Ideal heaters represent radiators (Rad) supplied by a district heating system, while electric floor heating represents underfloor heating (UFH) supplied by a heat pump. Using the electric/ideal systems replaces here the function of raising the heating curve to achieve maximum output power of the systems during the heat-up. The nominal power of the modern systems is 273 W, of modern high-loss systems 437 W, and for old systems 1656 W. For the comparison with a gas boiler supplied radiator based heating system, which can be easily over dimensioned without distinct cost increase, ideal heater cases with 684 W in modern-high-loss light and 1367 W in heavy offices are simulated and defined as ‘over-dim-Rad’. These are dimensioned according [7] to weekend setbacks.

Simulation. The building is simulated in IDA-ICE 4.7.1 software [10] using Estonian TRY [11] as climate data. The heating season is assumed to be from 1st of October to 30th of April.

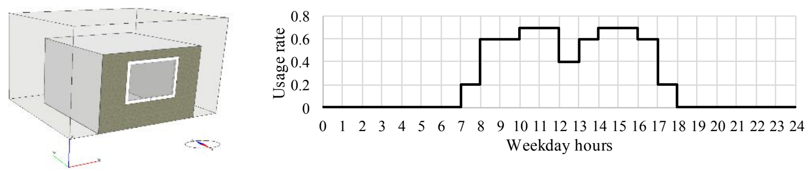

Fig. 1. The isometric view of the simulated zone (on the left) and the usage factor profile.

2.2 The control description

Reference case. The performance of the setback control is evaluated by comparing the required heating energy demand against the demand of a reference case, where a constant temperature of 21 °C is maintained by a proportional-integral (PI) controller in the same room. Here, the performance is defined as the heating demand for both, space heating and supply air heating by the air-handling unit.

Control algorithm. The setback control also keeps the air temperature during the occupancy hours at 21 °C with PI control, only it is reduced to18 °C during unoccupied hours. However, to ensure comfort conditions when occupancy starts the required heat-up time until comfort temperature is reached is calculated.

If that calculated heat-up time is longer than the actual time left to the start of occupancy hours, the set temperature is changed to 21 °C overriding the initial PI control. . If the temperature rises faster than estimated, the set temperature is turned back to 18 °C again.

Heat-up time calculation. The heat-up time is the time the system needs to heat the room up to 21°C again from setback. It is calculated every 5 minutes. For that, the one-time-constant model for the building is used. From the heat balance equation of

$$C\,\frac{d\theta_{in}}{dt} = H\,(\theta_{out} - \theta_{in}) + \Phi \tag{1}$$

for the indoor temperature θ_{in}, the solution for the heat-up time is derived:

$$t = -\,\tau \cdot \ln\left(\frac{\Phi/\mathrm{H} - \theta_{set} + \theta_{out}}{\Phi/\mathrm{H} - \theta_{in} + \theta_{out}}\right). \tag{2}$$

Φ is the heating power in watts, H is the heat loss coefficient (W/K), θ_{out} is the exterior air temperature, θ_{set} is 21 °C and θ_{in} is the current indoor air temperature. τ is the time constant in seconds, however in this work it is always converted to hours. It is calculated as $\tau = \mathrm{C/H}$. C represents the heat capacity of the air and structures (J/K). For the calculation of time constant for night setback, the surface layers up to 20 mm depth are included into the heat capacity calculation. The active layer depth of 100 mm is used for weekend setback [12]. The time constants are quantized; they are rounded to the closest 25 hours. This is done to use approximate values, as the exact values are not known in real cases. The used values are shown in **Table 1**. The 100 mm heat capacity values are approximately four times higher than the 20 mm values shown in the table (7449 kJ/K for heavy and 5002 kJ/K for light).

Table 1. Calculated input parameters used for preheat-control in intermittent heating.

Energy-efficiency level	*Str. mass*	*Heat emitter*	*Abbrev.*	τ_n *(h)*	τ_{wnd} *(h)*	*Φ (W)*	*H (W/K)*	C_{20mm} *(kJ/K)*
Modern-high-loss	heavy	UFH	S_H_UFH	50	225	437	9	1677
Modern-high-loss	heavy	Rad	S_H_Rad	50	225	437	9	1677
Modern-high-loss	light	UFH	S_L_UFH	50	150	437	9	1561
Modern-high-loss	light	Rad	S_L_Rad	50	150	437	9	1561
Old	heavy	Rad	O_H_Rad	25	125	1656	18	1677
Old	light	Rad	O_L_Rad	25	75	1656	18	1561
Modern	heavy	UFH	M_H_UFH	50	300	273	7	1677
Modern	heavy	Rad	M_H_Rad	50	300	273	7	1677
Modern-high-loss	heavy	over-dim Rad	S_H_O_Rad	50	225	1367	9	1677
Modern-high-loss	light	over-dim Rad	S_L_O_Rad	50	150	684	9	1561

3 Results and discussion

3.1 Energy performance

The simulated energy demands for all observed cases are shown in **Table 2**. It can be seen that the energy consumption in the air-handling unit is almost equal for all the modern and standard cases; it is zero for old buildings, as the supply air is not heated. The total reduction of energy demand resulting from the intermittent heating operation is shown in **Fig. 2.** All observed cases result in heating demands reduced by approximately 4-7 % when setback control is compared against the constant temperature reference cases. However, the absolute reduction differs significantly between construction types, as the net heat demand between the evaluated cases ranges from 29 to 195 kWh/(m^{2}a). While for the old buildings, the reduction is about 12 kWh/(m^{2}a), for the south-oriented low energy buildings the reduction is only 1 kWh/(m^{2}a). For heavy construction, setback efficiency is in all cases marginally less than for the corresponding light construction case.

3.2 Temperature performance

Weekly fluctuations. The resulting air temperatures in the observed office during a two-week period in winter are depicted for all simulated cases in **Fig. 3**. In Fig. 3.A, we can see that for the well-insulated room, air temperatures do not decrease to 18 °C (red interrupted line), staying even for weekend setback above 19 °C. Moreover, the graph shows that the PI-control cannot hold a constant temperature during the day (set temperature level of 21°C also shown in upper red line) and the room overheats for the floor-heating case.

Fig. 3.B illustrates the known observation that a room with higher heat capacity cools down slower. In case of a light building structure, the temperature can decrease to 18 °C even for the floor heating case the Fig. 3.B shows. Still, the temperature change is slow and the set temperatures difficult to maintain.

Compared to these, changes in temperature for radiator cases in Fig. 3.C are faster. PI control with the radiators maintains the temperature setpoint well. However, during the heat-up, fluctuations occur.

In Fig. 3.D, we can see that the over-dimensioned radiators allow for stronger room temperature reductions than in the corresponding cases with regular heating dimensioning in Fig. 3.C. However, **Table 2** shows that the resulting reduction of energy demand is not higher than 1 kWh/m^{2}a.

Fig. 3.E shows that in old buildings the temperature drops to 18 °C almost immediately and, due to the high available heating power, raises up to 21 °C fast as well. Therefore, in the old building case, the setback potential is fully exploited.

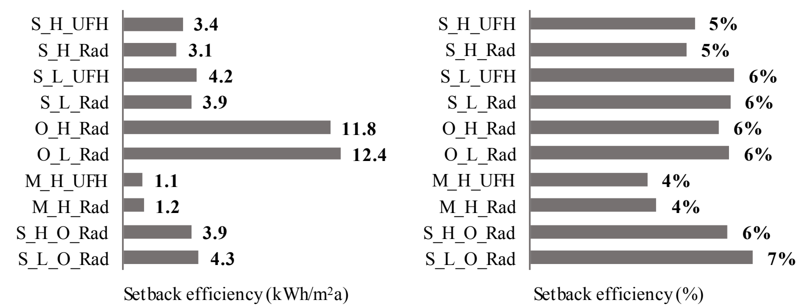

Fig. 2. Energy performance of the intermittent heating, absolute difference from the reference cases on the left and relative on the right. The abbreviations in the labels are explained in **Table 1**.

Table 2. Energy need results for constant temperature and setback control cases.

	Space heating [kWh/(m^{2}a)]		Air handling unit [(kWh/(m^{2}a)]		Total [(kWh/(m^{2}a)]	
	21 °C	setback	21 °C	setback	21 °C	setback
S_H_UFH	52	47	15	17	68	64
S_H_Rad	48	44	16	17	65	62
S_L_UFH	53	47	15	17	68	64
S_L_Rad	48	43	16	17	64	60
O_H_Rad	207	195	0	0	207	195
O_L_Rad	206	194	0	0	206	194
M_H_UFH	17	15	14	15	31	30
M_H_Rad	15	13	15	16	30	29
S_H_O_Rad	49	44	16	17	65	61
S_L_O_Rad	48	42	16	17	64	60

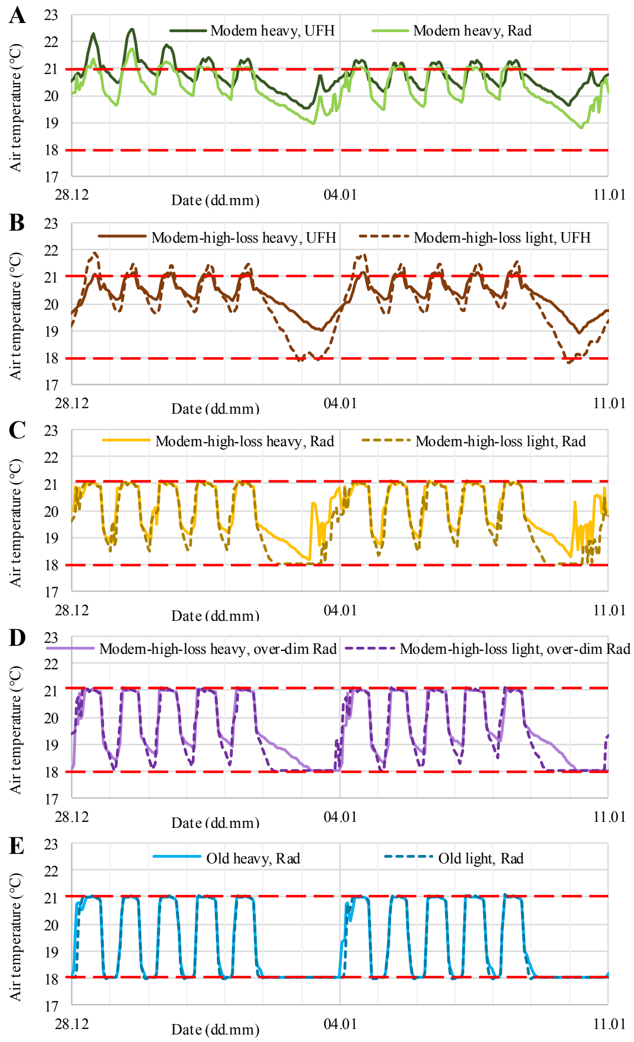

Fig. 3. Air temperature fluctuations during two winter weeks for all simulated cases.

Heat-up performance. In all the temperature graphs (Fig. 3), we can see that for the heavy building cases the temperatures fluctuate before reaching the set temperature. This is because the actual temperature increase is significantly faster than modelled and the system lets the room cool down again until it calculates that heat-up should be started again. In **Fig. 4.** we can see that the fluctuation after weekend setback (on Monday) is more significant than after night-setback (Friday). While on Friday, the setpoint (21 °C) is reached by the start of occupancy in most of the evaluated office rooms, it is not the case on Monday. However, the temperatures are above 20 °C when occupancy begins in all observed scenarios. On Friday, as an exeptional case, S_L_UFH cools down fast but does not manage to heat up on time.

Heating season. The overall temperature performance during the heating season is depicted in duration graphs in **Fig. 5**. Fig. 5.A illustrates the difference between the two heat emitters. We can see that the floor heating is not keeping the given set temperatures, as the graphs are smooth, whereas the plateaus in the radiator graphs show that to some extent set temperatures are maintained. In Fig.5.B, we can see that there is a very clear difference between the different insulation levels. While the plateaus are very clear in the old house case, the modern south-oriented building has very small energy losses and it has significantly higher temperatures. The modern-high-losses cases can be found between these two extremes. Fig. 5.C compares heavy and light structures in old and modern buildings. The slower cool-down of the heavy buildings results in higher temperatures in the duration graph.

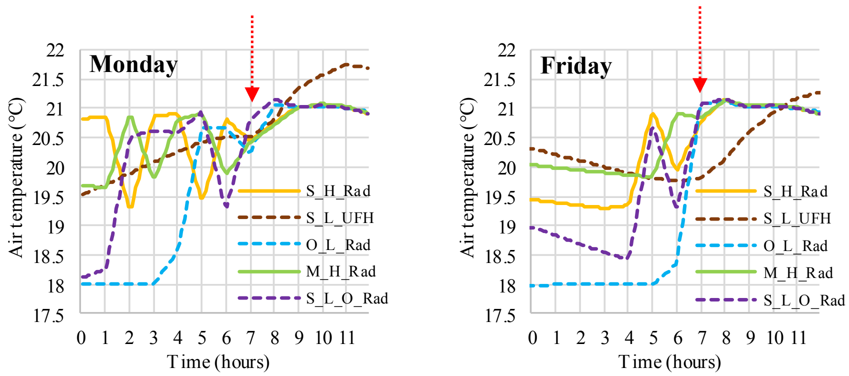

Fig. 4. Temperature performance during heat-up times in the first 12 hours on Monday, January 4 (left) and Friday, January 8 (right). Occupancy start at 7 a.m. and is marked with red arrows.

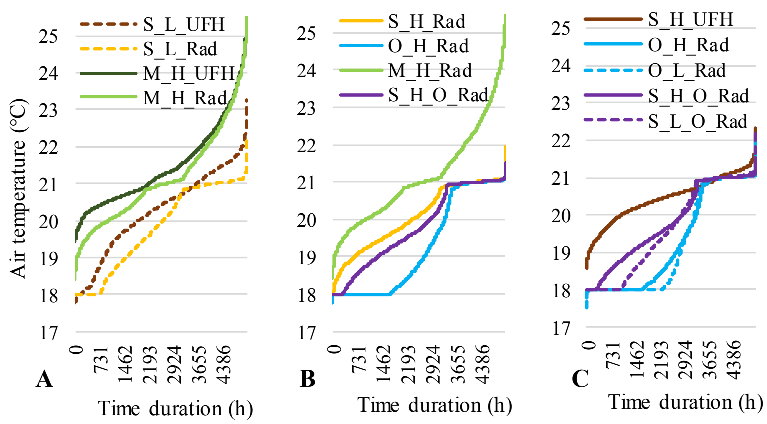

Fig. 5. Temperature duration graphs over the heating season.

4 Conclusion

This research shows that the absolute setback efficiency in modern office buildings is significantly lower than in old buildings. This is mainly because the air temperature does not drop as fast and it stays above allowed minimal limit during the nighttime setbacks. For floor heating cases, this applies even for weekend setbacks. It has been shown that buildings with lower thermal mass and faster reacting heating system have higher energy conservation potential when applying intermittent heating operation. The setback control for old office buildings is always profitable. However, for modern and especially modern buildings with slow reacting heating system, the benefits of setback control are low, especially in absolute numbers. Before applying, the saving needs to be weighed against potential discomfort and additional cost for every specific case.

References

[1] B. Xu, S. Zhou, and W. Hu, "An intermittent heating strategy by predicting warm-up time for office buildings in Beijing," *Energy Build.*, 2017.

[2] J. W. Moon and S. H. Han, "Thermostat strategies impact on energy consumption in residential buildings," *Energy Build.*, vol. 43, no. 2–3, pp. 338–346, 2011.

[3] W. Wang, J. Zhang, W. Jiang, and B. Liu, "Energy performance comparison of heating and air-conditioning systems for multi-family residential buildings," *HVAC&R Res.*, vol. 17, no. 3, pp. 309–322, 2011.

[4] W. Guo and D. W. Nutter, "Setback and setup temperature analysis for a classic double-corridor classroom building," *Energy Build.*, vol. 42, no. 2, pp. 189–197, 2010.

[5] Z. Wang, B. Lin, and Y. Zhu, "Modeling and measurement study on an intermittent heating system of a residence in Cambridgeshire," *Build. Environ.*, vol. 92, pp. 380–386, 2015.

[6] Y. Wang, J. Kuckelkorn, and Y. Liu, "A state of art review on methodologies for control strategies in low energy buildings in the period from 2006 to 2016," *Energy Build.*, vol. 147, pp. 27–40, 2017.

[7] "Energy performance of buildings — Method for calculation of the design heat load — Part 1: Space heating load." FprEN 12831-1, European Standard, 2016.

[8] T. M. Kull, R. Simson, M. Thalfeldt, and J. Kurnitski, "Influence of time constants on low energy buildings ' heating control," vol. 0, no. June, pp. 11–14, 2017.

[9] "Estonian Regulation No 58: Methodology for calculating the energy performance of buildings." Ministry of Economic Affairs and Communications, 2015.

[10] "IDA Indoor Climate and Energy 4.7.1." Equa Simulations AB, 2016.

[11] T. Kalamees and J. Kurnitski, "Estonian test reference year for energy calculations," *Proc. Est. Acad. Sci. Eng.*, vol. 12, no. 1, pp. 40–58, 2006.

[12] "Energy performance of buildings — Calculation of energy use for space heating and cooling," vol. 2008. ISO 13790, International Standard, 2008.