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INVESTIGATIONS REGARDING THE THERMAL CONDUCTIVITY OF STRAW

BY

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Abstract. The reduction of buildings heat losses and pollutants emissions is a worldwide priority. It's intending to reduce the specific final energy consumption under limit of 120...150 kWh/m^2.yr and even under 15...45 kWh/m^2.yr, foreseen in 2020 for the passive houses, which is necessary for a sustainable development and for allowing to became profitable the use of unconventional energies [1]. These values can be achieved through the use of thermal insulations, for protecting the constructions fund and through making envelope elements, as much as possible, from materials with a high thermal resistance, for new buildings. With intention to substitute the conventional thermal insulations: mineral wool, expanded polystyrene, which are both great energy consumers, it's proposed, among others unconventional technologies and materials, the use of vegetable wastes both as a thermal insulation material and as a material used for building load-bearing and in-fill straw-bale construction. In speciality literature there are presented experimental determinations of this material's thermal conductivity. The paper proposes a simple method, adequate for the measurement of thermal conductivity for bulk's materials as straw bales.

Key words: thermal conductivity; vegetable wastes; straw bales buildings; energy efficiency; sustainable development.

1. Introduction

Usually, buildings are made from bricks, concrete, steel or wood and thermal protection is assured with expanded polystyrene, mineral wool or polyurethane foam. These materials have better thermal properties, but all of them require large quantities of energy to be made, and they are expensive. Therefore it's shaping a general tendency to replace these materials with other ones, more economical, derived from wastes. Between these new kinds of materials we find also vegetable wastes and especially dry straw and hemp, which made the subject of different research programs in USA, Canada, France, UK and Germany.

For a building to be genuinely energy efficient, the energy consumed by obtaining the raw material, making and transporting building materials, along with the energy consumed in all building process, must be counted in the final energy efficiency estimation. The implementation of the sustainable development principles can reduce the building's negative impact on the environment. In the same way that owner's habits and their aware of the need of saving energy influence energy efficiency of a building, the same choosing materials and building technology by the architect, engineer and owner, in the spirit of energy efficiency of the resource, have a major impact on the final energy efficiency of the building, on its entire life spam. In this way of thinking, using straw as a building material is recommended. The first utilization of straw in buildings was for reinforcing cob walls, with the intent of reducing cracking. Starting with nineteen century, constructors begin to use straw-bales as a building material. Straw-bales can be used both as a bloc for load-bearing walls and as filler for in-fill walls. Today, straw-bales buildings became very popular. From barns, garages, small offices, summer residences and dwelling houses at big houses and office buildings, all of them can be found on the most areas of Canada, USA, Mexico, Australia, Europe and Asia. Straw-bales were used also for boxing up the exterior of old buildings with poor thermal protection or for improving energy efficiency of commercial buildings and storehouses. The major project of straw-bales buildings is in Canada where, with the intention of promoting this material, there were launched large real estates, especially in Regina and fringe areas of Toronto.

2. State of the Art

One of the most important advantages of straw walls is thermal protection. In 1993, Joseph Mc C a b e, in a master thesis at University of Arizona, has determined the thermal resistance of straw-bale walls with different widths. For straw-bales walls with the density of 133 kg/m^3, the thermal conductivity was λ= 0.0481...0.0578 W/m.K. The determinations of thermal resistance for this kind of walls are considered by many specialists inconclusive and therefore the obtained results are ambiguous. However, in 1998 David E i s e n b e r g, from Oak Ridge National Laboratory (ORNL), has made a test that is considered flawless, the obtained values being used in calculations by most of the specialists. ORNL has determined, for a 55 cm thick straw-bales walls, a thermal resistance between 6.5175...7.821 W/m^2.K, what means that the thermal conductivity was λ= 0.0703...0.0844 W/m.K.

3. Experimental Device

It has been searched for a simple method, adequate for the measurement of bulk materials thermal conductivity as straw are, available in every construction laboratory. The standard method in Romania is not applicable; it is adequate only for measurements on board shape materials, in dry form. The adopted experimental device is made from two concentric tubes (Fig. 1).

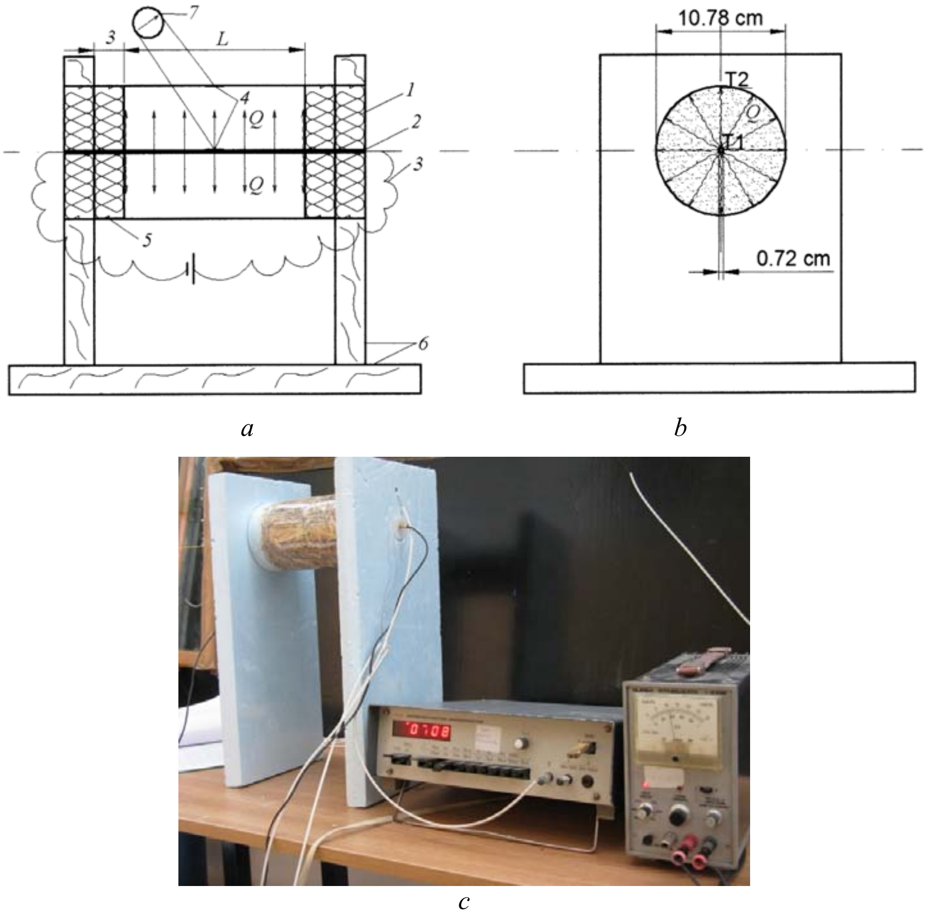

Fig. 1 – The measurement apparatus: *a* – longitudinal vertical section; *b* – transversal vertical section; *c* – general view

The outer one is a plastic bottle with extremity cut away, inner diameter D = 10.78 cm and length L = 16 cm (*5*), and the inner one is a glass tube with outer diameter d = 0.72 cm, width 0.5 mm and the same length as the outer tube (*2*). Through the glass tube is passing a constantan wire (*3*); the tube is filled with fine glass sand for the uniformity of temperature at its outer surface. The edges of the plastic bottle are closed with two 3 cm thick layer of extruded polystyrene (*1*), for blocking out the lateral heat losses. The copper– constantan thermocouple (*4*), measures the temperature difference $T_1 - T_2$ between outer surface of the glass tube (T_1) and the inner surface of the plastic bottle (T_2), using a micro-voltmeter (*7*). The space between the tubes is filled with straw; the device is seated on an extruded polystyrene frame (*6*). All these devices are usual for the building company laboratories.

Kept under a constant known voltage, the constantan wire is heated and generates a heat flux. Due to electrical analogy the value of the heat flux is equal with the value of the electrical circuit power [1]

$$Q = \frac{U^2}{R}, \quad [\mathrm{W}], \tag{1}$$

with: U is the voltage, [V]; R – electrical resistance of the constantan wire, [Ω].

The heat transfer through the heap of granular material is the result of thermal conduction inside the small solid bits and the thermal convection of the interstitial air (depending on the thermal gradient, the heat transfer direction and many other conditions). Therefore the measured results should be considered as equivalent apparent thermal conductivity. They are proving the capacity of these waste materials for economic thermal insulations and they are useful to estimate the thermal permeability (W/m^2.K) of such insulation layers. According to the basic Fourier law, and measuring the temperatures on the outer surface of the glass tube, T_1 and T_2 , at the inner surface of the recipient, it can be written relation [2], [3]

$$\lambda = \frac{Q}{2\pi\left(T_1 - T_2\right)L}\ln\frac{D}{d}, \quad [\mathrm{W/m.^oC}] \tag{2}$$

with: Q – the heat flux, [W]; λ – thermal conductivity of the test sample, [W/m.K]; d_2 – inside diameter of the PVC recipient, [m]; d_1 – outer diameter of the glass tube, [m]; L – length of the recipient, [m].

4. Obtained Results

To be able to determine thermal conductivity with relation (2), one should wait for the thermal flux to enter in a steady state regime which was determined with a Thermo Fluke IR camera (Fig. 2) and by monitoring the temperature difference.

With the aim to obtain the thermal conductivity variation *vs.* density there were carried out two sets of determinations for two different densities of the straw, obtained by manual packing. The first set consists in ten measurements, for each one the temperature difference recorded by the thermocouple is different. The straw had a density of 51.06 kg/m^3 and a humidity of around 6%, both values being determined with a thermobalance model MAC 210 possessing a sensibility of 0.01%. The results are presented both tabular (Table 1) and graphic (Fig. 3). After eliminating the peaks it results a medium value of the straw layer thermal conductivity of 0.0614 W/m.K, comparable with the one presented in the speciality literature mentioned above.

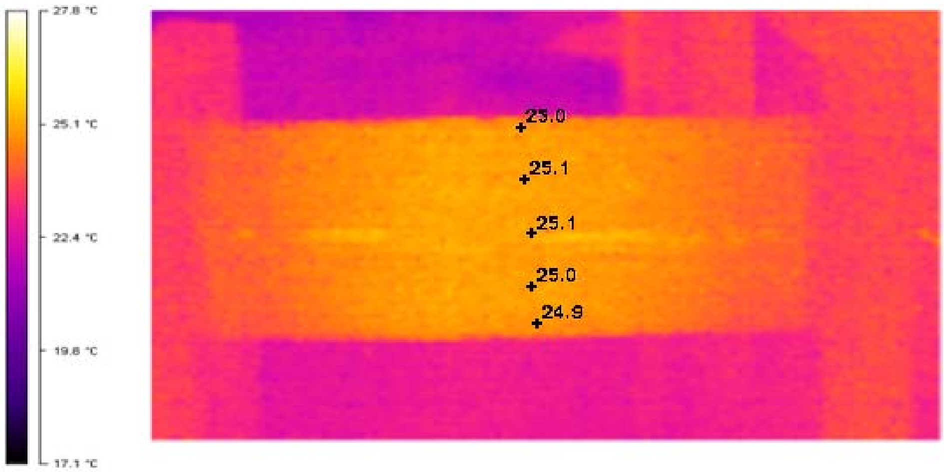

Fig. 2 – Checking uniformity of the temperature at the outer surface.

Table 1

Nr. exp.	U V	R Ω	Q W	$T_1 - T_2$ °C	λ W/m.K	λ_{med} W/m.K
I	0.801	3.0	0.214	9.21	0.0625	0.061
II	0.85	3.1	0.233	10.00	0.0627	
III	0.907	3.0	0.274	11.50	0.0641	
IV	1.003	3.1	0.325	15.20	0.0574	
V	1.11	3.2	0.385	20.10	0.0515	
VI	1.207	3.3	0.441	16.05	0.0740	
VII	1.251	3.0	0.522	24.35	0.0576	
VIII	1.303	3.0	0.566	27.75	0.0549	
IX	1.407	3.0	0.660	29.46	0.0602	
X	1.533	3.2	0.734	28.73	0.0688	

The second set of determinations consists also in ten measurements, this time the straw layer density was 76.40 kg/m^3 and humidity 8.25%. The results are also presented both tabular (Table 2) and graphic (Fig. 4).

The obtained results after the second set of measurements are also comparable with those presented in the speciality literature. It's observed that the medium value of the thermal conductivity for the straw with a higher density is smaller; this thing is the result of the smaller volume of air, what means a smaller convective component of the heat transfer. The different humidity of straw interferes with an unsignificant proportion in the difference of the medium values, due to theirs reduced values.

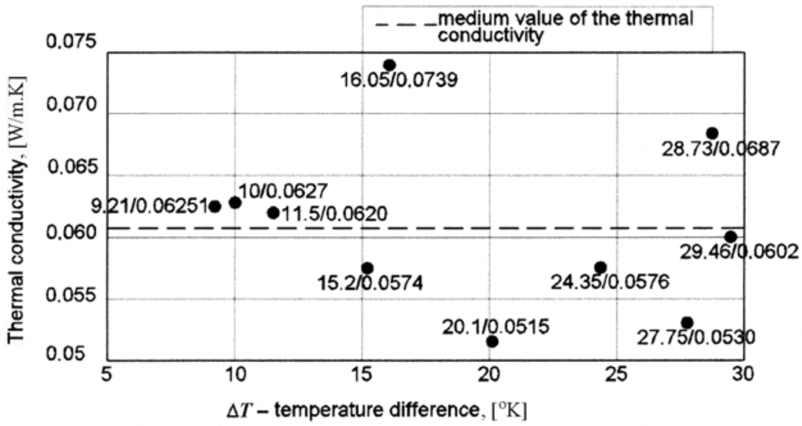

Fig. 3 – Thermal conductivity of straw with 51.06 kg/m^3 density, at different temperature differences.

Table 1

Nr. exp.	U V	R Ω	Q W	$T_1 - T_2$ °C	λ W/m.K	λ_{med} W/m.K
I	0.797	3.0	0.212	7.03	0.0810	0.053
II	0.874	3.0	0.255	11.61	0.0590	
III	0.997	3.0	0.331	17.15	0.0520	
IV	1.092	3.1	0.385	20.55	0.0503	
V	1.183	2.9	0.483	21.40	0.0607	
VI	1.270	2.9	0.556	27.67	0.0541	
VII	1.283	3.0	0.549	27.67	0.0533	
VIII	1.390	3.0	0.644	35.67	0.0486	
IX	1.491	3.0	0.741	44.17	0.0451	
X	1.785	3.0	1.062	67.09	0.0426	

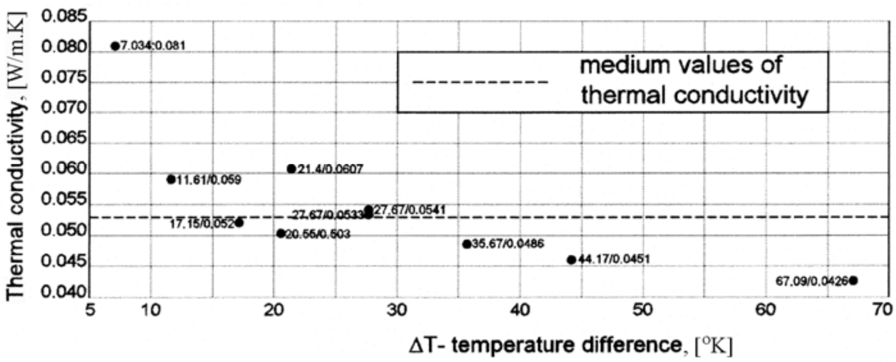

Fig. 4 – Thermal conductivity of straw with 76.6 kg/m^3 density, at different temperature differences.

5. Conclusions

After the two sets of measurements it can be admitted that the thermal properties of the straw, with a maximum density achieved by manual packing, are satisfactory. In consequence, straw can be used with success for thermal protection of dwellings, especially in countryside but not only there. Therefore, with carefully designed constructions details, so that the insulation straw layer will be protected against weather factors and condense and will not be exposed to direct contact with liquid water, this vegetable material is recommended to be used both at thermal protection of the walls and roofs.

Furthermore, because of the obtained results, comparable with the ones presented in the speciality literature, both experimental device and measurements method used can help at the determination of thermal properties of bulk materials.

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INVESTIGAȚII PRIVIND CONDUCTIVITATEA TERMICĂ A PAIELOR

(Rezumat)

Diminuarea pierderilor de căldură ale clădirilor şi, implicit, a emisiilor poluante, reprezintă o prioritate globală. Se urmăreşte reducerea consumului specific de energie finală sub limita de 120...150 kWh/m^2.an, şi chiar spre 15...45 kWh/m^2.an, preconizată spre anul 2020 pentru casele pasive, ceea ce este necesar pentru o dezvoltare durabilă şi pentru a permite utilizarea rentabilă a energiilor neconvenționale. Aceste valori pot fi atinse prin utilizarea izolațiilor termice pentru a proteja fondul construit sau prin realizarea elementelor anvelopei, pe cât posibil, din materiale cu rezistență termică mare, în cazul clădirilor noi. Cu scopul de a înlocui izolațiile termice convenționale: vată minerală, polistiren expandat, care sunt materiale energointensive, se propune şi utilizarea deşeurilor vegetale atât ca material izolator cât şi ca material

pentru pereți de umplutură. În literatura de specialitate se prezintă determinări experimentale ale conductivității termice pentru acest material. În lucrare se propune o metodă simplă, adecvată pentru măsurarea conductivității termice a materialelor vrac aşa cum sunt şi paiele.