COMPARATIVE TEMPERATURE AND CONSUMPTION DATA MEASUREMENT OF MODEL BUILDINGS WITH DIFFERENT THERMAL TIME CONSTANTS

by

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In this study, three identically designed model buildings and their heating energy consumption was compared. Those pilot scale buildings are equal by size and were located on the same location. During the measuring campaign both external and internal temperatures were recorded, beside the energy consumption. The model buildings were labeled as A (constant baseline), B (baseline varying according to a time program), and C (unheated, blank). During the measurements, the thermal mass of the buildings was altered. The same amount of thermal mass was installed in all three model buildings during all measurements. According to our results under real weather conditions, the intermittent heating requires less energy than maintaining a constant temperature, and the energy saving is inversely proportional to the time constant at intermittent heating. Instead of specific heat mass, a thermal time constant was used to compare intermittent and constant heating. It was established that as the thermal constant of the model building increases, the energy savings between maintaining a variable base temperature and maintaining a constant base temperature decrease. The expected savings are between 4 and 7%.

Keywords: *Energy savings, temperature and consumption measurement, Building energy, Model building, comparative study.*

1. Introduction

In recent years, significant progress has been made towards achieving climate neutrality by 2050, as outlined in the European Energy and Climate Change Policy [1]. In December 2019, the first measure was the decision to require EU countries to cut greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels.

The European Council approved the European Climate Change Act on 28 June 2021. Residential buildings, whether new or existing, have significant potential for energy savings. According to the

Council of the European Union, buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions in the EU [2].

Similar to the European Council, Harish and Kumar [3] conclude that buildings are responsible for 40% of global CO_2 emissions. Figures 1 and 2 show the energy consumption of the European Union and Hungary in specific sectors [4].

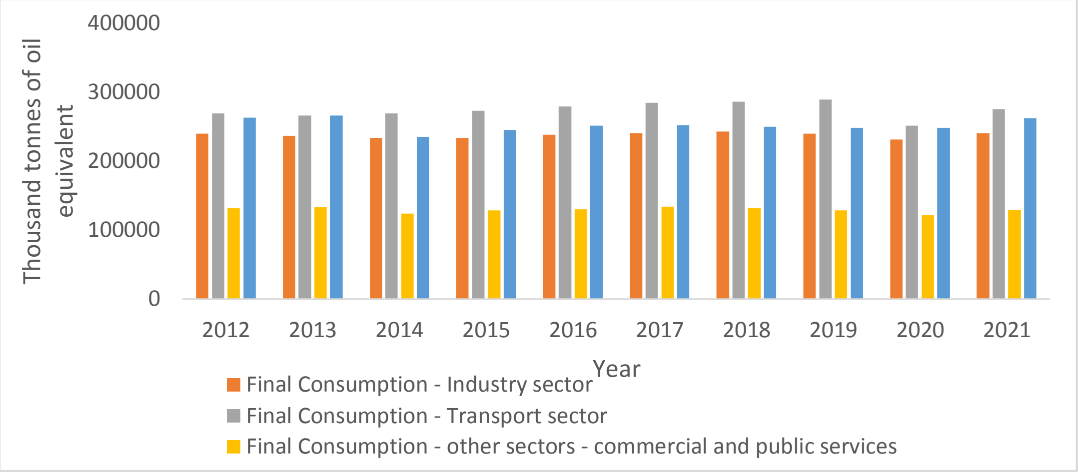

Figure 1. Final consumption of oil equivalent – EU Caption based on our own editing using data from sources: [4]

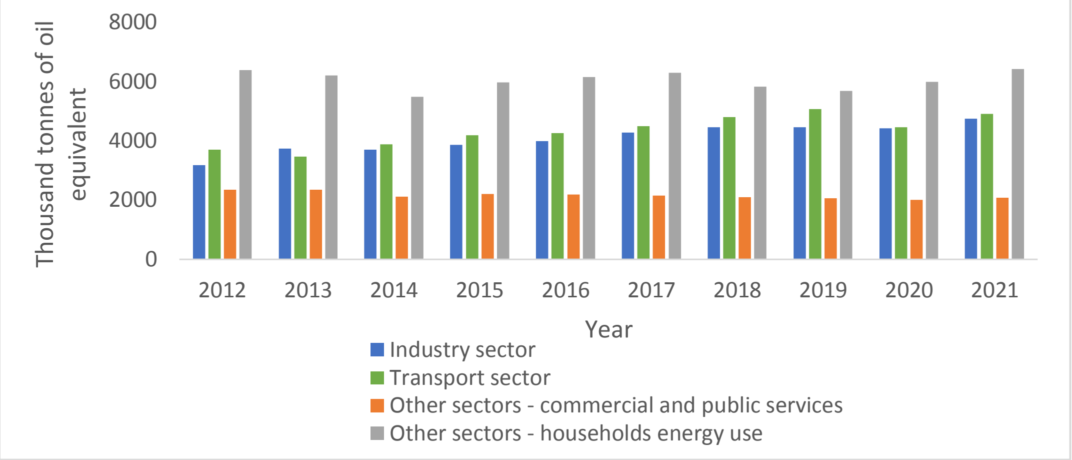

Figure 2. Final consumption of oil equivalent – Hungary Caption based on our own editing using data from sources: [4]

Examining the data on residential energy consumption from these sources, the following changes can be observed in Figure 3 for the European Union and Hungary.

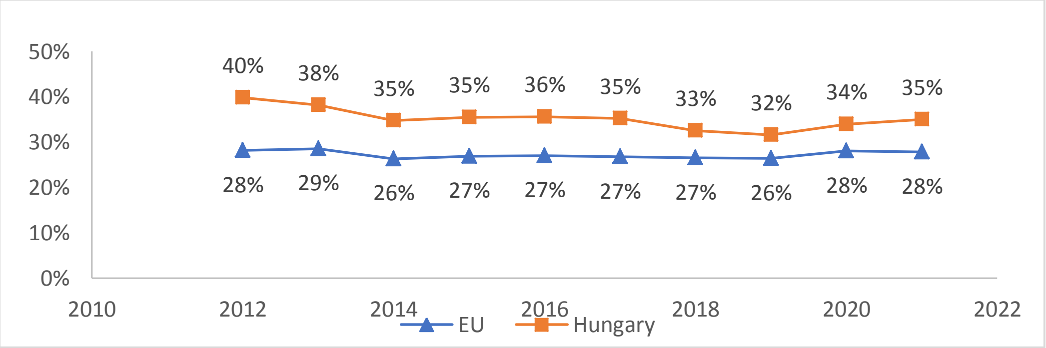

Figure 3. Final consumption households' energy use – Eu & Hungary, Caption based on our own editing using data from sources: [4]

Regarding residential buildings, there has been no significant change in energy consumption in Hungary, as shown in Figure 4. According to the latest available statistics, residential use is responsible for 35% of the total energy consumption.

This is lower than the global average, but significantly higher than the European average.

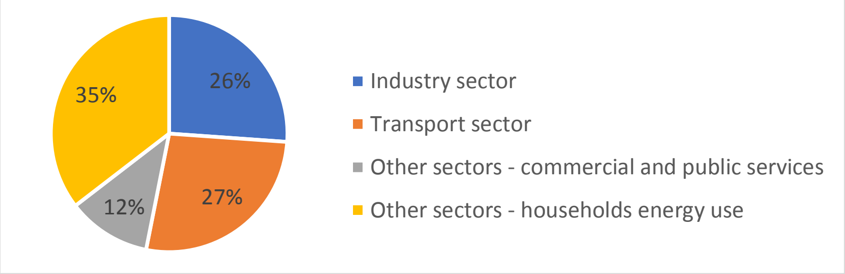

Figure 4. Final energy usage per sectors – Hungary, Caption based on our own editing using data from sources: [4]

Emissions can be reduced by constructing modern and energy-efficient buildings and renovating the existing building stock, while the other approach is to reduce energy demand by reducing temperatures or by controlling non-constant set points. The building typology in Hungary was developed and analysed by Csoknyai. [5]. The building typology distinguishes 23 building types, of which the study focuses on the type 7 "Kádár-block", as this type accounts for 21.5% of the Hungarian building stock. The modelling was developed using the design builder software. Their research focused on heating reduction, where the temperature was decreased from 20°C to 18°C on a set schedule. A 5% reduction in energy demand was observed at night and 6.5% during the day. The heat storage mass was tested taking into account existing conditions and modelling the excess temperature generated by various events. According to the International Energy Agency, residential heating/cooling is responsible for 16% of CO_2 emissions in Hungary [6]. The energy criteria for newly constructed buildings in Hungary are regulated by TNM Decree 7/2006. The TNM Regulation includes requirements for a heat transfmittance factors and also describes the specific annual energy demand of 100 kWh/m^2a for residential buildings [7].

In 2022, end-users were confronted with a massive increase in energy prices, which raised awareness of the potential for savings. In January 2023, according to the Hungarian Central Statistical Office (KSH) [8], the following price increases were observed for the most relevant heating fuels compared to the previous year:

- Wood briquettes: 234%
- Sawn firewood: 208%
- General electricity: 126%
- Controlled electricity: 148%
- Natural gas: 200%
- Propane-butane gas: 153%

For existing buildings, renovation, such as insulation, replacement of windows and doors, and upgrading of heat generators and heat emitters are common ways to achieve savings. These investments and upgrades can lead to significant savings. Alsaffar and Alwan, using modeling, concluded that the design of green buildings costs 5-10% more upfront, but it achieves 30-40% energy savings. These additional costs result in a payback period of 3-4 years longer. By properly insulating building elements such as walls, roofs, windows and floors, energy savings of 32% can be achieved [9]. However, savings can be achieved without renovation by changing user habits or adjusting controls. For various building types, Csoknyai mentions that inefficient and energy-intensive residential buildings often overheat [5], the thermostats are set at higher temperatures, and the use of time programs is neglected. Afroz [10] mentions a 6% energy savings with a 1°C temperature reduction during the heating season. A Hungarian article also discusses the advisability of reducing heating in intervals [11]. Generally, 12-hour heating interruptions result in savings of around 5-10% for large buildings and around 10-15% for light buildings, with a proportionately more modest effect for shorter interruptions. The reduction in energy savings is more significant for buildings with external insulation.

The average heating temperature in residential buildings in the European Union is above 22 °C, although a comfort range of 19 °C to 20 °C could easily be maintained [5]. However, domestic heating, often exceeds this range. Dropping the set point by just 1°C can lead to heating energy savings of around 7% [12]. Not only does this reduce energy costs, but it is also a more sustainable and environmentally conscious heating practice.

Setting the right temperature not only saves energy, but also creates a more sustainable environment. Medical science unequivocally states that a temperature between 15-19°C is the ideal temperature for sleep. [13, 14, 15, 16, 17].

Our research focuses on the savings that can be achieved, depending on whether the building maintains a constant temperature or follows a time-programmed, periodically lower temperature set point. We examined how energy savings vary in sample buildings based on the amount of thermal mass placed in the building. A similar topic was investigated by Lv et al., who studied the energy consumption of prefabricated buildings. Their research focused on predicting energy consumption through modelling. However, their study focused exclusively on the control methods and did not take into account the effect of the thermal mass. Several iterative methods were used for the prediction. Their observation showed that, compared to PID methods and neural networks, the cluster prediction algorithm gave a 27% more accurate prediction [18]. The impact of thermal mass in residential buildings was examined by Déau and Heiselberg. In this study, simple control strategies have been developed based on the thermal mass of buildings and their impact on building resilience and energy efficiency without compromising comfort. EnergyPlus was used to simulate two Danish residential buildings with dissimilar thermal insulation. Two modulation approaches have been studied: heat storage (higher set point) and conservation (lower set point). The results provide insights into dynamic behaviour and diverse control strategies [19]. In addition to the studies mentioned above, most studies are based on simulation studies to determine the expected annual energy consumption of a building [20], [21]. Simulation tests are preferred for their rapid response time and flexibility. The effects of structural changes can be modelled over a short period of time over a year, unlike measurement-based approaches. Models validated with measurements show an accuracy of over 90%.

2. Materials and methodology

Three identical sample buildings were built for the research campaign, their dimensions are presented in Figure 5. The buildings were positioned in the same orientation.

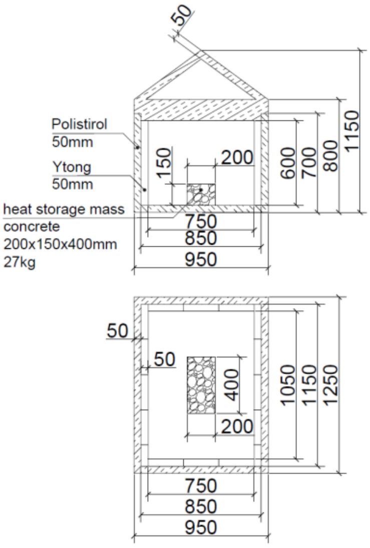

Figure 5. Dimensions of model buildings

Table 1. presents the parameters of the model buildings and Table 2. presents the parameters of the constructing materials.

Table 1. Model dimension and building physical characteristics of certain structures.

Surfaces	k [$Wm^{-2}K^{-1}$]	A [m^2]	ρ [kgm^{-3}]	C [$kJkg^{-1}K^{-1}$]	L [m]	Ψ [Wm^{-1}-K^{-1}]
External wall with insulation	0,535	2,2	260	1,23		
Floor	0,17	0,7875	200	0,86285	3,6	0,75
Floor slab	0,353	0,7575	20	1,45		

Table 2. Model building structures

Type	Layer	Structure	c [$kJkg^{-1}K^{-1}$]	ρ [kgm^{-3}]	λ [$Wm^{-1}K^{-1}$]	d [m]
External wall	1.	Austrotherm AT-H80	1,46	20	0,038	0,05
External wall	2.	Ytong	1	500	0,13	0,05
Floor	1.	Austrotherm AT-H80	1,46	20	0,038	0,05
Floor	2.	Oriented Strand Board	2,34	650	0,16	0,02
Ceiling	1.	Austrotherm AT-H80	1,46	20	0,038	0,05

The measurements were performed as follows: in model building A a constant temperature was maintained, in model building B a variable temperature based on a time program was applied, while in model building C no heating was applied, and it was the reference building for the measurements. The arrangement of the model buildings is shown in Figures 6. Measurements GPS coordinates are: 47.61204835472161, 19.343435272717898 Gödöllő, Hungary.

Figure 6. model buildings from left to right building A, B, and C

2.1. Heating and measuring system

Electric heating was applied for the heating system using DEVImat™ DSVF-150, with a power of 150W per square meter. In both model buildings "A" and "B," a heating surface area of 1 square meter was installed. The heating control was achieved using DEVIreg™ Opti. The measurements were performed with varying thermal storage masses.

Table 3. DEVIreg ™ Opti setting Model A, B

Time program	A Setpoint [°C]	B Setpoint [°C]
00:00-05:59	17	21
06:00-07:59	21	21
08:00-15:59	17	21
16:00-22:29	21	21
22:30-23:59	17	21

The temperature measurements were performed using T-type Cu-CUNi thermocouples, and the recorded data was captured with an Almemo 2590-4S thermometer (Alhborn Messtechnik, Germany). For the measurement and recording of power consumption a Voltcraft SEM5000 (Conrad Electronic, Germany) power meter was used. Both the power meters and the control system were placed in a waterproof box outdoors, as shown in Figure 7.

Figure 7. electricity consumption meter and control for model buildings A and B

2.2 Thermal mass addition

During the measuring process, the environmental temperature was registered on both sides of the model houses, as well as the internal temperature and energy consumption at two points for each model building. Measurements were registered at a one-minute interval. In addition to the thermal mass of the internal walls, an additional thermal mass was introduced for separate measurements inside the building. Figure 8 shows one unit of thermal mass applied to Model Building C.

Figure 8. Inserting additional heat storage mass into the model building

2. 3. Thermal time constant

The aim of our measurements was to observe the relationship between thermal mass increase and energy consumption under continuous and time-programmed heating, supported by data. Instead of the thermal mass calculations, traditionally used in energy calculations in Hungary, the time constant of the building was considered in our analysis. We have identifiedthat the energy saving potential depends on the time constant of the building and the control method. The time constant of a single-storage proportional controller, known from control engineering, can be determined by equation (1). This concept has been widely used in building energy and building physics since the 1970s [21], typically for illustrating building energy processes [22].

$$\tau = \frac{c\cdot m}{k\cdot A} \tag{1}$$

However, when considering residential buildings, the time constant [23] needs to be supplemented with the effect of infiltration. Equation (2) describes the thermal time constant for residential buildings. In our measurements, the sample building was airtight, so infiltration was set to value of 0:

$$\tau_{TTC} = \frac{\sum_{i=n}^{N} c_n\cdot\rho_n\cdot V_n}{\sum_{i=M}^{M} k_m\cdot A_m+\rho_{air}\cdot c_{air}\cdot q_{filtration}} \tag{2}$$

3. Results and discussion

3.1. Measurement period

In this study, the specific thermal mass of the experimental model building was set as described in the Materials and methods section. The measurement period was from February 5, 2023 to March 16, 2023. The heat capacity was increased several times with additional mass, so that the system reached steady state. Data were collected for six specific heat capacity levels over 29 measurement days, excluding modification days.

3.2. Energy consumption and temperatures

It was determined that the energy consumption of Model B with a variable baseline temperature remained consistently lower in comparison to Model A with a constant temperature (Figure 9). The savings ranged from 4% to 13% on average.

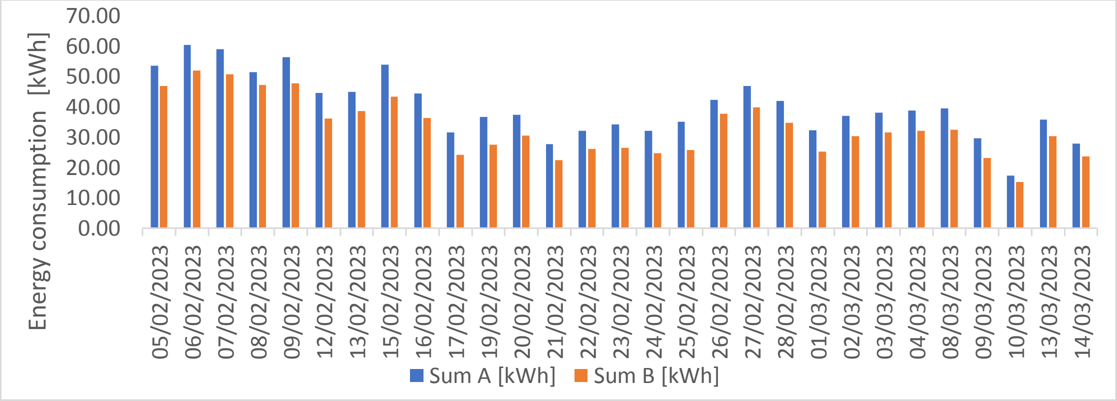

Figure 9. Building model A and B energy consumption/ day

Figure 10 illustrates the environmental (outdoor)temperatures and average temperatures of model buildings A (constant base temperature), B (variable base temperature according to the schedule), and C (reference) under steady-state conditions, using the first level of thermal mass, with hourly resolution.

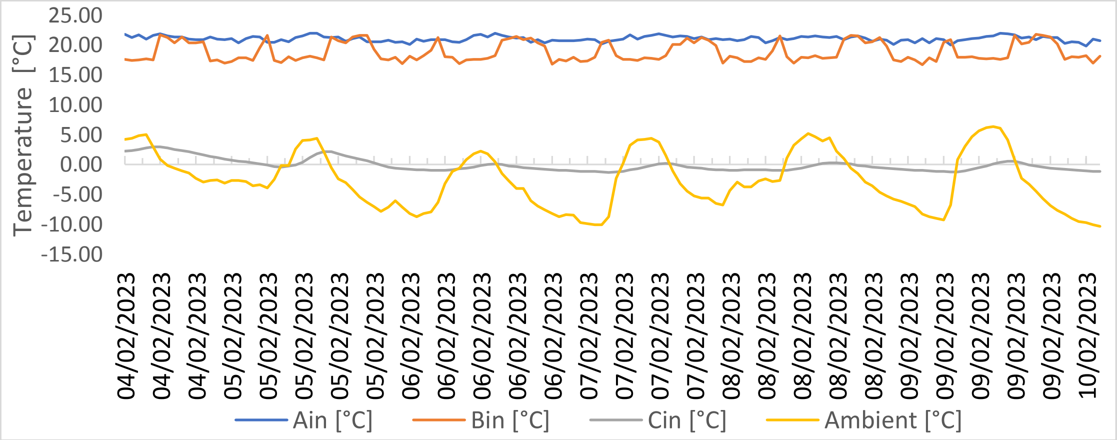

Figure 10. Building model A, B, C intern and ambient temperature. Measures with τ_{TTC} 14,506 h

The data was logged at one-minute resolution. Figure 11 represents a day on 23 February, 2023. The effect of temperature fluctuation and the pattern of energy consumption can be observed. From a practical point of view, for the analysis of a residential building, hourly and daily aggregated data are sufficient for studies.

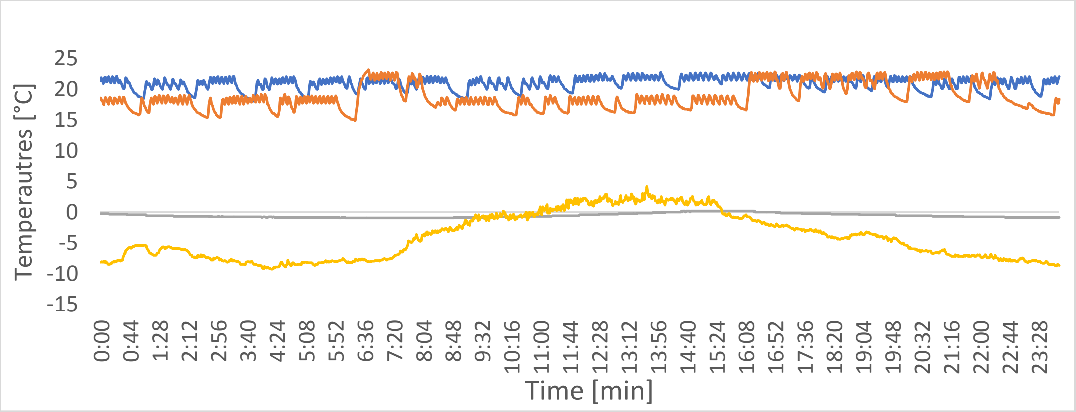

Figure 11. Temperature measures 06.02.2023 A, B, C and ambient per minute

Table 4. Measures with different τ_{TTC}

Measures	τ_{TTC} [h]	A [kWhday^{-1}]	B [kWhday^{-1}]	Temparature datapoint	Energy consumption datapoint
1	14,506	0,949	0,824	93600	28800
2	18,508	0,746	0,624	56160	17280
3	26,512	0,819	0,663	37440	11520
4	34,515	0,616	0,484	243360	74880
5	42,519	0,576	0,464	56160	17280
6	78,299	0,807	0,658	56160	17280

Table 4 demonstrates the summarized measurements, including the number of data points in the last two columns.

Figure 12 shows that in all measurement, both the A (constant base temperature) and B (variable base temperature according to time schedule) showed savings during the periodic operation. The measurements were taken outdoors under the actual winter weather conditions.

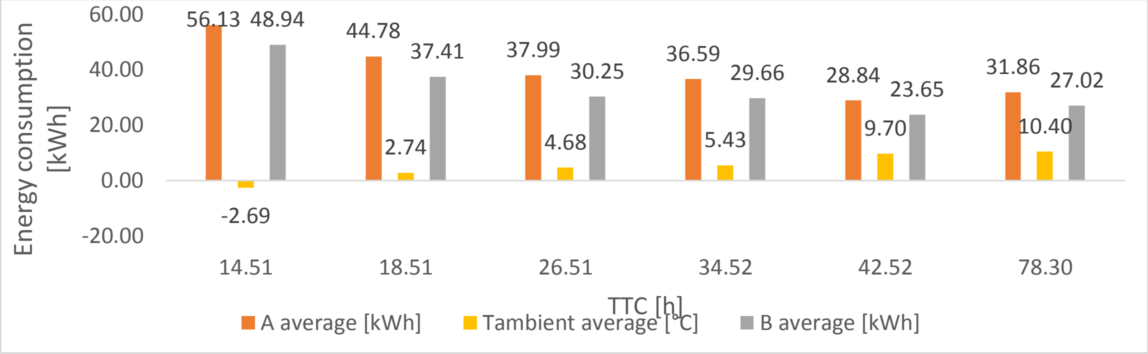

Figure 12. Comparison of the energy consumption of buildings A and B

3.3 Control modes and the relationship between thermal time constant and energy efficiency

The objective of this research was to examine the correlation between maintaining a constant temperature and maintaining temperature with a flexible baseline, considering the thermal time constant of the model building. Figure 13 demonstrate that the variation in savings between maintaining temperature with a flexible baseline and maintaining temperature with a fixed baseline decrease, as the thermal time constant of the building increases.

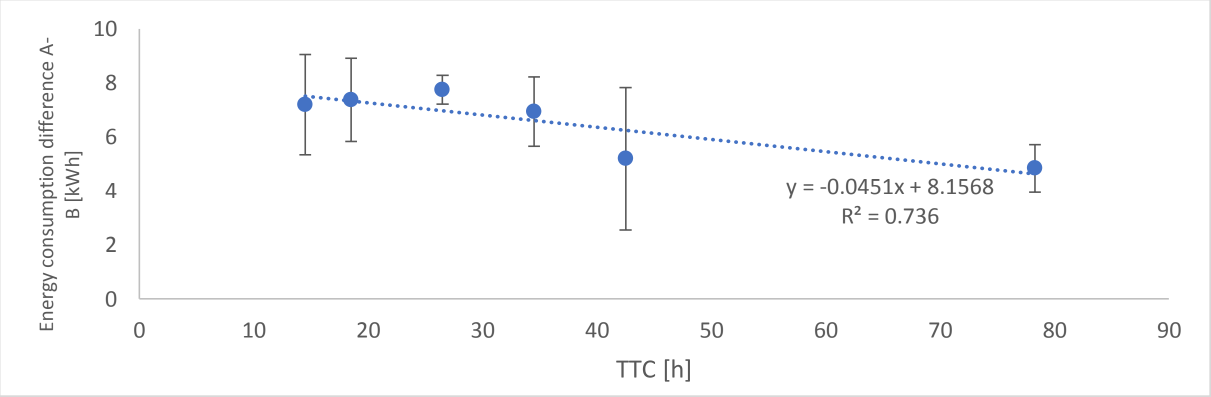

Figure 13. Energy consumption difference between experimental model building A and B, in the case of different thermal time constants.

In Figure 14, we present the average value and the standard deviation of the variance between the energy consumption of the model buildings heated by the constant baseline A and the variable baseline B according to the thermal time constant. The fitted linear function (Equation 3) approximates the average values with an R-squared (R^2) value of 0.736.

$$\Delta \mathrm{EC}_{AB} = -0{,}0451 \cdot \mathrm{TTC} + 8{,}1568 \tag{3}$$

In a related study, the relationships of thermal time constants were investigated by modelling. It found that increasing the thermal time constant can reduce the impact of external factors on the building; however, it did not investigate the differences in energy savings between different control methods. [24].

Considering the general usage patterns, the applied variable baseline temperature fully meets the requirements without significantly reducing comfort. During periods of absence and at the hours of night, the temperature has been reduced. External climatic conditions (temperature, solar radiation, wind, humidity, air pressure) were not in synch with the building thermal mass variation, as indicated by the R-squared value of 0.736.To perform our measurements under identical time and conditions, we would have required 18 experimental model buildings with six different thermal masses and settings for A (constant baseline), B (variable baseline according to the time schedule), and C (reference). But even this would only cover a fraction of the thermal masses found in real buildings. Our measurements are however suitable for creating a computer simulation model to identify parameters and validate the model. With this model, we can compare model experiments under the same conditions, investigating the relationship between various thermal masses and energy consumption.

Analyzing the thermal time constants of the Hungarian housing stock, values between 10 and 200 hours, from poorly insulated buildings with high infiltration losses to passive houses. In a previous publication, we investigated a specific residential building constructed in the early 2000s with a 44 cm thick Porotherm brickwork. The building had a BB energy classification and a floor area of 104m^2 [25]. Its thermal time constant was determined as 16 hours. Based on the measurement results shown in Figure 13, energy savings of about 7% can be achieved by operating the building with a variable base signal (reduced temperature of 17°C from 22:30 to 05:59 and 08:00 to 15:59, and a temperature of 21°C from 6:00 to 07:59 and 16:00 to 22:29).

4. Conclusion

This study compares the heating energy consumption of three model buildings of the same design. The buildings are labelled with A (fixed baseline), B (baseline changing according to the time schedule) and C (reference). The main objective was to investigate the energy savings achieved by intermittent heating with a variable baseline temperature (model B) compared to maintaining a constant temperature (model A), and how these savings are influenced by the building's thermal time constant.

The results demonstrate that intermittent heating with a variable base temperature consistently generates less energy consumption (Model B) than maintaining a constant temperature (Model A). The savings range from 4 to 13% based on the analyzed measured data. It is also concluded that energy savings are inversely proportional to the thermal constant of the building. It can also be deduced that a similar level of energy savings as the 1°C temperature reduction studied by others can be achieved with variable baseline heating, without sacrificing comfort in the habitable area. [5], [10], [12].

Despite its value, the study has its limitations, as the model buildings have no residents, no internal heat loads and no continuous thermal mass adjustments. Its unique feature, however, lies in the physical construction of the model buildings, which distinguishes it from other studies. Further research is required to identify simulation-based parameters, validate the results on real buildings, investigate the integration of renewable energy sources, analyze consumer behavior, and develop advanced control algorithms. In summary, the implications of this study on energy consumption and energy savings, considering thermal time constants and intermittent heating methods, can contribute to more efficient building practices and evidence-based sustainability policies.

Acknowledgment

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Nomenclature

τ_{TTC} – building thermal time constant [h]
c_n – specific heat of the building [$Jkg^{-1}K^{-1}$]
ρ_n – building density [kgm^{-3}]
V_n – building volume [m^3]
k_m – building heat transfer factor [$Wm^{-2}K^{-1}$]
A_m – building surface [m^2]
c_{air} – air specific heat [$Jkg^{-1}K^{-1}$]
ρ_{air} – air density [kgm^{-3}]
$q_{filtration}$ – building filtration factor [$1h^{-1}$]
Ψ – linear heat transfer coefficient [$Wm^{-1}K^{-1}$]
L – length of wall section in contact with the ground [m]
R^2 – statistical measure r-squared
ΔEC_{AB} – energy consumption difference between A (constant base signal), B (variable base signal according to time program) [kWh]

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