Advances in Science and Technology
Research Journal

Advances in Science and Technology Research Journal 2024, 18(5), 277–286
https://doi.org/10.12913/22998624/190474
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.05.28
Accepted: 2024.07.20
Published: 2024.08.01

Heat Flow Through a Wall with a Thermal Barrier

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ABSTRACT

The problem of reducing primary energy consumption is increasingly discussed in the technical literature. Relatively large amounts of energy are used to heat rooms. In the case of resources of much cheaper waste energy or energy from renewable sources with a temperature lower than required in the rooms, the so-called "thermal barrier" placed in external walls can be used to reduce heat transmission losses. The thermal barrier is a vertical wall element with pipes with a heating medium installed in the partition, with a temperature lower than the temperature in the room but higher than that resulting from the heat transfer through the partition without a barrier. An analytical calculation of heat flow through a thermal barrier has not been encountered in the literature. Therefore, a methodology for thermal barrier calculations was developed. In the paper, the heat fluxes flowing from the room to the partition and from the partition to the outside are determined. The developed model of partition with thermal barrier is then presented and the formula for thermal barrier efficiency is derived. Based mainly on theoretical models for the assumed input values and the partition's surroundings it was found that the efficiency of the thermal barrier does not depend on the temperatures of the barrier base and the wall environment, but only on the geometrical and thermodynamic parameters of the partition. It has also been shown that the efficiency of the thermal barrier is the highest when the resistance of the partition on both sides of the barrier is the same. It should be noted that the total amount of heat given off by a wall with a thermal barrier is greater than through a wall without a barrier, but the costs of heating the room may be lower.

Keywords: thermal barrier, heat loss, thermal barrier efficiency.

INTRODUCTION

People's awareness of the adverse impact of fuel combustion on the environment, as well as the availability of fossil fuels and their potential depletion has increased in recent years. Heating of buildings consumes relatively large amount of energy, resulting in a growing interest in the solutions that can reduce it. Improvement of the efficiency of systems and equipment used in heating is one of the key strategies. The best strategy to lower energy use is through the design of energy-efficient buildings. The use of information technology can be helpful in sustainable design, especially in energy efficiency [1].

Replacement of high-temperature heat sources with a low-cost or low-temperature waste heating mediums can reduce the overall consumption. It can also improve the efficiency of energy acquisition from fuel combustion and from non-conventional sources [2].

Use of wall with an active thermal barrier is a solution, which enables the use of low-temperature heat to meet above mentioned criteria. The thermal barrier is a core made of concrete with a high thermal conductivity coefficient, heated by a low-temperature medium flowing in pipes located within. The core is covered on a single or both sides with a layer of insulation with a much lower conductivity coefficient than the thermal barrier [3, 4].

Figure 1 presents the cross-section of a insulated traditional wall and one with a thermal barrier.

The walls with thermal barriers are increasingly used, particularly in energy-efficient

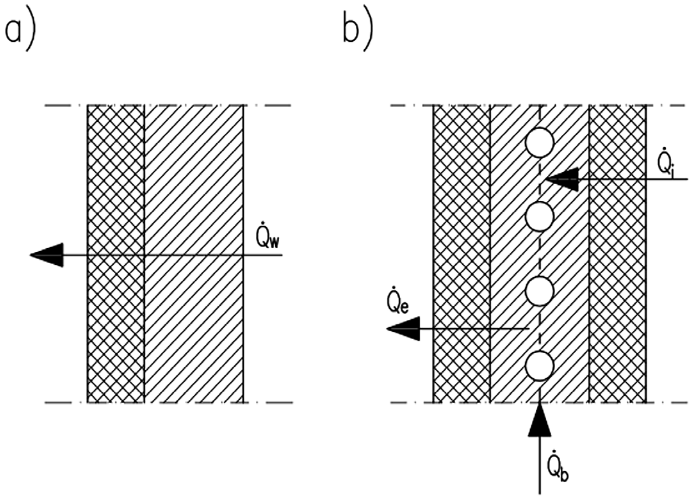

Figure 1. Insulated external wall: a) traditional, b) with the thermal barrier

construction (as discussed by Kisilewicz et al. [5]). For several years, the ISOMAX system [6] has been used successfully in low-energy houses. In this system, reinforced concrete is sandwiched between two 12.5 cm thick polystyrene boards, connected through 12.5 cm concrete fins. Inside the core a system of appropriately spaced PP pipes is installed. The space between these polystyrene layers is filled with BIO POR concrete. The construction of this type of wall is based on a core in which a constant temperature is maintained and which is well insulated with polystyrene on both sides. The thermal barrier is activated when a constant flow of low-heat medium through the pipes is initiated. The use of a thermal barrier wall prevents condensation and significantly reduces heat transfer losses from the building by creating a blockage of heat flow from higher to lower energy areas. For pipes with flowing medium installed in a vertical barrier three (as discussed in [7, 8, 9]), or four different temperature cases can be distinguished:

a) The temperature of the medium is higher than the temperature in the room. The medium heats the room (case of wall heating), no insulation is placed on the inside of the wall (Figure 2a),
b) The medium temperature is within the value of temperature in the room and the temperature at the location of potential barrier (barrier is disabled). In this case the heat penetration from the room is reduced, there is an active thermal barrier in the partition for heat penetration from the outside. The barrier is created by the temperature of the heated material of the wall core together with the pipes. This way of using a relatively low-temperature medium is a method of reducing heat penetration in the ISOMAX system [10] (Figure 2b),
c) The temperature of the medium is equal to the temperature at the location of potential barrier (barrier disabled). In this case, the barrier does not affect the heat transfer through the partition (Figure 2c),
d) The temperature of the medium is lower than the temperature at the location of potential barrier (barrier disabled). This results in the cooling of the room (Figure 2d). When determining the parameters of the cooling water, the effect of its temperature on the possible condensation of water vapor in the partition should also be analyzed.

A thin line in Figure 2 shows the temperature development through the partitions. Mathematical methods: analytical and numerical are used to describe heat transfer in partitions. Most research papers on thermal barrier partitions [11, 12] are based on numerical methods. The determination of the temperature field is achieved by adopting a digital control rather than continuous system and then subdividing the area into discrete elements. In modelling, the authors mostly use software: ABAQUS [13, 14, 15], ANSYS [16, 17, 18, 19] or their own tools, e.g. CalA 3.0 program [20, 21] or models based on the RC method [5]. The results of the numerical calculations are compared with experimental tests, which are carried out in existing buildings or on test sites.

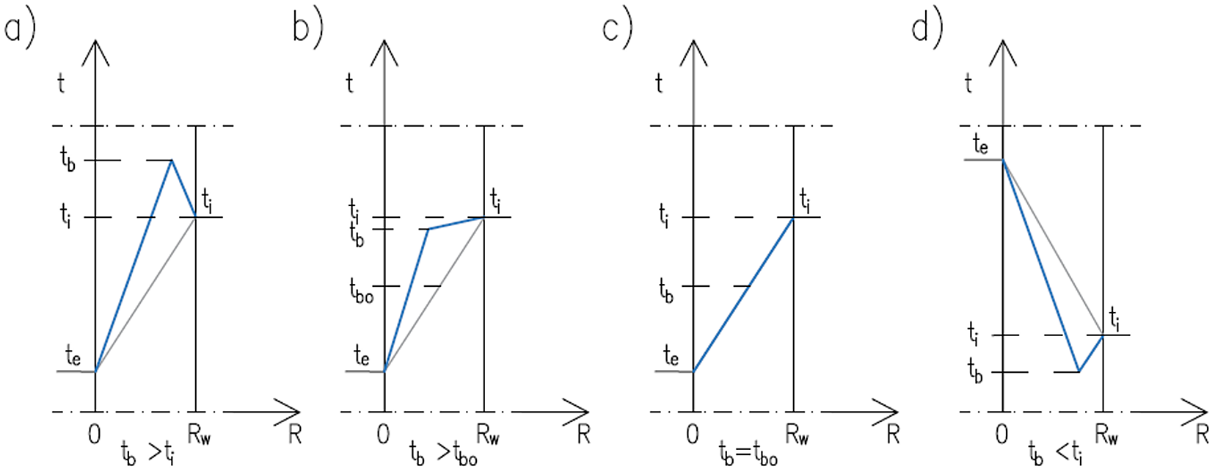

Figure 2. Temperature development in partition in case when: a) the barrier heats the room; b) the barrier reduces the heat loss, c) the barrier does not affect the heat transfer, d) the barrier cools down the room

The results of research in a single-family building located in northern Poland are presented by Krzaczek et al. [13, 14, 15]. Kisielewicz et al. [5] present the results of undertaken research in a two-storey residential building located in Hungary. Both buildings are constructed using technology similar to the Isomax system. Research carried out on the free-standing building is also presented in the paper [22]. Subsequent research teams carried out experiments at laboratory sites [12].

Krajcik and Sikula et al. [20, 21] conducted research on a model of the partition with thermal barrier and they used two climate chambers on both sides of the wall to simulate external and internal conditions. Chinese scholars Zhu et al. [23, 24] fabricated a partition with thermal barrier that separates two rooms made of steel sheets and insulated with XPS panels, acting as two environments: indoor and outdoor. Zhou and Li [16] conducted tests on an wall which was enclosed to provide a temperature difference on both sides of the wall.

On the other hand Chen et al. [17, 18, 19] conducted research in scaled-down experiment rooms with south wall with thermal barrier and Romani et al. [25, 26, 27] carried out measurements on two experimental facilities with internal dimensions of 5.25×2.7×2.7 m constructed specifically for this purpose.

The authors studied the validity of using partitions with a thermal barrier, the influence of temperature of thermal elements and type and thickness of the materials of the façade on energy efficiency [20, 21, 28] and carried out an economic analysis of the proposed solutions [28]. All researchers showed a reduction in heat loss to the outside for a partition with a thermal barrier in comparison to a traditional partition.

Analytical methods are an thorough approach, involving the solution of differential equations, which requires the adoption of necessary simplifications that can unfortunately affect the imperfection of the result. Analysing the case literature, we have not encountered a methodology for analytical thermal calculations for thermal barriers. A methodology for calculating heat flow through a thermal barrier was therefore developed. The assumptions made in the development of the theoretical model derive from the physics of the heat transfer process through the partition.

For the purpose of this study, the case where pipes are placed in the wall as an active thermal barrier (B), the effect of the wall parameters on the temperature distribution in the barrier and the magnitudes of heat fluxes flowing from the room to the partition and from the partition to the outside will be determined. Subsequently a detailed model for thermal barrier efficiency analysis will be presented as well as the influence of different parameters on thermal efficiency. Our paper is based on theoretical models. As mentioned previously the results and analyses of research performed in an experimental building equipped with thermal barrier were describe in [5, 13, 14, 15].

HEAT FLUXES IN A PARTITION WITH AN ACTIVE THERMAL BARRIER

The heat flux $\dot{q}_i$ transferred from the room to the barrier can be determined as:

$$\dot{q}_i = \frac{1}{R_i} \cdot (t_i - t_b) \tag{1}$$

where: R_i – thermal resistance on the inside of the outer wall [$m^2 \times K/W$], t_i – internal temperature [°C], t_b– temperature of thermal barrier [°C].

While the heat flux $\dot{q}_e$ from the barrier to the outside can be determined as:

$$\dot{q}_e = \frac{1}{R_e} \cdot (t_b - t_e) \tag{2}$$

where: R_e– thermal resistance on the outside of the outer wall [$m^2 \times K/W$], t_e – external temperature [°C],

$$R_i = R_{i\,\alpha} + R_{i\,b} + R_{i\,is} \tag{3}$$

and

$$R_e = R_{e\,\alpha} + R_{e\,b} + R_{e\,is} \tag{4}$$

where: $R_{i\,\alpha}$ – heat transfer resistance on the inside of the outer wall [$m^2 \times K/W$], $R_{i\,b}$ – thermal conduction resistance of the thermal barrier on the inside [$m^2 \times K/W$], $R_{i\,is}$ – thermal conduction resistance of the insulation layer on the inside [$m^2 \times K/W$], $R_{e\,\alpha}$– heat transfer resistance on the outside of the outer wall [$m^2 \times K/W$], $R_{e\,b}$ – thermal conduction resistance of the thermal barrier on the outside [$m^2 \times K/W$], $R_{e\,is}$– thermal conduction resistance of the insulation layer on the outside [$m^2 \times K/W$]

In case of pipes located in the centre of the core the outer and inner thermal resistances are equal:

$$R_{i\,b} = R_{e\,b} = \frac{R_b}{2} \tag{5}$$

The heat flux $\dot{q}_b$ from the medium is equal to the difference between the heat transferred outside and heat transferred from the room:

$$\dot{q}_b = \dot{q}_e - \dot{q}_i \tag{6}$$

And is equal to:

$$\dot{q}_b = \frac{1}{R_e} \cdot (t_b - t_e) - \frac{1}{R_i} \cdot (t_i - t_b) \tag{7}$$

The heat flux from the room, in case when the medium is not flowing (barrier is disabled) equals to:

$$\dot{q}_{w0} = \frac{1}{R_w}(t_i - t_e) \tag{8}$$

where: R_w– thermal resistance of the wall with thermal barrier [$m^2 \times K/W$],

By dividing (7) by (8) and further transformations the relative heat flux from the barrier can be calculated as:

$$\frac{\dot{q}_b}{\dot{q}_{w0}} = \frac{1}{\frac{R_e}{R_w}} \cdot \frac{t_b - t_e}{t_i - t_e} - \frac{1}{1 - \frac{R_e}{R_w}} \cdot \frac{t_i - t_b}{t_i - t_e} \tag{9}$$

After introducing reduced barrier temperature φ_b

$$\varphi_b = \frac{t_b - t_e}{t_i - t_e} \tag{10}$$

and further transformations, three formulas for heat fluxes relative to the heat flux out of the room through the partition with disabled barrier can be established: to the outside of the partition (11), through the room (12) and through the thermal barrier (13):

$$\frac{\dot{q}_e}{\dot{q}_{w0}} = \frac{1}{\frac{R_e}{R_w}} \cdot \varphi_b \tag{11}$$

$$\frac{\dot{q}_i}{\dot{q}_{w0}} = \frac{1}{1 - \frac{R_e}{R_w}} \cdot (1 - \varphi_b) \tag{12}$$

$$\frac{\dot{q}_b}{\dot{q}_{w0}} = \frac{1}{\frac{R_e}{R_w}} \cdot \varphi_b - \frac{1}{1 - \frac{R_e}{R_w}} \cdot (1 - \varphi_b) \tag{13}$$

Figure 3 shows the relative heat fluxes to the outside from the room and through the thermal barrier, in case when the thermal resistances on both sides are equal. Figure 3 shows that for the medium value of the thermal resistance of the barrier, the dimensionless temperature of the thermal barrier, which is 0.5, corresponds to the temperature of the partition at that location. This means that the barrier is at an equilibrium. The room's heat loss flux corresponds to the losses when the thermal barrier is not active. At higher barrier temperatures, as the temperature increases, the flux of heat given off by the barrier increases, while the flux of heat lost by the room decreases. And for lower temperatures than this value, the barrier draws heat which increases the heat flux given off from the room above the value when the barrier is disabled.

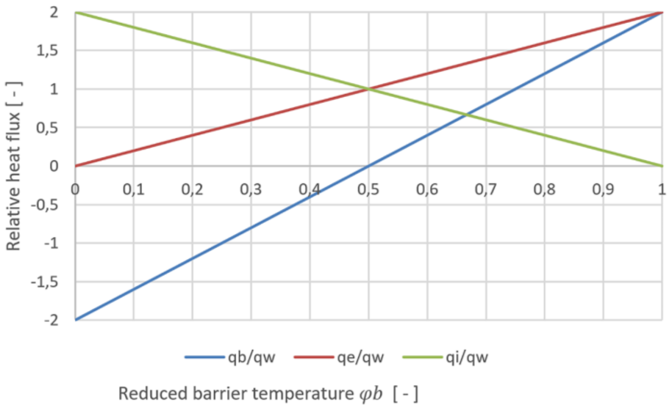

Figure 3. Relative heat fluxes to the outside from the room through the thermal barrier, in case when the thermal resistances on both sides are equal

HEAT TRANSFER MODEL THROUGH A WALL WITH A THERMAL BARRIER

A partition with a thermal barriers is insulated at least on one side. The core of the thermal barrier has pipes in which the heating/cooling medium flow, while simultaneously allowing for transfer of the loads (as discussed by Krzaczek et al. [13, 14, 15] and by Małek [12]).

A heat transfer model for a simulated thermal barrier wall segment with a width equal to half of the pipe spacing and a length of 1 m has been derived. It was assumed that the wall is insulated on both sides. The heat travels from the side with the heating medium (Fig 4a, top of the cross section) to the other end of the element, which is located on the plane of symmetry of the pipes. Heat does not flow through this plane. (Fig 4a, bottom of the cross section). The thermal conductivity of the core forming the thermal barrier is much greater than of the insulation, so longitudinal conduction in the insulation was ignored. The heat-transfer resistance outside the barrier was increased by its thermal resistance [29]. Heat gain from one side of the barrier and loss on the other side were considered as the internal heat sources of the barrier. It was assumed that there is a constant temperature at the base of the barrier, near the pipes. The above assumptions correspond to those made as for a classical fin [30, 31]. A diagram of adopted partition with a thermal barrier model is shown in Figure 4.

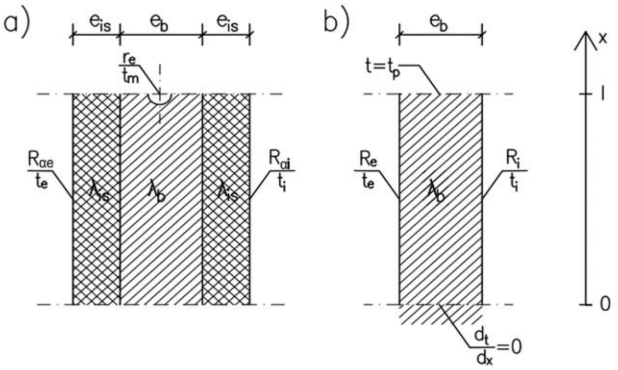

Figure 4. Diagram of the partition model with a thermal barrier: a) cross-section through a separate element of the partition, b) diagram of the partition model

The output equation for the adopted model is:

$$\frac{d^2t}{dx^2} = m \cdot t - q \tag{14}$$

where: m – coefficient [m^{-2}], t – temperature [K], q – coefficient [$K \times m^{-2}$],

$$m = \frac{\frac{1}{R_i} + \frac{1}{R_e}}{\lambda_b \cdot e_b} \tag{15}$$

and

$$q = \frac{\frac{t_i}{R_i} + \frac{t_e}{R_e}}{\lambda_b \cdot e_b} \tag{16}$$

where: λ_b – thermal conductivity coefficient of the barrier material [W/(m × K)], e_b – thermal barrier thickness [m]

When there is no medium flowing through the barrier, only losses from the room by heat penetration are occurring. The temperature at the barrier t_{b0} is calculated as (17):

$$t_{b0} = \frac{\frac{t_i}{R_i} + \frac{t_e}{R_e}}{\frac{1}{R_i} + \frac{1}{R_e}} = \frac{q}{m} \tag{17}$$

Equation 14 was solved with typical boundary conditions:

$$\text{for } x = 0 \rightarrow \frac{dt}{dx} = 0 \tag{18}$$

$$\text{for } x = l \rightarrow t = t_p \tag{19}$$

acquiring:

$$t(x) = \left(t_p - \frac{q}{m}\right) \cdot \frac{\cosh(\sqrt{m} \cdot x)}{\cosh(\sqrt{m} \cdot l)} + \frac{q}{m} \tag{20}$$

After introducing the temperature difference into the above relationship:

$$\vartheta = t - t_{b0} = t - \frac{q}{m} \tag{21}$$

The formula for the temperature field is:

$$\vartheta(x) = \vartheta_p \cdot \frac{\cosh(\sqrt{m} \cdot x)}{\cosh(\sqrt{m} \cdot l)} \tag{22}$$

The average temperature of the barrier segment is:

$$\vartheta_{mean\,b} = \frac{\vartheta_p}{\sqrt{m} \cdot l} \cdot tgh\left(\sqrt{m} \cdot l\right) \tag{23}$$

The heat flux transferred to the barrier segment is determined as:

$$\dot{Q}_b = \lambda_b \cdot e_b \cdot \sqrt{m} \cdot \vartheta_p \cdot tgh\left(\sqrt{m} \cdot l\right) \tag{24}$$

After taking into account (23), the formula can be presented as:

$$\dot{Q}_b = l \cdot \left(\frac{1}{R_i} + \frac{1}{R_e}\right) \cdot \vartheta_{mean\,b} \tag{25}$$

The obtained relations for the temperature field in the thermal barrier and heat flux are identical to those presented in the literature for straight fins [30]. The m parameter is defined in more general manner.

THERMAL BARRIER EFFICIENCY

Definition of thermal barrier efficiency

In order to simplify the calculations of the effect of geometric and thermodynamic parameters of the barrier on its temperature, the concept of thermal barrier efficiency η_b was introduced. It was defined as the ratio of the difference between the average temperature of the thermal barrier $t_{mean\,b}$ and the temperature of the wall t_{b0} at the location of potential barrier (barrier is disabled), and the difference between the temperature of the barrier base (outer surface of the pipe) t_p temperature of the wall t_{b0} in the centre of the core [32, 33].

$$\eta_b = \frac{t_{mean\,b} - t_{b0}}{t_p - t_{b0}} = \frac{\vartheta_{mean\,b}}{\vartheta_p} \tag{26}$$

After using formula (23), the thermal barrier efficiency is:

$$\eta_b = \frac{tgh\,(\sqrt{m} \cdot l)}{\sqrt{m} \cdot l} \tag{27}$$

The formula for the efficiency of the thermal barrier is identical to that for straight flat fin. The *m* parameter is defined differently as for fins. Knowing the efficiency allows to easily determine the average temperature of the thermal barrier segment:

$$\vartheta_{mean\,b} = \vartheta_p \cdot \eta_b = \vartheta_p \cdot \frac{tgh(\sqrt{m} \cdot l)}{\sqrt{m} \cdot l} \tag{28}$$

while the basic relationships of heat fluxes flowing in and out of the partition for a segment with width *l* and length of 1 m are calculated as:

$$\dot{Q}_e = \frac{(t_{b0} + \vartheta_{mean\,b}) - t_e}{R_i} \tag{29}$$

$$\dot{Q}_i = \frac{t_i - (t_{b0} + \vartheta_{\text{mean}\,b})}{R_e} \tag{30}$$

$$\dot{Q}_b = \dot{Q}_i - \dot{Q}_e \tag{31}$$

Assuming:

$$b = \sqrt{m} \cdot l = \sqrt{\frac{\frac{1}{R_i} + \frac{1}{R_e}}{\lambda_b \cdot e_b}} \cdot l \tag{32}$$

then:

$$\eta_b = \frac{tgh(b)}{b} \tag{33}$$

The average temperature of the barrier is calculated as:

$$\vartheta_{mean\,b} = \vartheta_p \cdot \eta_b \tag{34}$$

Figure 5 plots the efficiency determined by formula (33) depending on the value of the *b* coefficient.

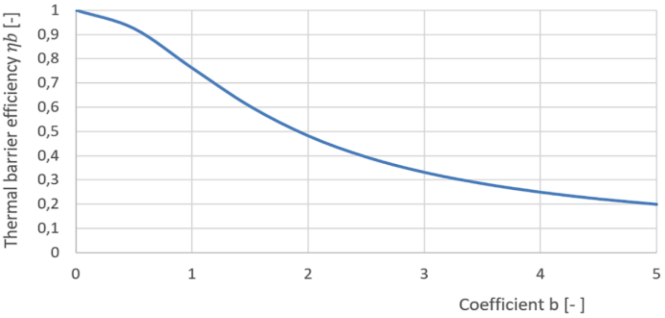

Figure 5. Thermal barrier efficiency depending on the value of the coefficient *b*

Influence of insulation thicknesses on both sides of a thermal barrier on its efficiency

When designing the insulation of building partitions, the value of thermal resistance is assumed as minimum value found in guidelines. Insulation is selected so that the total thermal resistance of the partition is at least equal to or greater of this value. For a wall with a thermal barrier, the thickness of insulation on both sides of the barrier should be taken into consideration, so that its efficiency is as high as possible. The efficiency of the barrier is correlated to the value of *b* coefficient – with its increase, the efficiency decreases. With a fixed heat conduction through the wall, for thermal resistance following formula can be proposed:

$$R_w = R_i + R_e = const. \tag{35}$$

$$R_i = R_w - R_e \tag{36}$$

where: R_i and R_e are defined by (3) i (4).

The formula for the *b* coefficient (32) contains the expression for the equivalent heat transfer coefficient *U* calculated based on the R_i and R_e:

$$U = \frac{1}{R_i} + \frac{1}{R_e} \tag{37}$$

After using (36) in the relation (37), the resulting equation is differentiated. Since the extremum is sought it is equated to zero:

$$\frac{dU}{dR_i} = \frac{d\left(\frac{1}{R_i} + \frac{1}{R_W - R_i}\right)}{dR_i} = 0 \tag{38}$$

then:

$$R_i = \frac{R_W}{2} = R_e \tag{39}$$

The second derivative of the differentiated expression is positive. Thus, we get that the extremum occurred for the value of 0.5:

$$\frac{R_i}{R_W} = \frac{R_e}{R_W} = 0{,}5 \tag{40}$$

Figure 6 shows the graph of the reduced function $1/(R_i/R_w) + 1/(R_e/R_w)$.

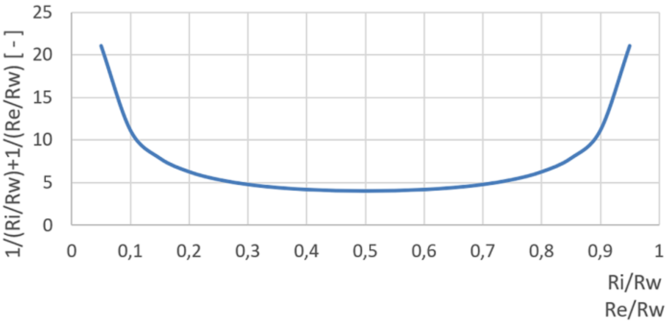

Figure 6. The value of the *U* function depending on the resistance ratio R_i/R_w i R_e/R_w

Analyzing the graph of *U* values presented in Figure 6, it can be seen that, according to the calculations, the minimum occurs for a reduced value of thermal resistance of 0.5. Meaning that the minimum value occurs when the thermal resistance on one side of the barrier is equal to the thermal resistance on the other side of the barrier. For such case the value of barrier efficiency is the highest.

Thermal barrier efficiency properties

Concept of thermal barrier efficiency allows to easily calculate the temperature of a thermal barrier. The basis is that an increase of the value of *b* coefficient causes a decrease in its efficiency. Analyzing the dependence on the efficiency of the thermal barrier, it can be concluded that the efficiency of the barrier does not depend on the temperature of the barrier base and the wall surroundings, but only on the geometric and thermodynamic parameters of the partition. From the analysis of the dependence on the parameter *b*, it can be concluded that:

- Increasing the insulation resistance outside the barrier results in increased efficiency.
- Increasing the distance between the heating medium pipes inside the barrier results in lowering the efficiency of the barrier.
- Using a material with a higher value of thermal conductivity for barrier's core increases the efficiency.
- Increase in the thickness of the thermal barrier increases its efficiency.

Thermal barrier efficiency calculation

For the assumed geometric and thermodynamic parameters of the thermal barrier, it is initially assumed that the temperature on the outer surface of the pipe t_p corresponds to the temperature of the medium t_m in the pipe and the parameter *b* is calculated from equation (32). Then the efficiency of the barrier η_b is determined (from relation (33) or the Figure 5) and the average temperature of the thermal barrier $\vartheta_{mean,b}$ is calculated (34). Taking into account the geometric and thermal parameters of the pipe, the heat transfer coefficient α_m and the thermal resistance of the pipe's wall R_p are calculated. From the equation (40) the temperature drop between the medium and the base of the barrier is determined:

$$\Delta t = t_m - t_p = \frac{\dot{Q}}{\pi \cdot r \cdot \left(\alpha_m + \frac{1}{R_p}\right)} \tag{40}$$

The value of the heat transfer coefficient from the heating medium flowing into the barrier can be calculated from Gnielinski's formula [31].

To determine the temperature outside the pipe, the reduced temperature ϑ on the outer surface of the pipe is further reduced by Δt. Then using the calculated efficiency η_b, the average temperature of the thermal barrier is calculated from equation (28). The resulting value estimates the average temperature of the barrier with sufficient accuracy. Knowing the layers and dimensions of the barrier, based on formula (17), the average temperature of the barrier t_{b0} is determined. Then from formulas (29) and (30) the heat fluxes flowing in the barrier are calculated.

CONCLUSIONS

In the article, based on the developed thermal barrier wall model, the thermal barrier efficiency was determined for assumed initial temperatures and barrier dimensions. The efficiency was defined as the ratio of the difference between the average temperature of the barrier and the temperature of the wall at the location of potential barrier (barrier is disabled), to the difference between the temperature of the medium in the barrier and the temperature of the core without the barrier. For assumed values, the efficiency of the barrier was calculated in relation to half the distance between the pipes, and the product of the thermal conductivity coefficient and the thickness of the thermal barrier. The results of the calculations are shown in the graphs. The conclusions drawn from the calculations have confirmed that the efficiency of the barrier decreases as the distance between the pipes increases, as well as when the thermal conductivity of the barrier's core material increases. It was also shown that the efficiency of a thermal barrier is highest when the thermal resistance of the wall on both sides of the barrier is the same. Knowing the efficiency of the barrier allows to determine in a simple manner the average temperature of the barrier and the amount of heat given off by the room and by the heating medium flowing in the barrier.

The methodology proposed in this paper can be used for thermal calculations of solar photovoltaic (PV) cells with a hybrid cooling system. This system uses a thermal collector to convert waste heat into reusable heat. Media such as domestic hot water or air can be heated in this way.

REFERENCES

1. Kurniawan T.B., Dewi D.A., Usman F., Fadly F. Towards Energy Analysis and Efficiency for Sustainable Buildings. Emerging Science Journal, Dec 2023; 7(6), http://dx.doi.org/10.28991/ESJ-2023-07-06-022
2. Chen, W., Huang, Z., Chua K.J. Sustainable energy recovery from thermal processes: a review. Energ Sustain Soc 2022; 12, 46. https://doi.org/10.1186/s13705-022-00372-2
3. Barkanyi T. Patent No. P398122, Element of building construction for active insulation of buildings, 2012.
4. Barkanyi T., Nagylucskay L. Building structure with active heat. EP2231952A1 European Patent Office, 11.06.2009
5. Kisilewicz T., Fedorczak-Cisak M., Barkanyi T. Active thermal insulation as an element limiting heat loss through external walls. Energy and Buildings, 2019; 205(15): 109541. https://doi.org/10.1016/j.enbuild.2019.109541
6. isomax.isodom.pl (Accessed: 10.02.2023)
7. Leciej-Pirczewska D., Szaflik W. Use of low-temperature medium in wall heating (in Polish). Ciepłownictwo, Ogrzewnictwo, Wentylacja, 2010; 41(5): 168–172.
8. Leciej-Pirczewska D., Szaflik W. Use of low-temperature medium in wall heating (in Polish). Part II, Ciepłownictwo, Ogrzewnictwo, Wentylacja, 2010; 41(12): 455–459.
9. Leciej-Pirczewska D., Szaflik W. Effect of thermal barrier temperature in building wall on heat loss (in Polish). X Forum Ciepłowników Polskich, Międzyzdroje, 2006.
10. Ulbrich R., Radlak G. Application of environmental energy in modern solutions of passive buildings based on Isomax system. Zeszyty Naukowe Politechniki Opolskiej s. Inżynieria Środowiska, 2005.
11. Yang Y., Chen S., Chang T. X., Ma J. R., Sun Y. Uncertainty and global sensitivity analysis on thermal performances of pipe-embedded building envelope in the heating season. Energy Conversion and Management, Article, Sep 2021; 244(23): 114509, https://doi: 10.1016/j.enconman.2021.114509
12. Małek M. Effect of thermally activated partition parameters on thermal comfort and energy consumption (in Polish). Department of Environmental and Energy Engineering. Doctoral dissertation. Supervisor: prof. dr hab. inż. Halina Koczyk. Poznań, 2022.
13. Krzaczek M. Thermal Barrier Concept in Buildings with Very Low Energy Demand (in Polish). Inżynieria Morska i Geotechnika, 2010; 2: 154–162.
14. Krzaczek M., Kowalczuk Z. Thermal Barrier as a technique of indirect heating and cooling for residential buildings. Energy and Buildings, Article,

Apr 2011; 43(4): 823–837, https://doi.org/10.1016/j.enbuild.2010.12.002

15. Krzaczek M., Florczuk J., Tejchman J. Improved energy management technique in pipe-embedded wall heating/cooling system in residential buildings. Applied Energy, Nov 2019; 254(27): 113711, https://doi: 10.1016/j.apenergy.2019.113711
16. Zhou L.Q., Li C.J. Study on thermal and energy-saving performances of pipeembeddedwall utilizing low-grade energy. Applied Thermal Engineering, Jul 2020; 176(11): 115477, https://doi: 10.1016/j.applthermaleng.2020.115477
17. Chen S., Yang Y., Olomi C., Zhu L. Numerical study on the winter thermal performance and energy saving potential of thermo-activated PCM composite wall in existing buildings. Building Simulation, Article, Apr 2020; 13(2): 237–256, https://doi: 10.1007/s12273-019-0575-8
18. Chen S., Chang T., Yang Y. Summer thermal and energy performances assessment of a modular hydronic thermal barrier wall for ultra-low energy buildings - A field experimental study. Applied Thermal Engineering 2024; 236: 121491, https://doi.org/10.1016/j.applthermaleng.2023.121491
19. Chen S., Chang T., Yang Y., He Ch., Gong Q. Experimental and numerical study on thermal performances of a modular hydronic thermal barrier wall with heat injection system in filler cavities. International Journal of Thermal Sciences, 2024; 196: 108727, https://doi.org/10.1016/j.ijthermalsci.2023.108727
20. Krajcik M., Sikula O. The possibilities and limitations of using radiant wall cooling in new and retrofitted existing buildings. Applied Thermal Engineering, Jan 2020; 164: 15, 114490, https://doi: 10.1016/j.applthermaleng.2019.114490
21. Krajcik M., Arici M., Sikula O., Simko M. Review of water-based wall systems: Heating, cooling, and thermal barriers. Energy and Buildings, Review, Dec 2021; 253: 31, 111476, https://doi: 10.1016/j.enbuild.2021.111476
22. Dharmasastha K., Samuel D.G.L., Nagendra S.M.S., Maiya M.P. Experimental investigation of thermally activated glass fibre reinforced gypsum roof. Energy and Buildings, Article Dec 2020; 228: 14, 110424, https://doi: 10.1016/j.enbuild.2020.110424
23. Zhu Q.Y., Xu X.H., Gao J.J., Xiao F. A semi-dynamic model of active pipeembedded building envelope for thermal performance evaluation. International Journal of Thermal Sciences, Feb 2015; 88(170–179), https://doi: 10.1016/j.ijthermalsci.2014.09.014
24. Zhu Q.Y., Li A.B., Xie J.L., Li W.G., Xu X.H. Experimental validation of a semi-dynamic simplified model of active pipe-embedded building envelope. International Journal of Thermal Sciences, Article, Oct 2016; 108(70–80), https://doi: 10.1016/j.ijthermalsci.2016.05.004
25. Romani J., Perez G., de Gracia A. Experimental evaluation of a cooling radiant wall coupled to a ground heat exchanger. Energy and Buildings, Oct 2016; 129(484–490), https://doi: 10.1016/j.enbuild.2016.08.028
26. Romani J., Perez G., de Gracia A.: Experimental evaluation of a heating radiant wall coupled to a ground source heat pump. Renewable Energy, Article vol. 105, pp. 520-529, May 2017, https://doi: 10.1016/j.renene.2016.12.087
27. Romani J., Cabeza L. F., de Gracia A. Development and experimental validation of a transient 2D numeric model for radiant walls. Renewable Energy, Jan 2018; 115(859–870), https://doi: 10.1016/j.renene.2017.08.019
28. Stojanovic B.V., Janevski J.N., Mitkovic P.B., Stojanovic M.B., Ignjatovic M.G. Thermally activated building systems in context of increasing building energy efficiency. Thermal Science, Article; Proceedings Paper, 2014; 18(3): 1011–1018, https://doi: 10.2298/tsci1403011s
29. Szaflik W. Analysis of heat transfer in double-layer fins. Department of Mechanical and Shipbuilding. Doctoral dissertation. Supervisor: prof. dr hab. inż. Władysław Nowak. Szczecin, 1982.
30. Kern D.Q., Kraus A.D. Extended surfage heat transfer. McGraw Hill Book Company. New York, 1972.
31. Incropera F.P., DeWitt D.P., Bergman T.L., Lavine A.S. Fundamentals of Heat and Mass Transfer. John Wiley & Sons, 2007.
32. Szaflik W. Thermal barrier efficiency (in Polish), 2023; 6: 15–18, https://doi.org/10.36119/15.2023.6.2
33. Szaflik W. Effect of thermal barrier partition parameters on barrier performance (in Polish). 2023; 7/8: 24–27, https://doi.org/10.36119/15.2023.7-8.3