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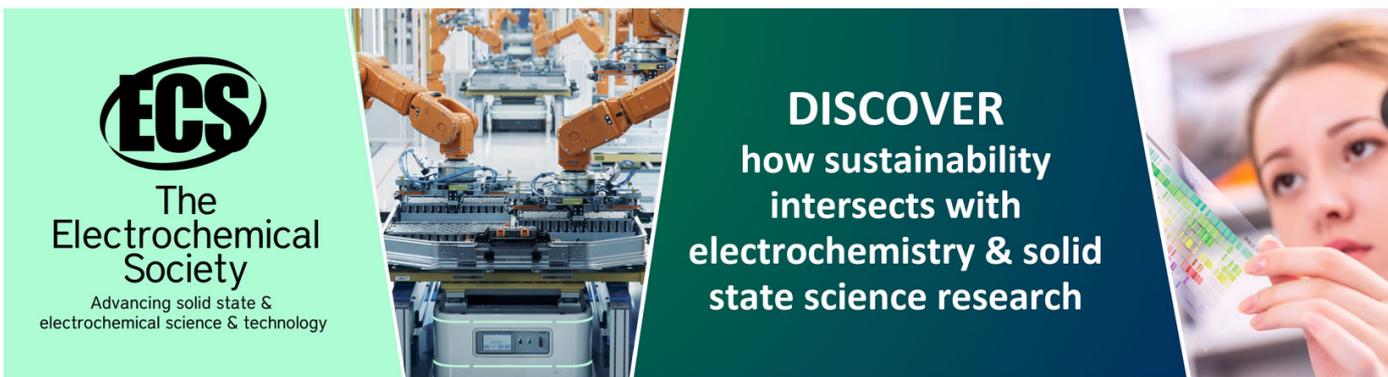
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Influence of Building Envelope Thermal Mass on Heating Design Temperature

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Abstract. The stability of indoor air parameters is a very important factor, essential for such institutions as museums, schools and hospitals. Nowadays the use of renewable energy for space heating became one of the top priorities in modern building design. The active and passive solar energy as well as heat pumps are widely used nowadays. However, such technologies have a limitation in cold climates and often are not able to cover maximal heating loads.

This paper is devoted to analysis of influence of building envelope's properties and outdoor air parameters on indoor air thermodynamic parameters stability in winter time. It presents analysis of thermal mass impact on building energy performance and indoor air parameter stability in cold climate. The results show that the thermal mass of building envelope is able to cover extreme winter temperatures as well as in case of emergency heat supply break.

1. Introduction

Since the early 1970ies, the U-value of building envelope has reached reasonable minimums. The latest publications show the potential for the wide implementation of different types of vacuum heat insulation materials and systems with very low heat conductivity coefficient. But in most cases the main benefits of such systems are not significant reduction in U-value but rather minimization of thickness of external envelope. According to passive house concept, the U-value is 0.1 W/(m²·K) for walls, roofs and 0.8 W/(m²·K) for windows [9]. In addition, solar heat gains for passive heating are widely implemented in the energy efficient building concept using the well-known principles of solar geometry [11]. So traditionally it is assumed that energy efficient buildings are supposed to have maximally high thermal and solar resistance of building envelope. At the same time, very low heat losses during winter time can lead to overheating in spring/autumn period due to high internal heat

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gains, increasing thermal discomfort. Incorrect windows size and placement in addition to incorrect use of shading approach can cause space overheating during hot and sunny days in summer time [8]. In practice, high thermal resistance is only needed in coldest winter days in the countries with cold climate or on hot summer days. The author [6] already presented principal solutions for changeable thermal properties of building envelope for accumulated heat discharge for passive cooling strategies and heat losses minimization during winter days.

In the last decade, the use of thermal mass for reduction of cooling/heating loads and improvements of thermal comfort has become a widely discussed research topic in different climatic zones. The research [11] shows that the timber-framed houses have higher daily amplitudes of humidity and temperature than the heavyweight. Also [4] shows the positive influence of thermal mass on energy savings and stability of indoor air temperature during the winter time. In turn, Kosny (2001) research estimates that energy savings for the whole building made from high thermal mass envelope is up to 8% in heating dominated region. Study [18] shows possible savings for heating and cooling by using masonry with smaller surface absorptivity. At the same time savings also depend upon utility incentives, building construction, climate, and the type of air conditioning system [2].

The thermal mass became a topical issue in the 1930ies [16]. Later the research on thermal mass was continued by [15, 5] in the 1950ies. All these researches considered thermal mass as a possibility for energy accumulation in winter time in cold climatic zones and creation of comfort indoor parameter in summer time in hot climatic zones. Before the 1960ies, thermal mass was topical in terms of energy accumulation due to the absence of centralized heating systems. The apartments were heated manually by inhabitants using local wood boilers and it was important that during the day between operation of boiler indoor air temperature did not drop below dew-point. The thermal mass for hot climatic zones was considered as a measure for creation of comfort indoor air parameters mainly due to lack of air-conditioning systems.

Nowadays, when energy prices went up and sustainable construction is a priority, all above-mentioned benefits of thermal mass became also topical in modern construction. But it should be noted that modern HVAC systems have advanced automatic as well as manual control possibilities in order to adjust indoor air parameters according to inhabitant needs and outdoor air parameters. The inappropriate combination of high thermal mass and modern HVAC automation systems can lead to such negative effect as:

- ✓ building overheating under rapid outdoor air temperature fluctuation;
- ✓ increase of energy consumption for building heating/cooling after the night/weekend indoor temperature reduction;
- ✓ building overheating in hot summer days when accumulated heat has not been discharged during the night.

It can be concluded that nowadays the choice of optimal thermal properties of building envelope for indoor air thermodynamic parameters stability became a great challenge for architects and HVAC designers. In order to use the benefits of the thermal mass, special control of heating system should be introduced on the basis of weather analysis and forecast.

Recent research [19] has proved that currently used winter design temperatures are overestimated. The above-mentioned research provides recommendation for winter design outdoor air temperature in Kaunas. According to the research study, the existing winter design temperatures exceed research recommendation by 33%-40%.

2. Methods

Fifty buildings were selected for the experiment; they were divided into two groups: lightweight construction buildings and massive construction buildings. For each building, measurements were conducted during the winter period from 2009 to the winter months of 2013. The heat consumption of the buildings was assessed during the work. For the purposes of the study, the data were obtained from heat supply organizations regarding the heat consumed during the heating season, while building owners and other public institutions provided information regarding the number of inhabitants and technical information regarding the building enclosures. In analyzing the data obtained in each building group, measurements of the building enclosures and measurements of indoor ambient temperature and air humidity were conducted for each building by installing two measuring instruments: Testo 635-2 at the building enclosures and Testo 175-H2 in the middle of the room. The total area of the described lightweight construction buildings is 235.8 m², the total area of the massive construction buildings – 8684.3 m².

To analyze the measurement data in real conditions, the work process involved the use of simulation software Computational Fluid Dynamics (CFD) Autodesk Simulation CFD 2013, which is based on a process that combines the real conditions with mathematical calculations. The software allows assessing activity by using modeling. The simulation software uses extensive calculations to ensure that the final result is as close as possible to the real conditions. The analysed room model is presented in figure 1.

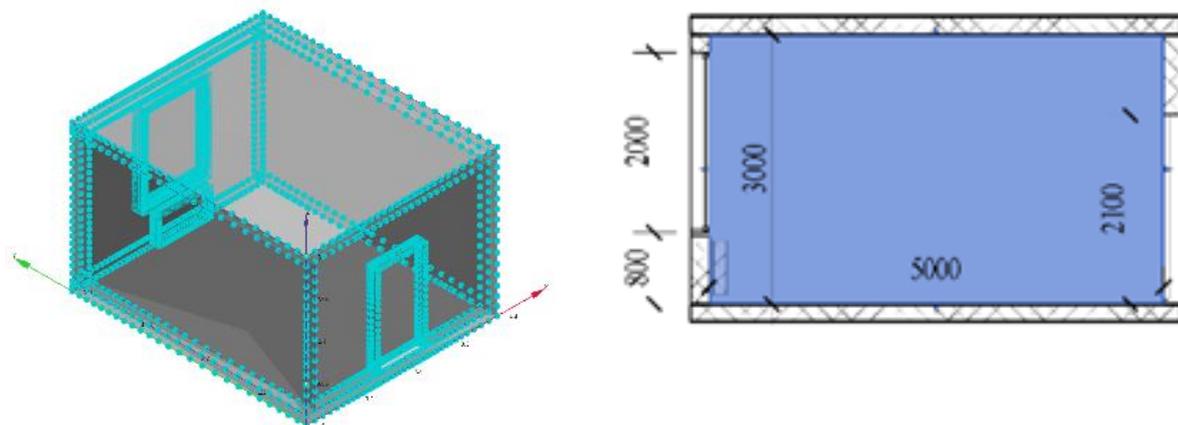


Figure 1. Analysed room model.

3. Interconnection between building elements

As a rule, the building envelope is a passive element and the HVAC system is an active element regarding the possibility of regulation in order to ensure optimal indoor air parameters. In case a building has high thermal mass, the building envelope can work as an active element and insure stability of air thermodynamic properties. In order to use positive effect of thermal mass, the choice of HVAC working regimes and capacity should be based on outdoor air conditions and properties of the building envelope. The paper [17] also present approach that adopts building envelope, air change rate and heating/cooling loads according to the requirement regarding indoor air parameters.

Taking into consideration the above-mentioned studies, figure 2 demonstrates interconnection between building elements, indoor air temperature (IAT) and outdoor air conditions.

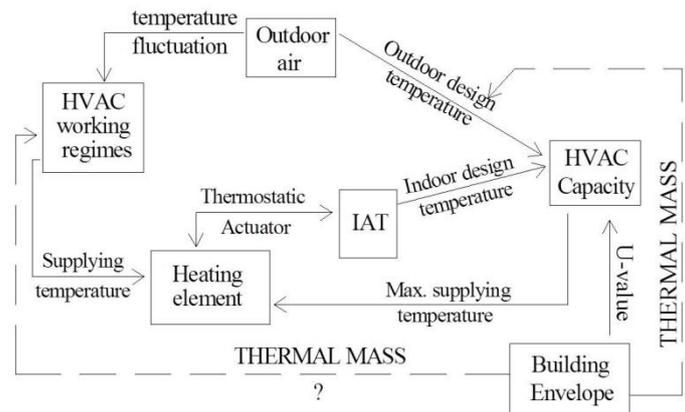


Figure 2. Interconnection between building elements.

4. Calculation of heating source capacity

For calculation of heating boiler capacity, constant temperature is usually used. The correctly chosen outdoor temperature allows improving energy performance of heating system and ensuring stability of indoor air thermodynamic parameters. At the moment, there is no clear methodology how to choose outdoor air temperature for calculation of heating boiler capacity.

Before 2000 for evaluation of heating system capacity the following range of outdoor temperatures was taken into account [1]:

- ✓ average temperature of the coldest 5 days;
- ✓ average temperature of the coldest 3 days;
- ✓ average temperature of all coldest days;
- ✓ absolutely minimal temperature.

The approach that had existed before the 1990ies was developed for external envelope with heat transfer coefficient $0.7 - 1.4 \text{ W}/(\text{m}^2 \cdot \text{K})$. In addition, the heating systems were without any regulation possibilities. So there was no any outdoor temperature sensors, circulation pumps, etc. The group of 5-9 multi-storey apartment buildings was connected directly to one centralized heat substation. In such case the impact of building envelope thermal mass was crucial as regards the indoor air parameters stability.

The choice of outdoor temperature depended on heat inertia of external building envelope before the 1990ies. In general, heat inertia is calculated using the following equation (1):

$$D = \sum R_i \cdot \sqrt{\frac{2\pi\lambda\gamma c}{z}} \quad (1)$$

Where,

z – time period of heat flow fluctuation; R – thermal resistance, $(\text{m}^2 \cdot \text{K})/\text{W}$. S thermal capacity, $\text{W}/(\text{m}^2 \cdot \text{K})$.

At the same time, the study by (Olsen 2008) presents the following equation (2):

$$S = c \cdot q \cdot t \quad (2)$$

Where,

t – thickness of material, m.

The proposed [14] equation does not take into account the time period of heat flow fluctuation and material thermal conductivity. Table 1 shows the outdoor design temperature for Riga City according to Latvian building code LBN003-01 “Building Climatology” [13]. The average temperature of heating period is 0 °C.

Table 1. Outdoor design temperature for Riga city and heating boiler capacity.

	Outdoor design temperature °C according to existing practice in Latvia	Heating boiler heat capacity %
Average temperature of the coldest 5 days (probability 0.92)*	– 20.7	100
Average temperature of the coldest 5 days (probability 0.98)	– 24.6	119
Absolutely minimal temperature (once in 10 years)	– 31	150
Absolutely minimal temperature (once in 50 years)	– 34.8	168
Heating season’s average temperature	0	49

* now used for calculation of heating systems’ maximal capacity

One of the main tasks of a designer is to choose correct outdoor air design temperature. Currently only average temperature of the coldest 5 days with probability 0.92 (-20.7°C) is used in Latvia in order to calculate the capacity of heating boiler and heating elements. This approach does not take into account the heat capacity of building external and internal elements that can lead to indoor temperature reduction below set point under extreme outdoor temperatures. For example, under Latvia climatic condition the outdoor air parameters below design condition can reach consequent 17 hours long time period. Figure 3 presents the outdoor temperature fluctuations for February 14 – 16, 2010 in Riga.

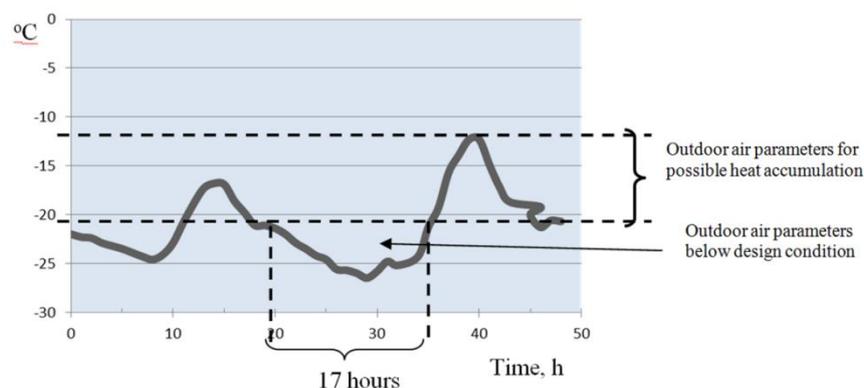


Figure 3. Outdoor temperature fluctuations in February 2012 in Riga.

In order to find the number of hours below design condition, it is necessary to use hourly spread of outdoor air parameters. The example of average temperatures and relative humidity during the 10-year monitoring period for the capital city of Latvia Riga is given in figure 4. This table shows monthly iteration of outside air parameters in three time zones of the day: from 0.00 till 8.00, from 8.00 till 16.00 and from 16.00 till 24.00.

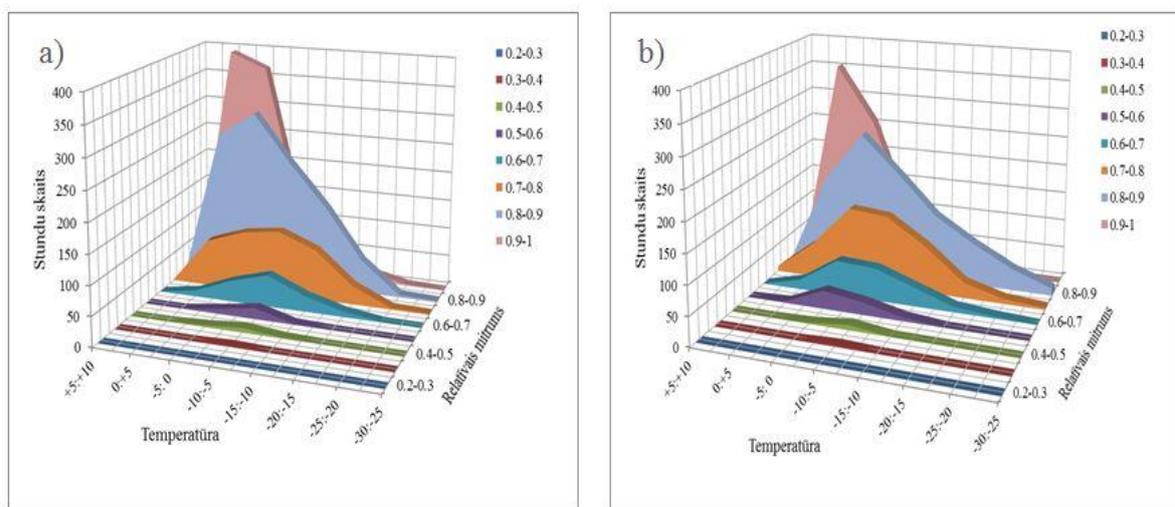


Figure 4. Number of hours in November (a) and December (b) at the respective temperature and relative humidity for three daily time zones in Riga, Latvia (during 10-year monitoring period).

In case of Latvia, the outdoor air temperature was below heating system design temperature for 305 hours during the 10-year weather monitoring period. That means 30 hours per average year. It is the task for a building owner to define correctly the requirements for stability of indoor air parameters and the designer consequently should select the best ratio between thermal mass and heating system maximal capacity. At the same time it should be mentioned that thermal mass has an important effect on stability of indoor air temperature in case of heat supply break [10].

5. Influence of thermal mass on indoor air parameters stability in winter time

The enclosure of the lightweight construction house has been renovated with a heat insulation layer. The construction of the load-bearing walls consists of 180 mm thick wood beams with ecowool cladding and a 50 mm stone wool heat insulation layer on a framework of 5 cm thick planks on the outside. According to the calculation, the thermal resistance of the wall $R = 5.089 \text{ (m}^2\text{K)/W}$.

Practical measurements have shown that outdoor ambient temperature ranged from -5.2°C to $+2.7^\circ\text{C}$, and the difference between the wall internal surface temperature and the indoor ambient temperature was 0.68 or 3.7%. Indoor relative humidity fluctuated from 35.1% to 42.08%, which is an acceptable range for human comfort. Indoor ambient temperature during the study fluctuated by as much as 5.8°C , which is a relatively large range, and the fluctuations are frequent, which is dictated by the outdoor ambient temperature and may cause discomfort to the people in the room.

The software Autodesk Simulation CFD 2013 was used to simulate a model corresponding to the characteristics of the building with the experimentally obtained data and in accordance with the previously described selection of the room model (figure 5).

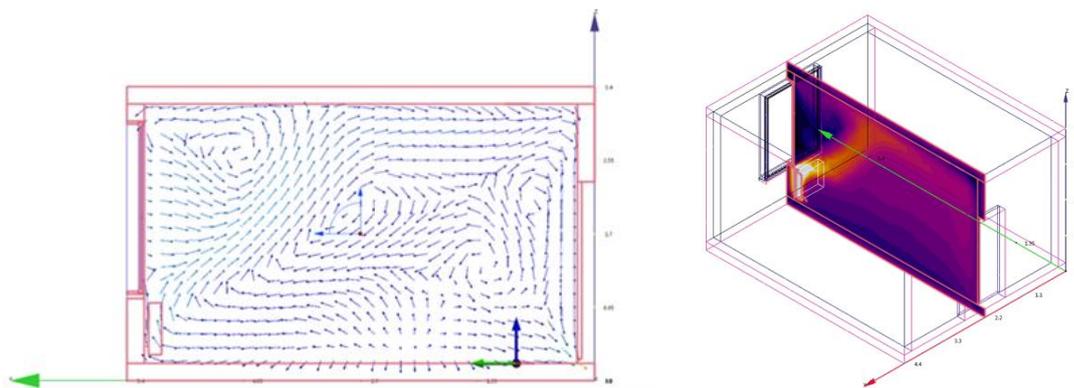


Figure 5. Air flow direction and air temperature distribution in the room.

Air flow in the building is shown with the help of vectors and corresponds to actual indoor air flow exchange.

The enclosure of the massive construction house is cast reinforced concrete with a heat insulation layer. The load-bearing wall of the building consists of 300 mm thick cast reinforced concrete with a 100 mm thick insulation layer of stone wool. The interior lining is a single layer of plaster; on the outside, there is painted plaster on a grid. Three people inhabit the room where the measuring instruments have been placed.

During the practical measurements, outdoor ambient temperature ranged from $-10.1\text{ }^{\circ}\text{C}$ to $+5.9\text{ }^{\circ}\text{C}$, and the difference between the wall internal surface temperature and the indoor ambient temperature was 1 or 5.1%. Indoor relative humidity ranged from 31.4% to 51.7%, which is an acceptable range for human comfort.

Indoor ambient temperature during the study fluctuated by $2.9\text{ }^{\circ}\text{C}$, which is a small range, and the fluctuation period was gradually rising or falling depending on the surface temperature; consequently, a person staying in the room feels comfortable.

As the chart shows, heat flow is variable in the middle of the room, which evidences constant movement of the warm air following the air flow vector lines. However, temperature in the middle of the room in accordance with the model has been modelled precisely and corresponds to the experimental measurement: $-19.4\text{ }^{\circ}\text{C}$ (figure 6).

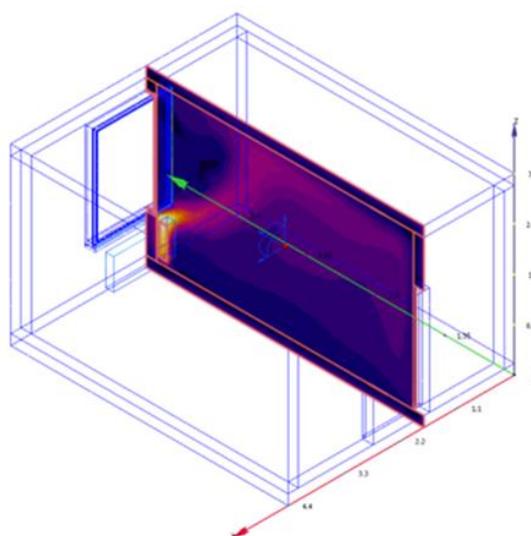


Figure 6. Indoor temperature distribution in 3D format.

6. Optimization of heating system, taking into consideration the solidity of buildings

The thermal stability of a room is the ability to reduce indoor ambient temperature fluctuations upon fluctuations in the heat flow of the heating system. The smaller the fluctuation range of ambient temperature in the room at the same conditions, the more stable it is. Thermal stability is most linked with the solidity of the building enclosure; if the wall is more massive, it maintains heat better. The lower the inside surface temperature changes at the same ambient temperature range, the more stable it is, and vice versa. As the acceptable range of temperature fluctuations is ± 3 °C, using previously experimentally proven data, it can be assumed that this value for premises with lighter enclosures fluctuates within a much larger range than for massive enclosures. Heat transfer rate fluctuations of the heating device are assessed based on the variation coefficient m , which is determined in accordance with the formula [Tabunikov] (3):

$$m = \frac{Q_{max} - Q_{min}}{2Q_z} \quad (3)$$

where: Q – the maximum heat transfer rate of the heating system, Wh; Q – the minimum heat transfer rate.

The value m depends on the heating system and its operation. The coefficient m has a great significance in determining the indoor temperature fluctuation range, i.e. in assessment of the indoor thermal stability.

It was previously believed that if district heating is used, the value of coefficient m is 0.1, but in finite element computational dynamics software, it was proven that the coefficient varies both at different temperatures and depending on whether the external wall is lightweight or massive. The obtained results are presented in table 2.

In order to determine a more accurate value of the variation coefficient, like before, a model was simulated with the effect of external weather conditions.

Table 2. Calculation values of coefficient m at various outdoor ambient temperature values.

t °C	0°C – (10°C)	(-10°C) – (-15°C)	(-15°C) – (-20.7°C)
Construction			
Light weight construction	0.06	0.20	0.30
Massive wall construction	0.10	0.23	0.36

7. Conclusion

The indoor temperature fluctuation range for massive constructions is $\pm 4^\circ\text{C}$, for lightweight constructions: $\pm 6^\circ\text{C}$. The fluctuation range of massive constructions also exceeds the permissible range of $\pm 3^\circ\text{C}$, but only by one degree, which might not be felt in practice, while for lightweight constructions the range is exceeded twofold, which causes discomfort in the premises.

The mathematical model of buildings developed as part of the thesis proved that it is unnecessary for the heating systems of massive construction buildings to use the lowest temperature of 5 days, because when the temperature temporarily falls below -15°C , the indoor temperature does not decline sharply; the same cannot be said about lightweight construction buildings – their indoor temperature, in accordance with experimental data, fluctuates along with the outdoor temperature.

A detailed model can be used for the processing of experimental data – as proven in this work, by using a simplified, approximated model, it is possible to obtain real values of weather conditions and indoor parameters.

The experimental measurements are dependent on the outdoor air parameters, which are variable and differ each year. Because of that, the obtained results may differ in other time periods, and therefore the final conclusions and results provide only general information, which may slightly vary from year to year.

Thermal stability is an important property of building constructions; if it is impossible in an emergency to quickly restore heat supply, the massive construction walls are able to maintain heat in the building for 8 h or 33% longer than a lightweight construction building.

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