Thermal bridge occurrence in straw-bale timber frame walls

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Abstract. Timber frame walls usually require additional filling that improves their thermal insulation. Straw bales, which constitute a waste product from cereals, are a sustainable solution employed for that purpose. The temperature distribution in a wall is influenced by the heterogeneity of the partition that comprises the elements characterised by higher thermal conductivity, i.e. timber frame. Thermal bridges (i.e. thermally weaker areas) in walls are conducive to the mould growth as well as condensation; thus, it is important to take these phenomena into account at the wall designing stage. The work describes a 2D heat-transfer analysis carried out with the finite element method by means of THERM software. The analysis involved several different variants of external walls and corners. The thermal parameters of the investigated straw were derived from our former research. The obtained results were shown as the values of thermal transmittance coefficient and linear thermal transmittance equivalent to timber construction. The temperature distribution for the investigated wall was presented in a graphical form. The study also involved examining the possibility of surface condensation.

1. Introduction
Straw is a waste product from cereal crops, e.g. rye or wheat, therefore, its use is consistent with the principles of sustainable development. In addition, the crop is an annual plant and, in Poland, it is grown in every province, thus it can be locally sourced. Straw is primarily composed of cellulose, hemicellulose and lignin [1].

Straw is used in construction mainly as a wall filling in a timber frame construction [2]. It is used in the form of compressed bales of various sizes, tied by steel wire or polypropylene twine. Bales with a density of 80-100 kg/m³ are preferred due to their optimal insulation parameters [3]. Straw bales of larger sizes are used as a load-bearing material, transferring loads from the roof and ceilings. Straw is also used as a thermal insulation filler in wall composites based on lime binder [4], in addition to hemp shives [5, 6] and flax shives [7].

Thermal properties of straw bales depend on the moisture content, the density, the porosity, the fibre and bale orientation [2]. Munch [8] showed the values of thermal conductivity of straw bales at different straw bale orientations and densities (62-150 kg/m³) in the range of 0.038-0.082 W/(m∙K). Similar observations are reported by Schiavoni et al. [9]. In turn, the heat capacity of straw is given in the literature [10] in the range of 1338-2000 J/(kg∙K). The porosity of straw ranges between 46 and 84 % [11]. Straw cubes for use in construction must meet numerous requirements. Mass moisture should not exceed 14% [12] due to the risk of biological corrosion development. Under the conditions of high humidity, the optimal temperature at which biological corrosion may occur is 20-70°C [13]. Long-term
exposure to high levels of humidity (above 80% RH) may present an increased risk of straw degradation [14]. In addition to the moisture content in the straw bale, its pH value is also important, and 7.29 is typical for straw [15].

In some areas of the frame, increased cross-sections of timber elements are used in the construction of walls. Despite the satisfactory thermal insulation properties of wood, they can form thermal bridges. The effect of increased heat flow may be the occurrence of condensation of water vapour, mould growth, which results in deterioration of the indoor air quality [16, 17]. It is particularly dangerous in the case of organic materials because they are particularly exposed to biological corrosion [18, 19].

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

2. Materials and methods

2.1. Straw

The study used rye straw from the crops of the Lublin province (Poland), mowed in August, during the harvest period. The diameter of the straw was approx. 1.0-2.5 mm. A sample of straw used in tests is shown in Figure 1.

![Figure 1. Straw used in tests.](image)

2.2. Thermal conductivity of straw

The thermal conductivity of rye straw was investigated in accordance with EN 12667 standard, using a Laser Comp Fox 602 plate apparatus and the heat flow meter method. WinTherm32 software was used for measurements of the thermal conductivity coefficient of cereal straw. Throughout the test, the average reference temperature amounted to +10°C. In turn, the temperature of the top and lower plates was set at +20°C, and 0°C, respectively. The frame was placed in a thin bag to prevent moisture build-up in the tested material as well as the condensation on the cooler camera plate. Testing the samples involved placing them in a stabilising frame. The frame was made of extruded polystyrene and had the following dimensions: 600×600 mm (external), and 520×520 mm (centre cut) as well as the height of 45 mm. Before the test, the straw was dried at 50°C.

2.3. Analysed partitions

Partitions with the construction frame usually applied in this technology were accepted for calculations. The load-bearing structure is a timber frame placed in two rows – on the inner side and the outer side of the wall. The two adopted stud cross-section variants were 60×120 mm and 50×150 mm. In addition, a scenario with a double stud 50×150 mm was put to test. Five cases of axial spacing between studs were considered: 600, 650, 700, 750 and 800 mm. The heat distribution and the size of the thermal bridge were also checked in external corners made using timber elements with the adopted cross-sections and exemplary studs spacing of 700 mm. The adopted schemes are shown in figure 2.
2.4. Thermal analysis

Temperature distribution was modelled by means of THERM 7.4 software (http://windows.lbl.gov), which can be used to conduct two-dimensional modelling of the determined heat flow in partitions, building elements and construction junctions [20, 21, 22]. It employs FEM for solving the heat flow equations. Junction modelling consists of the following steps [23]:

- model definition (geometry, materials and boundary conditions)
- mesh generation
- using Finite Element Analysis Solver to determine the temperature in nodes and heat streams
- 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)

The obtained results served to determine the linear heat transfer coefficient $\psi$ [W/(m·K)] of a junction in accordance with ISO 10211 standard, given by the following formula (1):

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

where $L^2D$ corresponds to linear thermal coupling coefficient obtained from numerical analysis as a product of the average heat transfer coefficient of a junction and its length [W/(m·K)]; $U_i$ corresponds to the heat transfer coefficient of the $i$-the component of the junction [W/(m²·K)] and $l_i$ is the length assigned to the component with the heat transfer coefficient $U_i$ [m].

The THERM software was employed for the generation of the U-factor; however, its values were approximated to the ones obtained from the calculations for the components of heterogeneous heat layers, in line with the ISO 6946 standard.

Table 1 summarises the thermal properties of individual materials (based on manufacturer data: www.tierrafino.com and ISO 10456 standard). Table 2 shows boundary conditions used in modelling, assuming the average external temperature for January in Lublin (Poland).

| Building material/ element | Thermal conductivity [W/(m·K)] |
|----------------------------|--------------------------------|
| Straw bale                 | 0.047                          |
| Lime plaster               | 0.80                           |
| Clay plaster               | 0.91                           |
| Timber construction element| 0.16                           |
Table 2. Boundary conditions adopted in modelling.

| Surface         | Temperature [°C] | Surface resistance [(m²·K)/W] | Description                      |
|-----------------|------------------|-------------------------------|----------------------------------|
| Internal        | +20              | 0.13                          | Heat flow horizontal, simplified*|
| External        | -2.6             | 0.04                          | Simplified*                      |
| Cut-off planes  | –                | –                             | Adiabatic                        |

* the simplified model means that convective and radiative heat transfer is described by one common surface resistance

2.5. Possibility of water vapour condensation
Condensation of moisture on the internal surfaces of building partitions can arise in the locations where the temperature is below the dew point. Due to the drop in temperature, resulting from the increased heat transfer, the thermal bridge occurrence is to a considerable extent correlated with this phenomenon. On the basis of the ISO 13788 standard, the conditions that contribute to the occurrence of surface condensation were investigated. In order to avoid the mould growth, it is necessary to ensure that the temperature factor at the internal surface \(f_{R_{si}}\) is greater than the design temperature \(f_{R_{si,min}}\) for the critical month (i.e. the one with the highest \(f_{R_{si,min}}\) value). In order to calculate both factors, it is necessary to use the increased thermal resistance at the initial surface (\(R_{si} = 0.25/(m^2·K)\)):

\[
f_{0.25} = \frac{\theta_{si} - \theta_{e}}{\theta_{i} - \theta_{e}} \geq f_{0.25,min} = \frac{\theta_{R_{si, min}} - \theta_{e}}{\theta_{i} - \theta_{e}}
\]

where \(\theta_{si}\) is the surface temperature in the critical area [°C], \(\theta_{R_{si, min}}\) is the minimum acceptable surface temperature [°C], \(\theta_{i}\) is the internal temperature [°C], \(\theta_{e}\) is the external temperature [°C].

The minimum surface temperature of the inner side of the wall occurs in the corner, therefore, only corners are taken into account for calculations.

3. Results and discussion

3.1. Thermal conductivity
Thermal conductivity and bulk density together with standard deviations are presented in table 3.

Table 3. Straw parameters.

| Bulk density [kg/m³] | Standard deviation [kg/m³] | Thermal conductivity [W/(m·K)] | Standard deviation [W/(m·K)] |
|---------------------|-----------------------------|-------------------------------|-------------------------------|
| 50.9                | ±4.26                       | 0.0473                        | ±0.0015                       |

Munch [8] showed that placing straw bales “on flat” resulting in \(\lambda\) value about 0.063 W/(m·K) and “on edge” about 0.051 W/(m·K). Our tests on samples set “on edge” have shown a close fit with the literature data. The obtained smaller \(\lambda\) value may be associated with a lower density of straw bales because the degree of compaction of loose insulation materials affects their insulating properties [24]. Asdruabi [25] also reported that samples made with the stalks of straw perpendicular to the heat flow have better thermal insulation properties.

3.2. Thermal analysis
The graph below (figure 3) presents changes in the value of the averaged thermal transmittance coefficient of walls of different timber elements depending on the axial spacing of timber studs.
Figure 3. Averaged thermal transmittance coefficient of walls of different timber elements depending on the axial spacing of timber studs.

The considered external walls are characterised by the mean U-factor value from 0.117 to 0.130 W/(m²·K), which is reduced as the stud spacing increases. Similar observations were reported in the analyses of walls made of hemp-lime composite with a stud spacing of 400-600 mm [26]. The results may be attributed to the increase in the straw bale area in the cross-section of the considered wall; this material exhibits superior insulating properties in relation to wood. The differences between the U-values characterising the walls with extreme stud spacing range only from 2.15 to 4.26%. Larger variations can be seen in the walls with doubled cross-sections of studs. Doubling the cross-section of studs results in an increase of the averaged thermal transmittance coefficient by 5.5 % and 6.8 %, respectively for columns 60×120 mm and 50×150 mm with cross-sections.

Figure 4. Linear thermal transmittance coefficient of walls of different timber elements depending on the axial spacing of timber studs.

Timber studs create linear thermal bridges, expressed as linear thermal transmittance coefficient $\psi$ ranging from 0.0062 to 0.0128 W/(m·K). This coefficient increases along with the cross-section of timber studs. Their spacing has little effect on the linear thermal transmittance coefficient. Although certain small variations can be noticed, no clear relationship is observed. Similar observations are described in the literature [26]. Doubling the cross-section of studs increases the thermal bridges by 72% and 78%, for the columns with 60×120 mm and 50×150 mm cross-sections, respectively.

Table 4 presents the values of the averaged thermal transmittance and linear thermal transmittance coefficients for external corners with studs spacing of 700 mm.
Table 4. U and ψ value for external corners.

| Symbol of corner | U [W/(m^2·K)] | ψ [W/(m·K)] |
|------------------|----------------|--------------|
| SC6×12           | 0.1005         | -0.0434      |
| SC5×15           | 0.1017         | -0.0486      |

The corner with studs having a cross-section of 50×150 mm is characterised by an averaged thermal transmittance coefficient greater by 1.19% than in the case of the corner with studs of 60×120 mm and linear thermal transmittance coefficient lower by 12.1% than the corner with studs of 60×120 mm. Figures 8 and 9 show the graphical results corresponding to one of the considered types of external walls. The disruptions pertaining to the unidirectional heat flow at the area between thermal bridges and timber studs can be observed.

3.3. Possibility of water vapour condensation

The temperature factors for the described corners are presented in table 5. The minimum temperature on the inner surface is the same in both cases.

Table 5. Temperature factors f_{0.25} [°C].

| Symbol of corner | f_{0.25} |
|------------------|---------|
| SC6×12           | 0.92    |
| SC5×15           | 0.92    |

National regulations in Poland allow for the use of the design temperature factor f_{0.25, min} = 0.72 and the risk of surface condensation does not occur in any of the corners. Satisfactory thermal insulation parameters of the straw and the obtained U-value ensured the high temperature of the inner surface of the wall (18.2°C). Due to different diffusion resistance of wall layers and the presence of timber elements, it would be important to calculate the possibility of interstitial condensation in further studies.

4. Conclusions

Straw bales exhibit good thermal insulation properties, comparable with traditional insulating materials such as mineral wool and polystyrene. It would be reasonable to further investigate the thermal capacity of straw bales, as it can contribute to reducing heat loss under the actual conditions.

Although timber elements are characterised by relatively good insulating properties, they were shown to affect the local increase in heat flow within straw bale partitions, contributing to the creation of thermal bridges in walls. These linear heat transfer coefficients range from 0.0062 to 0.0128 W/(m·K); hence, they do not exceed the acceptable value recommended for energy-efficient buildings, i.e. 0.10 W/(m·K) [27]. The use of the studs with the largest cross-section and the smallest spacing resulted in an increase in averaged thermal transmittance coefficient by 10.6% compared to a wall with studs with the smallest cross-section and the largest spacing. The stud spacing to a limited degree contributes...
to the changes in the linear transmittance coefficient values through the wall. Moreover, no relationship between its value and the stud spacing was observed. Surface condensation did not occur in the analysed corners.

The presented analyses prove that the timber frame configurations used in practice in straw bale walls are small thermal bridges. The results may also be helpful in designing as well as selection of this technology by investors. However, to assess the impact of thermal bridges more accurately, an energy analysis of the entire building should be performed.

5. References

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