PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **13, 1 (47), 2022, 79-92**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Energy Infiltration Effect and Energy Body – a Unique Criterion for Building Thermal Insulation

Piotr BIERANOWSKI

University of Warmia and Mazury in Olsztyn,
Department of Mechanics and Basic Machine Design,
Faculty of Technical Sciences,
11 M. Oczapowskiego Str., 10-719 Olsztyn, Poland
Corresponding author's e-mail address and ORCID:
piotr.bieranowski@uwm.edu.pl; https://orcid.org/0000-0002-6500-119X

Received: August 15, 2021 / Revised: September 1, 2021 / Accepted: March 10, 2022 / Published: March 31, 2022

DOI 10.5604/01.3001.0015.8106

Abstract: This publication is provided with the author's suggestions regarding modification of the basic criterion – heat transfer coefficient. According to the author, the basic criterion of building thermal protection should be extended in such a manner that it will be simple and easy to evaluate a building's capacity to recover thermal energy accumulated in the wall structure.
Keywords: heat transfer coefficient, heat accumulation, resistance, thermodynamic criterion

1. INTRODUCTION

In view of the current need to save energy, this issue should be handled in a strictly logical manner. With thermal performance in mind, a high-level criterion should be established that will directly indicate the possibilities of heat recovery from a pre-heated *energy body* (a building's load-bearing exterior wall) in the process of seasonal building heating. The natural phenomenon of a building cooling down and the resulting benefits in the form of direct heat recovery, and thus thermal performance, should be referenced here. The study is provided with the author's method to describe this issue. According to the author, the criterion in question should be regarded as standard. The provisions included in [1, 2] are currently insufficient to describe thermal protection – this particularly applies to the buildings considered energy-efficient. The value of the heat transfer coefficient does not reflect in any way the possibilities to recover heat from the mass (body – a building's load-bearing exterior walls and other division elements) that accumulates heat in the heating season (both cool and cold).

2. PHYSICAL AND MATHEMATICAL NOTATION E_{ie} AND B_e (ENERGY INFILTRATION EFFECT AND ENERGY BODY)

The density of heat flux [1, 4] flowing through a flat division element separating environments with temperature T_{out} (temperature in an external thermodynamic medium) and temperature T_{in} (temperature in an internal thermodynamic medium) in a stationary state is calculated from the following formula

$$q = U\left(T_{in} - T_{out}\right) = \frac{T_{in} - T_{out}}{R_T} \tag{1}$$

where:
T_{in} – design air temperature in a room, [K];
T_{out} – design external air temperature, [K];
R_T – total division thermal resistance, [(m^2·K)/W];
U – division heat transfer coefficient, [W/(m^2·K)].

On the basis of the first dependence, it can also be stated that heat transfer coefficient U is the ratio of the density of steady heat flux flowing through the division to the temperature difference on both sides of the building envelope.

Total thermal resistance of the division R_T is calculated from the following formula

$$R_T = \frac{1}{h_{si}} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{h_{se}} = R_{si} + \sum_{i=1}^{n} R_i + R_{se} \tag{2}$$

where:
d_i – material layer thickness, [m];
λ_i – thermal conductivity coefficient of a material layer, [W/(m·K)];
h_{si} – heat absorption coefficient on the division surface on the room side (coefficient of heat penetration at the liquid-solid interface), [W/(m^2·K)];
h_{se} – heat absorption coefficient on the division's external surface a (coefficient of heat penetration at the solid-liquid interface), [W/(m^2·K)];
R_{si} – heat absorption resistance on the division surface on the room side (resistance of heat penetration), [(m^2·K)/W];
R_{se} – heat absorption resistance on the division's external surface (resistance of heat penetration), [(m^2·K)/W];
R_i – thermal resistance of a material layer, [(m^2·K)/W].

Heat transfer coefficient U for the division element is calculated as an inverse of the total thermal resistance R_T of the division

$$U = \frac{1}{R_T} \tag{3}$$

Amount of heat Q accumulated in a homogeneous division [11] (layer) can be calculated from the following formula

$$Q = m_i \cdot c_i \cdot \overline{T}_i = V_i \cdot \rho_i \cdot c_i \cdot \overline{T}_i = F_i \cdot d_i \cdot \rho_i \cdot c_i \cdot \overline{T}_i \tag{4}$$

where:
m_i – division or layer mass, [kg];
c_i – specific heat of the division's or layer's material, [J/(kg·K)];
$\overline{T}_i$ – average temperature of the division or layer, [K];
V_i – volume of the division's or layer's material, [m^3];
ρ_i – density of the division's or layer's material, [m^3/kg];
F_i – division surface area, [m^2];
d_i – division or layer thickness, [m].

For a sandwich division, the amount of heat accumulated in the division is the sum of heat accumulated in the homogeneous layers. Calculations can be performed for the entire division or a given unit surface area of 1.0 m^2.

Considering the thermal performance of the division elements within global physics of phenomena comprising the exchange of thermal energy in correlation with its accumulation capacity, components of the phenomena can be expressed using the following formula (energy infiltration effect examined in a model energy body – author's study)

$$E_{IE} = \frac{Q}{U} \tag{5}$$

where:
Q – energy accumulated in composite (load-bearing exterior wall of the building, consisting of individual components), [J];[kWh];
U – heat transfer coefficient, [W/(m^2·K)].

Breaking the individual parts of the formula down into the components comprising the equation, and considering equations (3) and (4), it can be stated that

$$E_{IE} = \frac{F_i \cdot d_i \cdot \rho_i \cdot c_i \cdot \overline{T}_i}{\dfrac{1}{R_{si} + \sum_{i=1}^{n} R_i + R_{se}}} \tag{6}$$

and then

$$E_{IE} = \frac{F_i \cdot d_i \cdot \rho_i \cdot c_i \cdot \overline{T}_i}{\dfrac{1}{\dfrac{1}{h_{si}} + \sum_{i=1}^{n} \dfrac{d_i}{\lambda_i} + \dfrac{1}{h_{se}}}} \tag{7}$$

as in (2) and (4), upon arrangement

$$E_{IE} = \left(\frac{F_i \cdot d_i \cdot \rho_i \cdot c_i \cdot \overline{T}_i}{1} \right) \cdot \left(\frac{1}{h_{si}} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{h_{se}} \right) \tag{8}$$

Finally in basic terms

$$E_{TE} = Q \cdot U^{-1} \tag{9}$$

or

$$E_{TE} = Q \cdot R \tag{10}$$

The definition of E_{IE} is as follows (in relation to electrical phenomena):

The criterion determining the energy infiltration effect of thermal energy in the energy body in question is directly proportional to the product of a portion of energy accumulated in a capacitor (division) and is inversely proportional to the value of the heat transfer coefficient

or

The criterion determining the energy transfer effect of thermal energy in the energy body in question is directly proportional to the product of a portion of energy accumulated in a capacitor (division) and the prevailing resistance.

3. EXAMPLES

Structure of building envelope no. 1 (load-bearing exterior wall).

A vertical exterior division element of the building (Figs. 1, 2, 3, 4) made of the following layers

Layer 1 – gypsum-based plaster;
Layer 2 – brickwork made of full clay bricks;
Layer 3 – expanded polystyrene;
Layer 4 – brickwork made of perforated blocks;
Layer 5 – cement-lime plaster.

with the parameters specified in Table 1. The sequence of layers is taken from the interior. Temperatures on both sides of the division amount to: T_i = 20.0°C; T_e = -20.0°C;

Table 1

Layer no.	d [cm]	λ [W/(m·K)]	ρ [kg/m^3]	c [kJ/(kg·K)]
1	1.3	0.25	730	0.840
2	25	0.77	1800	0.880
3	18	0.04	20	1.46
4	12	0.56	1300	0.880
5	1.5	0.82	1850	0.840

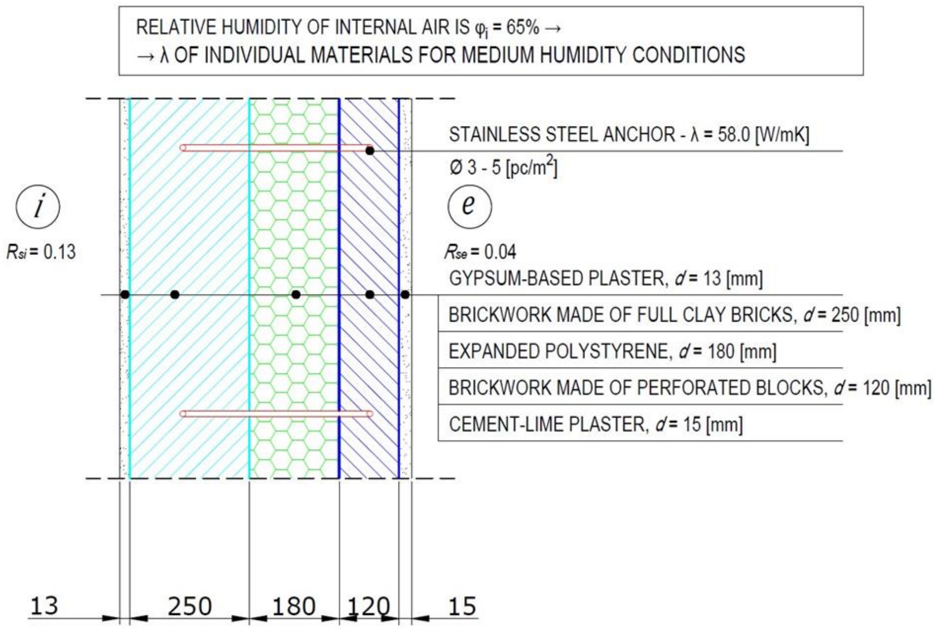

Fig. 1. Sandwich composite comprising: load-bearing exterior wall (the building's envelope). Structure of envelope no. 1 (*author's archive*)

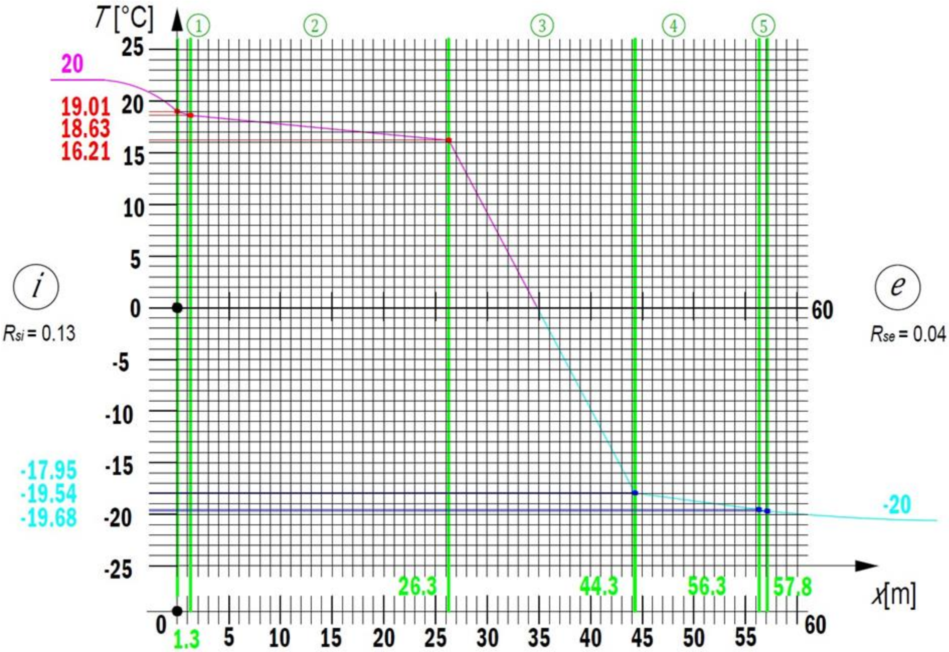

Fig. 2. Distribution of temperature in the building's envelope.
Structure of envelope no. 1 (energy body) (*author's archive*)

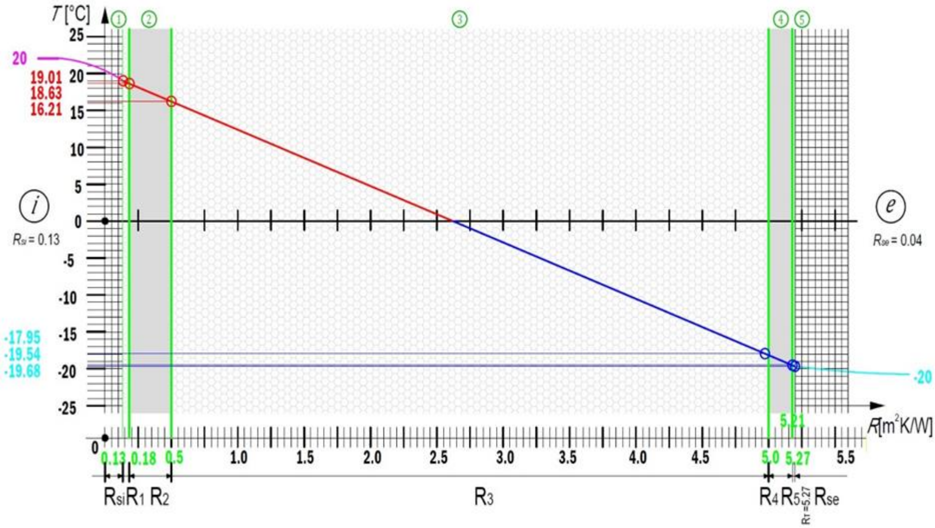

Fig. 3. Distribution of temperature inside the division depending on the thermal resistance (energy body). Structure of envelope no. 1 (*author's archive*)

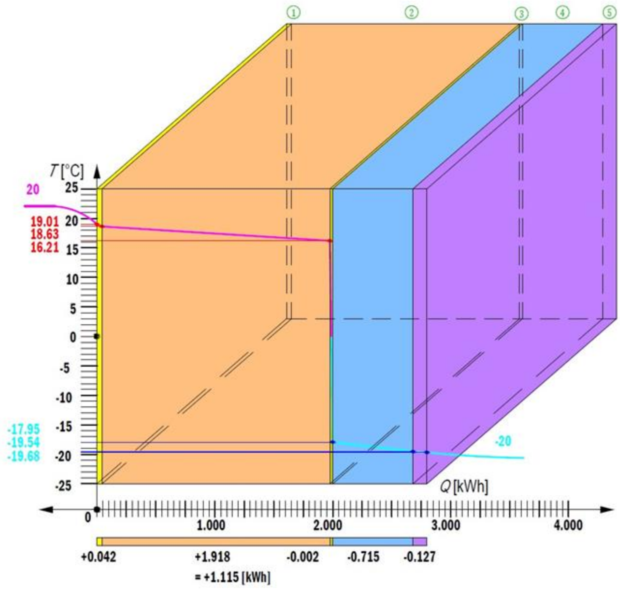

Fig. 4. Energy body. Structure of envelope no. 1 (*author's archive*)

For the envelope of building no. 1 the value of the heat transfer coefficient was U = 0.196 W/(m^2·K) (including the actions of the connecting anchors), and heat accumulated for the worst stationary (steady) state, for a given climatic area Q = + 1.115 kWh.

Structure of building envelope no. 2 (load-bearing exterior wall).

A vertical exterior division element of the building (Figs. 5, 6, 7, 8) made of the following layers

Layer 1 – gypsum-based plaster;
Layer 2 – brickwork made of cellular concrete;
Layer 3 – expanded polystyrene;
Layer 4 – brickwork made of perforated blocks;
Layer 5 – cement-lime plaster.

with the parameters specified in Table 2.

Table 2

Layer no.	d [cm]	λ [W/(m·K)]	ρ [kg/m^3]	c [kJ/(kg·K)]
1	1.3	0.25	730	0.840
2	24	0.38	1800	0.880
3	17	0.04	20	1.46
4	12	0.56	1300	0.880
5	1.5	0.82	1850	0.840

The sequence of layers is taken from the interior. Temperatures on both sides of the division amount to: T_i = 20.0°C; T_e = -20.0°C;

RELATIVE HUMIDITY OF INTERNAL AIR IS φ_i = 65% →
→ λ OF INDIVIDUAL MATERIALS FOR MEDIUM HUMIDITY CONDITIONS

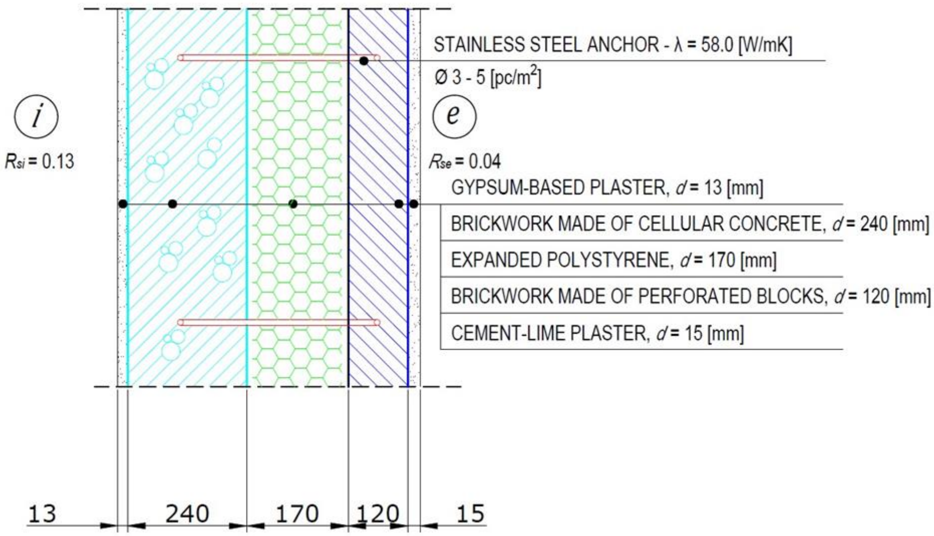

Fig. 5. Sandwich composite comprising: load-bearing exterior wall (the building's envelope). Structure of envelope no. 2 (*author's archive*)

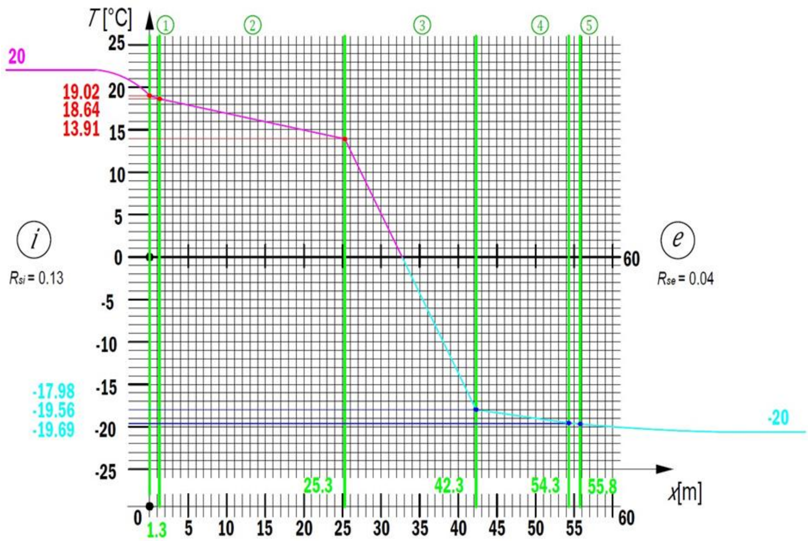

Fig. 6. Distribution of temperature in the building's envelope. Structure of envelope no. 2 (energy body) (*author's archive*)

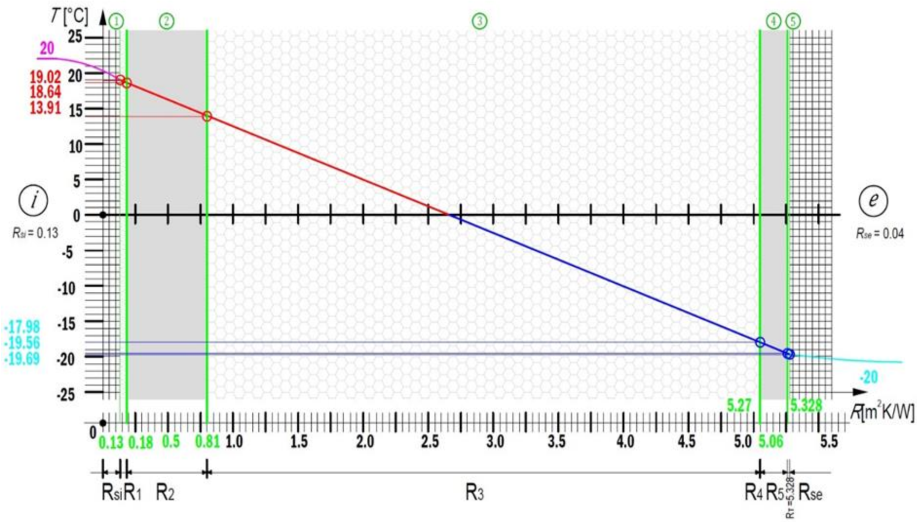

Fig. 7. Distribution of temperature inside the division depending on the thermal resistance (energy body). Structure of envelope no. 2 (*author's archive*)

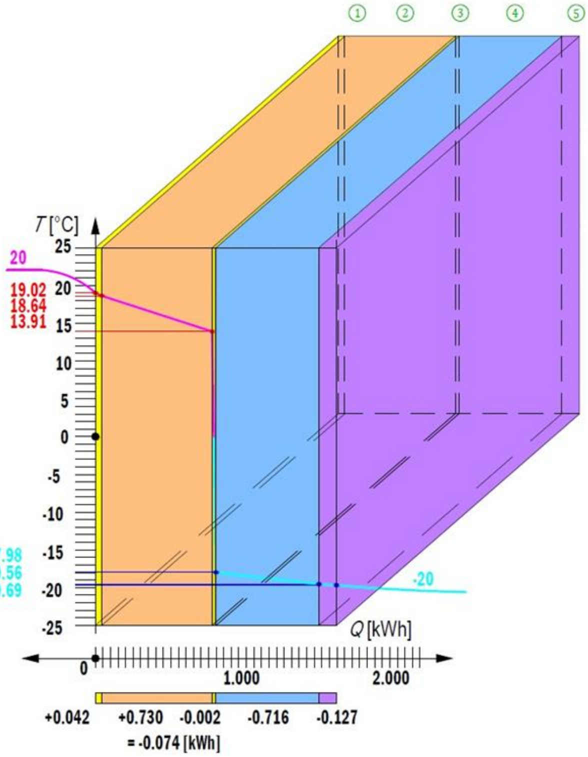

Fig. 8. Energy body. Structure of envelope no. 2 (*author's archive*)

For the envelope of building no. 2, the value of the heat transfer coefficient was U = 0.194 W/(m^2·K), and the heat accumulated for the worst stationary (steady) state, for a given climatic area Q= - 0.0738 kWh.

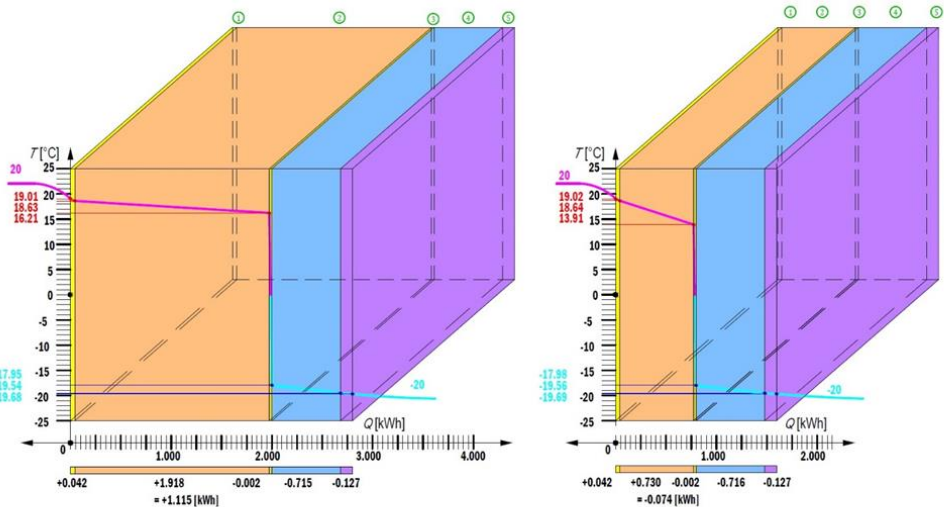

Fig. 9. Comparison of energy bodies for both building envelopes (*author's archive)*

In both cases, the value of the heat transfer coefficient is comparable in terms of numerical value, but the power of the accumulation of thermal energy in the energy bodies is entirely inverse (Fig. 9). The value of the criterion for the structure of envelope no. 1 is

$$E_{IE} = \frac{Q}{U} = \frac{+1.115}{0.196} = +5.689 \quad [(\text{m}^2\cdot\text{K})\cdot\text{h}]$$

The value of the criterion for the structure of envelope no. 2 is:

$$E_{IE} = \frac{Q}{U} = \frac{-0.0738}{0.194} = -0.380 \quad [(\text{m}^2\cdot\text{K})\cdot\text{h}]$$

From the mathematical considerations, it can be clearly seen that in the above case the traditional clay brick allows for more efficient heat recovery from the cooling building (e.g. when the heating system operates in a non-uniform way or in emergency mode). It can be pointed out that the efficiency of the material in question can be used in two ways, e.g. when this type of wall is exposed to solar radiation acting through open divisions (solar electromagnetic waves falling in the infrared spectrum, through a window to the wall with a capacity to efficiently accumulate thermal energy), additional favourable portions of energy can be collected to be used when the load-bearing wall of the building cools down.

4. CONCLUSIONS

The author is of the opinion that thermal performance in the context of building structures and construction physics is nowadays the biggest challenge [3, 4, 5, 6, 7, 8] for structural engineers (reduction of heat losses through thermal bridges) and for construction physicists (tests in the field of thermal physics) [3, 4, 9, 10]. This is a global issue – every quantum of energy saved in a global context is a significant gain.

In the guidelines for the engineering design of load-bearing exterior walls of buildings, the legal parameter defining a division's energy capacity to ensure thermal comfort is heat transfer coefficient U [W/m^{2}K]. In both calculation examples provided above, at equal value U entirely opposite values of thermal energy accumulation Q were obtained. Accumulation of energy Q should become one of the main guidelines for the engineering design of structures of exterior walls of buildings (and other divisions) due to thermal performance in view of the energy balance. The engineering design standard as a legal act should include effective methods of examination of the issue, and should not be based on an archaic heat transfer coefficient method. Pursuant to the applicable law, a good (in legal terms) exterior building division is not always energy-efficient. Poor pre-heating and fast cooling down of the structure under winter conditions is an unequivocally negative effect of heat gains.

According to the author, an appendix to the standard classifying and sorting various structures in terms of thermal physics should be developed, so that both the owner and the designer is aware of the reliability of information in technical terms without going into the world of physics. The author initially proposed such a catalogue in publication [15].The hypothesis is put forward to draw up a scientific problem known to the author. It is a deductive hypothesis as heat accumulation is a known physical fact. It is a confirmable hypothesis.

The considerations included in this study are entirely original. The nomenclature used has not been encountered yet in references and scientific publications. It was created by the author of this study in the course of a cognitive process. The physical processes under consideration are obviously well known, but no basic criterion, apart from the heat transfer coefficient, has been formed so far to cover the problem regarding strictly energy efficient and passive buildings. The above-mentioned criterion can also be useful when designing transmission systems for power utilities, for instance with regard to pipe and cable enclosures. To sum up, the presented solution can be useful in the construction industry and in other engineering areas, including industry.

The publication can be concluded with the following rhetorical question – should a furnace be made of materials which do not accumulate heat? In times of energy efficient and passive buildings – that is, in modern times – the furnace effect, the energy body effect, is clearly perceived as very advantageous. Obviously, each theory requires mathematical and physical notation – a response to this statement is an algorithm provided in this study.

The aim of this study is to develop a basic criterion for the assessment of thermal performance of buildings with regard to their cooling down. The material data were taken from the standard [2]. This study was drawn up only to compare physical phenomena that may occur on load-bearing exterior walls of buildings. The method discussed can be applied to other divisions – not only in buildings, but also in any application where transfer of heat can be considered as a positive impact of accumulation leading to the reduction of energy losses. Inspections of buildings should be carried out in accordance with recommendations provided in industry references [12, 13, 14].

FUNDING

The author received no financial support for the research, authorship, and/or publication of this article.

REFERENCES

[1] PN-EN ISO 6946:2008 *Komponenty budowlane i elementy budynku. Opór cieplny i współczynnik przenikania ciepła. Metoda obliczania*.

[2] PN-EN 12524:2003 *Materiały i wyroby budowlane – Właściwości cieplno-wilgotnościowe – Tabelaryczne wartości obliczeniowe*.

[3] Dylla, Andrzej. 2009. *Praktyczna fizyka cieplna budowli. Szkoła projektowania złączy budowlanych*. Bydgoszcz: Wydawnictwa Uczelniane UTP Bydgoszcz.

[4] Nowak, Henryk. 2012. *Zastosowania badań termowizyjnych w budownictwie*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej.

[5] Bieranowski, Piotr. 2014. „Alternatywne rozwiązanie konstrukcji komunikacji w pionie w budynkach remontowanych i modernizowanych. Stalowo – betonowa konstrukcja ustroju". *Przegląd Budowlany* 4 : 24-27.

[6] Bieranowski, Piotr. 2015. „Redukcja mostka cieplnego istniejącym ustroju konstrukcyjnym poprzez zmianę modelu konstrukcji". *Przegląd Budowlany* 3 : 10-14.

[7] Bieranowski, Piotr. 2015. „Konstruowanie węzła pasmowego konstrukcji w płaszczyźnie tarczy stropu na przykładzie rozwiązania ustroju balkonu wspornikowego". *Przegląd Budowlany* 5 : 14-21.

[8] Bieranowski, Piotr. 2015. „Ciepłochronna konstrukcja zewnętrznej komunikacji w pionie – obiekty wszelkiego przeznaczenia". *Przegląd Budowlany* 9 : 42-47.

[9] Bieranowski, Piotr. 2014. „Współczynnik przenikania ciepła w świetle nowego Rozporządzenia Ministra Transportu, Budownictwa i Gospodarki Morskiej. Badanie współczynnika przenikania ciepła w warunkach in situ. Cz. I – Wprowadzenie". *Przegląd Budowlany* 2 : 16-21.

[10] Bieranowski, Piotr. 2014. „Współczynnik przenikania ciepła w świetle nowego Rozporządzenia Ministra Transportu, Budownictwa i Gospodarki Morskiej. Badanie współczynnika przenikania ciepła w warunkach in situ. Cz. II – Badania". *Przegląd Budowlany* 3 : 25-29.

[11] Starakiewicz, Aleksander, Jerzy Szyszka. 2010. *Fizyka budowli w zadaniach*. Rzeszów: Oficyna Wydawnicza Politechniki Rzeszowskiej.

[12] Baryłka, Adam 2018. *Poradnik rzeczoznawcy budowlanego, tom I. Problemy techniczno-prawne diagnostyki obiektów budowlanych*. Warszawa: Wydawnictwo Centrum Rzeczoznawstwa Budowlanego.

[13] Baryłka, Adam 2018. *Poradnik rzeczoznawcy budowlanego, tom II. Problemy techniczno-prawne diagnostyki posadowienia obiektów budowlanych*. Warszawa: Wydawnictwo Centrum Rzeczoznawstwa Budowlanego.

[14] Baryłka, Adam 2019. *Okresowe kontrole obiektów budowlanych w procesie ich eksploatacji*. Warszawa: Wydawnictwo Centrum Rzeczoznawstwa Budowlanego.

[15] Bieranowski, Piotr. 2018. „Akumulacja energii cieplnej w konstrukcjach ścian zewnętrznych w kontekście stałej wartości współczynnika przenikania ciepła". *Przegląd Budowlany* 5 : 47-51.

Efekt infiltracji energii i bryła energetyczna – osobliwe kryterium ciepłochronności budynków

Piotr BIERANOWSKI

Katedra Mechaniki i PKM, Wydział Nauk Technicznych,
Uniwersytet Warmińsko-Mazurski w Olsztynie.
ul. M. Oczapowskiego 11, 10-719 Olsztyn

Streszczenie. W publikacji zamieszczono autorskie propozycje modyfikacji podstawowego kryterium, jakim jest współczynnik przenikania ciepła. Zadaniem autora powinno się rozbudować podstawowe kryterium ochrony cieplnej budynków, tak, aby w podstawowy i łatwy sposób można było ocenić zdolność obudowy budynku do odzysku energii cieplnej – zakumulowanej w konstrukcji ściany.
Słowa kluczowe: współczynnik przenikania ciepła, akumulacja ciepła, rezystancja, kryterium termodynamiczne