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THERMAL COMFORT AND ENERGY CONSUMPTION OF THE ECOLOGICAL HOUSE – SIMULATION ANALYSIS OF *DOMTRZON*

KOMFORT TERMICZNY I ZUŻYCIE ENERGII DOMU EKOLOGICZNEGO – ANALIZA SYMULACYJNA *DOMTRZON*

A b s t r a c t

The paper describes the concept of *DomTrzon* which means 'ecological house'. Measurements carried out in the existing building are presented. Based on this data the building envelope model assumptions are verified. A simplified model of a wood-lag accumulation stove (NunnaUuni) is proposed. The indoor thermal comfort and the building's *final energy* consumption are investigated using TRNSYS simulation software. During periods when the building is occupied, most zones fulfill thermal comfort requirements. The final energy consumption of *DomTrzon*, for heating purposes, is equal to 66 kWh/m^2/year.

Keywords: *ecological*, *wooden building*, *accumulation stove*, *energy efficiency*, *simulation*

S t r e s z c z e n i e

Artykuł opisuje koncepcję ekologicznego domu – *DomTrzon*. Zaprezentowano pomiary przeprowadzone w istniejącym obiekcie. W oparciu o pomiary zweryfikowano założenia dotyczące modelu konstrukcji budynku. Zaproponowano uproszczony model pieca akumulacyjnego na drewno (NunnaUuni). Wewnętrzny komfort termiczny i energię końcową budynku zbadano przy użyciu programu symulacyjnego TRNSYS. W trakcie użytkowania większość pomieszczeń spełniała wymagania komfortu termicznego. Energia końcowa *DomTrzon* na cele grzewcze jest równa 66 kWh/m^2/rok.

Słowa kluczowe: *budynek drewniany*, *ekologiczny*, *piec akumulacyjny*, *efektywność energetyczna*, *symulacja*

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1. Introduction

The concept of ecological buildings, according to the authors, has two purposes. Firstly, ecological buildings are energy efficient and provide high indoor air quality. Secondly, they are constructed and operated in a way that ensures low input of additional energy used in the process of production and distribution. In other words ecological houses are characterized by low **energy demand** and low **final energy** consumption, but simultaneously **primary energy** consumption should be lower than **final energy** consumption [4].

DomTrzon is an innovative and multi-option project of a single family house that meets the requirements of an ecological building concept. The project is based on the idea of a wooden family house that supports residents' integration and thermal comfort but is dedicated for people who prefer to stay close to nature and lifestyle in harmony within weather cycle. The main heat source in *DomTrzon* is a wood-lag accumulation stove that is used as a heating unit and kitchen appliance [2]. The first *DomTrzon* has been built in the countryside, in the north part of Greater Poland.

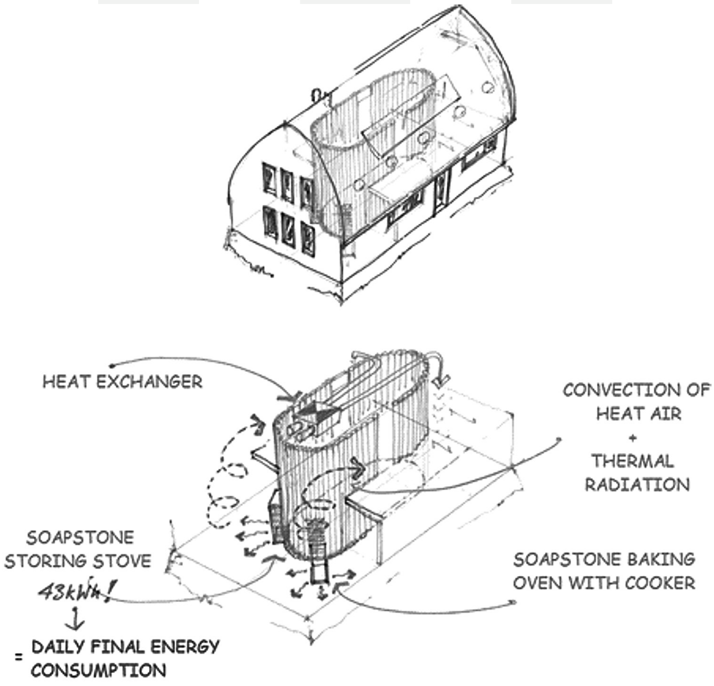

Fig. 1. *DomTrzon* – sketch of concept [2].

The aim of this paper is to analyze the concept of *DomTrzon* in the context of thermal comfort and energy consumption. The analysis is based on measurements carried out in the existing building (unoccupied) and by TRNSYS simulation. Measurement data are used to check the assumption of the building envelope model. Indoor temperature data are obtained based on TRNSYS simulation.

2. Analyzed option of *DomTrzon*

The investigated building has an area of about 150 m^2. The orientation and functional division of the house is shown in Fig. 2, but in reality, all zones of the building are open (without doors), the only partition wall is the central palisade. The first floor is 2.82 m high, the second floor is an attic and the highest vertical dimension is 2.86 m. The living room is two floors high, so the second floor is entresol. Daylight is supplied to the entresol by four skylights: two in the technical room and two on both sides of the entresol.

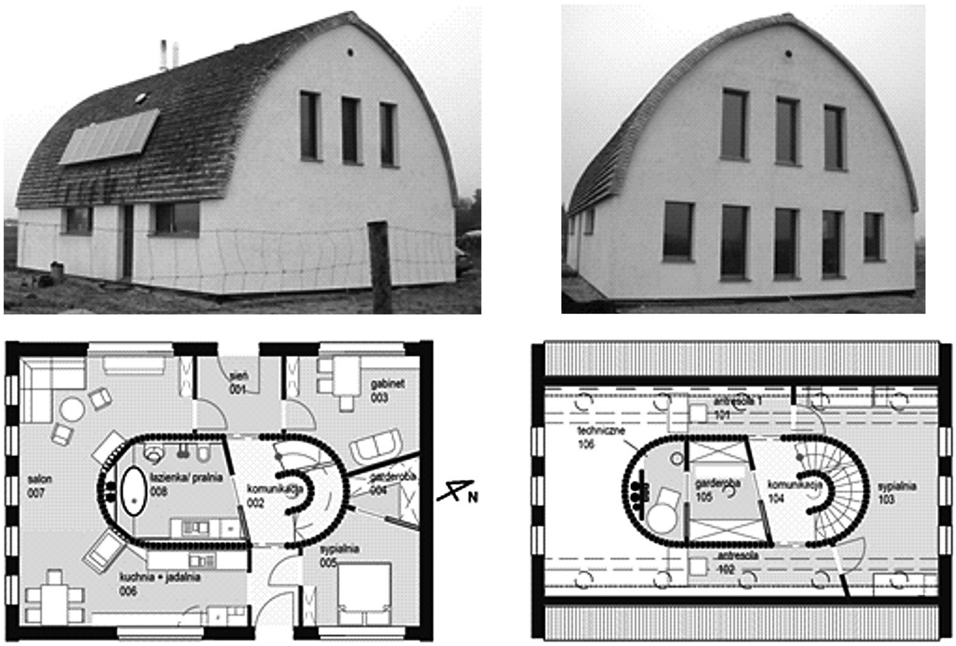

Fig. 2. *DomTrzon* – analyzed variant. Living room (two floors high) with kitchen on south side, two bedrooms: 1st floor (east side) and 2nd floor (entresol), study room is on west side on the 1st floor, in the center: bathroom (1st floor) and technical room (2nd floor) [2]

The construction is heavy and wooden. The thermal properties of the external envelope are presented in Table 1.

The building is occupied by a family of five (parents and three children). The parents sleep in the bedroom and the children sleep in the entresol. The family wakes up at 7:30 AM and goes to bed at 10:00 PM. Four persons spent most of the time in living room and one person works for 7 hours in the study room every day. Four people leave the house for 1.25 hours at noon. There are three kinds of heat gain taken into account: occupant (according to ISO 7730); bathwater/shower (138 W, 0.5 h every evening and morning); equipment in the technical room (20 W, all the time). Moisture gains are assumed in the bathroom (1.8 kg/h, 0.5 h every evening and morning) and in the living-kitchen zone from cooking (proportional to cooking intensity max 1.8 kg/h, 2h, three times per day).

Table 1

External envelope construction (capital letters indicates PAVATEX products)

Wall	Layers (from inside)	thickness [m]	conductivity [W/(mK)]	heat capacity [kJ/(kgK)]	density [kg/m^3]
External wall d = 0.41 [m] U = 0.115 [W/(m^{2}K)]	wood	0.1	0.13	2.51	550
	PAVAFLEX	0.24	0.038	2.1	55
	DIFFUTHERM	0.06	0.043	2.1	250
	plaster	0.01	0.82	0.84	1850
Roof d = 0.59 [m] U = 0.086 [W/(m^{2}K)]	wood fibers (with rafter)	0.45	0.043	2.1	60
	ISOLAIR	0.022	0.047	2.1	240
	air gap (battens)	R = 0.2 [m^{2}K/W]			
	aspen chips	0.019	0.14	0.9	530
Windows					
U = 0.73 – 0.84 [W/(m^{2}K)], g = 0.45 – 0.58					

The analyzed option of *DomTrzon* is equipped with one source heating system – an accumulation wood-lag stove with a baking oven and cooker – Eva 1 [3]. The stove is used above all as kitchen equipment: three times per day with different batch of wood to fireplace. Although the stove is placed in the living-kitchen zone, the back wall is part of the bathroom wall. A more detailed description of stove is given in the next section.

Fresh air is supplied to zones by a balanced mechanical ventilation system with recuperation. Heat exchanger is supported by an auxiliary heater (800 W).

3. Model verification

The investigated building is modeled in TRNSYS software. There are three sub models: envelope model (using type 56); model of stove (type 963); ventilation system model (TRNSFLOW). The first two of these sub models are verified based on measurement data (envelope) and the manufacturer's technical specifications (stove).

3.1. Envelope model

The measurement of indoor and outdoor temperature was carried out in the building for one week: 25th–31st December 2013. The house was unoccupied and not operated, so its cooling process could be observed. The same process is simulated using the envelope model. The assumed boundary conditions (weather data) are from a meteorological station situated about 30 km from the building. Outdoor temperature on site is compared with the ambient temperature for the meteorological station in Fig. 3. It could be seen that values were very close and therefore the assumed boundary condition was reasonable.

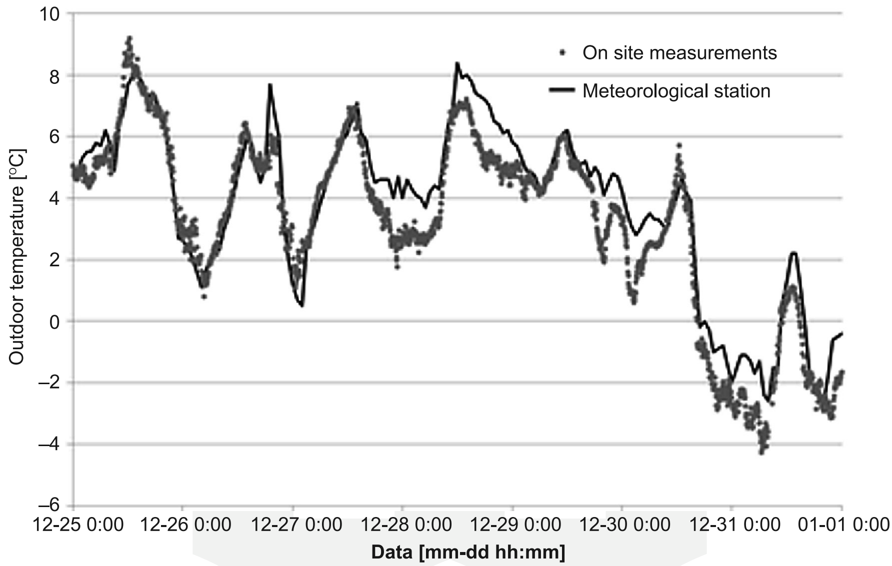

Fig. 3. Comparison of outdoor temperature collected by meteorological station (about 30 km away) and during onsite measurements

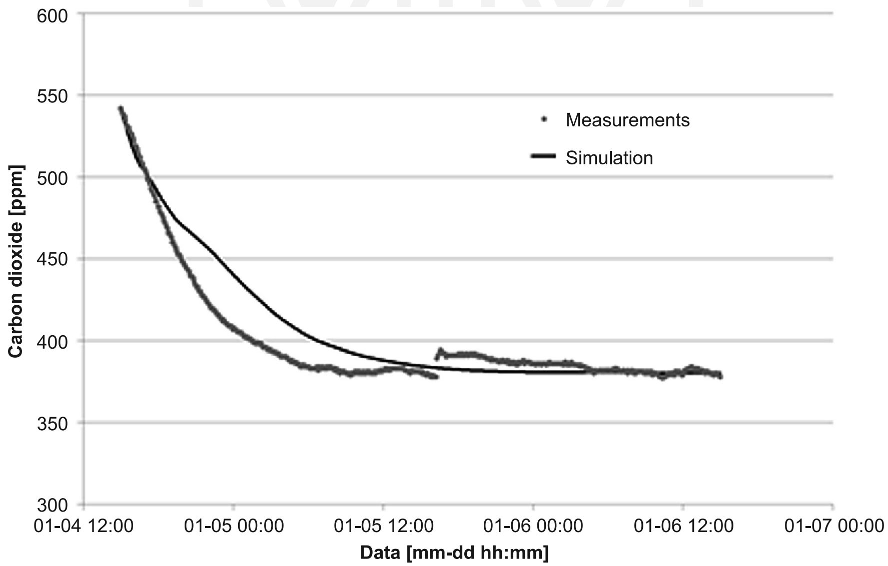

Fig. 4. Comparison measured data and simulated results. Decrease in CO_2 concentration in living-kitchen zone, after leaving house by occupant

Fig. 5 shows comparison of measured data and the data generated during simulation. It was observed that data suggests a higher increase of indoor temperature caused by direct sunlight. Explanation of this difference is that sensors were placed in specific locations

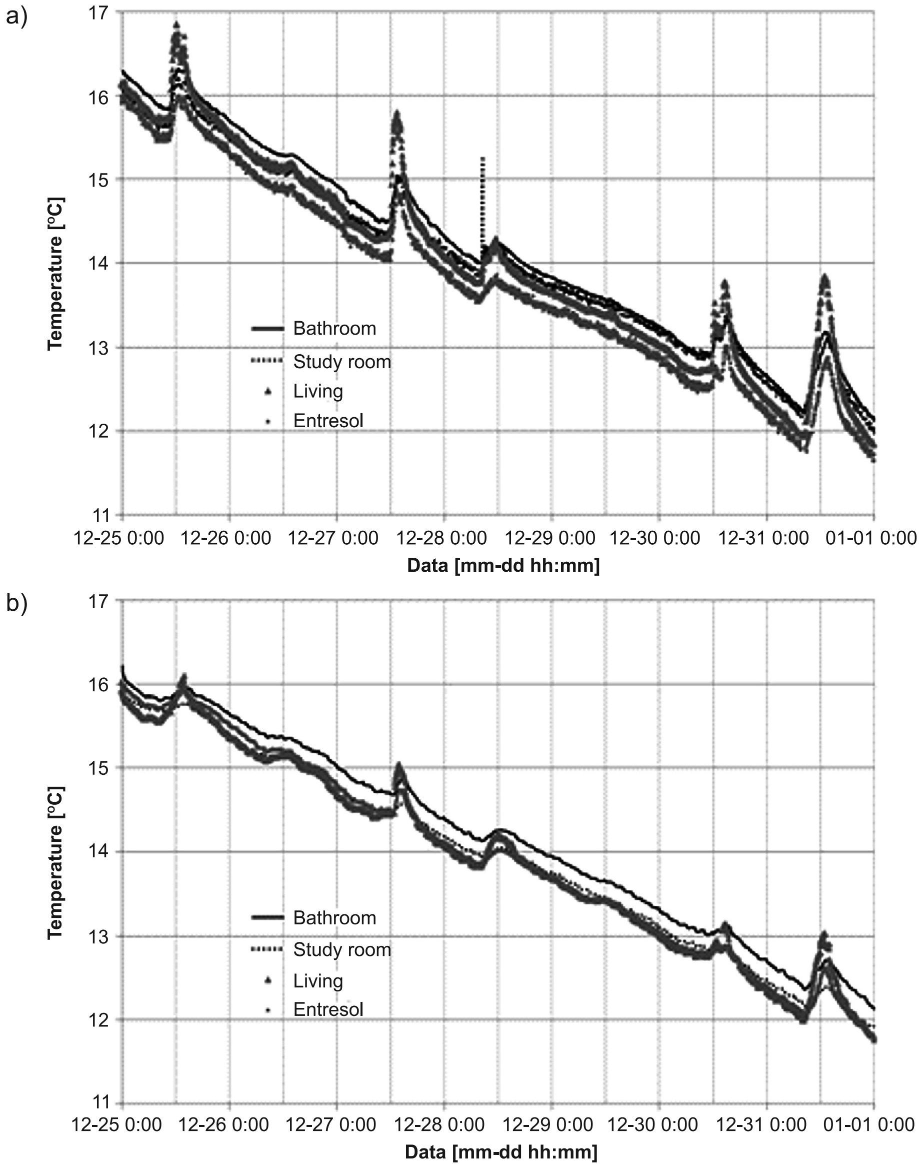

Fig. 5. Comparison of (a) measured and (b) simulated indoor temperatures of investigated building during cooling process

(e.g. close to windows) whereas the simulation calculates the mean temperature of the whole zone.

Monitoring of CO_2 concentration has also been carried out. These data are used to check assumptions regarding building airtightness. A comparison of the simulated and measured decrease in CO_2 concentration (in the unoccupied building) proves the accuracy of the envelope model (Fig. 4).

3.2. Accumulation stove model

The model of the stove is based on the manufacturer's technical specifications [3]. Because there is no detailed information about product Eva 1 that is being used in the investigated option of *DomTrzon*, approximations of stove parameters are deduced from the technical specifications of similar stoves. The operation of these stoves can be divided in three phases. The first phase lasts 2 hours, during this time single bath is burned and stoves warms up. Then, the accumulated energy released with almost constant (nominal) power over 6–8 hours. The power decreases during the last phase. All three phases together last about 48 h. Based on manufacturer specifications it is assumed that max. batch for the stove is 10 kg. Nominal power of the stove is maintained for 7 h and is equal 2.03 kW. The stove heat capacity stove is about 1500 kJ/K (Fig. 6).

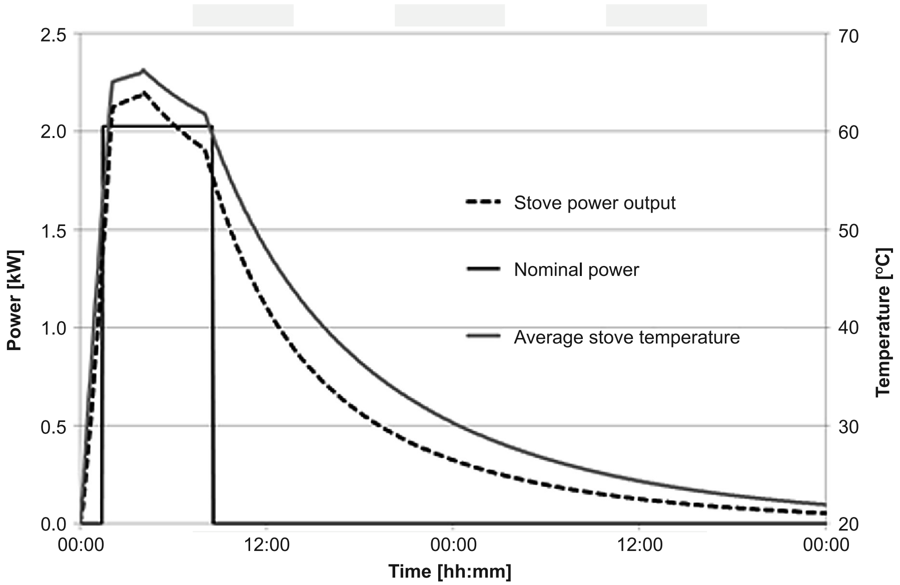

Fig. 6. Power and temperature output of accumulation stove installed in the investigated building

Heat transfer between stove and zones is realized by convection and radiation. Based on simplified calculation, two correlations have been identified:

$$h_{c+r} = f(t_{\text{stove}}) \tag{1}$$

$$\frac{Q_r}{Q} = f(\Delta t) \tag{2}$$

where

h_{c+r} – the total (radiation and convection) heat transfer coefficient,

Q_r – the radiation power released by stove to zone,

Q – the total power released by stove to zone,
t_{stove} – the average temperature of the stove,
Δt – the temperature difference between average stove temperature and mean temperature of zone.

The above correlation is used to calculate heat transfer between stove and zone. The heat from the stove emitted to the living-kitchen zone and bathroom is proportional to the stove's surface area turned towards the specified zone. These simplifications are based on the model presented by Georges and Novakovic, but their method is more detailed and verified [1].

4. Simulation

Poland is in the climatic zone where energy consumption by residential buildings is higher during the heating season, therefore, the analysis below takes into account the period from the 1st of November to 31st of March. Weather data are generated by Meteonorm as TMY2 data set for Poznań–Ławica meteorological station.

4.1. Ventilation system and stove operation

A ventilation system is two-mode. Both modes have a balanced supply/return airflow of 200 m^3/h. The first one uses a heat exchanger to restore heat from exhaust air. Heat exchanger efficiency is 82%, it is constant because airflow is also constant. Fresh air flows into the auxiliary heater before the heat exchanger. The heater ensures that the temperature of the air flowing into the heat exchanger is not lower than –5°C. If the indoor temperature is too high, then fresh air is supplied to the house through heat exchanger bypass. The second mode is turned on if the temperature of the exhausted air is higher than 22°C. The ventilation system returns to the first mode if the exhausted air temperature falls to 21°C.

The stove is used three times per day, at: 8AM, 1 PM and 8PM, for cooking purposes. The lower calorific value of burned wood is equal to 15.1 kJ/kg. The mass of batches depends on the time of day and indoor temperatures. If the exhausted air temperature falls below 19°C, the stove is fed according to the extreme mode until the temperature increases to 21°C, batches are then supplied again according to the standard mode.

Table 2

Mass of batches to the accumulation stove

Hour of day	Mass of batch [kg]	
	standard mode	extreme mode
8 AM	3	10
1 PM	8	10
8 PM	3	10

The efficiency of the combustion process depends on many factors, among others on the amount and temperature of air supplied to the fireplace. In reality, air to the fireplace is supplied from the living-kitchen zone. Because of the complexity of this solution and the lack of sufficient data (problem with modeling), it is assumed that air for combustion is supplied directly from outside and the efficiency of the combustion process is constant and equal to75%.

4.2. Results

A simulation was carried out to analyze the thermal comfort and energy consumption of the chosen variant of *DomTrzon*. Peeters et al. propose comfort temperature ranges for residential buildings that could easily be used in building energy simulation programs, they prove their approach based on literature and data review [5]. This approach is used to assess thermal comfort in the investigated house. Thermal comfort ranges are defined separately for bathrooms, bedrooms and other rooms – therefore, results are presented in three graphs (Fig. 7–9).

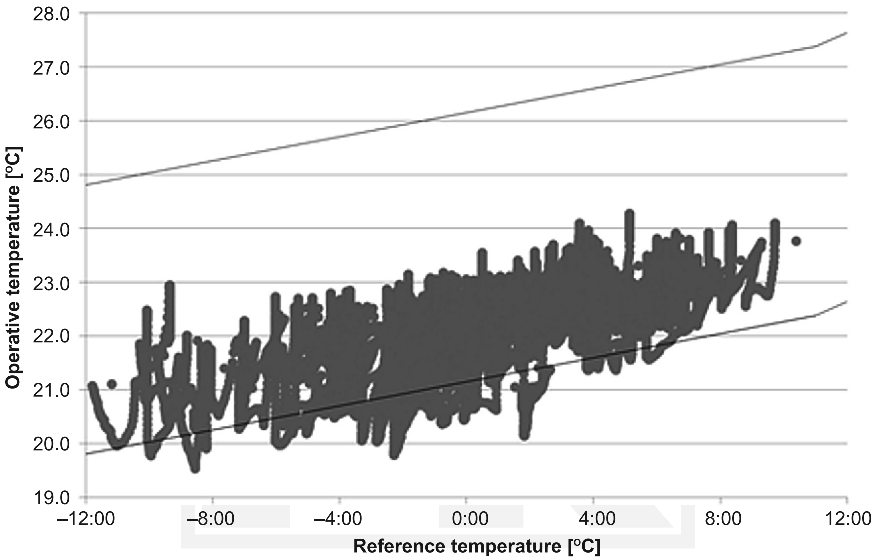

Fig. 7. Operative temperature in bathroom and thermal comfort range [5] during simulation period (November–March)

DomTrzon consumes energy in three ways: burning wood in the stove, running the ventilation system fans and heating fresh air in the auxiliary heater. The most energy is consumed by stove. **Final energy** (for heating and ventilation purposes) consumed by the building is compared with **energy demand** of the building and **primary energy** consumption of the heating and ventilation system (Fig. 10). **Energy demand** is calculated for buildings with indoor air temperature higher or equal to 24°C in the bathroom and 20°C in other rooms, the outside air flow rate into the building is equal to the ventilation air flow (200 m^3/h) and the heat exchanger efficiency is 82%. Internal heat gains are the same for **energy demand** and **final energy** (as described in section 2). Calculation of **primary energy** consumption is based on Polish methodology for building energy performance calculation [4].

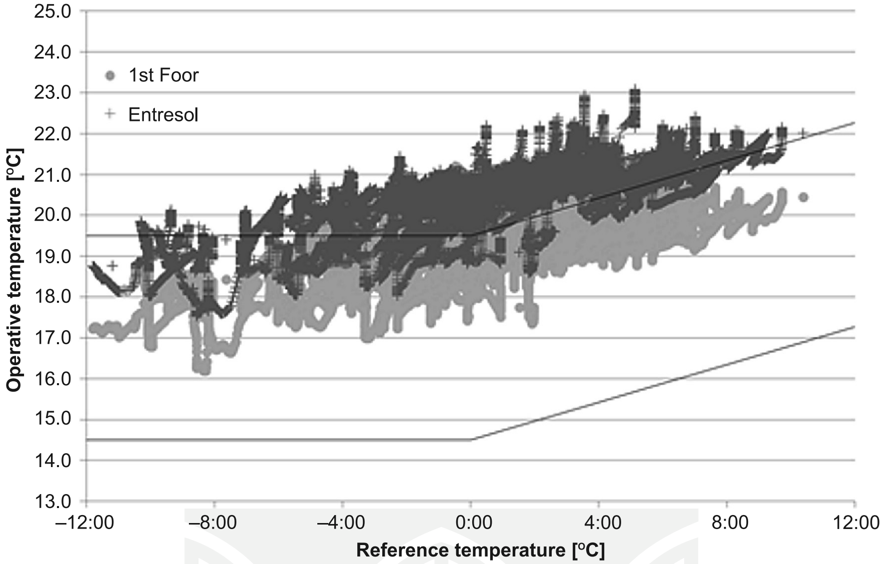

Fig. 8. Operative temperature in bedrooms and thermal comfort range [5] during simulation period (November–March)

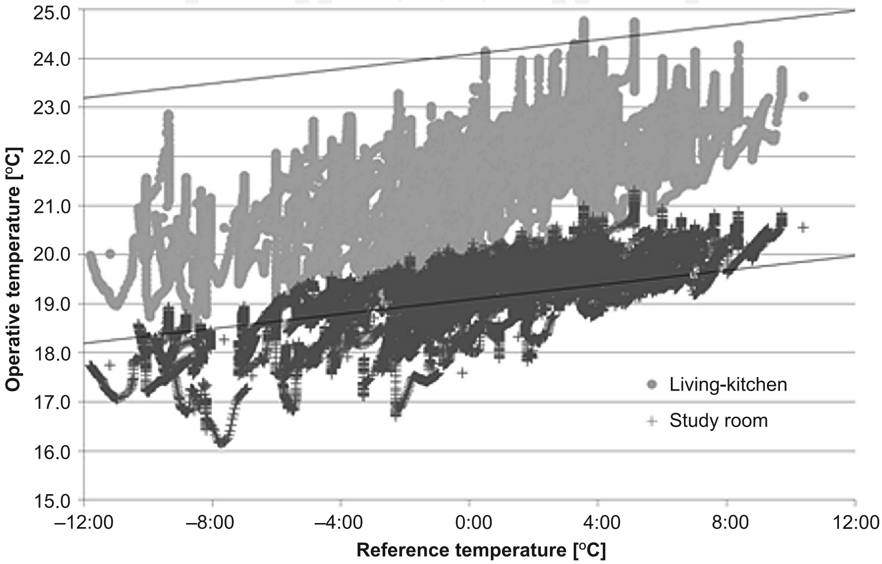

Fig. 9. Operative temperature in living zones (living kitchen and study room) and thermal comfort range [5] during simulation period (November–March)

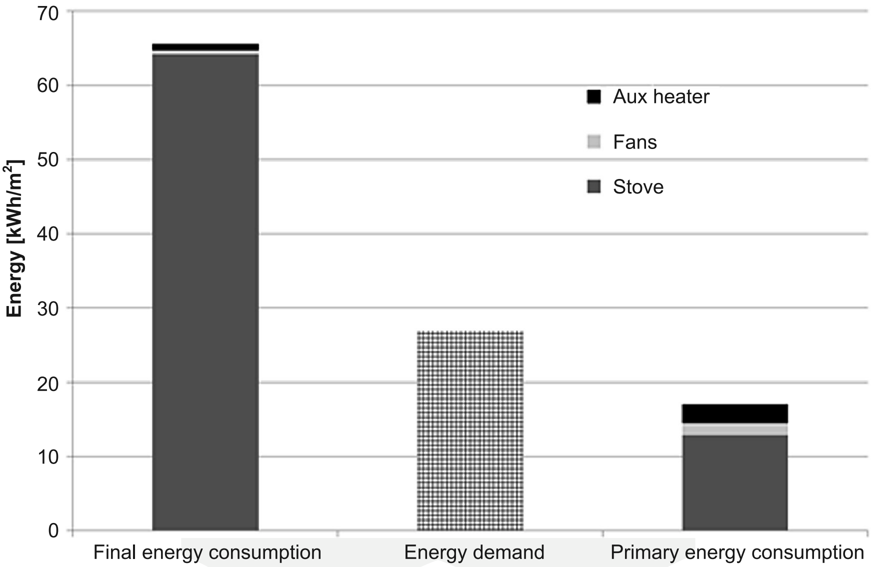

Fig. 10. **Final energy** consumption, **energy demand** and **primary energy** consumption (for heating and ventilation purposes) of investigated variant of *DomTrzon*

4.3. Discussion

It can be seen that high temperature differences occur in the building. The difference between the bathroom and the study room is about 3 K. The coldest zones are placed in the north side of the first floor because of a lack of solar radiation and the heat buoyancy effect. The highest temperatures occur in the center of the house and in zones close to the stove. The bathroom operative temperature is partially outside the thermal comfort range, but the coldest periods occur during the night-time, when zones are unoccupied. In the case of the bedroom zones, the situation is similar – comfortable temperatures are during the night time, when rooms are used. The entresol could also be used as a living room, because its operative temperature is in the comfortable range during the day-time. The worst situation is in the study room. Some days during winter are completely off the scale in this zone. On the other hand, it is stated by occupants that wooden walls cause the perceived temperature to be a bit higher than the measured one. Nonetheless, comfort in the study room is a serious problem especially if the activity of the occupants is very low.

Final energy consumption of the building is more than two times higher than **energy demand**. This is because the accumulation stove is used mainly for cooking purposes and therefore, a high temperature heat source is needed (which causes greater fuel consumption). It can be seen that on the one hand, an excess of heat causes high temperatures in zones close to the stove. On the other hand, there are some zones that, despite the energy excess, remain under-heated. Some of under-heated zones are 'cold' zones, as bedrooms, where lower temperatures are desired (Fig. 8). However, the indoor condition in the study room (Fig. 9) could be very uncomfortable if desk work is performed. It seems that better management or utilization of the occurring energy excess (e.g. by ventilation system modification) could improve the building's performance. The issue could be even more important during summer time because the energy excess is higher and stays in the living-kitchen zone and could become uncomfortable, especially in the middle of day.

Although the final energy consumption should be improved, the primary energy consumption (Fig. 10) is even lower than the energy demand, which proves that *DomTrzon* is a solution with highly sustainable energy efficiency potential.

5. Conclusions

Energy demand of the investigated *DomTrzon* is higher than in passive houses (15 kWh/m^2), but is still low. Moreover, its **primary energy** is lower than its **final energy** consumption. Therefore *DomTrzon* could be titled an ecological house. It can also be stated that *DomTrzon* ensures thermal comfort. However, there are a few issues that should be considered to develop the concept. The main ones are the management and utilization of excess energy from the stove and the low operative temperatures in the study room. Natural demand controlled ventilation should also be investigated as a solution to reduce investment costs. Any used and proposed solution should be also analyzed in summer and transitional seasons.

Proposed models are useful, but can also be developed. The combustion process should especially be considered in a more detailed way to take into account the amount and temperature of air and stack effect. Thereby, a real case could be investigated. More detailed calculations of heat exchange between zones and stove worth carrying out.

The weather data was donated by Joe Huang from www.whiteboxtechnologies.com. These data support is highly appreciated.

References

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