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ANALYSIS OF HEAT DEMAND AND THERMAL COMFORT IN NATURALLY VENTILATED SINGLE-FAMILY HOUSES OF VARIOUS CONSTRUCTIONS

Joanna FERDYN-GRYGIEREK [a*], Krzysztof GRYGIEREK [b], Anna GUMIŃSKA [c], Łukasz BARAN [d], Magdalena BARWA [e], Kamila CZERW [f], Paulina GOWIK [g], Klaudia MAKSELAN [e], Klaudia POTYKA [d], Agnes PSIKUTA [h]

[a] DSc PhD Eng.; Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland
*E-mail address: *Joanna.Ferdyn-Grygierek@polsl.*

[b] PhD Eng.; Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland

[c] PhD Eng.; Silesian University of Technology, Faculty of Architecture, Akademicka 7, 44-100 Gliwice, Poland

[d] MSc Eng.; Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland

[e] Eng.; Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland

[f] MSc Eng.; Silesian University of Technology, Faculty of Architecture, Akademicka 7, 44-100 Gliwice, Poland

[g] Eng.; Faculty of Energy and Environmental Engineering, The Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland

[h] Swiss Federal Laboratories for Materials Science and Technology Empa, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, 9014 St. Gallen Switzerland

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Abstract

The aim of the paper was a comparative analysis of energy demand for heating and human thermal comfort of a model single-family house with natural ventilation in various construction technologies (wood and brick), located in the Polish temperate climate. The frequency, as well as, the window opening area in the building have been optimized taking into account two objective functions: heating demand and number of thermal discomfort hours. The analyses were based on thermal simulations using the EnergyPlus program on the nine-zone model of the selected house. Each building construction case was calculated for two variants of external partitions insulation. The thermal model, separately for each zone, contained hourly internal heat gain schedules. All simulations were carried out with a 15-minute step for the full calendar year. Analyzes have shown that the heating demand for a building made in wooden technology is higher than a building in brick technology. The wooden building has a greater number of thermal discomfort hours. Increasing the insulation properties of the house increases the number of hours of discomfort.

Keywords: **Brick building; Building optimization; Building performance simulation; Heating demand; Thermal comfort; Wood building.**

1. INTRODUCTION

Currently, many countries in both Europe and the world try to find a way to reduce CO_2 emissions to the atmosphere. Carbon dioxide is the main factor contributing to global warming, resulting in, among others, an increase in average annual outdoor air temperature. In many sectors of the economy, reforms are being implemented to reduce emissions of this gas. One of the main sectors contributing to such high emissions is the housebuilding industry. Therefore, it is currently strived to reduce energy consumption for heating and cooling of buildings, which has a beneficial effect on reducing the operating costs of the building as well as the external environment.

Measures to reduce energy consumption must not negatively affect the thermal comfort of residents. The main goal of the EU is to increase the energy efficiency of buildings with the lowest possible costs; however, this must not be at the expense of deteriorating indoor environmental conditions [1]. Such studies are widely carried out all over the world. For example, research conducted by Kwong et al. [2] focused on the possibilities of improving energy efficiency in modern, air-conditioned buildings, located in a tropical climate, based on the thermal comfort of residents. Besides, Pfafferott et al. [3] focused on the analysis of thermal comfort standards and showed the most critical points to design a building in which thermal comfort is maintained. A similar study was conducted by Harkouss et al. [4], which presents an analysis of the optimal passive design of residential buildings. A simulation was made for 25 different climates, resulting in the development of best practices to reduce energy demand in buildings.

In residential buildings or offices, in order to achieve thermal comfort, mechanical cooling with electric air conditioners is usually used. Then cooling can account for up to half of the electricity consumption in a building [5]. This resulted in the development of passive cooling solutions, e.g. ventilative cooling. Free cooling through ventilation is one of the most effective cooling techniques because cold external air can directly lower the temperature of the indoor air. For example, the work of Alonso et al. [11] showed energy savings when used ventilative cooling in a building located in Norway as a result of utilizing the potential of low outside temperatures during the day or night. Article by Yao et al. [6] presented a study on the natural ventilative cooling potential of office buildings in five climate zones in China. In turn, the work of Santamouris et al. [7] analyzed energy consumption in more than two hundred air-conditioned residential buildings using night ventilation techniques in Greece. The authors investigated the relationship between the cooling demand and night ventilation. In general, studies show that the effectiveness of passive techniques directly depends on the climate zone and changes not only from season to season, but also during the day. Therefore, not every alternative can be the right solution for a given building location; local climatic conditions should be carefully considered [8].

The paper aimed to analyze energy the demand and thermal comfort of users of a single-family house with natural ventilation. These factors were compared for buildings made of brick and wood. The impact of opening windows has also been tested.The study was conducted for the real current Polish climate. This study answered the question whether (and if so, how much) the thermal comfort conditions differ in conventional and wooden buildings in the age of global warming?

2. RESEARCH OBJECT

A single-family house with an area of 154 m^2 was selected for the study. It is a two-storey compact body building with a flat roof and floor on the ground. The house was designed for a 2+2 family model. On the ground floor, there is a living room with an open kitchen, bathroom, utility room, vestibule and garage; on the ground floor, there are child's rooms, study, master bedroom, two bathrooms, laundry room and hall.

Two cases of building construction were considered: brick and wood. According to the data of the Central Statistical Office, single-family houses in Poland are most often built in traditional (brick) technology. However, investors are increasingly choosing solutions based on wooden construction [9].

In traditional brick technology, external walls were made as double-layer ceramic blocks with polystyrene insulation. Load-bearing internal walls were made of hollow bricks, while the partition walls had a steel structure with a sheathing of plasterboard. In turn, the ceilings were designed as monolithic reinforced concrete. In a building using wooden technology, the whole structure was based on the solid wood beams. In the external walls, the space between the beams was filled with rock wool covered with OSB boards, and, from the outside, additional insulation (polystyrene) was used. The internal load-bearing walls were also filled with rock wool covered with plasterboard sheathing, while the partition walls were designed in the same way as in a brick building. The ceilings are made of beams filled with mineral wool.
Two cases of building insulation were considered:

- the building meets the current Polish standard [10] regarding the maximum value of the heat transfer coefficient for external walls (0.23 W/(m^{2}K)), flat roof (0.18 W/(m^{2}K)) and floors on the ground (0.30 W/(m^{2}K)),
- the building meets the requirements regarding the maximum value of the heat transfer coefficient a

for passive building. Because standards do not determine the specific heat transfer coefficient of individual building partitions in this case, the heat transfer coefficients at the level of 0.12 W/(m^{2}K) was adopted based on the literature [11].

In both cases, a window with a average (glazing and frame) heat transfer coefficient value of 0.9 W/(m^{2}K) was modeled, but with different solar heat gains coefficients of glazing, 0.51 for standard building and 0.61 for passive one. The building architecture included climbing plants (shedding leaves for the winter) above living room windows across the entire south side façade. Internal blinds were also used to prevent excessive solar gains. The building had a heating system and natural ventilation.

3. METHODS

The analyzes were based on the results of the building performance simulation. The thermal model was prepared in the OpenStudio program [12], and the calculations were carried out in the EnergyPlus (EP) program. The EnergyPlus program [13] is a set of many modules that work together to calculate the energy demand for heating and cooling in a building, taking into account heat and moisture loads, schedules and HVAC systems, and various environmental and operational conditions. The EP is a widely used and well-validated research program.

The building (Figure 1) was divided into nine thermal zones, for which the individual schedules of occupied hours, electric equipment and lighting operation were adopted for weekdays and weekends. The schedules were determined based on Polish customs. The lighting switched on when the room illumination dropped below 200–300 lx depending on the room type (the light power depended on the solar radiation). Heat gains from people and equipment were adopted following the ASHRAE standard [14] and literature [15]. The calculations were carried out using actual climate data for southern Poland from 2018 (Fig. 2) with a 15-minute step for the full calendar year.

In the model, it was assumed that from April to October the degree of shading of the building resulting from the external plants was: 0.4, for the rest of the year: 0.8. In turn, the internal shading of the window depended on the intensity of solar radiation. The blinds were used if the illumination in the room increased above 200 lx and the indoor temperature exceeded 22°C. During the heating season (from September to May), an appropriate temperature was set in each zone depending on its intended use (Table 1).

In this study, an adaptive model of thermal comfort was adopted for comfort analyzes. This model assumes that people can adapt to changing conditions in the internal environment, using various adap-

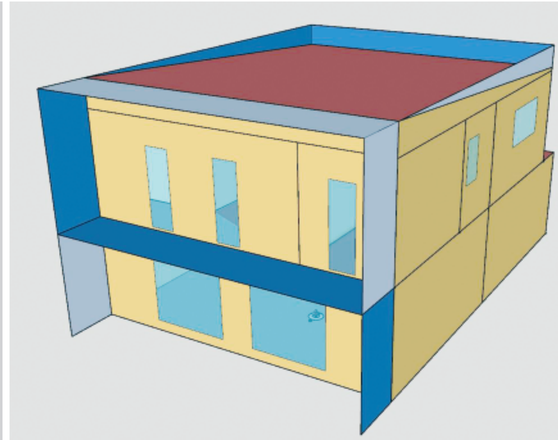

Figure 1.
The SketchUp model of the building – view from the south façade

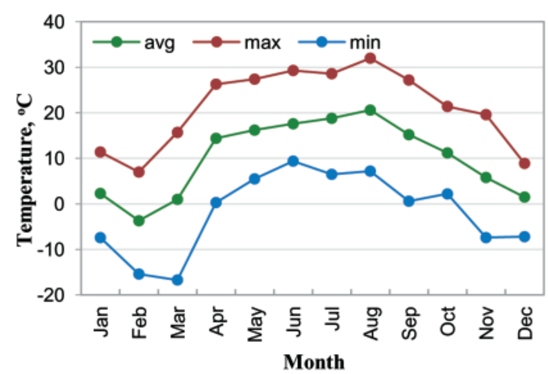

Figure 2.
Maximum, average and minimum temperature in individual months for weather data adopted for simulation

Table 1.
Temperature set-point for heating

Room	Temperature (operating time)	
Garage	8°C (0:00-24:00)	
Vestibule and Utility room	16°C (0:00-24:00)	
Bathrooms	24°C (6:00-24:00)	18°C (24:00-6:00)
Living-room with kitchen, Hall, Study, Bedroom, Child's rooms	21°C (6:00-24:00)	18°C (24:00-6:00)

Table 2.
Effective leakage area assumed to simulations

Thermal zone	Length of the window leakages, m	Number of air inlets	Number of ventilation ducts	Flow coefficient for window, $m^3/(hPa^{0.67})$	Effective leakage area, cm^2
Living room with kitchen	43.8	5	1	13.1	111
Bathroom on ground floor	-	-	1	-	29
Utility room	10.7	1	1	3.2	47
Garage	9.2	0	1	9.2	54
Study	6.6	1	0	2.0	15
Bedroom	13.2	2	0	4.0	29
Child's rooms	22.4	4	0	6.7	55
Bathrooms on 1st floor	4.6	1	3	1.4	100
Hall	4.6	1	0	1.4	13

tation possibilities [16]. An algorithm for the linear function of the average outdoor temperature has been defined to determine the optimal temperature of the indoor environment. The use of adaptive comfort temperature as a room temperature set-point potentially reduces the use of the HVAC system. The energy savings mainly result from the acceptance of higher indoor temperature values than those recommended in summer and lower than recommended in winter [17]. The analysis presented in this study was based on an adaptive model described in the EN 15251:2007 standard [18]. This adaptive model has three comfort categories: I (high level of expectation), II (normal level of expectation), III (moderate level of expectation). For each calculation case, the number of discomfort hours (H_{dis}) was determined as the sum of the discomfort hours for the category II from all rooms. Only the time in which occupants reside in the rooms was taken into account. During the heating period, the night hours with reduced indoor temperature assumed were excluded from the calculations.

Modeling infiltration and ventilation was a fundamental problem to be solved in this study. For buildings with mechanical ventilation systems, the situation is more straightforward because ventilation airflows are known and these values can be entered into the thermal model as input. The situation becomes more complicated for buildings with natural ventilation. For such buildings, external airflow can inlet to the building through:

- infiltration, i.e. uncontrolled, random airflow through openings and leaks in building envelope: walls, windows, roof. Too low infiltration can cause poor indoor air quality, while too high increases heat loss in winter,
- ventilation, more controlled supply of airflow implemented by an additional window opening. Ventilation is used to supply fresh air, but additionally can be used for the free-cooling in moderate climates, i.e. cooling rooms with outside airflow at a lower temperature.

In both methods, the airflows supplied to the building are difficult to predict; they depend on the temperature difference outside and inside the building, and on the wind speed. Airflow values have a significant impact on the building's heat demand and thermal comfort. The thermal model in this study included both methods of natural ventilation.

For modeling of infiltration, the Sherman and Grimsrud (1980) model was used based on the so-called effective leakage area method. The effective leakage area is defined as "the equivalent amount of open area through which would pass the same quality of air as would pass collectively through the building envelope at the reference pressure of 4 Pa" [19] and calculated from formula (1) [20].

$$\dot{V}_{inf} = \frac{ELA}{1000}\sqrt{C_s \times \Delta T + C_w w^2} \qquad (1)$$

$\dot{V}_{inf}$ – infiltration airflow, m^3/s,

ELA – effective leakage area at 4 Pa pressure differential, cm^2,

C_s – coefficient for stack-induced infiltration, 0.00029 $(dm^3/s)^2/(cm^4K)$,

ΔT – temperature diff erence between zone air and outdoor air, K,

C_w – coefficient for wind-induced infiltration, 0.000231 $(dm^3/s)^2/(cm^4(m/s)^2)$,

w – local wind speed, m/s.

For calculations as the leakage areas were adopted:

window and door gaps, window air inlets and gravity ducts. The effective area was determined from the equation (2) [14].

$$ELA = \frac{\dot{V}_4}{\left[\left(\frac{2}{\rho}\right)\Delta p_4\right]^{0.5}} \times 10000 \quad (2)$$

$\dot{V}_4$ – airflow at 4 Pa, m^3/s,

Δp_4 – leakage reference pressure, 4 Pa,

ρ – air density, 1.2 kg/m^3.

$$\dot{V}_4 = C \times \Delta p^{0.67} \quad (3)$$

$$C = a \times l \quad (4)$$

C – flow coefficient, $m^3/(hPa^{0.67})$,

a – airtightness factor, $m^3/(mhPa^{0.67})$,

l – length of the window leakages, m.

The value of the airtightness factor for the windows was assumed at the level of 0.3 $m^3/(mhPa^{0.67})$ based on available studies on the airtightness of Polish residential buildings [21, 22]. The length of the window leakages was the total perimeter of each window sash. The value of the airtightness factor for garage doors was assumed at the level of 1.0 $m^3/(mhPa^{0.67})$. The flow coefficient of the window air inlets was adopted from the characteristics of Aereco Ventilation inlets [23] at the level of 5.6 $m^3/(hPa^{0.55})$. The effective area of the ducts and roof was assumed in accordance with ASHRAE standards [24]. Table 2 presents the effective leakage areas introduced to the individual thermal zones.

For modeling additional ventilation, a built-in the EP model was used, described as "wind and stack open area", which is based on equation (5) [13].

$$\dot{V} = \sqrt{\dot{V}_s^2 + \dot{V}_w^2} \quad (5)$$

$\dot{V}_s$ – airflow due to stack effect , m^3/s,

$\dot{V}_w$ – air flow driven by wind, m^3/s.

The main parameter that occurs in this model is the window opening area. For each window opening area, the airflow changes with the external climate conditions. The adopted solution differs from the method used in the study of Grygierek and Ferdyn-Grygierek [25], where the airflow was constant for a given window opening area. In practice, the degree of window opening (opening area) is decided by the residents who, depending on the thermal conditions in the room and depending on the external temperature, open the windows more or less. In the thermal model to process the windows opening a driver based on the "IF ... THEN" principle was built. It has been implemented in the energy management system (EMS) part of the EP program. A multi-criteria optimization was performed for each case of building. The heating demand and the number of discomfort hours in rooms were the objective functions. A detailed description of the controller is included in the paper of Grygierek et al. [26]. As a result a set of non-dominated solutions (Pareto front) was obtained. The most favorable configurations were selected from among them (Multi-Criteria Decision Making). Three solutions were analyzed in this study:

- KQ: solution with minimal heat demand (Q_{heat}) which reflects the case of not opening windows.
- KU: the utopia point criterion; the best configuration closest to the ideal solution (solution for which both functions are minimized). Such a result is very often taken into account in technical analyzes.
- KH: solution with a minimum number of thermal discomfort hours (H_{dis}).

The adaptive thermal comfort model applies if the average outdoor temperature exceeds 10°C. Therefore, in winter periods, when this model does not apply, it was assumed that the heating system provided thermal comfort. Hence, in a temperate Polish climate, in most cases, this model showed thermal discomfort for overheating rooms in summer. There were, however, situations that it was too cold in the room.

4. RESULTS

As a result of optimization, the Pareto solution was obtained for all building versions (Figure 3). A circle marks the utopia point (KU solution). Table 3 summarizes the results of the objective function for the optimal three solutions described below. In the analysis the

Table 3.
Objective function results for optimal solutions

Building case	Criterion	Q_{heat}, kWh	H_{dis}, h
Brick standard insulated building	KQ	5469	3397
	KU	5584	533
	KH	5873	91
Wood standard insulated building	KQ	5726	3801
	KU	5839	976
	KH	6074	344
Brick passive insulated building	KQ	2924	5411
	KU	3151	1085
	KH	3491	247
Wood passive insulated building	KQ	3210	5445
	KU	3381	2164
	KH	3714	741

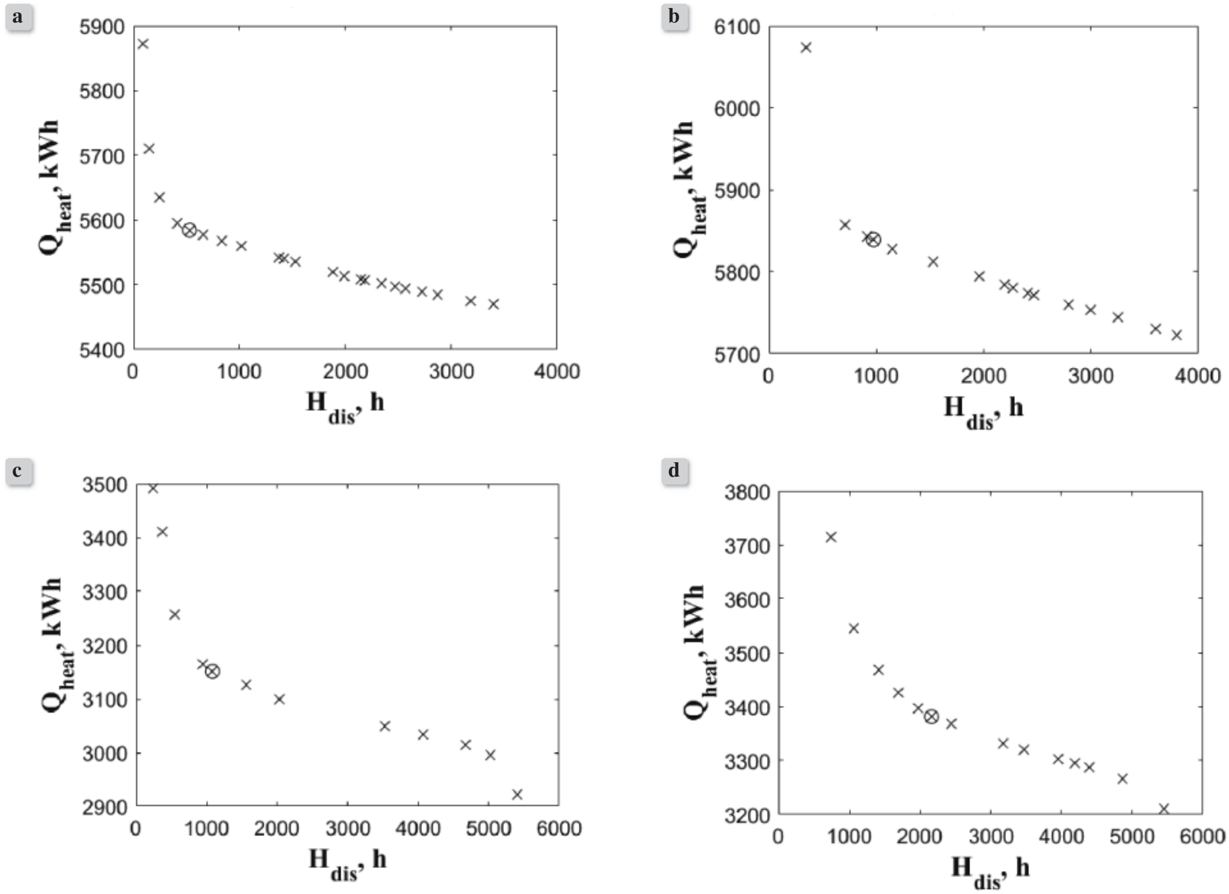

Figure 3.
Pareto Front: a) brick standard building, b) wood standard building, c) brick passive building, d) wood passive building

Q_{heat} means the annual heat demand of the building, while H_{dis} is the sum of thermal discomfort hours from all rooms intended for permanent residence of people (living room, study room, child's rooms and bedroom).

Analyzing the KQ solution (windows are not opened) for a standard brick building and a passive brick building, it can be seen that the heat demand for the second one has decreased by 46%; however, the number of discomfort hours has increased significantly – by 59%. On the other hand, comparing the brick and wooden building, it can be seen that the heat demand for wooden (despite the same insulation of external partitions) increased by 5%, and the number of discomfort hours increased by 12%. It should be highlighted that the KQ criterion was only a theoretical solution since, in real life, the windows can be opened in any single-family house. However, the KQ criterion provided a direct comparison of the results, without affecting the windows opening, which is different in each type of building. The airflow influenced the other obtained results (KU and KH) throughout the open windows, which is a result of the user's individual preferences as to the frequency of opening them. KU and KH solutions allowed for a significant improvement in thermal comfort at the expense of a slight increase in Q_{heat}.

The results obtained for the second extreme solution of KH, showed that the difference in heat demand of both cases of the building structure with standard insulation fell to 3%, however, the number of discomfort hours was 278% higher in a wooden building compared to a brick one. Insulation of a brick building allowed to reduce heat consumption by 40%, but it was paid for by almost 3 times increase in the number of thermal discomfort hours. The largest number of discomfort hours occurred in a passive wooden building; it is even 3 times higher than in a passive brick one. It should be reminded that the KH solution requires a considerable regime of opening windows in accordance with the assumed plan. In practice, there is probably an intermediate solution, which can be illustrated by the KU point. For the KU, a 83% increase in the number of discomfort hours in a wooden building compared to a brick building was observed during the

Table 4.
Percentage share of discomfort hours compared to all occupied hours in rooms

Building case	Criterion	Max air change rate in the rooms due to windows opening, h^{-1}	H_{dis}, %			
			annual		summer	
			max	avg	max	avg
Brick standard insulated building	KQ		47.7	26.9	98.0	74.8
	KU	3.5	13.7	4.2	40.6	12.6
	KH	9.8	1.5	0.7	4.8	0.9
Wood standard insulated building	KQ		47.7	30.1	91.7	76.7
	KU	3.5	21.3	7.7	51.0	19.8
	KH	8.5	5.2	2.6	13.2	4.9
Brick passive insulated building	KQ		54.8	42.8	100	100
	KU	7.8	17.7	8.6	43.6	24.7
	KH	9.8	5.1	1.9	12.0	4.9
Wood passive insulated building	KQ		56.0	43.2	100	100
	KU	4.4	30.8	17.1	62.8	45.6
	KH	8.4	14.6	5.8	33.9	13.7

Table 5.
Maximum, average and minimum indoor temperature for KU solution (summer period)

Building case	Temperature, °C				
		Study	Child's rooms	Living-room	Bedroom
Brick standard insulated building	max	32.5	30.8	32.2	31.5
	min	21.8	22.5	21.5	22.2
	avg	26.7	26.7	26.1	26.6
Wood standard insulated building	max	33.7	32.6	33.5	33.4
	min	19.4	20.5	20.5	21.0
	avg	26.6	26.7	26.1	26.6
Brick passive insulated building	max	33.0	31.4	34.4	32.3
	min	21.6	22.9	21.3	21.4
	avg	26.7	27.1	27.1	26.7
Wood passive insulated building	max	34.5	33.9	36.6	34.7
	min	20.3	21.1	20.7	20.5
	avg	27.3	27.7	28.0	27.3

year. In turn, an increase (by 2 times) of the H_{dis} in a passive building was observed compared to a standard insulated building (both in brick and wooden technology). The energy benefit for this solution was greater compared to the KH, as much as 60%.

Because the H_{dis} values poorly illustrate the scale of the problem, the percentage share of thermal discomfort hours compared to all occupied hours in rooms was calculated throughout the year and in June-August (Table 4). For the KU solution in a standard brick building, the uncomfortable conditions did not exceed average 5% of the time spent indoors; for a passive wooden building, it was already 17% of the year, however, this time was longer locally in rooms. Most of the H_{dis} occurred in the summer; for the passive wooden building uncomfortable conditions occurred on average for almost 50% of the occupied time, and in some rooms this period exceeded even 60% of the time.

In each of the optimal solutions, the degree of window opening was different, which resulted in a different instantaneous air change rate in each room. Table 4 shows the maximum air change rates calculated in the building. The windows were opened frequently and the maximum air change rate reached 10 h^{-1} to minimize thermal discomfort. In the KU solutions, the maximum air change rates were definitely smaller. It should also be noted that in the case of ventilation with an air exchange of 3.5 h^{-1} (for brick standard insulated building), the share of discomfort time in the room was a maximum of 14%, while in the case of a brick passive insulated building – with more than 2 times more ventilation (7.8 h^{-1}) – the maximum share of discomfort hours increased to 18% over a year.

Table 5 shows the calculated indoor temperatures from June to August for the KU solutions. In summer, optimal temperatures for occupants with low physical activity are in the range of 23–27°C [18]. Considering the average room temperatures, it was found that the required conditions in each room have been met regardless of the thickness of used insulation.

As the heat transfer coefficients of the external partitions decrease, and thus the greater insulation of the building is, an increase in the maximum and average temperatures in the room was observed. This was due to the reduction of the building's ability to exchange heat to the external environment. The building cooled down much more slowly during the night when the outside air temperature was low. The maximum temperature increase in rooms in passive buildings was on average by 1°C (for brick case) and by 2°C (for wood case). Unfortunately, in all rooms, there were periods in which the temperature exceeded the comfort temperature reaching even 36°C in the passive wood building; in all cases of a brick and wood building, the maximum temperature exceeded 30°C. The minimum calculated temperature values were below 23°C in all cases. Higher maximum temperatures (by 1.6°C and 2.2°C for standard and passive building respectively) and lower minimum temperatures (on average 1.7°C for standard case and 1.2°C for passive case) for a house designed in wooden technology were also seen. The wooden structure is lighter (has a lower heat capacity), compared to the brick structure, and thus the building responds faster to changes in external temperature. Despite this, in brick and wooden buildings, the average temperature in the rooms reached similar values.

5. CONCLUSIONS

Analyzes have shown that the heating demand for a building made in wooden technology is higher (about 5%) than a building in brick technology, despite the same thermal insulation of external walls. The greater heat accumulation of a brick structure causes that it cools down more slowly during transition periods, which results in reduced heat demand. Additionally, the wooden building has a higher number of thermal discomfort hours (about 2 times); this is due to the lighter structure of the building. Each increase in the external temperature results in a faster change of indoor temperature in rooms than in brick buildings; ventilation airflow also affects indoor temperature changes more quickly than in a brick building. To ensure thermal comfort in a wooden building, the window opening area should be changed more often than in a brick building (in this study, the possible number of window changes was the same for both buildings – 5 times a day).

Due to the insulation parameters of the house, the number of discomfort hours increases. In a building insulated as a passive building, there are about twice as many hours of thermal discomfort than a building that meets current insulation standards [10].

The thermal comfort can be improved by adequate ventilation of the building, but the building's heating demand increases then. In the case of passive insulated buildings, the heating demand increases by about 15% between the extreme solutions of the Pareto front (solutions with the best and worst thermal comfort). The best solutions in terms of thermal comfort are obtained in the buildings with high ventilation airflow rates. The maximum air change rate value obtained in the tests is 9.8 h^{-1}. These values may cause local thermal discomfort. This aspect was not considered in the study.

In a wooden, well-insulated building, in the best solution, due to thermal comfort, the rooms experienced discomfort in the summer for 14% of the occupied time. Considering this, one must be aware that when insulating a house very well, the air conditioning system should be used to maintain a comfortable temperature.

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