Hygrothermal Behaviour of the Timber-Framed Sauna with Straw-Bale Walls

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Abstract. In the autumn of 2016 a timber-framed sauna with straw-bale walls was built for testing hygrothermal properties of walls during permanent usage. The main dimensions of the building's plan were 6.58 x 4.08 m with two rooms on the ground floor: a resting room and a room for washing and wetting (sauna part). The thickness of walls depended on the straw-bale dimensions which were 50 cm. External surfaces of the walls were plastered with the lime plaster. Both clay and lime plasters were used inside to check a better plaster variant for straw. Measuring devices and sensors to determine the temperature and relative moisture content were mounted into walls during construction. The heat flux rate through the wall was measured with a heat flux plate; data were recorded by an Almemo data recorder. Measurements began in December 2016 and ended in April 2017. The heating procedure of the sauna took place once a week. Meanwhile the sauna was heated with electric batteries. The measuring results were interesting. During the heating time the temperature inside the steam room rose to 83 °C, but in the middle of the wall it was 23 °C. At the same time the external temperature was about 0 °C. The data based calculation of thermal transmittance of the wall was $U = 0.15 \text{ W/m}^2\text{K}$ which was a little lower than predicted.

Keywords: construction process of straw-bale walls, thermal conductivity of straw-bale walls, relative moisture content, lime plaster, clay plaster

Introduction

Energy efficiency has been one of the major tasks to be improved in the EU. The aim is to purchase energy efficient buildings in the public sector in the EU countries. Using local natural building materials is a small step towards improvement to have a positive influence on environment. Part of inhabitants prefer to live in houses built from natural materials therefore there is an interested target group. To work out proper construction technique and structure solutions, a lot of tests is needed to be done. One solution of how to save energy is to use straw, which is an agricultural waste product. Straw-bale walls have been in use since the end of 19th century in the USA. A bit later straw was taken into use in Europe [1]. When industrially produced materials became available, the natural materials were forgotten. Then in the 70-80-ies of the 20th century the straw-bale building experienced revival to stay until present [2]. In those days magazines, like *Die Last Straw* and books like *Build It with Bales. A Step-by-Step Guide to Straw-Bale Construction* were published to advertise and introduce natural materials. In Europe the restart of building from straw took place in the 90-ties of the 20th century. The climate in the countries like Germany, England, Sweden, Denmark and so on is humid and certain requirements were established to envelope buildings which should be followed. In England the first straw-bale house was built in 1994, and in Estonia in 2003 [3].

Simultaneously, the investigation of physical-mechanical properties of straw-bale as a building material began. The largest investigation center was founded in Germany under the guidance of Prof.

Minke in Kassel. Material properties like density, thermal conductivity, sorption, air and moisture tightness were investigated from the point of hygrothermal state of a house. Guidelines were published [4, 5] with instructions how to build a straw-bale house. The first tests showed that the thermal conductivity of straw-bale was $\lambda = 0.045 \text{ W/(m K)}$ and the thermal transmittance of the wall with clay rendering of 25 mm outside and inside finish, and straw layer of 500 mm, was $U = 0.11 \text{ W/(m}^2\text{K)}$ [4]. The obtained results lead to a decision to measure hygrothermal properties of different wall structures made of local natural materials. Test elements were built into the window openings of the laboratory of the department of a rural building. One of the tested wall elements was constructed from 500 mm thick straw-bales and rendered with 40 mm clay plaster outside and inside. Calculated thermal transmittance of this test element was $U = 0.182 \text{ W/(m}^2\text{K)}$ [6], but the result from the office with straw bale walls located at Tammistu (in Tartu county) was $U = 0.092 \text{ W/(m}^2\text{K)}$ [7]. Having compared our results to those obtained in Germany we were intrigued to continue this research, and the master thesis was written about constructing the sauna and performing measurements.

Description of construction process

The sauna is located at Paluperä, in Valga county. Two rooms, a resting room and a sauna part, are on the ground floor. Places to sleep are meant to be built in the attic, so the whole building is insulated. The plan of the sauna is presented in Figure 1.

Fig. 1. The plan of the ground floor of the sauna, with indicated Measuring Points 1 and 2 inside the wall

The section A – A of the sauna is presented in Figure 2.

Fig.2. The section A-A of the sauna

Figure 3 shows the timber frame. The step of the frame columns is taken considering the mostly used size of straw-bales, which is 500 mm in length.

Fig. 3. Timber frame of the sauna is ready

Fig. 4. External appearance of the sauna before rendering

The external wall was done sorting out and applying dense and dry straw-bales. Straw-bales for the lower row of the wall were sorted by size for constructing. To get the wanted height of the wall, six rows of bales were needed. During construction the placed bales were tightened after placing the third and sixth row. The height of bales in the wall decreased by about ~7.5% due to tightening. To fill possible gaps between bales, the loose straw was used and pressed into the gaps. Before rendering the surface of straw-bale wall, it was flattened using a chainsaw. After that the walls were stiffened using diagonal timber laths of 22×100 mm (Fig. 4). The sauna before rendering is presented in Figure 4.

To follow our own experience and information acquired from literature [8], the walls were rendered from outside with lime plaster. Internal surfaces of the wall were rendered with clay in Measuring Point 1 and with lime in Measuring Point 2. Rendering was done manually in four layers, and the average amount of the used render was 15 kg/m^2 per layer. Total thickness of the rendering on the surfaces was ca 40 mm on both sides. The most difficult work was to apply the first layer of render. The external wall rendered with lime plaster is presented in Figure 5a, and the internal wall rendered with clay is presented in Figure 5b.

a)

b)

Fig. 5. Rendered walls: a) external wall and lime plaster; b) internal surface covered with clay plaster.

Aims and methods

The aim of research was to describe the hygrothermal behaviour of straw-bale walls in the sauna conditions when heat and relative moisture content gained their maximum at the certain point for a short time during heating the sauna's electric stove and making steam. Meanwhile the sauna was heated

by electric radiators and the door was left open, so internal temperature at this time was the same in all the house. Measurement sensors were placed as shown in Figure 1: Point 1 in the resting room and Point 2 in the wetting room. The scheme of placement of sensors is presented in Figure 6.

Fig. 6. Placement of sensors in the external wall

The following parameters were measured (a measurement device is given in the brackets):

- q – heat flux rate [W/m^2], (Ahlborn sensors FQA018 CSD);
- θ_e, φ_e – external temperature and RH [$^{\circ}\text{C}$, RH%], (OnSet data logger Hobo U12-011);
- θ_{se} – temperature on the external surface of the wall [$^{\circ}\text{C}$], (Ahlborn NiCr-Ni-thermowire T 190-1);
- θ_1, φ_1 – temperature and RH between external surface of straw-bale and lime render [$^{\circ}\text{C}$, RH%], (Ahlborn sensors FHA646R);
- θ_2, φ_2 – temperature and RH in the middle of the straw-bale [$^{\circ}\text{C}$, RH%], (Ahlborn sensors FHA646R);
- θ_3, φ_3 – temperature and RH between the internal layer of the straw-bale and render [$^{\circ}\text{C}$, RH%], (Ahlborn sensors FHA646R);
- θ_{si} – temperature of the internal surface of the wall [$^{\circ}\text{C}$], (Ahlborn NiCr-Ni-thermowire T 190-1);
- θ_i, φ_i – internal temperature and RH in the room [$^{\circ}\text{C}$, RH%], (OnSet data logger Hobo U12-011).

Results and discussion

The test period lasted from 29.12.2016 until 23.04.2017. The minimum temperature was measured on 07.01.2017 at 0.00 and it was -20.9°C , and the maximum temperature was 16.4°C measured on 10.04.2017 at 17.00. The RH of external air varied

in the range of 31.8-100%. Average temperature in the house was 19.6°C and average RH was ca 33%. Graphs describing the thermal situation of the wall are presented in Figure 7.

Fig. 7. Temperature changes in Measuring Points 1 and 2 in the period from 21.02.2017 to 21.04.2017

From Figure 7 we can see that lines ($\theta_{i_{1c}}$ and $\theta_{3_{1c}}$ or $\theta_{i_{2c}}$ and $\theta_{3_{2c}}$ lines) characterizing inside temperature and temperature between the inner surface of straw-bale wall and render coincide. In the wetting room the temperature during heating increased on average $\sim 60^\circ\text{C}$. The temperature in the middle of the straw-bale wall was quite stable, increasing only by about $\sim 10^\circ\text{C}$. On 15.04.2017 the

temperature in the wetting room was $\theta_{i_{2c}} = 85.2^\circ\text{C}$ being 23.4°C at the same time in the middle of the wall. Comparison of graphs in Fig 7 and Fig 8 allows to conclude that when the temperature rises, the RH decreases. In the resting room, where temperature doesn't rise so much as in the wetting room, the RH is higher than in a hotter space.

Fig. 8. Relative humidity changes in Measuring Points 1 and 2 in the period from 21.02.2017 to 21.04.2017.

We can see from Figure 8 that if the temperature rises, the RH decreases. This change is especially notable in the steaming room. The RH is more or less stable in the middle of the wall.

During the period 29.12.2016-21.04.2017 the heat flux rate through the wall was measured with heat flux plate "FQA 018 CSI". Thermal transmittance of the wall was calculated using measured results and the Equation 1 given in the Almemo manual [9].

$$U = \frac{q}{\theta_i - \theta_e}, \quad (1)$$

where U – thermal transmittance [$\text{W}/(\text{m}^2 \cdot \text{K})$];
 q – heat flux rate through the wall [W/m^2];
 θ_i – internal temperature in resting room [$^\circ\text{C}$];
 θ_e – external temperature [$^\circ\text{C}$].

The calculated result $U = 0.15 \text{ W}/(\text{m}^2 \cdot \text{K})$, based on the test data, was a little better than the predicted

result, that was $U_c = 0.16 \text{ W}/(\text{m}^2 \cdot \text{K})$. The predicted calculation was done using $\lambda = 0.08 \text{ W}/(\text{m} \cdot \text{K})$ [10]. According to the regulations of the Government of the Republic of Estonia, Minimum energy performance requirements for the thermal transmittance of the external wall could be $0.12 - 0.22 \text{ W}/(\text{m}^2 \cdot \text{K})$, so the tested straw-bale wall conforms to the set requirement. [11]. The testing period was still influenced by the construction process. So we predict that in the next heating period the thermal transmittance of the wall should be even lower.

Figure 10 shows that during testing the thermal situation in the wall stabilized. Tops on the graphs are caused by heating. A black line in the middle of the graph presents the moving average of 100 measurements. At the first stage of the measuring period the influence of the moisture content of the render was greater (freshly rendered wall) and external temperatures were lower, therefore the fluctuation of thermal transmittance was notable.

Fig. 9. Thermal transmittance of the wall calculated by test based data in Measuring Point 1 (resting room)

Fig. 10. Short time test in measurements in Point 2 in the time period 21.04.2017-22.04.2017

The short time test was done in the wetting room (Fig. 10) to figure out if the water vapor condensates between the inner surface of straw-bales and a

rendering layer. The room was heated with an electric sauna stove until the temperature in the room was above 80 °C. Then the steaming test began.

Approximately 2.5 liters of water was used in four portions to make steam in the space of 11 m³. The results were the following: internal temperature at the height of 1.55 m from floor was $\theta_{1,2} = 90.1 \pm 0.35$ °C, and below the ceiling it was 100.0 ± 0.35 °C, the temperature on the inner surface of the clay plaster was 83.5 ± 1.5 °C, the temperature between the internal surface of the straw-bale and clay plaster was 66.5 ± 0.1 °C, at the same time the temperature in the middle of the straw-bale was only 23.3 ± 0.1 °C and the temperature between the straw-bale external surface and lime plaster didn't change. During steaming the water content in the wetting room's air rose from $v_{1,2} = 5.59$ g/m³ to $v_{1,2} = 97$ g/m³. The RH in the beginning of the test was 32.6 ± 2.0 % and it decreased to 6.5 %. The measuring results show that condensation didn't take place. The rapid decreasing of temperature after the test was caused by the fact that the window was open and the room was ventilated. After eight hours the situation in the sauna was normal.

Conclusions

The tests show that the use of straw-bales for construction of external walls is conceivable in the climate conditions of Estonia and in such a complicated building as a sauna. Thermal transmittance of the wall built from straw-bales with

the thickness of 500 mm and rendered with clay and lime plaster conforms to the requirements set in the minimum requirements for energy performance in Estonia. Thermal transmittance of the wall was $U = 0.15$ W/(m²·K). The most distressful zone during the long-term test was located between the straw-bale external surface and an outer rendering layer. But the graph in Figure 10 shows that heating and steaming didn't influence the situation in the rooms longer than for 8 hours. On the basis of the test results we conclude that measurements should go on. The authors are continuing measurements in the sauna because in the next testing period the building will not be heated continually but only during the use. Before using the sauna, the building is heated to be comfortable and after using sauna the rooms are ventilated for some hours. The aim is to solve out what will happen inside the wall between the inner clay render layer and straw-bale. This point is hygrothermally critical. No washing happened in the sauna room, only wetting.

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