CO-HEATING TEST AS A TOOL FOR REDUCTION OF ENERGY PERFORMANCE GAP IN BUILDINGS

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ABSTRACT

This paper presents part of the results of a large-scale, long-term experimental research conducted at the Faculty of Civil Engineering and Architecture Osijek. Among other research goals, this research aims at further development and improvement of a relatively new method used for the measurement of thermal transmittance of walls (U-value) in literature, often called temperature-based method (TBM). This research also partially overlaps with other researches carried out at the Faculty of Economics in Osijek, where the main research goals were development of machine learning and neural network models for predicting energy consumption in buildings, which will reduce the energy performance gap between design and actual energy needs. Building thermal performance as a whole can be quantified by the heat loss coefficient (HLC) or the total heat loss (THL). Experimental research presented in this paper was conducted by using a built test chamber in a laboratory, and the research lasted for 40 days. This is an innovative element of this research, since the test chamber is built inside a laboratory where external weather conditions are simulated by omitting the negative influence of wind, precipitation, and solar radiation on the experimental results. The actual heating energy consumption by the test chamber was recorded daily for 40 days during the winter season, together with internal and external temperatures, relative humidity (RH), U-values of walls, and wind speed. Chamber airtightness was measured at the beginning of the experiment. These measurements made it possible to perform the Co-heating test. This test is used to calculate the total heat loss of a building, both fabric and ventilation loss. Parallel with the Co-heating test, the design heating energy need of the test chamber was determined by calculating the heat loss coefficient and the total heat loss. Actual and design values of heat loss coefficient and total heat loss were used to characterize the energy performance gap. Energy performance gap in this study was found to be between −40% and 13%. Research results indicate the variables affecting the actual and design values of heat losses significantly. Presented results provide guidance for more accurate determination of actual energy consumption in buildings, and therefore help in the reduction of the energy performance gap.

Keywords: actual energy needs, Co-heating test, design energy needs, energy performance gap, heat loss coefficient, temperature-based method (TBM), ventilation and transmission heat loss.

1 INTRODUCTION

The growing concern over the worldwide increase in energy consumption and greenhouse gas emissions by buildings has resulted in huge efforts to improve building energy performance [1]. Buildings have been recognized as a key pathway and setting for the reduction of energy and carbon emissions worldwide [2]. In Croatia, buildings handle 40% of energy use; 70% of this energy is used for space heating and preparation of hot water [3, 4]. This is especially emphasized in existing buildings stock that was built before 1970.

One of the first steps toward dealing with the issue of old existing buildings with poor energy performance is to determine the actual consumption and design energy demands. And here lies the first problem – energy performance gap, since actual and design energy needs can be substantially different, according to some authors, from 1% to even 120% [5]. This raises the question of the financial viability of old existing building restoration. Also, it is important to understand where this gap comes from. The actual building energy performance depends on many factors; essentially, it is determined by the following: thermal

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characteristics of the building envelope, installed services, and building usage [6]. If testing is done in uninhabited buildings and installed services are controlled by researchers, then the only variable that influences the energy performance gap is building envelope condition. This principle was adopted in the research presented in this paper.

A performance gap is likely to be caused by a combination of factors, including not only underperformance of individual building elements and a lack of airtightness (usually measured and shown as n_{50} value), but also harder-to-detect thermal bridging at joints between the materials and small areas of missing insulation [5]. Therefore, thermophysical properties of building elements are the key factor in achieving the energy-efficient building concept aimed at a highly energy-efficient and decarbonized building stock [7]. Starting from the 1990s, numerous studies have shown that there is a performance gap between the actual energy performance and simulated, design, one [8–15], as well as a gap between the actual and design thermophysical performance/properties of building elements [16–24]. It has been shown that even slight changes in thermal transmittance value (U-value), as one of the very sensitive parameters in predicting energy consumption, result in a considerable change in heating demand [10, 14], which can be described with heat loss coefficient (HLC). Thus, identification of actual thermal performance of building envelope plays an important role in energy audit when making decisions for energy refurbishment and implementation of energy-saving measures regarding appropriate building technology selection and its cost-effectiveness [25].

Research aims to answer the question whether is possible to decrease the energy performance gap and to improve Co-heating test results by using the actual values of some variables instead of design ones. Research presented in this paper shows how changes in values of independent variables used for the determination of design HLC can influence the energy performance gap. The variables used and varied in this research were n_{50} value and U-value. For this purpose, measurements were undertaken in the test chamber built inside a laboratory. Values required for the Co-heating test were measured together with an actual amount of energy required to maintain a constant indoor temperature in the test chamber. This enabled the determination of the actual HLC and total heat losses (THLs). The Co-heating test uses a steady-state energy balance to calculate the total (both fabric and infiltration) heat transfer rate of a building including thermal bridging, with the result most commonly reported as an HLC with units of Watts per Kelvin [5] or THL in units of Watts. The design THL in this paper is calculated by using a simplified method according to EN 12831-3:2017 [26]. Results show how the energy performance gap is present, but results also show a perspective of lowering this performance gap by using actual, measured values of input variables (n_{50} value and U-value) instead of design ones when determining design THL of a building.

2 CO-HEATING TEST AND THE DESIGN TOTAL VENTILATION AND TRANSMISSION HEAT LOSS

The Co-heating test was published by Leeds Beckett University in 2010 [5]. The basis of the Co-heating test campaign consists of heating up homogenously a building until a steady-state interior temperature is achieved, e.g. 25°C, for estimating the required electrical energy consumption to keep the indoor environment characteristics as uniform [27]. During the test campaign, parameters related to the internal and external environment are monitored, such as indoor and outdoor temperatures, wind speed and directions, relative humidity (RH), solar radiations, and the electric heating power required to keep the building at a constant temperature [27].

It is also better if the Co-heating test is combined with other techniques, e.g. pressurization testing, leakage detection, tracer gas measurement, cavity temperature measurement, heat flux measurement, thermal imaging, partial deconstruction, air flow measurements, design assessment, and site observations [28]. This enables a much richer insight and understanding to be gained of the principal heat loss mechanisms within a dwelling [28]. Infiltration rate measurements could be carried out before a Co-heating test, after a Co-heating test, or both, and the results are averaged [5]. The reason for doing both is that the Co-heating test may be causing additional cracking or drying out of materials, thereby altering the infiltration rate [5].

The uncertainties associated with occupant behavior when estimating the HLC in situ can be removed by the physical measurement of an unoccupied dwelling [29]. In this research, these uncertainties were completely avoided since the experiment was done in laboratory conditions.

The energy balance is typically carried out using measurements that are averaged over a 24-h period [5]: electrical heating + solar heating = fabric heat loss + infiltration heat loss.

Following an initial period during which the building fabric reaches thermal capacitance, a Co-heating test assumes the following whole building energy balance [29]:

$$Q + R \cdot S = (\Sigma U \cdot A + C_v)\ \Delta T \tag{1}$$

where Q is the total measured power input from space heating (W), R is the solar aperture of the building (m^2), S is the solar irradiance (W/m^2), $\Sigma U \times A$ is the total fabric transmission heat loss (W), C_v is the background ventilation heat loss (W), and ΔT is the temperature difference between the internal and external environment [29]. The whole house energy balance equation can be rearranged to show HLC [29]:

$$HLC = (Q + R \cdot S) / \Delta T \tag{2}$$

The HLC is typically estimated using a linear regression–based quasi-steady-state analysis of the data obtained during the test period [29]. The power provided by solar radiation to the dwelling during a Co-heating test is not measured directly; rather, its effect is observed in a measured reduction in the power required to maintain a constant internal temperature, which is manifested in a reduction of the HLC [29]. Solar radiation was completely avoided in this research since the test chamber was inside a laboratory.

The test procedure is shortly described in [28] and consists of the following steps:

- Adjust all the thermostats to the elevated mean internal set point temperature, 25°C or higher; 30°C was used in this research to obtain higher temperature difference between the outdoor and indoor environment since the U-values of walls were measured at the same time.
- Switch on all the fan heaters and adjust them such that they are operating on their maximum heat and fan speed setting; in this research, device for cooling, heating, and regulation of RH was used which could be wirelessly operated.
- Activate all the data loggers to record the internal and external data.
- Observe the internal and external temperatures with data loggers.
- Once a relatively uniform mean internal temperature is achieved, continue to log all the data for a sufficient period of time, such that a range of internal to external temperature differences (delta-Ts) are recorded. This should be done for at least 1 week, preferably 2 or 3 weeks; this research lasted for 40 days.

- Download the data from the data logger/s at regular intervals; the daily interval was used in this research.

Advantages of Co-heating test are whole building envelope characterization and possibility of complementary test setups. Disadvantages are long test duration (typically around 2–3 weeks), possibility to carry out the test during the winter months, amount of instruments and equipment, electricity consumption, reliability of the test's results, and the building becoming unoccupiable during the test campaign [5, 27].

So, the Co-heating test enables determination of actual energy needs; but to calculate the energy performance gap, design values are calculated. Design total transmission HLC is calculated in this research by using a simplified method according to *Energy performance of buildings – Method for calculation of the design heat load – Part 3: Domestic hot water systems heat load and characterization of needs, Module M8-2, M8-3 (EN 12831-3:2017)* [26]:

$$H_{T,ie} = \Sigma A_k \cdot f_k \cdot (U_k + 0.10)\ (W/K) \tag{3}$$

where A_k is the area of the building element (k) (m^2), U_k is thermal transmittance of the building element (k) ($W/[m^2 \cdot K]$), 0.10 is added for each element as a corrected thermal transmittance of the building element (k) considering linear thermal bridges, and f_k is the correction factor for temperature gradients (–) [26]. Default values for the f_k for building elements used in this research are given in Table 1. according to [26].

Total transmission heat loss, $\Phi_{T,I,}$ can be calculated according to following formula [26]:

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e)\ (W) \tag{4}$$

where $\theta_{int,i}$ is the internal design temperature (°C; for residential units, usually 20°C is used) and θ_e is the external design temperature (°C; for the city of Osijek, external design temperature in the winter season is −18°C). Total ventilation HLC is calculated as follows [26]:

$$H_{V,i} = 0.34 \cdot V_i \cdot n_{min}\ (W/K) \tag{5}$$

where V_i is the volume of heated space (i) calculated based on internal dimensions. As an approximation, this volume is 0.8 times the volume of the space calculated based on external dimensions (m^3). Also, n_{min} is the minimum external air exchange rate per hour (h^{-1}). The values of the minimum external air exchange rate shall be given in national annexes. In Croatian legislation, this is given as 0.50 h^{-1} [30]. Total ventilation heat loss is calculated as follows [26]:

$$\Phi_{V,i} = H_{V,i} \cdot (\theta_{int,I} - \theta_e)\ (W) \tag{6}$$

Table 1: Temperature correction factor, f_k, for the simplified calculation method.

Heat loss	$\mathbf{f_k}$	**Comments**
Directly to the exterior	1.00	If thermal bridges are insulated
	1.40	**If thermal bridges are not insulated**
	1.00	**for windows, doors**
Through the ground	0.3	If thermal bridges are insulated
	0.42	**If thermal bridges are not insulated**
Through the roof space	0.90	If thermal bridges are insulated
	1.26	**If thermal bridges are not insulated**

And finally, total ventilation and transmission heat loss is calculated as [26]:

$$H_i = \Phi_{T,i} + \Phi_{V,i} \text{ (W)} \quad (7)$$

where $\Phi_{T,i}$ is the design transmission heat loss for heated space (i) in Watts (W) and $\Phi_{V,i}$ is the design ventilation heat loss for heated space (i) in Watts (W).

3 IN SITU EXPERIMENTAL RESEARCH

Experimental research was conducted in a built test chamber (Fig. 1). The chamber was built inside an unheated building (laboratory) to simulate outside temperature conditions during the measurements and to control and avoid impacts of disadvantageous weather conditions such as wind, solar radiation, and precipitation. The two longer opposite sides of the chamber were made of 30-cm-thick concrete thermal blocks thermally insulated with 10 cm of expanded polystyrene, while the other two opposite sides of the chamber were constructed in such a way to allow testing and alternating placement of different wall elements (Figs. 2 and 3). In this research, two different types of walls were used (Figs. 2 and 3).

Blower door test was used to determine ventilation heat losses (Fig. 4). During the in situ U-value measurements, energy consumption was measured in kW h to maintain the internal temperature at a constant rate as much as possible. Since in situ U-value measurements must

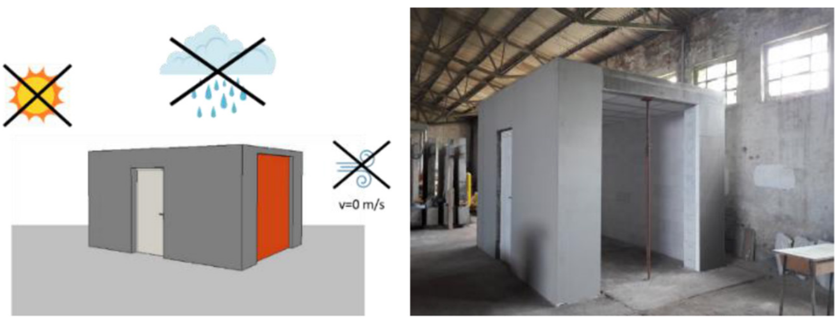

Figure 1: Test chamber model and placement in laboratory.

Figure 2: Wall made of hollow bricks with integrated rock wool insulation.

Figure 3: Wall made of concrete blocks with recycled brick aggregate.

be conducted under a minimum temperature difference between the indoor and outdoor environment, the heating device was installed inside the chamber. Using the heating device, at least 15°C difference in temperature between indoor and outdoor was achieved during the test. In this paper, the heat flow meter (HFM) method and the temperature-based method (TBM) were used to determine the U-values of chamber walls and tested walls (Fig. 5). The measuring equipment used for the U-value assessment by TBM consisted of a data logger, surface temperature sensor for measuring and registering the surface temperature of a wall being examined, and two temperature sensors for measuring and registering the internal and external temperature. In order to avoid the placement of sensors in the vicinity of thermal bridges, cracks, and places that are similar sources of errors, IR thermography was used (Fig. 6). In situ measurements of U-value were performed on two types of uninsulated walls constructed on the opposite sides of the chamber. The first wall was built from hollow bricks with integrated rock wool insulation within the brick (Fig. 2), and the second one from concrete blocks with recycled brick aggregate (Fig. 3). Measurements were performed under a maintained and controlled internal temperature of 30°C set on a heating device inside the chamber.

Walls were monitored for 40 days with a sampling interval of 10 min from February to March. Heating was turned on 17.10.2018, 4 months earlier due to another testing, to minimize the effects of thermal storage. Therefore, airtightness measurement was done only (n_{50} = 5.19 h^{-1}) before the Co-heating test since the test could not cause any additional cracking and drying out of materials. A summarized description of experimentally tested walls, measurement conditions during in situ U-value assessment, together with theoretical U-values calculated according to the international standard ISO 6946:2017 is given in Table 2.

Finally, the calculated Co-heating test results are presented in Table 3. Although suggested to calculate daily energy needs due to a long period of testing in this research, measured values of energy and power input and inside and outside temperatures, together with outside RH are averaged over a 10-day period and then given as daily averages. Actual HLC $(Q/\Delta T)_{1d}$ in Watts per Kelvin and actual THL (power input for 1 day in Watts, Q_1) of the test chambers are later compared with the design values. The last column in Table 3 gives all values averaged over the overall test period (40 days). This way, Co-heating test results are observed as five different Co-heating tests for four time spans, each 10 days long, and the overall test results are given in the last column of the table.

Figure 4: Blower door equipment.

Figure 5: HFM method and TBM.

Table 2: An overview of experimentally tested walls.

Code	Wall material	Theoretical U-value ($W/m^2 K$)	Measured U-value ($W/m^2 K$)	Method used for U-value assessment
W1Y	Light concrete aerated blocks – 30 cm and EPS – 10 cm	0.17	0.25	TBM
W2C	Plaster – 2 cm and concrete blocks with recycled brick aggregate – 12 cm	1.96	1.96	HFM
W3P	Plaster – 2 cm and hollow bricks with integrated rock wool insulation – 25 cm	0.28	0.40	HFM

Table 3: Co-heating test results.

Values obtained by measurement	Test duration 10 days: 05.02.2019 to 15.02.2019	Test duration 10 days: 15.02.2019 to 25.02.2019	Test duration 10 days: 25.02.2019 to 07.03.2019	Test duration 10 days: 07.03.2019 to 18.03.2019	Test duration 40 days: 05.02.2019 to 18.03.2019
Energy input, E (kW h)	68.32	62.48	47.80	46.20	224.80
Time period, T_{10d} (h)	242.00	238.00	239.00	261.00	980.00
Average outside RH in 10 days (%)	75.07	61.34	53.73	51.59	60.13
Power input for 10 days, Q_{10} (W)	282.31	262.52	200.00	177.01	229.39
Power input for 1 day, Q_1 (W)	28.23	26.25	20.00	17.70	22.94
Average inside temperature in 10 days, $T_{i,10}$ (°C)	28.99	29.06	29.41	28.42	29.25
Average outside temperature in 10 days, $T_{o,10}$ (°C)	2.96	3.80	8.86	10.44	6.59
$\Delta T = T_i - T_o$ (°C)	26.03	25.26	20.55	17.98	22.66
$(Q/\Delta T)_{10d}$ (W/K)	10.85	10.39	9.73	9.84	10.12
$(Q/\Delta T)_{1d}$ (W/K)	1.08	1.04	0.97	0.98	1.01

Design total ventilation and transmission HLC are calculated by using a simplified method according to EN 12831-3:2017 [26] and presented in Table 4. Values presented in the table are described in previous chapters of this paper. Heating season duration is taken as 178.9 days long according to the Croatian legislation for the City of Osijek.

Table 4: Design values of total ventilation and transmission heat loss and heal loss coefficient.

Temperature data					
Design external temperature		θ_e	°C	−18	
Design internal temperature		$\theta_{int,i}$	°C	20	
Design temperature difference		$\theta_{int,i} - \theta_e$	°C	38	
Transmission heat losses					
Code	Building element (–)	f_k (m²)	A_k (W/m²·K)	U_k (W/K)	$f_k \cdot A_k \cdot (U_k + 0.10)$
C	Ceiling toward the exterior	1.26	16.61	0.25	7.33
F	Floor on the ground	0.42	16.61	4.05	28.95
W1Y	External wall 1	1.40	44.22	0.17	16.72
W2C	External wall 2	1.40	5.28	1.96	15.23
W3P	External wall 3	1.40	5.28	0.28	2.81
D	Eternal opaque door	1.00	2.10	1.40	3.15
Total transmission heat loss coefficient $H_{T,i} = \sum f_k \cdot A_k \cdot (U_k + 0.10)$ (W/K)					74.18
Total transmission heat loss $\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e)$ (W)					2818.76
Ventilation heat losses					
Internal volume		V_i	m³	26.7	
Minimum air exchange rate		n_{min}	h^{-1}	0.5	
Total ventilation heat loss coefficient $H_{V,i} = 0.34 \cdot V_i \cdot n_{min}$ (W/K)					9,561
Total ventilation heat loss $\Phi_{V,i} = H_{V,i} \cdot (\theta_{int,i} - \theta_e)$ (W)					363.318
Total ventilation and transmission heat loss $\Phi_{T,i} + \Phi_{V,i}$ (W)					3182.08
Daily total heat loss coefficient (W/K)					**0.47**
Daily total heat loss (W)					**17.79**

Figure 7 is a graphical presentation of the comparison of Co-heating test results from Table 3 and design values from Table 4. Results marked with the label Test 1 are presented with actual power input for 1 day (Q_1) (blue column) and daily design THL (orange column, same design values in Figs. 7–9) together with values of energy performance gap (grey curve).

Results are given as bar charts for four time periods and the fifth one presents overall test results for 40 days.

Energy performance gap value marked with the label Test 2 and presented in Fig. 8 is given for the actual Q_1 and daily design THL values, but with one exception: n_{50} variable was not taken as the design value (0.5 h^{-1}, Table 4) but as the measured value (5.19 h^{-1}). Energy performance gap value marked with the label Test 3 and presented in Fig. 9 is given for the actual Q_1 and daily design THL values, but with two exceptions: n_{50} variable was not taken as the

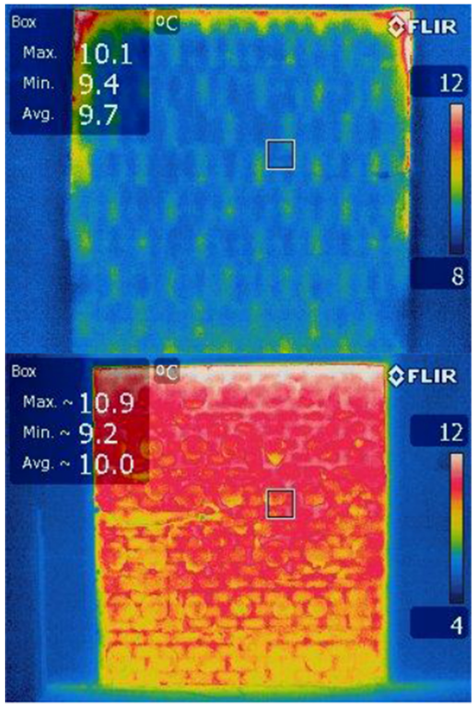

Figure 6: IR thermography on tested walls.

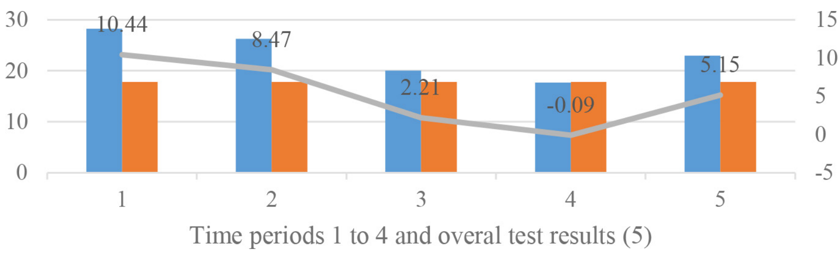

Figure 7: Comparison of energy performance gap obtained by calculation with design values of all variables (Test 1).

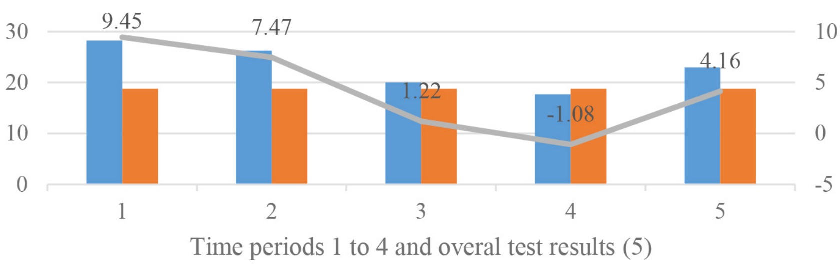

Figure 8: Comparison of energy performance gap with design values of all variables except n_{50} (measured value of 5.19 h^{-1} was taken) (Test 2).

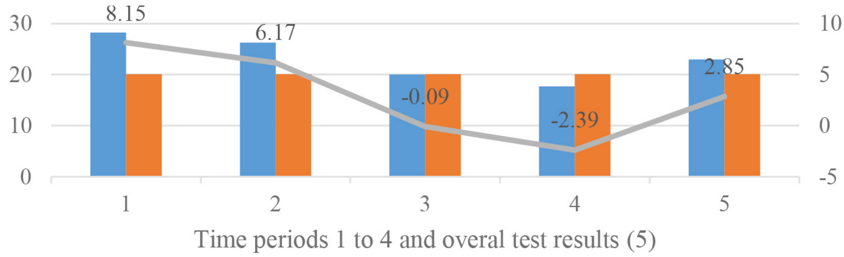

Figure 9: Comparison of energy performance gap with design values of all variables except n_{50} and U-values (measured ones were taken) (Test 3).

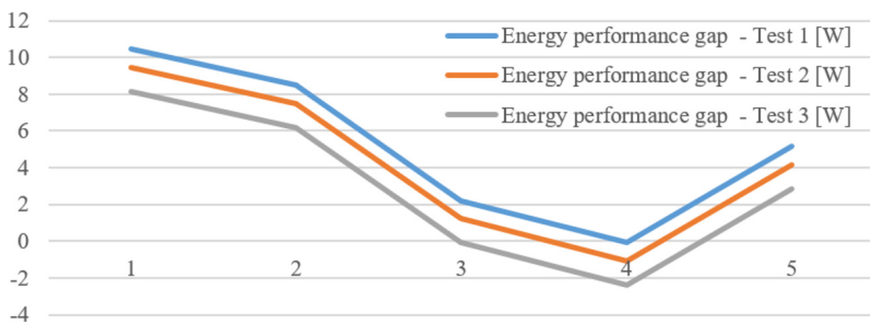

Figure 10: Comparison of energy performance gaps for all observed time periods (1–4), overall time of 40 days, and three Co-heating tests (1–3).

design value (0.5 h^{-1}, Table 4) but as the measured value (5.19 h^{-1}) and U-values of walls W1Y, W2C, and W3P were taken as the measured U-values according to the data presented in Table 2.

The energy performance gap for all three cases, tests, is summarized in Fig. 10.

It is obvious and clear how the energy performance gap decreases as the design values of variables needed for calculation of design THL are replaced with the actual values on n_{50} and U-values. This is clearly present with time periods 1–3, but the energy performance gap increases in time period 4, from −0.09 to −2.39 W.

The experiment was done according to future research direction given in [27, 31] where it is advised to perform test campaigns under steady-state conditions. Measured performance exceeded the predicted performance in all the tests presented, as it was in the case study presented in [28].

Based on the results presented in this case study, it can be explained by the fact that only this set of data is calculated based on an average temperature difference lower than 20°C. During this time period, the average outside temperature was higher (10.44°C) compared to 2.96°C, 3.80°C, and 8.86°C in time periods 1, 2, and 3, respectively. Especially, the inside temperature did not significantly vary, from 28.42°C to 29.41°C, for all four time periods. This also affected the lower values of daily energy input. Also, in this time period, RH was lowest compared to the other three tests. Higher the temperature difference during measurements and usage of actual, measured variable values, lower the energy performance gap.

4 CONCLUSION

Research results and findings presented in this paper show how the actual energy needs in this study were higher than those calculated using a simplified method, and this is usually even more evident when considering a real building where the occupants' behavior plays a significant role as stated in many studies before. The energy performance gap tends to decrease if the design values of some variables used for calculation are replaced with actual ones, which proves that the design values of variables influencing the energy performance of buildings (U-values) are often overestimated probably because of marketing purposes. Therefore, it can be concluded that it is possible to decrease the energy performance gap and to improve Co-heating test results by using the actual values of some variables instead of design ones. Change of n_{50} value by 90% gives a change of design daily THL equal to only 5%, but changes of walls' U-values by approximately 30% per wall change the total design daily heat loss by 11%. The appearance of new building materials and insulations on the market in the last decade could cause even higher energy performance gap in the future, since usually these materials lack historical data under different conditions. Higher outside temperature gives less reliable results of measured U-values, since the temperature difference is lower which influences negatively the equipment used for U-value measurements. Usually, a minimum temperature difference of 15°C is recommended; a higher temperature difference is desirable because it tends to give more reliable measurement results. Rather, a constant inside temperature above 25°C is recommended and fluctuation in inside temperature should be avoided as much as possible like it was done in this research. Besides all this, the experimental results for the fourth time period could be anticipated, since the experiment started in winter and almost finished in the spring season when the temperatures were higher than in the first three periods. Influence of low RH values on THL in time period 4 is something to be more thoroughly investigated in future research.

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