IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Energy Analysis And Cost Efficiency of External Partitions In Low Energy Buildings

To cite this article: Malgorzata Fedorczak-Cisak *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 112095

IOP Conf. Series: Materials Science and Engineering 471 (2019) 112095 doi:10.1088/1757-899X/471/11/112095

Energy Analysis And Cost Efficiency of External Partitions In Low Energy Buildings

Malgorzata Fedorczak-Cisak [1], Marcin Furtak [1], Grzegorz Hayduk [2], Pawel Kwasnowski [2]

[1] Cracow University of Technology, Malopolska Laboratoty of Energy Efficient Buildings, Warszawska 24, 31-155 Kraków, Poland
[2] AGH University of Science and Technology, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering,
al. A. Mickiewicza 30, 30-059 Kraków, Poland

mfedorczak-cisak@pk.edu.pl

Abstract. Energy efficiency is a very important factor in the construction sector. Construction consumes about 40% of total energy consumption in the world. New buildings in Poland and other European countries are designed according to strict requirements. An important aspect is to ensure thermal protection of the external partitions. To meet the requirements of thermal protection, the heat transfer coefficient of the building barriers must be at the appropriate level, specified in the Technical Conditions. Calculation of heat transfer coefficients of external walls, however, do not assume dynamic influence of external and internal environment conditions. The dynamic influences of environments on both sides of the barrier affect the thermal resistance, and thus the energy consumption and heating costs. In the experimental building of the Malopolska Laboratory of Energy Efficient Building, located on the campus of the Cracow University of Technology, experiments are carried out to describe the phenomena occurring in the partitions. The building has over 3000 temperature sensors built into its construction. Many temperature sensors are placed in the external walls. At the same time, measurements of temperature, humidity and solar radiation are recorded. These data will allow the analysis of phenomena occurring in the external wall under various weather conditions.
Temperature sensors were placed in the construction layer. Subsequent sensors are arranged between the insulation layers, which are arranged in four layers of 5 cm. The last sensors were located on two sides of the ventilated slot. The gap is similar to external conditions. The experiment is to provide an answer to the extent to which wind, sun or rain affect the deterioration or improvement of the thermal resistance of the external wall. The results from the measurements will be compared with the calculated temperatures in the partition. This experiment will allow assessing whether the methodology for calculating the thermal resistance and temperature drops in the partition is accurate. In the second part, the Authors will analyse the purposefulness of using modern thermal insulation materials such as aerogels in terms of cost.

1. Introduction

In 2010, a new version of the recast Directive 2002/91 / EC of 16 December 2002 [1] was published by the Parliament and the Council of the European Union on the Energy Performance of Buildings of the EPBD [2].

In the recast Directive, European Union Member States have committed themselves to undertake activities in the construction sector aimed at improving energy efficiency and increasing the share of renewable energy sources in the overall energy balance of buildings.

One of the requirements of the Directive is to adapt the standard of newly designed buildings in European countries to buildings with nearly zero-energy demand (NZEB buildings).

The implementation of Directive 2010/31 / EU [2] is related to the amendment of national laws, the introduction of new regulations into the legislation, required by the provisions contained in the Directive.

However, Member States have to set minimum requirements for nearly zero-energy buildings themselves, adapting them to the development of technologies in each country. This standard will apply to all newly designed buildings from December 31, 2020. Each EU Member State must designate the level of requirements for nearly zero-energy buildings, based on Delegated Regulation 244/2012 [3] [4], which complements Directive 2010/31 / EU [2].

In Poland, the Minister of Infrastructure and Development decided to gradually tighten the provisions contained in the amendment to the Regulation in the matter of technical conditions that should be met by buildings and their location [5]. In January 2017, the regulations on energy efficiency were further tightened. The last and at the same time introducing the standard of buildings with nearly zero energy demand, will take place in all European Union countries on 01.01.2021. In Poland, the gradual tightening of regulations is aimed at adapting all participants of the construction market to stringent legal requirements.

The requirements for building Energy Performance are given for external partitions (table 1) and for total Primary Energy consumed by the building. The new requirements bring the demand to introduce new technologies or improve old ones to fulfil better parameters.

Innovative laboratories and research centres are indispensable for developing new, better technologies. They allow testing and research on building materials. Specialized measurements and simulations are carried out in research centres. Such a centre is the Malopolskie Laboratorium Budownictwa Energooszczędnego (Malopolska Laboratory of Energy-efficient Buildings) at the Cracow University of Technology.

This article focuses on technologies of erecting external walls in energy-saving buildings. In the article, the authors concentrated on detailed presentation of solutions for temperature measurements in structural components of the buildings and on the structure of the entire measurement system, methodology of the design and properties of the system of data acquisition, registration, visualisation and the data processing of the measured data.

The test results were compared with static calculations to show what is the effect of dynamic conditions on the thermal parameters of partitions.

In the second part of the article, the authors presented studies on modern thermal insulation systems. In the analyses, the thickness of different thermal insulation materials was compared, assuming that the partition achieves the same values of heat transfer coefficients. Styrofoam with different thermal protection parameters and innovative thermal insulation material - airgel - were analysed. An analysis of costs for various thermal insulation layers and an analysis of the costs of renting space using these materials were carried out.

2. Calculation of thermal resistance and heat transfer coefficient of external partitions

The design of energy-efficient buildings enforces the obligation to use appropriate building envelope, compliant with the requirements of the Technical Conditions [5] for the thermal protection of the building. In the light of the regulations, the parameters of the external building envelope (external walls, windows, floors and roof) should be selected, so that they have appropriate values determining their level of thermal insulation, while ensuring thermal comfort felt by users and protection of barriers against degradation caused by moisture and water. Thermal protection of external partitions is determined by the heat transfer coefficient U [W/m^{2}K], calculated in accordance with the methodology given in [6], and the thermal conductivity coefficient λ [W/(mK)], characterizing construction materials in terms of thermal parameters. The value of coefficient λ is a normative value [7] or declared by the manufacturer based on tests carried out in accredited laboratories. The relationship between the two factors is determined by the formula:

$$U = 1/R_T = 1/[R_{si} + \Sigma d/\lambda + R_{se}], \quad (1)$$

where:
U – heat transfer coefficient [W/(m^{2}K)]
R_{si} – resistance of absorbed heat on the inner surface [(m^{2}K)/W]
d – thickness of the i-th layer [m]
λ –heat transfer coefficient of the i-th layer [W/(mK)]
R_{se} – resistance of absorbed heat on the external surface [(m^{2}K)/W]

Polish requirements for partitions and the technical equipment of the building must comply with the requirements of thermal insulation specified by the U-value, at:

Table 1. Polish requirements for partitions

Type of partition and temperature inside room	Heat transfer coefficient $U_{C(max)}$ [W/(m^2·K)]		
	from 1.01.2014	from 1.01.2017	from 1.01.2021
External walls:			
with $t_i \geq 16°C$	0.25	0.23	0.20
Roofs and floors:			
with $t_i \geq 16°C$	0.20	0.18	0.15
Floor on the ground:			
with $t_i \geq 16°C$		0.30	
Windows:			
with $t_i \geq 16°C$	1.3	1.1	0.9
Doors in external walls	1.7	1.5	1.3

The calculated value of heat transfer coefficient U, we enlarge with corrections due to leaks and breakthroughs of thermal insulation and we compare them with admissible values from table 2.

$$U_c = U + \Delta U \leq U_{max} \quad (2)$$

Many factors influence the actual thermal insulation of the barrier and materials. One of them is dampness of the barrier by inter-layer condensation of diffusing water vapour. Dynamic factors of the internal and external climate are also very important, such as sunshine, wind or changing temperature. The calculation method in accordance with the standard [6] does not include these parameters.

3. In situ studies of temperature drops in the partition

3.1. Malopolska Laboratory of Energy Efficient Building (MLBE)

MLBE is an experimental laboratory and research building operating at the Cracow University of Technology from 2014.

The external walls of the MLBE building are made in various technologies, such as cellular concrete, brick, and ceramic block. The walls are insulated with styrofoam in four layers of 5 cm, so that it is possible to place temperature sensors between them. There is an air gap between the facade and the thermal insulation layer. The external facade is made of clinker brick.

The MLBE building is fully metered. Over 3000 sensors are located in the building compartments and installations. The readings from the sensors, inter alia, represent heat transfer through the partitions. All sensors readings are stored in archives.

Location of measurement areas is shown in Figure 1.

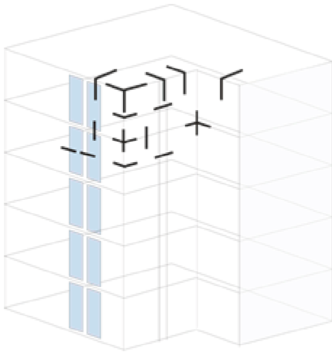

Figure 1. Location of measurement areas of the envelopes

An example of defining "Details" of measurement areas on the plan of a chosen storey is shown in Figure 2.

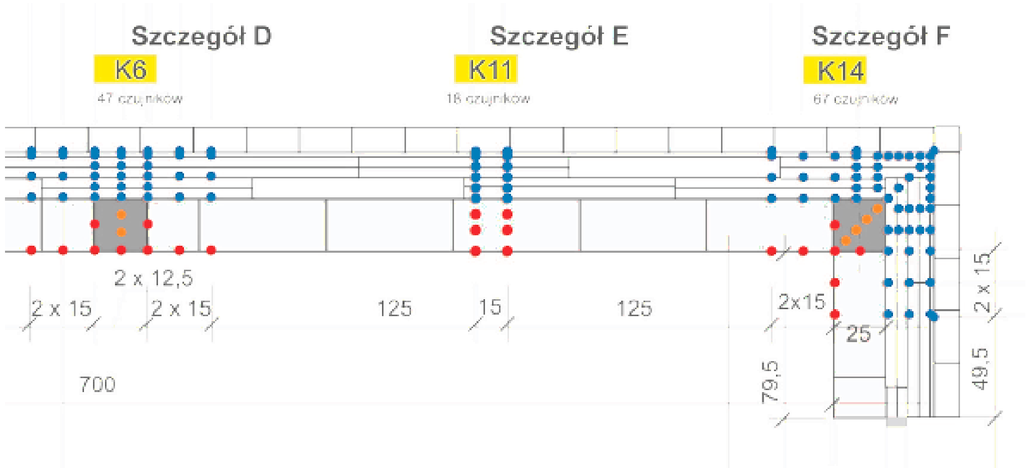

Figure 2. Example of defining "Details" (Szczegół) on the plan of a building

In this article, the Authors performed a comparison of calculations and test results for the temperature distribution in the partition.

3.2. Calculation of the temperature distribution in the partition in the MLBE building

Using the formulas (1) (2), the thermal resistance and temperature course was calculated for the K11 sensors, located far away from the thermal bridges.

The temperature waveform in the partition is calculated on the basis of the formula:

$$\Delta T = R_j/R_T(T_i\text{-}T_e) \quad (3)$$

Table 2. Calculation of temperatures in individual septum layers

Layer	d	λ	R	ΔT	T
	m	W/(mK)	(m²K)/W	K	°C
internal air	-	-	-	-	20
the inner surface of the wall	-	-	0.13	0.35	19.65
cement-lime plaster	0.015	0.82	0.02	0.05	19.60
cellular concrete Termalica	0.30	0.14	2.14	5.78	13.81
EPS 0,38 facade super (4 x 0,05 m)	0.20	0.038	5.26	14.21	-0.39
air gap	0.03		0.18	0.49	-0.88
clinker brick	0.12	1.05	0.11	0.31	-1.19
outside air	-	-	0.04	0.11	-1.30

Thermal resistance coefficient $R_T = R_{si} + \Sigma R + R_{se} = 7,89$ [(m²K)/W]
Heat transfer coefficient $U = 1/R_T = 0,12$ [W/(m²K)]

According to calculations, the barrier not only achieves the U_{max} parameter for Polish technical conditions (table 1)

1) $U_{max} \leq 0,23$ but also achieves a parameter acceptable for passive buildings for which
2) $U_{maxpassive} \leq 0,15$ [W/(m²K)]

The design temperature of the residential rooms [8] 20^{0}C and the average monthly temperature for January according to [9] for the Małopolska locality was adopted for the temperature chart.

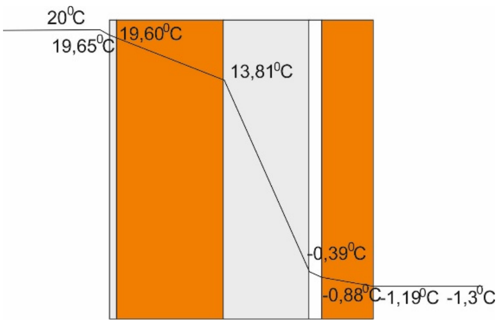

Figure 3. Computational temperature chart for the building envelope MLBE

3.3. Results of tests of the distribution of temperatures in the partition in the MLBE building

3.3.1. Temperature sensors in a building construction

Having analysed the market of electronic temperature sensors when realising the MLBE building project, TSic™ family of sensors from a Swiss manufacturer Innovative Sensor Technology was identified, which met the requirements of the system sensors. The TSic™ sensors use a precise reference source, based on bandgap reference, using compensation of temperature influence by the method of generating current proportional to absolute temperature – PTAP [16]. Such a solution ensures high precision and long-term stability of the sensor with no need for calibration during usage. Temperature sensors were made in the form of one-sidedly closed stainless steel tubes of 6 mm in diameter and 30 mm in length. Sensors are connected with the KCT data hubs, which serve readings from the sensors and transmit measurement data to the data collecting system.

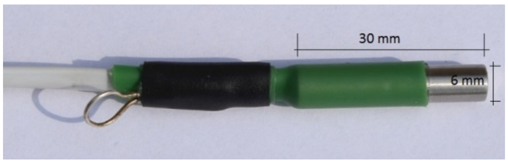

Figure 4. An example of CCT temperature sensor

Sensors were installed in probes installed in walls and ceilings during construction process of the building. In figure 5 the single probe for installation in ceiling "Details" is presented.

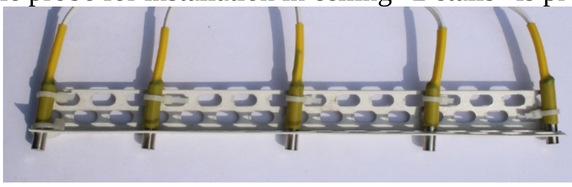

Figure 5. Single probe (row of sensors) for ceiling temperature measurement

3.3.2. „In situ" testing results

Figure 6 shows the internal temperature diagram in the room where the tests were carried out. The setpoint temperature was 20ºC. Figure 7 shows the readings of external temperature and external humidity from the meteo station located on the roof. All measurements were taken on January 1, 2018. Measurements lasted 24 hours.

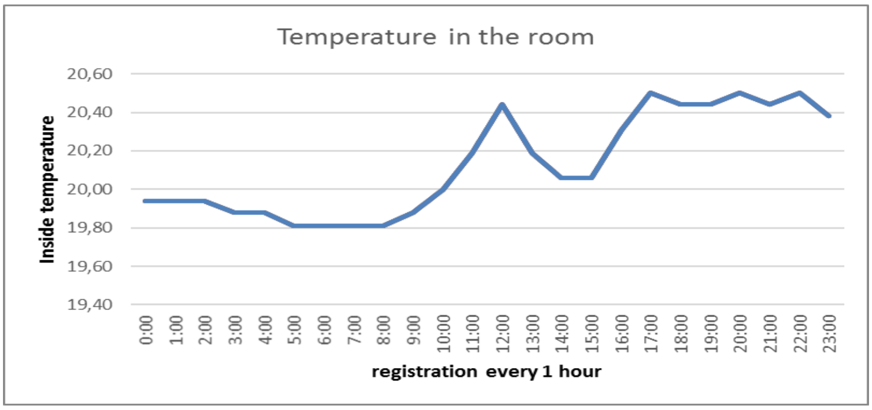

Figure 6. Temperature in the tested room

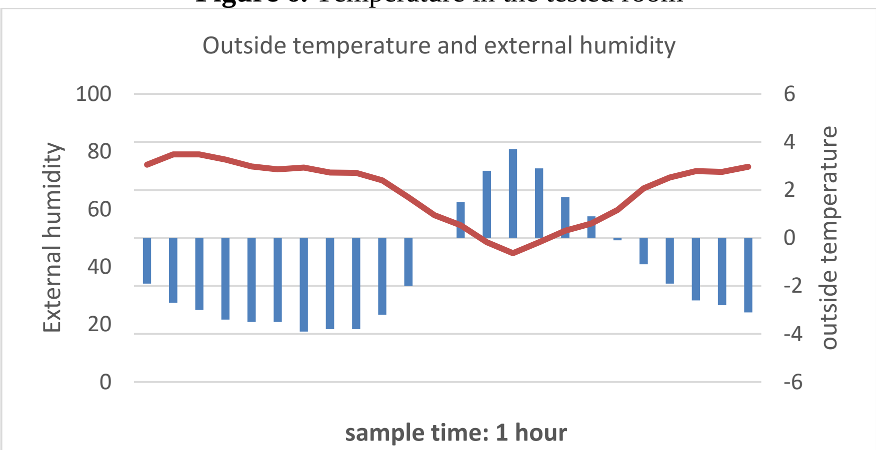

Figure 7. Outside temperature and external humidity

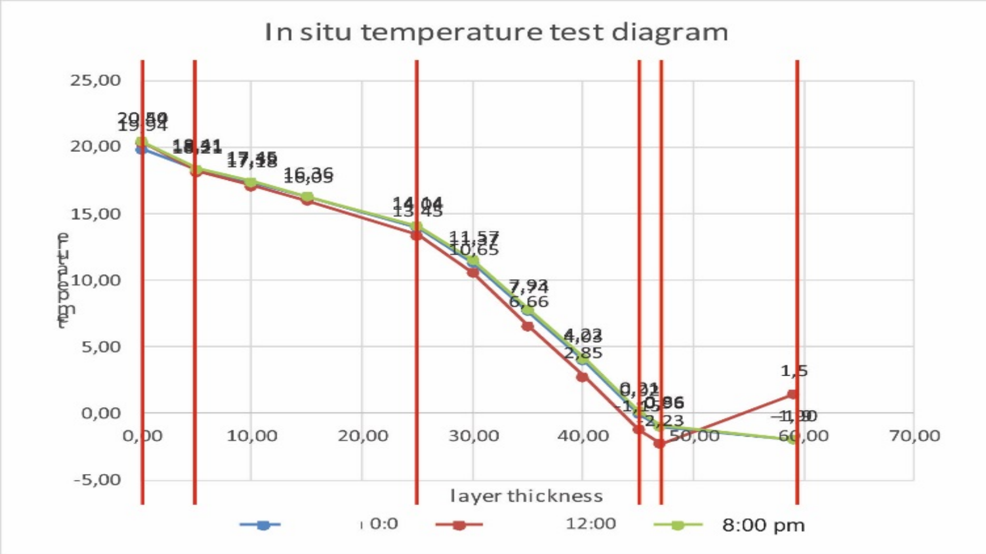

Figure 8. Temperature diagram in the partition on 01/01/2017 between 0:00, 12:00 and 8:00 pm

The charts from the example day in January show the dynamic variability of internal and external conditions.

They affect the behaviour of the heat flow through the partition. Despite changes in the environmental parameters, there are no large differences between the temperature charts recorded during the day. The chart recorded at 12:00 shows the biggest differences. It is connected with the increase of temperature to the outside, while the temperature in the air gap reaches lower values, caused by the clinker brick accumulation, and the insulation from the warmer styrofoam side.

4. Laboratory tests of thermal insulation materials

4.1. Measurement methods

The Małopolska Laboratory of Energy-efficient Building, in addition to "in situ" tests, has specialized equipment for testing building partitions, such as walls, windows, doors, but also thermo-insulation materials. The universal set of laboratory chambers is used for testing building partitions. It is designed to determine the properties of building partitions related to heat transfer in a steady state by two different methods:

1. Hot box method with the use of a heat meter. It is designed for testing homogeneous and non-homogeneous construction partitions (walls, flat roofs, ceilings, floors). The basic measured quantity is the thermal resistance between the surfaces of the sample. Testing is performed in accordance to the PN-EN 1934:1999 standard. The test stand provides the possibility of testing walls, thermal resistance of roofs, ceilings and floors.
2. The method of a shielded heating box is intended for testing test samples of inhomogeneous building partitions (doors and windows). The basic measured quantity is the heat transfer coefficient of the sample. Testing is performed in accordance to the standards: PN-EN ISO 12567-1:2010, PN-EN ISO 12567-2:2006 and PN-EN ISO 8990:1998

Figure 9. Research equipment at MLBE

For testing the thermal conductivity coefficient, a chamber for thermal conductivity testing according to ISO 8301 (a comparative method) with a rotational system, software, an external cooler and thermocouples is used.

Modern thermal insulation materials are not only mineral or rock wool or polystyrene with good parameters. In MLBE, materials such as aerogels are tested. These are the latest generation thermal insulation materials with a lower thermal coefficient than standard thermal insulation materials (polystyrene, mineral wool).

In the literature, values of the thermal conductivity coefficient λ [W / mK] in the range (0.014 - 0.016 [W / (mK)] [10,11] are given. The tests carried out in MLBE in different temperature ranges gave the results presented in Table 3.

Table 3. The test was carried out in a device for measuring the lambda coefficient.

Temperatures					q [W/m^2]	λ [W/(mK)]
No	Hot side [^{0}C]	Cold side [^{0}C]	Av T [^{0}C]	ΔT [^{0}C]		
1	35.00^{0}C	25.00^{0}C	30.00^{0}C	10.00^{0}C	17.56[W/m^2]	0.02103[W/(mK)]
2	45.00^{0}C	15.00^{0}C	30.00^{0}C	30.00^{0}C	52.95[W/m^2]	0.02112[W/(mK)]
3	55.00^{0}C	5.00^{0}C	30.00^{0}C	50.00^{0}C	88.70[W/m^2]	0.02123[W/(mK)]
4	65.00^{0}C	-5.00^{0}C	30.00^{0}C	70.00^{0}C	124.40[W/m^2]	0.02128[W/(mK)]

Despite small differences, the aerogel has very good thermal insulation properties due to the amount and structure of the pores inside the material. The siliceous skeleton in such a way that a very large number of pores is created (up to 99.8% by volume) limits the air. They are also small enough to minimize the influence of convection and radiation. In addition, the skeleton that makes the airgel solid is made of silica particles that is a poor heat conductor. It can be used in building industry for insulation of external walls and in other areas, which are problematic from the point of view of thermal protection.

4.2. Comparison of thermal insulation materials prices

Thermal insulation material in the external walls of the MLBE building is EPS 0.38 super facade polystyrene with a lambda coefficient = 0,038 [W / (mK)]. The material thickness in the MLBE outer wall was 4 x 0.05 m. The MLBE building was built in 2013-2014. During construction, the polystyrene was the one with the best thermal parameters available (the lowest value λ). There are currently materials with better parameters on the market. The table compares how the thickness of the MLBE and the price of thermal insulation material would change if the building was erected at present.

The heat transfer coefficient in the MLBE building for external walls is U = 0.12 [W/(m^{2}K)]. Thickness of other materials considered would reduce the total thickness of the partition in accordance to figures 10 and 11. In the case of EPS 030 Passive λ PRO polystyrene, the lowest value given by manufacturer is 5 cm, so currently MLBE designers would apply 4 layers by 5 cm to achieve a heat transfer coefficient U = 0,10 [W / (m^{2}K)]. The use of aerogel mats would reduce the thickness wall from 67 cm to 58 cm while maintaining the heat transfer coefficient U = 0.12 [W / (m^{2}K)]. However, the economic calculation excludes this thermal insulation material for use on large surfaces. Figure 10 shows the variant of W5 where the air gel thickness of 20 cm was used (as in the existing building, the thickness of thermal insulation). The heat transfer coefficient would decrease from U = 0.12 [W / (m^{2}K)] to U = 0.08 [W / (m^{2}K)].

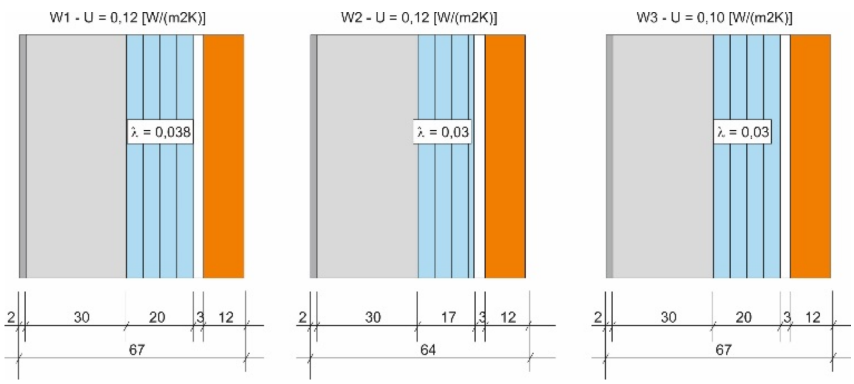

Figure 10. Comparison of EPS 0,38 super facade polystyrene used in MLBE with the EPS 030 Passive λ PRO (the best thermal properties currently available on the market)

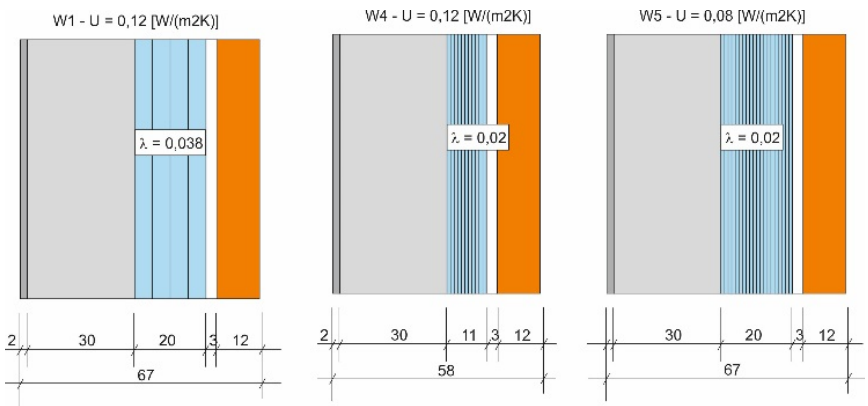

Figure 11. Comparison of the EPS 0,38 the super facade polystyrene used in MLBE, with aerogel mats, characterized by the thermal conduction coefficient tested in MLBE.

Table 4 and figure 11 summarize the current prices per m^2 of material with a thickness of 5 cm with its thermal insulation properties.

Table 4. Coefficient λ and prices of analyzed type of thermal insulation.

Type of thermal insulation	λ [W/mK]	λ [%]	Price [PLN (EUR)/m^2]
EPS 0.38 facade super	0.038	100%	10.00 (2.3 EUR) (5 cm)
EPS 0.30 Passive λ PRO	0.030	79%	11.70 (2.3 EUR) (5 cm)
Aerogel mat	0.020	52%	200 (45 EUR)-235 (53 EUR) (1 cm) 1000 (227 EUR)– 1175 (267 EUR) (5 cm)

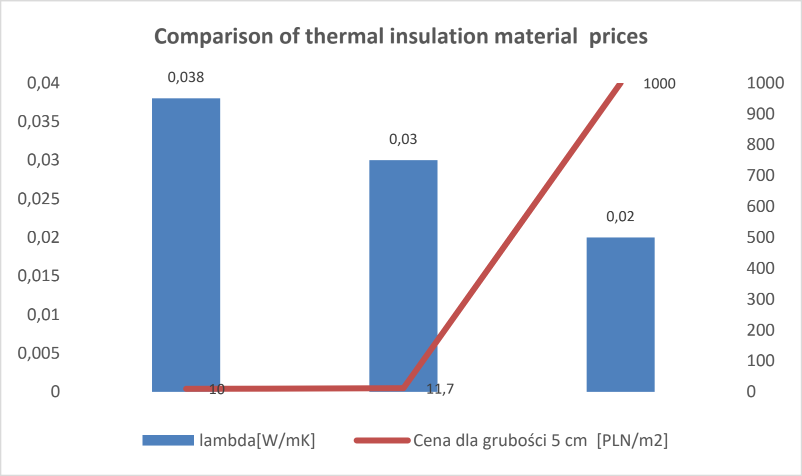

Figure 12. Comparison of thermal insulation properties of the analysed materials and prices per 1 m^2 of 5 cm thick material.

5. Conclusions

1. Tightening regulations for the thermal protection of buildings force the manufacturers of building materials to create new, innovative materials or improve existing ones.
2. In the area of thermal insulation materials, standard materials such as expanded polystyrene with lower thermal conductivity coefficients appear, or new materials such as aerogels.
3. Manufacturers of building materials should closely cooperate with research and science centres to study the properties of materials and to invent innovative materials.
4. The heat flow through the outer wall closely depends on the materials used in each layer.
5. The results of investigations of temperature drops in the external wall of the experimental building of the Malopolska Laboratory of Energy Efficient Building showed a large convergence with the calculations carried out based on the PN-EN 6946 standard.
6. The aerogels research carried out in the Malopolska Laboratory of Energy Efficient Buildings demonstrated a coefficient of heat conduction at the level of λ = 0.02 [W / (mK)], which is a higher value than the value given by the producers.
7. Aerogel insulations give new possibilities for thermal insulation of external walls, thermal insulation of a smaller thickness than traditional thermal insulation such as polystyrene or welder. Aerogels also allow minimizing thermal bridges in places where it is not possible to use thick insulation.
8. The use of aerogel is very expensive. As manufacturing technology improves, aerogel products should be cheaper, and thus more economically justified to be used as insulation of flat partitions.

References

[1] Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings
[2] Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings
[3] Regulation No. 244/2012 of 16 January 2012 supplementing Directive 2010/31 / EU establishing a comparative methodology framework for calculating the cost-optimal level of minimum requirements for the energy performance of buildings and building components, Dziennik Urzędowy Unii Europejskiej L 081 z 21 marca 2012
[4] Wytyczne uzupełniające rozporządzenie delegowane Komisji (UE) nr 244/2012 z 16 stycznia 2012 r. uzupełniające dyrektywę Parlamentu Europejskiego i Rady 2010/31/UE (Guidelines supplementing Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012

supplementing Directive 2010/31 / EU of the European Parliament and of the Council) w sprawie charakterystyki energetycznej budynków i ustanawiające ramy metodologii porównawczej do celów obliczania optymalnego pod względem kosztów poziomu wymagań minimalnych dotyczących charakterystyki energetycznej budynków i elementów budynków.

[5] Rozporządzenie Ministra Infrastruktury z dn 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie, Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location (Dz. U. z 2002 r. nr 75, poz. 690)

[6] PN-EN ISO 6946 Komponenty budowlane i elementy budynku - Opór cieplny i współczynnik przenikania ciepła - Metoda obliczania, Building components and building elements -- Thermal resistance and thermal transmittance - Calculation methods, (in Polish).

[7] PN-EN ISO 12524 Materiały i wyroby budowlane -- Właściwości cieplno-wilgotnościowe -- Tabelaryczne wartości obliczeniowe, Building materials and products - Hygrothermal properties - Tabular calculation values, (in Polish).

[8] PN–EN ISO 12831 Instalacje ogrzewcze w budynkach -- Metoda obliczania projektowego obciążenia cieplnego, Heating installations in buildings - The method of calculating the design heat load (in Polish).

[9] http://old.imgw.pl/klimat/, access 05/2018

[10] http://www.izomat.net/index.php/aerozel access 05/2018

[11] https://www.mgprojekt.com.pl/blog/aerozel/ access 05/2018

[12] http://styronet.pl/styropmin-styropian-grafitowy-eps030-passive-lambda-pro.html, access:05/2018