Two-dimensional heat transfer analysis of timber structure walls filled with hemp-lime composite

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Abstract. Hemp-lime composite is a thermal insulating material used as a filling in timber frame construction walls. It is a material based on the wooden part of industrial hemp stalk (hemp shives) and lime binder. In practice, different wall thicknesses, composites with different thermal properties and various configurations of timber structure are used. These factors affect the temperature distribution in the wall. In the thermally weaker areas of walls, there is a greater risk of condensation and mould growth. This issue is important while designing walls based on organic materials. The paper presents the two-dimensional (2D) heat-transfer analysis based on the finite-element method, using THERM software. Several variants of external walls were adopted for the analysis. Thermal parameters of hemp-lime composites used in the analysis were obtained from our own research. The results of the analysis were presented as the values of the thermal transmittance coefficient and linear thermal transmittance equivalent to timber construction. The temperature distribution for an exemplary wall was also shown graphically in the form of isotherms and colour-flooded isotherms.

1 Introduction

Currently, materials with high thermal insulation properties are used in the construction industry, which significantly affects the reduction of heat losses in the heating season. However, weak points in the building envelope, called thermal bridges, also determine energy efficiency of construction [1]. Thermal bridges can increase heat losses through building partitions even up to 30% [2]. There are geometric and construction thermal bridges. Geometric bridges are associated with the shape of the building. Corners of buildings, where the heat transfer surface (external) is larger than the heat absorbing surface (internal), constitute an example. They occur, for example, when the insulating material is interrupted by a material with higher thermal conductivity. Thermal bridges reduce the temperature of the wall surface in their area. This creates a risk of condensation and mould growth, which results in deterioration of the indoor air quality [3-6]. These phenomena are particularly dangerous in partitions made of natural materials of plant origin. Hemp fibres are used as thermal insulation material with good thermal parameters [7]. Cellulose components are also used as aggregates in mortars [8-9], as reinforcement in wall boards [10] or as thermal insulation in composites [11-12]. The examples include partitions based on a timber frame construction and filled with insulating material in the form of a hemp-lime composite. This material is characterised by satisfactory thermal parameters, i.e. thermal conductivity coefficient in the range of 0.082÷0.151 W/(m·K) [13]. These values are higher than in the case of the current insulation materials (e.g. polystyrene). However, it is possible to make partitions that meet the thermal requirements in different countries, and the use of waste (especially of plant origin) in construction shows a positive environmental impact. In such partitions, the structural bridge may be a wooden frame, because wood has an approximately twice higher thermal conductivity coefficient than the hemp-lime composite.

In many countries, the technology of using hemp waste (shives) in the construction industry is in the phase of recognition. Thus, it is desirable to conduct a study on this material and, above all, analyse its behaviour in typically designed wall partitions. The novelty of the work involves undertaking a thermal analysis of wall partitions made of a composite based on the shives obtained from hemp grown in Poland. The analysis can be helpful in the design of buildings in accordance with the principles of building physics.

The paper presents the two-dimensional (2D) heat-transfer analysis based on the finite-element method, using THERM software. The subject of the analysis involves external walls based on a timber frame construction filled with a hemp-lime composite. The temperature distribution was analysed for several variants of the external wall construction solutions, which enabled to select the most favourable solution due

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to the heat transfer. The thermal parameters of the composite come from our own research.

2 Materials and methods

2.1 Materials and recipes

The composite used in the analysis consists of a lime binder, hemp shives and water. Shives were cut into pieces, which included wooden parts of industrial hemp stalks (Fig. 1). Shives were obtained from the Polish variety of industrial hemp – *Białobrzeskie*.

Fig. 1. Hemp shives used in investigation.

Hemp shives are characterised by low bulk density in the range of 110÷120 kg/m^3, low thermal conductivity in the range of 0.055÷0.062 W/(m·K) [14] and high water absorptivity of about 400% dry mass after 48 h of immersion in water. The binder consisted of hydrated lime (70% by weight of the binder), Portland cement classified as CEM II/B-V 32.5R (15%) and metakaolin (15%). Lime ensures adequate vapour permeability and protection against biological corrosion of shives. Cement and metakaolin provides hydraulic binding and initial setting of the material. Composites based on four recipes were prepared and tested. These recipes are shown in Table 1.

Table 1. Compositions of composites.

Composite	Binder : filler weight ratio	Binder : water weight ratio
C1	2 :1	2.8
C2	1.83 :1	2.65
C3	1.67 :1	2.5
C4	1.5 :1	2.35

2.2 .Methods

2.2.1 Testing of the material – thermal conductivity

The thermal conductivity coefficient λ of the composite was tested according to PN ISO 8302: 1999 standard on 300×300×50 mm samples using the Fox 314 plate apparatus. The samples were tested after 28 days of maturation under laboratory conditions (air temperature 20°C±2°C, relative humidity 55%±5%) for 28 days, and then they were dried to a constant weight at 60°C in an oven. On a hob, the temperature was set at 25°C, while on a cooling plate – at 0°C; the average temperature was 12.5°C. The results were averaged for six samples. The measurement error of the thermal conductivity measuring device was approx. 2%. The instrument operation is based on the one-dimensional Fourier law (1):

$$q = -\lambda \frac{dT}{dx}, \tag{1}$$

Where q is the heat flux density flowing through the sample [W/m^2], λ is the thermal conductivity coefficient of the sample [W/(m·K)], dT/dx is the temperature gradient on the isothermal flat surface of the sample [K/m].

2.2.2 Analysed partition

Partitions with the construction frame usually used in this technology were accepted for calculations. The load bearing structure is a timber frame placed in the middle of wall thickness. The cross-sections dimensions of studs are 50x150 mm. Five cases of axial spacing between them were considered: 400, 450, 500, 550 and 600 mm. Four cases of the hemp-lime filler thickness were considered as well: 400, 410, 420 and 430 mm. The adopted scheme is shown in Figure 2.

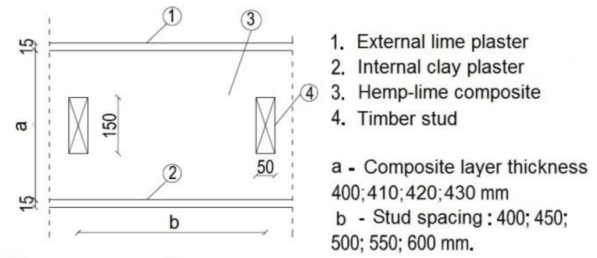

Fig. 2. Scheme of analysed partition.

The influence of the λ value on the averaged thermal transmittance coefficient and the linear thermal transmittance coefficient based on the wall with thickness of 430 mm and variable stud spacing were also considered.

2.2.3 Two-dimensional heat flow analysis

The temperature distribution in partitions was modelled in Therm 7.4, developed by Lawrence Berkeley National Laboratory, University of California, USA [15]. The program is used for two-dimensional modelling of the determined heat flow in partitions and building elements and is commonly used in the thermal analysis of construction nodes [16-19]. The heat flow equations are solved in the program using the finite element method, and node modelling includes the following stages [15]:
- defining a node (defining geometry, assigning materials and determining the boundary conditions)
- mesh generation
- determination of temperature in nodes and heat streams with Finite Element Analysis Solver
- reporting the analytical results (e.g. average heat transfer coefficient for a given node) and the processed results in a graphical form (e.g. isotherms)

On the basis of the obtained results, it is possible to determine the linear heat transfer coefficient ψ [W/(m·K)], which characterises a given node and allows to evaluate its thermal quality.

Linear heat transfer coefficient ψ was calculated in accordance with ISO 10211 (2007) as:

$$\psi = L^{2D} - \sum_{i=1}^{j} U_i \cdot l_i \qquad (2)$$

Where L^{2D} is the linear thermal coupling coefficient obtained on the basis of numerical analysis as a product of the average heat transfer coefficient of a node and its length [W/(m·K)]; U_i is the heat transfer coefficient of the *i*-the component of the node [W/(m²·K)] and l_i is the length assigned to the component with the heat transfer coefficient U_i [m].

The *U*-factor was generated by means of the Therm software, but its values were approximated to the values obtained from the calculations for components consisting of heterogeneous heat layers according to the EN ISO 6946 (1999) standard.

Thermal properties of individual materials and boundary conditions adopted in modelling are summarised in Tables 2 and 3. The average external temperature for January in Lublin (Poland) was assumed.

Table 2. Thermal properties of building materials and elements.

No.	Building material/ element	Thermal properties
1	Hemp-lime composite	λ = 0.088 W/(m·K)
2	Lime plaster	λ = 0.80 W/(m·K)
3	Clay plaster	λ = 0.91 W/(m·K)
4	Timber construction element	λ = 0.16 W/(m·K)

Table 3. Boundary conditions adopted in modelling.

No.	Surface	Temperature	Surface resistance	Description
1.	Internal	+20°C	0.13 (m²·K)/W	Heat flow horizontal, simplified*
2.	External	-2.6°C	0.04 (m²·K)/W	Simplified*
3.	Cut-off planes	–	–	Adiabatic

In Figure 3, the generated finite element mesh for an example of the analysed walls is presented. The size of the fields (number of nodes) in the mesh affects the accuracy of the results. The number of nodes increases along with the accuracy of calculations. Two parameters are instrumental in controlling a model in Therm, namely the "Maximum % Error Energy Norm" and the "Quad Tree Mesh Parameter". The former relates to the maximum size of the initial subdivision, whereas the latter is used for iterative calculations, setting an iteration threshold for further division of the nonconforming elements. The iterative method was employed for the calculation of the model. The "Maximum % Error Energy Norm" was set as 10% (Fig. 4), while the default "Quad Tree Mesh Parameter" was adjusted to 6 (its value may range between 3 and 12). The obtained temperature results did not exceed the tolerance level of 0.1K.

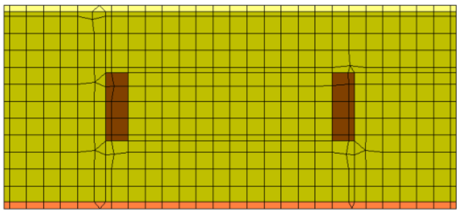

Fig. 3. Finite element mesh for an example analysed wall (hemp-lime layer thickness: 430 mm; stud spacing: 500 mm).

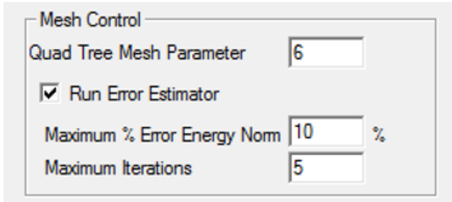

Fig. 4. Mesh parameters set in THERM software.

3 Results and discussion

3.1 Thermal conductivity

The results of the thermal conductivity are shown in Figure 5. Error bars mean confidence intervals for the average.

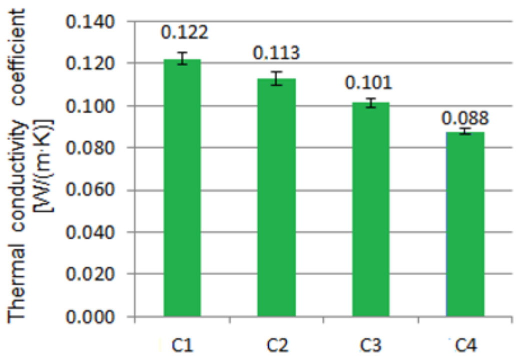

Fig. 5. Thermal conductivity coefficient of composites.

Thermal conductivity coefficient of composites ranges from 0.088 to 0.122 W/(m·K). The thermal conductivity coefficient increases along with the proportion of binder to filler in the composite. Similar observations about hemp-lime composites were described in the literature [20]. An increase in the binder content resulted in a tighter filling of the empty voids in the composite; thus, the thermal insulation is reduced. Satisfactory thermal insulation properties of composites are associated with high porosity, both of shives and the composite, and with low thermal conductivity of shives.

For the numerical analysis, the composite with the lowest λ-value (C4, λ=0.088 W/(m·K)) was selected.

3.2 Two-dimensional heat flow analysis

The graph (Fig. 6) presents the changes in the value of the averaged thermal transmittance coefficient of walls of different thicknesses depending on the axial spacing of timber studs.

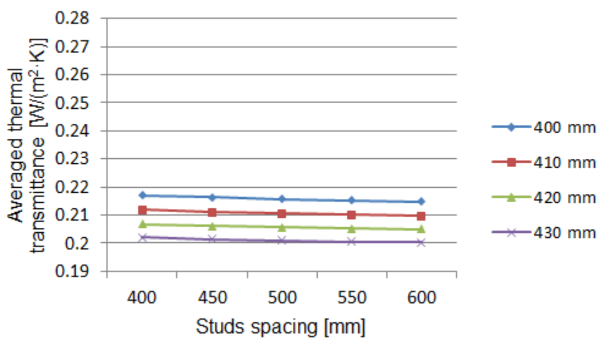

Fig. 6. Averaged thermal transmittance coefficient of walls of different thicknesses depending on the axial spacing of timber studs.

The analysed external walls are characterised by the averaged *U*-factor in the range of 0.2÷0.217 W/(m^2·K). Its value decreases as the stud spacing increases. This is related to the increase in the area of the hemp-lime composite, which is characterised by better insulating properties than wood, in the cross section of the wall used in calculation. The differences between the U-values of walls with extreme stud spacing are small, in the range of 0.9÷1 %. The dynamics of *U*-value changes, depending on the stud spacing, decreases with the increase of the thickness of the hemp-lime composite layer.

The graph (Fig. 7) presents the changes in the value of the linear thermal transmittance coefficient of walls of different thicknesses depending on the axial spacing of timber studs.

The timber studs form linear thermal bridges expressed as linear thermal transmittance coefficient ψ in the range of 0.0022÷0.0026 W/(m·K). Its value increases as the thickness of the hemp-lime composite layer is reduced. This is related to the decrease in thickness of the thermal insulation surrounding the timber element. The stud spacing does not affect the linear thermal transmittance coefficient. Its value stays constant at varying spacing of poles. Small variations are visible, but there is no clear relationship.

The graph (Fig. 8) presents the changes in the value of the averaged thermal transmittance coefficient of 430 mm thick walls filled with hemp-lime composites C1-C4 (with different λ-values), depending on the axial spacing of timber studs.

Analysed external walls with thickness of 430 mm, filled with hemp-lime composites with the λ values between 0.088÷0.122 W/(m·K) are characterised by the averaged *U*-factor in the range of 0.2÷0.271 W/(m^2·K). With a layer thickness of 430 mm, using only composites with λ values of 0.088 W/(m·K) and 0.101 W/(m·K), it is possible to meet current Polish requirements for external walls (U_{max}≤0.23 W/(m^2·K)). By using each of the hemp-lime composites, the *U*-value decreases with the increase in the stud spacing. The differences in its value for walls with extreme stud spacing are 0.4÷0.9% and they decrease as the composite λ values grow. This is related to the reduction of the differences in the thermal properties between wood and composite.

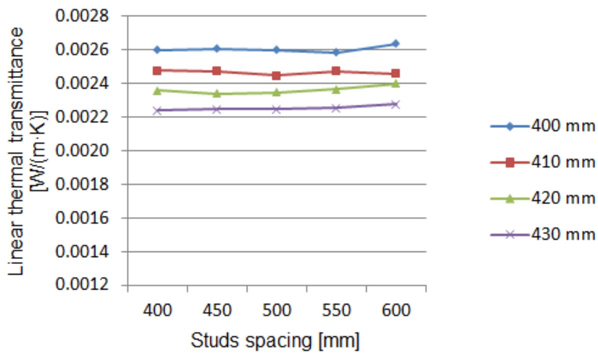

Fig. 7. Linear thermal transmittance coefficient of walls of different thicknesses depending on the axial spacing of timber studs.

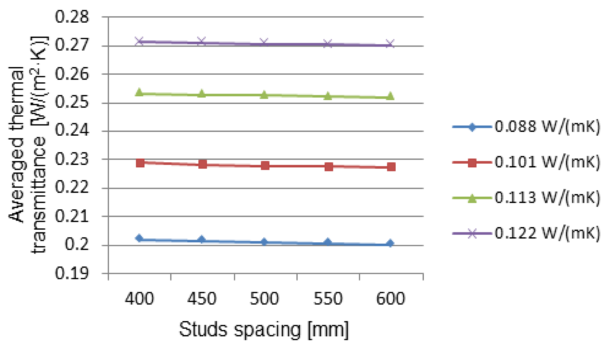

Fig. 8. Averaged thermal transmittance coefficient of the walls with the thickness of 430 mm filled with hemp-lime composites C1-C4 (with different λ-values) depending on the axial spacing of timber studs.

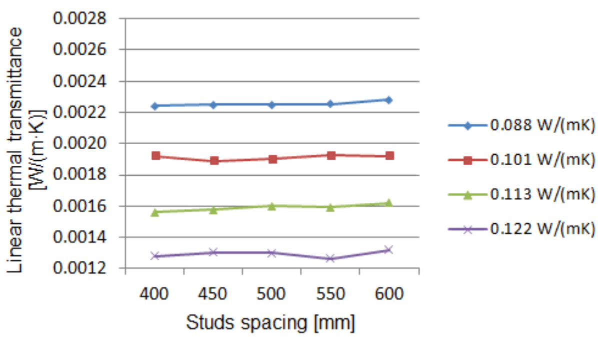

Fig. 9. Linear thermal transmittance coefficient of the walls with the thickness of 430 mm filled with hemp-lime composites C1-C4 (with different λ-values) depending on the axial spacing of timber studs.

The graph below (Fig. 9) presents changes in the value of the linear thermal transmittance coefficient of the walls with the thickness of 430 mm, filled with hemp-lime composites C1-C4 (with different λ-values) depending on the axial spacing of timber studs.

In the analysed external walls filled with hemp-lime composites (C1-C4) with different λ values and with the thickness of 430 mm, the timber studs form linear thermal bridges in the range of 0.0013÷0.0023 W/(m·K). The higher the hemp-lime composite λ value, the smaller the linear thermal transmittance coefficient value. This is due to the fact that at higher λ values of the composite, its thermal characteristics are more similar to the thermal characteristics of wood.

In the Therm software, it is possible to present the results of temperature distribution in the partition in the form of isotherms or in a colour scale. Figures 10-11 present the graphical results for one of the analysed variants of external walls. The disruption in the unidirectional heat flow in the area of occurrence of thermal bridges – timber studs is visible.

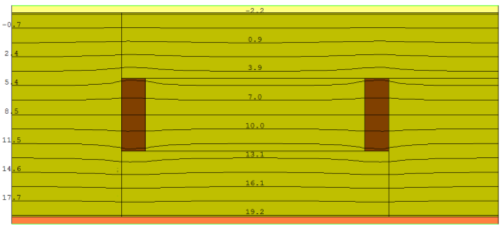

Fig. 10. Hemp shives used in the investigation.

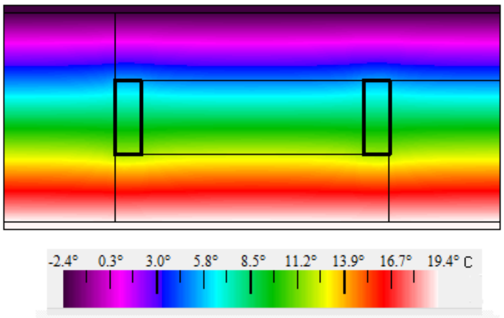

Fig. 11. Hemp shives used in the investigation.

4 Conclusions

Hemp-lime composite is characterised by satisfactory thermal insulation properties; however, the λ values are higher than traditional insulating materials such as mineral wool and polystyrene. In order to meet current Polish thermal requirements for external walls, thickness of the wall made of composite should be about 400

mm. It would be reasonable to further investigate the thermal capacity of composites, as it can contribute to reducing heat losses under the actual conditions.

Despite the relatively good insulating properties, timber elements have a visible impact on the local increase in heat flow in the partitions made with the use of hemp-lime composite, creating thermal bridges in walls. These effects are relatively small, as the linear heat transfer coefficients do not exceed the value of 0.10 W/(m·K), recommended as acceptable for energy-efficient buildings [21]. Its values range from 0.0022 to 0.0026 W/(m·K) and decrease as the wall thickness increases. The size of the stud spacing has little effect on the changes in the heat flow through the wall. The differences in the U-values were from 0.9 to 1%. Its value decreased with increasing the stud spacing. In the case of the linear thermal transmittance coefficient, the differences were even smaller and there is no relationship between its value and the stud spacing.

However, in order to assess the technology of the building walls made of hemp-lime composites, it would also be necessary to evaluate other construction nodes as well as the total heat demand in the building, depending not only on the linear thermal transmittance coefficient, but also on the length of individual thermal bridges in the external partitions.

The analyses presented in the work may be helpful in the design as well as selection of this technology by investors. The hemp-lime composite is increasingly often used in the construction industry. Due to the high labour-intensity of wall construction using the technique of manual tamping in shuttering, a small number of specialized contractors and producers of shives as well as low popularity of hemp cultivation, this technology is relatively expensive. However, the hemp cultivation as well as the number of people interested in this material increases every year.

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