Article

The Effect of the Thermal Mass of the Building Envelope on Summer Overheating of Dwellings in a Temperate Climate

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Abstract: The main objective of this paper is to demonstrate the effectiveness of increasing the thermal capacity of a residential building by using traditional building materials to reduce the risk of its excessive overheating during intense heat waves in a temperate climate. An additional objective is to show that the use of this single passive measure significantly reduces the risk of overheating in daytime rooms, but also, though to a much lesser extent, in bedrooms. Increasing the thermal mass of the room from light to a medium heavy reduced the average maximum daily temperature by 2.2 K during the first heat wave and by 2.6 K during the other two heat waves. The use of very heavy construction further reduced the average maximum temperature for the heat waves analyzed by 1.4 K, 1.2 K and 1.7 K, respectively, giving a total possible reduction in maximum daily temperatures in the range of 3.6 °C, 3.8 °C and 4.3 °C. A discussion of the influence of occupant behavior on the use of night ventilation and external blinds was carried out, finding a significant effect on the effectiveness of the use of both methods. The results of the study suggest that in temperate European countries, preserving residential construction methods with heavy envelopes and partitions could significantly reduce the risk of overheating in residential buildings over the next few decades, without the need for night ventilation or external blinds, whose effectiveness is highly dependent on individual occupant behavior.

Keywords: heat waves; building overheating; temperate climate; passive measures; thermal mass; thermal comfort; cooling energy; air conditioning; user behavior

1. Introduction

1.1. Effect of Global Warming on Outdoor Temperature in Europe

The occurrence of summer heat waves in temperate European countries has increased over the past few years, with a significant increase in both their frequency and duration, and in the height of maximum temperatures experienced. In 2018–2019, extreme high temperatures occurred in most of the temperate European countries. The highest summer temperature on record was in the United Kingdom in 2018 [1]. In a large part of Western Europe and Scandinavia, extreme high temperatures occurred in the last week of June 2019 [2]. In June and July 2019, historical records for the highest temperatures were set across France, Switzerland, Benelux, Germany, the United Kingdom, or northern Italy [2]. The probability of very high summer temperatures due to anthropogenic causes has increased by as much as 30 times [3]. Christidis et al. [1] estimate that in the UK the probability of days with temperatures above 40 °C is currently low, but without reductions in greenhouse gas emissions, after 2100 such temperatures could occur as often as every 3.5 years. Vautard, R. et al. [2] assess that the estimated recurrence intervals of heat waves such as July 2019 in the UK and Germany are currently around 10–30 years, but this probability under global climate change could increase by as much as 10-fold, which would mean they occur every 1 to 3 years. Extremely hot summers like 2003 and 2018 are projected

to become the norm by 2050 which, under current climate projections, could lead to a 257 % increase in heat-related mortality by 2050, the majority of which will be vulnerable people such as the elderly [4].

1.2. Present and Future of Indoor Temperatures in Residential Buildings in a Temperate Climate

The immediate trigger for a new approach to building overheating in temperate European countries was the August 2003 heat wave in Western Europe, which led to the highest number of heat-related deaths in history. Most studies on the future risk of a recurrence have been undertaken in the UK. These have shown that many buildings in temperate European countries are already exceeding recommended summer temperatures and that this effect will increase significantly over the next decades [5–9]. Buildings with low energy consumption are usually considered particularly vulnerable to overheating during summer heat waves, although this is not due to increasing the thermal insulation of the envelope [10], but rather to its high air-tightness [11–13] and low thermal inertia [14–19]. The concepts of passive houses [20] and zero-energy houses are becoming increasingly popular [19]. However, many studies indicate that these building solutions will be the most vulnerable to overheating [7,12,21,22], especially since simulation studies for future weather scenarios indicate that building temperatures will increasingly rise over the next few decades, even with the most drastic measures to reduce greenhouse gas emissions.

1.3. Passive Measures to Prevent Overheating in Residential Buildings

The most common way to counteract the effects of severe heat waves in residential buildings in relatively wealthy countries with temperate climates, e.g., the EU is to install, at least in selected rooms, individual air-conditioning units to eliminate the most intense discomfort experienced at that time. Some studies indicate that residential air conditioner saturation in temperate European countries will be dominated by homeowners' subjective decisions made during periods of severe thermal discomfort during long and severe heat waves, which will become an integral part of the climate in just a few decades [23–26].

An alternative method, increasingly recommended by experts in many countries, to reduce the risk of overheating in dwellings during heat waves in temperate climates is the use of so-called passive methods to reduce temperature extremes. It can be achieved by an appropriate combination of window size and orientation [11,27,28], sun protection by shading [29–32], night ventilation [12,27,33,34], and high exposed thermal mass [16,18,35–37]. The first two measures are aimed at preventing heat from solar radiation from entering the building. High thermal capacity and night ventilation serve to distribute the process of heat transfer over time through the internal surfaces of the building envelope and to remove it to the outside. Many studies combine efficiency of increasing building thermal capacity with its coupling with additional night ventilation [38–40].

1.4. Passive Measures and User Expectations and Behavior

The decision of what the structure of buildings will be, light or heavy, is taken in the design phase. The occupant does not have the option to change it during the lifetime of the building, and thus has no possibility to affect the resulting thermal comfort of the rooms. In contrast, the situation is very different with the other two main passive methods of preventing overheating in summer: night ventilation and window shading. In residential buildings, night ventilation is generally provided by opening windows, which is highly dependent on occupant behavior [41]. Similarly, the shading of windows through the use of external and internal blinds depends on the users' preferences [42]. Factors affecting occupant can be assigned to five broader categories [33,41]:

- Physical environmental: weather, air quality, air temperature and humidity, noise, odors,
- contextual: building archetype, construction, location, window orientation, neighborhood, A/C and ventilation systems and their control, etc.,
- physiological: age, gender, health status, activity level, past thermal experience, clothing, food energy value,

- psychological: attitudes, preferences, values, habits, concerns, expectations concerning thermal comfort, visual comfort, acoustical comfort, health, safety, financial and environmental concerns), cognitive resources (the level of awareness regarding environmental aspects, lifestyle, etc.),
- social: sociocultural norms and practices or cultural background referring to the interaction between occupants, the structure of the decision-making hierarchy related to the control of the internal environment (e.g., the thermostat set point, the opening/closing of windows or blinds).

The last two categories are closely connected to the social science both sociology and psychology. Schweiker [43] calls them "internal or individual factors". Of particular importance in the analysis of behaviors for the residents' provision of acceptable microclimate conditions in dwellings appear to be psychological determinants in the area of behavioral psychology [44–46]. An overall regression analysis showed that six factors: comfort, health, individual's role, belief in science, legitimacy of the energy crisis, and effort to conserve, significantly explained nearly 60% of the summer consumption variance and the comfort factor alone was the best predictor of summer electric consumption, primarily air conditioning [47].

Studies have shown that differences in occupant behavior can lead to two-, three-, and even six-fold higher energy use in identical dwellings [33]. In a study of 500 children bedrooms in Denmark Beko et al. [48] showed that occupant behavior is a much stronger predictor of air exchange than building characteristics. They also found significantly lower air exchange rates in bedrooms on the first floor of residential buildings compared to upper floors. The authors suggest that these results may reflect different ventilation habits of the occupants during the night. According to Lomas and Porritt [49] rooms in new low-energy dwellings tend to be of a lower height and are often single aspect, which prevents cross-ventilation. For aesthetic reasons, large windows are increasingly installed, which are often heavy and difficult to open. Additional factors limiting the practical application of natural ventilation in apartments are noise from city traffic, air pollution and safety concerns especially on the first floor. All these factors cause significant limitations in the practical possibility of using night ventilation during the summer heat, especially among the elderly. "More than half of respondents ... were unable to open windows when needed for security reasons' and 'even on a very hot day more than one in five respondents ... would not tend to open any windows at night' and 'one-third ... would not open windows due to high external noise levels" [49]. The same authors point to the much more frequent use of window shading, which according to occupant survey can be as high as 75% during hot weather. Conversely, Zuurbier [50] in a study conducted during the heatwave of 14–20 August 2012 in 113 dwellings in the Netherlands that were representative of the elderly found no significant effect of outdoor temperature neither on the windows opening to increase air exchange, nor on their shading to protect them from excessive sunlight.

1.5. Thermal Mass

While the effectiveness of night ventilation or window shading is directly related to the values, expectations and consequently the behavior of the occupants, the thermal capacity of a building is a parameter that is completely independent of occupant behavior. Methods based on the use of traditional building materials with high thermal capacity and PCMs, which absorb heat during the melting phase, are proposed. The use of traditional building materials with high thermal capacity is often criticized because of the high embodied energy attributed to them [51–54]. On the other hand, high embodied energy is also attributed to passive PCM applications in buildings [55–57]. More importantly, the efficiency of PCM materials is most often affected by the difficulty of matching the optimal melting temperature of the PCM used with the actual indoor air temperature which can be highly variable during the summer [58–61]. In newly designed buildings, traditional materials with high thermal mass can be effectively used, although some studies, while not questioning their effectiveness in hot climates, contest their usefulness in moderate

and cold climates [62]. Residential buildings in Poland are usually constructed using traditional methods with masonry walls. Massive ceilings and floors also prevail over lightweight constructions. Despite the noticeable increase in popularity of lightweight wooden structures in recent years, their share in the Polish residential construction market is negligible and does not exceed 2% of newly erected buildings [63].

It was hypothesized that using a single passive method of increasing the thermal mass of walls and ceilings by using traditional building materials to cover their interior surfaces would significantly reduce the risk of overheating in living-rooms during intense heat waves in a temperate climate.

The main objective of this study was to show that in European countries with a temperate climate, the preservation of residential construction methods with heavyweight envelopes and partitions can significantly reduce the risk of overheating in residential living rooms over the next few decades, without the need for night ventilation or external blinds, the effectiveness of which is highly dependent on individual occupant behavior. This should lead to substantial reduction of the number of newly installed air conditioners in residential buildings. Due to the lower maximum temperature thresholds used in bedrooms, it may be necessary to additionally equip them with external blinds, which may be easier to operate than in living rooms because of their night-time use.

2. Methodology

2.1. Characteristics of Experimental Rooms

Experimental rooms are located at the south facade of the Center for Sustainable Building and Energy (CSBE) in The Science and Technology Park in Nowy Kisielin, in central-western Poland (Figures 1 and 2). Nowy Kisielin is a small district in the city of Zielona Góra (Cfb-climate), located 8 km from its center. CSBE is a three-storey, low energy center for research, science and development, that was put into use at the end of 2013. The usable area of the building is approximately $2500 \, \text{m}^2$.

Figure 1. Center for Sustainable Building and Energy in The Science and Technology Park in Nowy Kisielin, Poland; view of the building facade and horizontal section.

Each experimental room is 6 m long, 3 m wide and 3.2 m high. The floor area of the rooms is $18 \, \text{m}^2$ and the net volume is about $57 \, \text{m}^3$. The internal surfaces of the roofs and walls of the rooms are made of different building materials. A window to floor area ratio is 0.25.
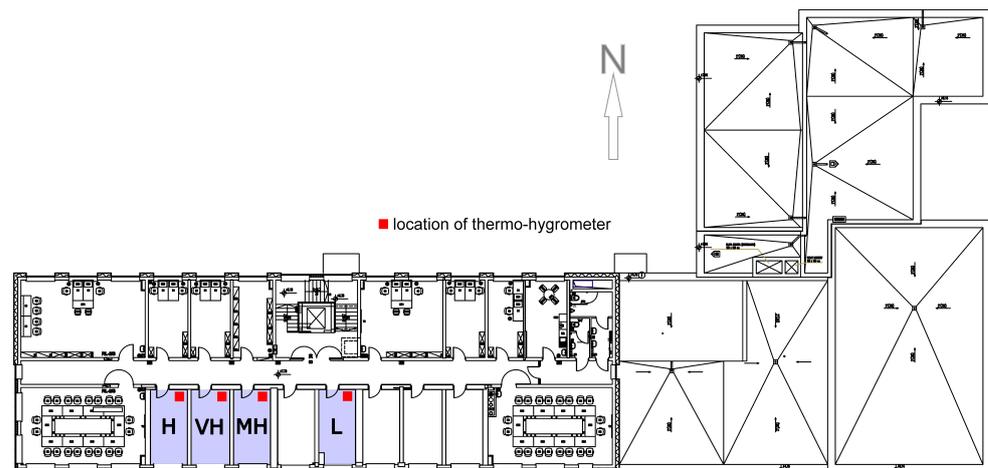
Figure 2. Plan of the top floor of the building with the locations of experimental rooms and thermo-hygrometers (indicated as red squares).

2.2. Materials and Constructions

The analysis includes 4 types of construction of walls and roof assemblies located in experimental rooms H, VH, MH, L:

Type 1: light residential buildings, rather uncommon in Poland, but growing in popularity in recent years (with walls and ceiling based on a timber frame filled with mineral wool and with plasterboard on the inside—Room L; thermal mass parameter = 152 kJ/(m^2 K)

Type 2: medium heavy construction (concrete floor with gres tiles, walls—lime sand blocks with gypsum plaster ceiling based on a timber frame filled with mineral wool and with plasterboard on the inside)—Room MH; thermal mass parameter = 474 kJ/(m^2 K)

Type 3: heavy construction, very common in Polish residential buildings (concrete floor with gres tiles, walls—lime sand blocks with gypsum plaster, reinforced concrete roof with gypsum plaster,)—Room H; thermal mass parameter = 724 kJ/(m^2 K)

Type 4: very heavy construction, rather uncommon in the residential buildings in Poland which ensure the greatest possible effective thermal mass (concrete floor with gres tiles, reinforced concrete walls and ceiling with no plaster, resulting in a strongly exposed concrete surface)—Room VH; thermal mass parameter = 922 kJ/(m^2 K)

In Figure 3, a photo of example Room L was presented.

Figure 3. Room L (light construction); view of the room with location of ventilation and measurement system.

In Tables 1 and 2, thermal transmittance coefficients and area of assemblies of experimental rooms as well as thermo-physics properties of materials were presented, respectively.

Table 1. Thermal transmittance coefficients and area of assemblies of experimental rooms.

Assembly	U [W/(m²K)]	A [m²]
External wall Room H	0.164	5
External wall Room VH	0.173	5
External wall Room MH	0.163	5
External wall Room L	0.116	5
Internal wall Seminar Room/H	0.462	19
Internal wall Room H/VH	0.506	19
Internal wall Room VH/MH	0.463	19
Internal wall surrounding room/L	0.205	19
Internal wall Room L/surrounding room	0.160	19
Internal wall Hall/Room H	0.420	8
Internal wall Hall/Room VH	0.456	8
Internal wall Hall/Room MH	0.431	8
Internal wall Hall/Room L	0.267	8
Floor Room H, VH, MH	0.584	18
Floor Room L	0.558	18
Roof Room H	0.115	18
Roof Room VH	0.116	18
Roof Room MH, L	0.083	18
Windows triple glazing, SHGC (av.) = 0.50		4.5
U_w-mounted = 0.79 W/(m² K); U_g = 0.51 W/(m² K)		

Table 2. Thermophysics properties of materials.

Material	λ [W/(mK)]	ρ [kg/m³]	c [J/(kg K)]
Air layer	0.28	1.3	1000
Aerated concrete blocks	0.105	400	840
Ceramic brick	0.55	1900	880
Concrete screed layer	1.15	1800	1000
EPS	0.044	20	1460
Floor carpeting	0.06	200	1300
Gypsum board	0.25	900	1000
Gypsum plaster	0.40	1000	1000
Gres tiles	1.10	2000	920
Lime sand blocks	0.55	1600	1000
Mineral wool	0.036	90	1030
OSB	0.13	650	1700
PE-Membrane	0.33	920	2200
Bucket foil	0.50	980	1800
Reinforced concrete	1.70	2500	840
Roof covering (asphalt)	0.18	1000	1460
Textured plaster	0.82	1850	840
Trapez metal sheet	1.70	2500	840

2.3. Measurements

The following measurements were recorded continuously:

- inside the experimental rooms (air temperature and air humidity),
- outside the building (outdoor parameters: air temperature and global horizontal solar radiation).

Indoor air temperatures in experimental rooms were measured by thermo-hygrometers (LUMEL, Type P18; uncertainty $\pm 0.5\,\%$). The recorders were calibrated one month before the test period by the producer, who determined their accuracy to be $\pm 0.3\,K$. Immediately before the start of the study, preliminary measurements were carried out, to select them so that the differences in their readings under the same measuring conditions at room temperature would not exceed 0.1 K. They were located at a height of 1.2 m in the corner of experimental room 50 cm from the walls (Figure 2). The thermo-hygrometers also measured relative humidity; with an accuracy of $\pm 3\,\%$ declared by the producer. The preliminary measurements showed that the differences in their readings under the same measuring conditions at room temperature did not exceed 2.0%. Outdoor temperature was measured by thermo-hygrometer (Delta OHM, Type HD9008TRR; uncertainty $\pm 0.1\,\%$) placed in a Multiplate radiation shield Delta OHM, Type HD9007A1), whereas solar radiation was measure by pyranometer (Delta OHM, Type LP PYRA 03; sensitivity $10\,\mu V/m^2$). These instruments were located at a local meteorological station next to the CSBE building. Regular measurements of all above mentioned parameters have been carried out since the end of December, 2013 and recorded in the BMS (Building Management System) every 5 min. The study was conducted during 3 heat waves in summer 2019:

(a) 1–30 June (mean outdoor temperature 22.7 °C; mean maximum outdoor temperature 30.1 °C),

(b) 23–30 July (mean outdoor temperature 24.0 °C; mean maximum outdoor temperature 29.9 °C),

(c) 24 August to 1 September (mean outdoor temperature 23.5 °C; mean maximum outdoor temperature 31.1 °C).

During the first two heat waves, the effectiveness of using light, medium-heavy and extra-heavy construction was compared. During the third heat wave, the effectiveness of heavy construction was additionally tested. All tests were conducted with the exterior blinds open and a constant ventilation air exchange of 0.6 ACH.

The data obtained in the study were checked for distribution and homogeneity of variance. The Shapiro–Wilk test showed that the temperature data distribution is similar to a normal distribution in all four room types. The Levene's test confirmed the homogeneity of variance in all tested groups. The results of both tests allow the comparison of the obtained data by parametric tests. Therefore, (in order to compare the temperatures in the four rooms studied) a one-way ANOVA analysis of variance was performed. Appropriate post hoc tests were also performed to refine the analyses. For comparison of three rooms (L, M, VH), Bonferroni test was used, and for multiple comparisons of four buildings (due to unequal number of measurements in groups), Hochberg test was performed. The results of the Bonferroni test showed significant temperature differences between all three groups ($p < 0.001$). Hochberg's test showed that gr. M and H are not significantly different from each other, while all other groups show statistically significant differences in temperature ($p < 0.05$).

3. Results and Discussion

Figures 4–6 show the hourly air temperature courses in rooms L, M, and VH for the three heat waves of June, July, and August 2019, and additionally the hourly temperature course in room H for the August heat wave. June 2019, with an average temperature of 22.7 °C, turned out to be the warmest in the entire history of meteorological measurements. The course of temperatures in June 2019, however, was not typical of a heat wave, as the temperature increased and decreased several times throughout its duration. During a typical heat wave, which generally lasts much shorter, the temperature builds up in the first few days and remains high for the next few days. This is how the outside temperature evolved during the periods of the 8-day heat wave from 23 to 30 July with an average temperature of 24.0 °C and from 24 August to 1 September with an average temperature of 23.9 °C.
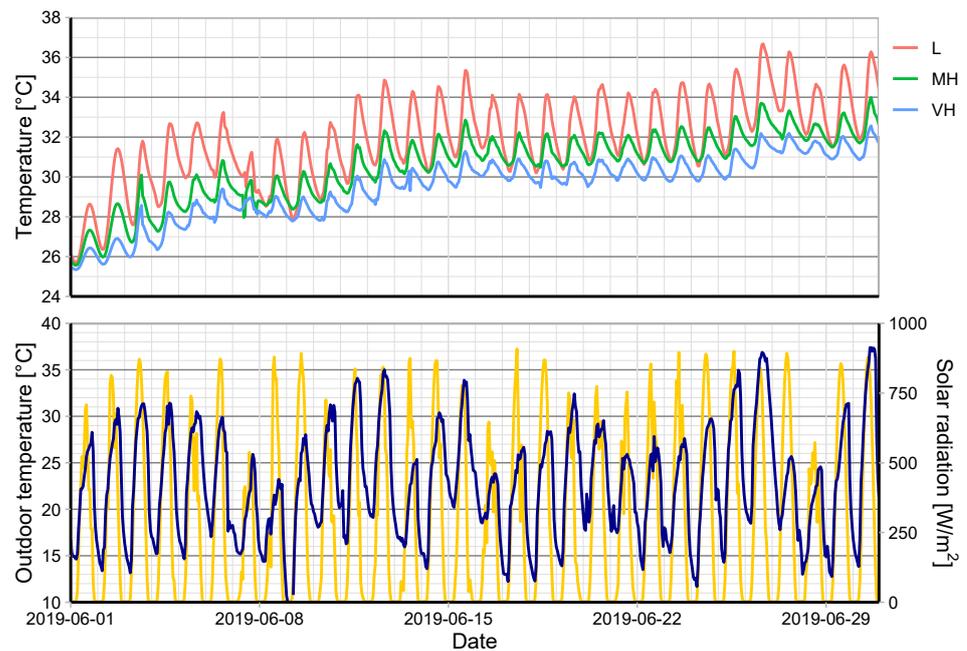
Figure 4. The temperature course in light, medium heavy, and very heavy rooms as a function of outdoor temperature and solar radiation during heat wave 1 through 30 June 2019.
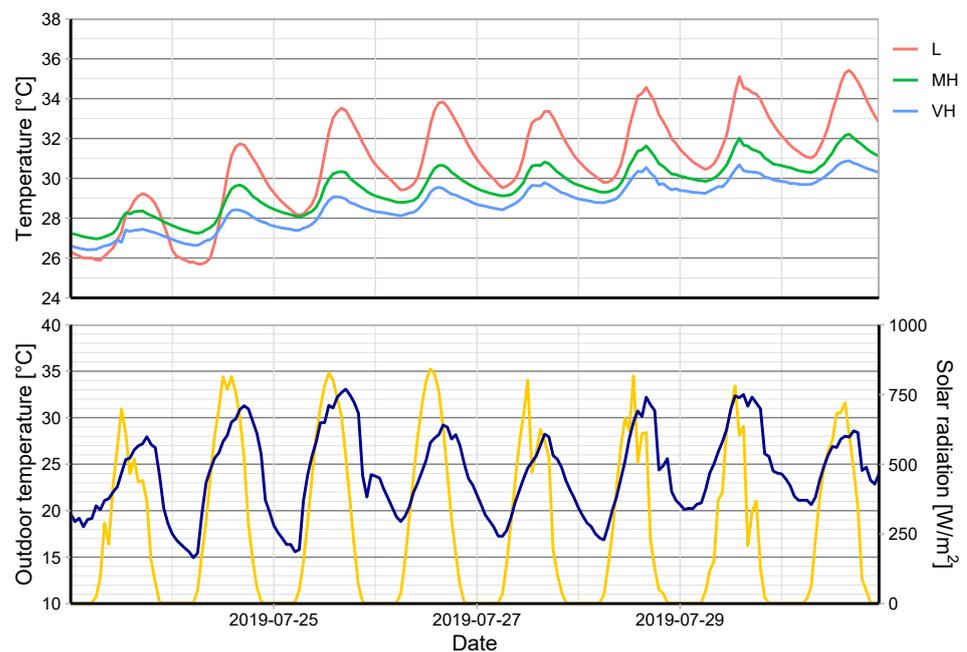
Figure 5. The temperature course in light, medium heavy, and very heavy rooms as a function of outdoor temperature and solar radiation during heat wave 23–30 July 2019.
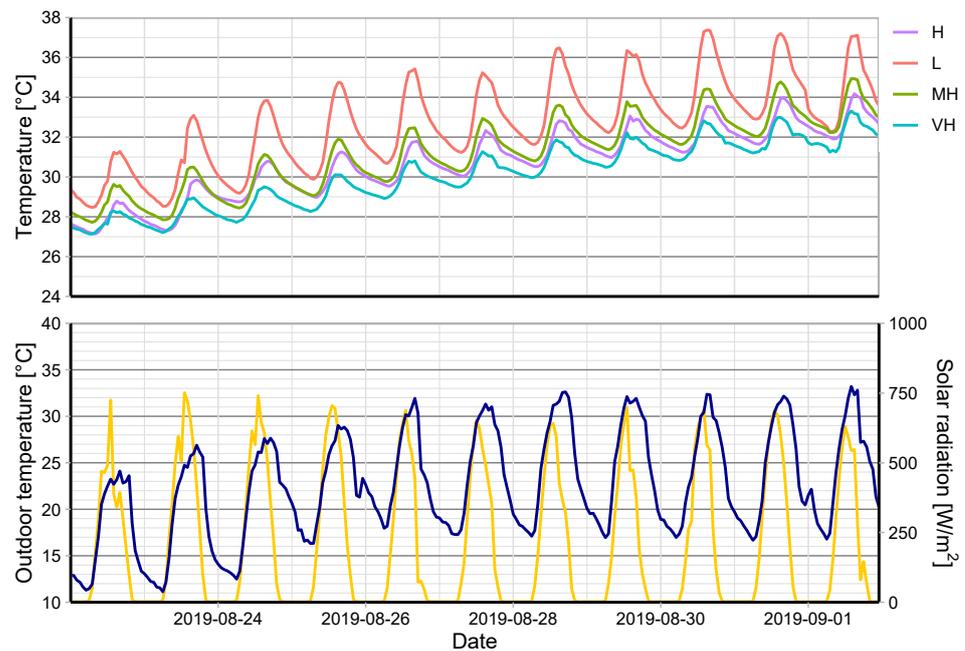
Figure 6. The temperature course in light, medium heavy, heavy and very heavy rooms as a function of outdoor temperature and solar radiation during heat wave 24 August–1 September 2019.

Increasing the thermal mass of the room from light to medium-heavy reduced the average maximum daytime temperature by 2.2 K during the first heat wave and by 2.6 K during the two other heat waves. The use of the very heavy structure further reduced the average peak temperature for the subsequent heat waves by 1.4 K, 1.2 K and 1.7 K. A six-fold increase in the thermal mass of the very light 152 kJ/(m^2 K) structure to the very heavy 922 kJ/(m^2 K) structure led to a reduction in peak daytime temperatures during the subsequent heat waves by 3.6 K, 3.8 K, and 4.3 K, respectively. Much more realistic than the use of reinforced concrete wall and floor surfaces in the conditions of typical construction technologies used in Poland seems to be plastering of the roof with a layer of gypsum plaster and replacement of reinforced concrete walls with plastered masonry walls. This type of construction currently accounts for more than 98 % of all new buildings constructed in Poland. During the 9 day heat wave from 24 August to 1 September, indoor temperatures were compared between the heavy room and the very heavy room. The maximum daytime temperature in the heavy room was on average 0.8 K higher than in the very heavy room. There is increasing pressure to increase the market share of lightweight construction, mainly based on light timber frame structures. On the basis of the study, it can be expected that if such lightweight solutions are applied to the walls and ceilings of buildings, the maximum temperatures during the period of intense heat waves would increase significantly.

An interesting finding was reached by observing the effect of increasing thermal mass on the course of internal temperatures at night. The increase in thermal mass from light to very heavy led to a decrease in minimum night time temperatures averaging about 0.8 K during the 3 heat waves. In the absence of night ventilation, the temperature in the high thermal mass rooms decreased significantly slower than in the light ones, but did not worsen the thermal comfort of the rooms.

As can be seen, the obtained effects of reduced indoor temperature due to increased thermal mass are consistent with other experimental results conducted in the last two decades in a temperate and cold climate (Table 3).

Table 3. Effects of reduced indoor temperature due to increased thermal mass in other experimental results conducted in the last two decades in a temperate and cold climate.

Authors	Place of Research	Type of Climate	Type of Research	Structural Elements	ΔT_{max}	Ref.
This research	Zielona Góra, Poland	(Cfb-climate)	Experimental	Walls & roof	2.2–2.6 K (M v. L) 3.6–4.3 K (VH v. L) 2.8–3.5 K (H v. L)	
Kuczyński & Staszczuk, 2020	Zielona Góra, Poland	Cfb-climate	Experimental	Walls	1.5–2.5 K	[37]
Staszczuk & Kuczyński, 2021	Zielona Góra, Poland	Cfb-climate	Experimental	Walls & roof *	1.5–2.5 K	[64]
Bellamy & Mckenzie, 2001	Lincoln, New Zealand	Cfb-climate	Experimental	Walls	3.0–5.0 K	[65]
Tink et al., 2018	Leicestershire, UK	Cfb-climate	Experimental	Walls	2.5 K	[66]
Jakovics et al., 2015	Riga, Latvia	Cfb-climate	Experimental	Walls	3.0–4.0 K	[67]
Grynning et al., 2019	Trondheim, Norway	Dfb-climate	Experimental	Floor	2.5–3.0 K	[68]
Brambilla & Jusselme, 2017	Fribourg, Switzerland	Cfb-climate	Experimental	Walls	1.1–3.0 K	[36]
Sage-Lauck & Sailor, 2014	Portland, USA	Cfb-climate	Experimental (PCM)	Walls & roof	1.1 K	[58]
Jamil et al., 2016	Melbourne, Australia	Cfb-climate	Experimental (PCM)	Roof	1.1 K	
Khudhair & Farid, 2007	Auckland, New Zealand	Cfb-climate	Experimental (PCM)	Walls & roof	2.4 K	[61]
Vik et al., 2017	Oslo	Dfb-climate	Experimental (PCM)	1 walls & roof	3.3 K ** 2.6 K ***	[69]
Ramaskrishnan et al., 2017	Melbourne, Australia	Cfb-climate	Experimental (PCM)	Walls & roof	2.5–2.8 K	[70]
Schossig et al., 2016	Freiburg, Germany	Cfb-climate	Experimental (PCM)	Walls & roof	1.0–3.5 K	[71]
Voelker et al., 2007	Weimar, Germany	Cfb-climate	Experimental (PCM)	Walls & roof	0.5–4.0 K	[72]

* External blinds closed. ** PCM; no gypsum board. *** PCM; gypsum board.

In order to assess the influence of thermal mass of rooms on the thermal comfort of users, national standards, e.g., CIBSE TM52, or ASHRAE Standard 55-2017, or international standards, e.g., EN 16798-1, are used. In this paper, the methodology given in CIBSE TM52 criteria 1 and 3 was used for this purpose, which, respectively, allow us to estimate the scale of thermal comfort exceedances and temperature exceedances at extremely high temperatures. For criterion 3, 2 adaptive temperature thresholds were used for this purpose $T_{max} + 3$, recommended for new or renovated buildings, and $T_{max} + 4$, suggested for existing buildings. This methodology for assessing thermal comfort was used because, as

already mentioned, in residential buildings, the overheating during the most severe heat waves is the main determinant of the installation of air conditioning equipment.

The analysis of hours of exceedance according to CIBSE TM52 criterion 1 does not allow for a full assessment of the benefits of the increasing of thermal mass. For the June and July heat waves, the amounts of hours exceeded for rooms with light and medium-heavy construction were only slightly different. A somewhat larger effect, a reduction of 22.6% for the June heat wave and 36.8% for the July heat wave, was obtained using the very heavy construction. For the August heat wave, increasing the thermal mass had no effect on the number of exceeding hours, regardless of the magnitude of its increase.

For a more comprehensive comparison of the effect of thermal mass on the exceedance hours, an analysis in which their number is related to the absolute maximum temperature Tupp (CIBSE TM 52).

In Figures 7–9, the hourly course of temperature in the studied rooms is compared with the maximum temperature and the absolute maximum temperature calculated for category II—new buildings and renovations, and for category III—existing buildings according to CIBSE TM–52.
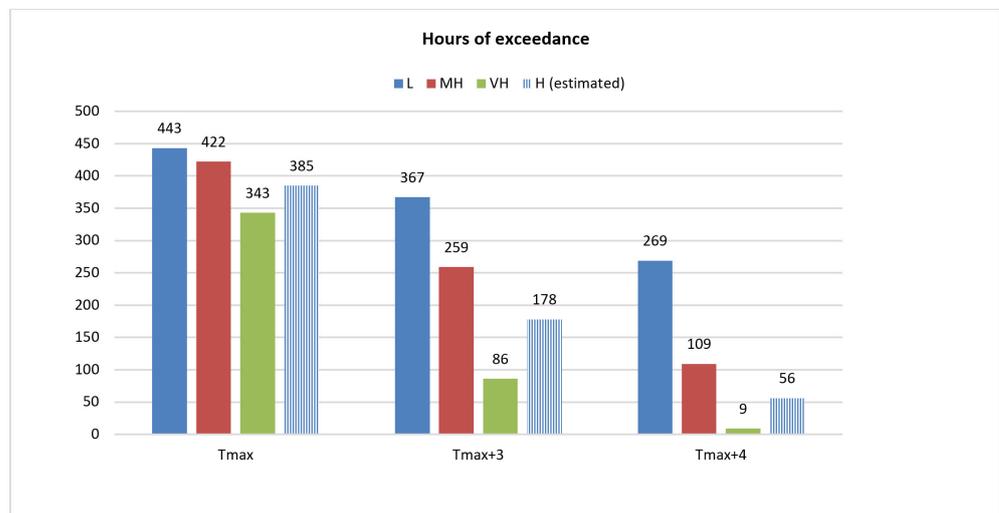

Figure 7. Hours of exceedance in all tested rooms during 1–30 June 2019, Hours 7:00–22:00.
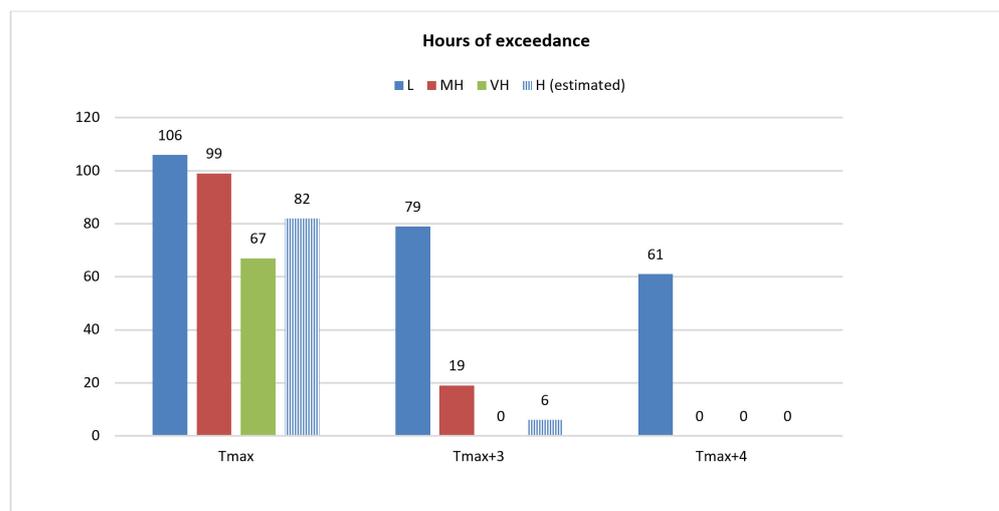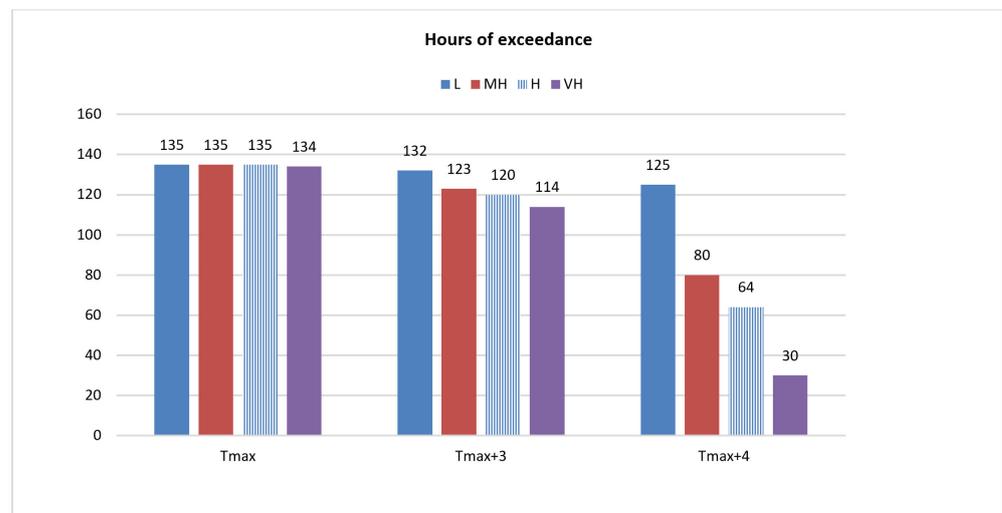

Figure 8. Hours of exceednce in all tested rooms during 23–30 July 2019, Hours 7:00–22:00.

Figure 9. Hours of exceedance in all tested rooms during 24 August–1 September 2019, Hours 7:00–22:00.

With the threshold temperature for category II, the reduction of hours exceeding the allowed temperature for the three consecutive heat waves in summer 2019 were 75.5%, 100%, and 49.0%, respectively. With the threshold temperature for category III, the reduction of hours exceeding the allowed temperature for the three consecutive heat waves in summer 2019 were, 75.5%, 100%, and 49.0%.

Using the threshold temperature for CIBSE category II, increasing the thermal mass from light to medium led to a reduction in the number of exceedance hours by 29.4% during the June heat wave, by 75.9% during the July heat wave, and by 6.8% during the August heat wave, respectively. With the CIBSE Category III temperature limit, the number of exceedance hours was reduced by 59.5% during the June heat wave and by 36.0% for the August heat wave. During the July heat wave, the hours of exceedance were completely eliminated in this case.

Increasing the thermal mass from light to very heavy led to a reduction of the hours exceeding the threshold temperature for category II by 76.6% in June and by 13.6% in August. For the threshold temperature for category III, the corresponding reduction in exceedance hours was 96.7% for the June heat wave and 76.0% for the August heat wave. As with the medium thermal mass construction for the very heavy thermal mass structure, the exceedance hours were completely eliminated for the July heat wave.

The study showed that while the use of increasing a building's thermal mass as the only passive method of counteracting high temperatures during heat waves does not lead to significant improvements in thermal comfort, it is able to significantly reduce the frequency of temperatures considered to be the maximum allowable for occupants and, as a result, reduce the risk of them deciding to install air conditioning equipment.

The analysis of hours of exceedances for three heat waves presented in Figures 7–9 on the background of graphs of internal and external temperature courses presented in Figures 4–6 shows that daily characteristics of external temperature, its maximum, average and minimum values, do not fully determine the scale of possible overheating of buildings. Other important factors include the duration of the heat wave, the way in which outdoor temperatures are distributed during its successive days, as well as the value of indoor temperatures in individual rooms in the period immediately preceding the heat wave. The period most vulnerable to the occurrence of extremely high indoor temperatures turned out to be the August heat wave, during which the maximum daytime temperature was above 30 °C on the last 7 days and above 32 °C on the last 5 days. For example, during the July heat wave, although the average daily temperature remained similar to August's 24 °C v. 23.9 °C, the splitting of days with very high temperatures with days with lower temperatures led to significantly lower indoor temperatures for all investigated rooms.

In order to better illustrate the effect of increasing the thermal mass of walls and roof on the thermal comfort of the residents during typical heat waves in Figure 10 daily temperature courses in individual rooms were plotted in relation to T_{max}, $T_{max} + 3$ and $T_{max} + 4$ for the July heat wave.
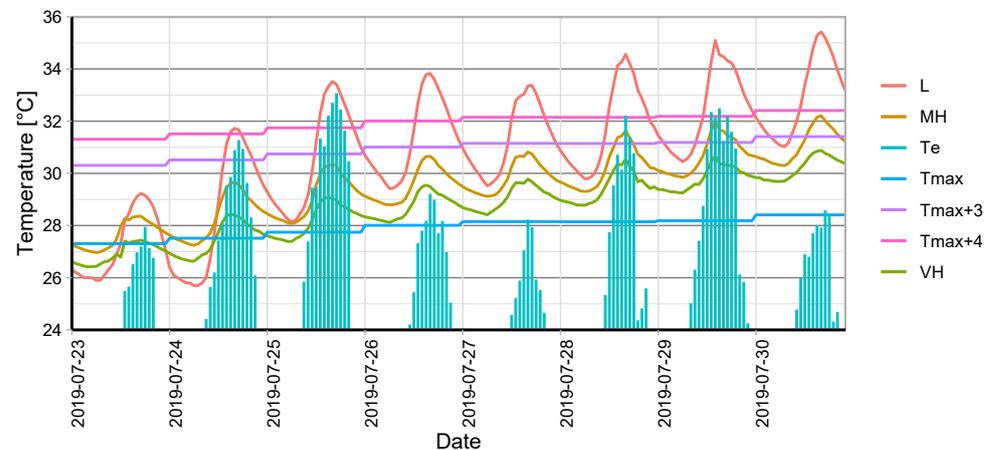
Figure 10. Daily temperature courses in individual rooms in relation to T_{max}, $T_{max} + 3$ and $T_{max} + 4$ for the July heat wave.

In the light room, the temperature $T_{max} + 4$ was exceeded regularly except on the first day of this period. The same temperature was not exceeded in one day in either the very heavy room or the medium-heavy room. $T_{max} + 4$ was exceeded in the light room on the same number of days as $T_{max} + 3$. In the very heavy room, it was not exceeded even once, and in the medium-heavy room it was exceeded on the last 3 days of the heat wave.

4. Conclusions

The main objective of this paper was to demonstrate the effectiveness of increasing the thermal mass of the rooms in real building by using traditional building materials to reduce the risk of its excessive overheating during intense heat waves in a temperate climate. An additional objective was to show that the use of this single passive measure significantly reduces the risk of overheating in daytime rooms, but also, though to a much lesser extent, in bedrooms.

The discussion in this paper of the effect of occupant behavior on the effective use of night ventilation through windows and protection from the sun by closing blinds during hot and sunny weather showed that occupants do not make proper use of both passive methods. This is particularly evident in buildings for the elderly.

Increasing the thermal mass of the room from light to a medium-heavy reduced the average maximum daily temperature by 2.2 K during the first heat wave and by 2.6 K during the two other heat waves. The use of very heavy construction further reduced the average maximum temperature for the heat waves analyzed by 1.4 K, 1.2 K and 1.7 K, respectively, giving a total possible reduction in maximum daily temperatures in the range of 3.6 °C, 3.8 °C and 4.3 °C.

The analysis of obtained results indicates that daily characteristics of external temperature, its maximum, average and minimum values, do not fully determine the scale of possible overheating of buildings. Other important factors include the duration of the heat wave, the way in which outdoor temperatures are distributed during its successive days, as well as the value of indoor temperatures in individual rooms in the period immediately preceding the heat wave

The study showed that while the use of increasing a building's thermal mass as the only passive method of counteracting high temperatures during heat waves did not lead to significant improvements in thermal comfort, it was able to significantly reduce the frequency of temperatures considered to be the absolute maximum allowable for occupants

and, as a result, reduce the risk that they will choose to install air conditioning units. The results suggest that the use of heavyweight residential buildings in European temperate countries may significantly reduce the installation of air-conditioning equipment in daytime rooms for over the next 20–30 years, without the need for night ventilation or external blinds, which are highly dependent on individual occupant behavior.

The considerations presented in this paper apply to daytime rooms only. The effect of increasing thermal mass at night was significant, but much smaller than at peak daytime temperatures. Because of this and the lower temperature thresholds in bedrooms, future research should include the combined effect of thermal mass and external blinds. In bedrooms used at night, closing blinds during the day may be much more socially acceptable than in living rooms.

Work Limitations and Future Work

When analyzing the results of the study, it should be remembered that the rooms studied were located on the top floor and were equipped with large south-facing windows. For rooms located on lower floors or in a different orientation with respect to the directions of the world, it can be expected that the thermal load from solar radiation will be significantly lower, which should result in a reduction of internal temperatures.

On the other hand, the research was conducted in an unused room. The decision to conduct research in such conditions was made taking into account both literature data on uncontrolled but very significant influence of users' behavior on the evolution of internal temperature in the room and authors' own experimental experience in this field. Future research should focus on finding out to what extent, by changing these parameters, the operating temperatures of these rooms can be reduced during heat waves. A full analysis of the effectiveness of increasing the thermal mass, allowing us to establish quantitative relations between the thermal mass of the rooms and the degree of reduction of their maximum temperature, taking into account the heat gains from the occupants and the expected external loads from solar radiation for other room locations and window areas, will be possible only by modeling, which was assumed as a continuation of the present work.

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