Parametric Analysis of Thermal Properties of Straw

Introduction

Thermal conductivity for insulations used as construction material for buildings indicates the capability of the material to prevent heat from entering/leaving the indoor space which in turn affects the thermal comfort conditions inside. There exists several methods for evaluation of thermal conductivity for different types of materials which shall be briefly touched upon later. For the case of straw, which can be considered as a fibrous porous material in bulk quantities, an effective thermal conductivity can be measured through these methods. Straw being organic and hygroscopic in nature, its effective thermal conductivity is influenced by an array of factors including type of crop, local climatic conditions, composition, bulk density, moisture content, etc.

Review of Previous Findings

Lebed and Augaitis (2017) measured the thermal conductivity of triticale straw samples with varying densities in the range of 80 kg/m^3 and 190 kg/m^3. Guarded hot plate apparatus was used to measure the thermal conductivity and the tests were conducted at a mean sample temperature of 10 °C and ambient conditions of 23±2 °C; 50±5 % RH. Based on the experimental data, they had arrived at an equation relating thermal conductivity of straw and its density as shown below:

$$\lambda_{10^{\circ}C} = -0.00155 + 0.000357.\rho + \frac{3.381}{\rho}$$

where, ρ is the density of straw infill. The researchers observed an increasing trend in thermal conductivity values when density in increased beyond 120 kg/m^3.

Costes et al. (2017) begin with a good review of previous measurements of thermal conductivity of straw including its variation with density and orientation. They argue that samples prepared from straw bales may not be representative of the actual material due to changes in orientation and density introduced during the sample preparation process and consequently influencing its thermal conductivity value. Therefore, the authors have designed and developed a Guarded hot plate apparatus capable of measuring thermal conductivity of samples of up to 50 cm thick. The authors prepared 13 straw bale samples of wide varying densities (68.1 kg/m^3-122.7 kg/m^3) but small variations in thickness (0.3 m - 0.495 m) and measurements were carried out on each sample five times . Regression of the measurement data resulted in the following correlation:

$$\lambda = 4.81 \times 10^{-2} + 2.9 \times 10^{-4} d - 1.13 \times 10^{-2} t$$

where d is the density in kg/m^3 and t is the thickness in m.

F. D' Alessandro et al. (2017) also used guarded hot plate apparatus to measure the thermal conductivity of straw samples of density 80 kg/m^3. Two tests conducted resulted in thermal conductivity values of 0.051 W/mK and 0.053 W/mK. The author notes that the straw bales were in flat position meaning the heat flow perpendicular to the straw fiber orientation.

Douzane et al. (2016) reported thermal conductivity values of straw of density 80 kg/m^3 considering different orientations. Guarded hot plate techniques was used to to conduct the measurement. At 10C and dry conidions, thermal conductivity values of 0.0723 $\pm$ 0.0014 W/mK was reported for parallel orientation while 0.0510 $\pm$ 0.0010 W/mK was reported for perpendicular orientation. Also measurements performed at various sample mean temperatures revealed a direct linear relation between thermal conductivity and sample mean temperature.

Conti et al. (2016) attempted in building a low-cost system with established standards acting as guidelines to measure thermal conductivity of straw bale with reasonable accuracy. Local agricultural practices and climatic conditions leading to wide variations in the thermal behaviour of straw bale is put forward as the reason behind devising such a system. Thermal conductivities of two straw bale samples of approximate densities of 65 and 85 kg/m^3 were measured to be 0.062 W/mK and 0.070 W/mK respectively.

Walker et al. (2016) reviewed the previous works in which thermal conductivity of straw had been measured. It included measurement of thermal conductivity of 120 kg/m^3 dense straw bale by Shea et al. (2013) who had reported a value of 0.064 W/mK. With regards to orientation of straw sample, the authors cited the results published by the German national organisation of straw bale building (FASBA, 2009) which were equal to 0.067 W/mK for straw oriented parallel to heat flow and 0.043 W/mK for straw oriented perpendicular to heat flow. Further, considering straw moisture content as a parameter, the authors reported the work carried out by a French company CEBTP in 2004 in which a modest increase from 0.064 to 0.072 W/mK was observed when straw relative humidity was increased from 0% to 90%.

Samuel et al. (2015) used a previously designed guarded hot plate apparatus by Dubois and Lebeau (2013) to measure their own sample of straw. They specify a bulk density range of 80-120 kg/m^3 noting that it is impossible to give an exact value of density of the sample under test. The thermal conductivity of dry sample with fibers oriented parallel to heat flow was found to be 0.0682 W/mK at 20°C.

Wei et al. (2015) proposed high frequency hot pressing technique instead of the traditional platen-pressing process for fabrication of straw based insulation boards. They went on to study the properties of the straw board manufactured by this technique along with factors affecting the properties. It is worth noting a fundamental difference in the structure of such boards; they are composed of straw particles while conventional straw bales are an aggregate of straw fibers. Also, the straw boards have a higher density range (180 - 360 kg/m^3). Steady state measurement of thermal conductivity of such a straw board with dimensions 300 mm × 300 mm × 40 mm was conducted at a mean temperature of 20°C. Over a small range of straw particle moisture content - 10% to 18% - only a slight change in thermal conductivity - 0.051 W/mK to 0.053 W/mK correspondingly - was observed. A linear increase in thermal conductivity was reported with increase in the board density. Moreover, the straw boards exhibited increased thermal conductivity when particle size in decreased as well as in conditions of increased ambient temperatures.

Robinson (2014) cited a previous work, Grmela et al. 2010 which could not be accessed for the current review, while reporting a thermal conductivity range from 0.038 W/mK to 0.1 W/mK.

Lee and Yeom (2014) reported a thermal conductivity value of 0.092 W/mK for straw of density, 207.5 kg/m^3. It is most probably a case a mistaken use of units for density in this paper. For example, in the case of straw, it is mentioned to be having a density of 207.5 g/m^3 which is unlikely.

Thermal conductivity measurement of eight straw bale specimens conducted by Langmans et al. (2014) resulted in values of 0.0589 W/mK for the case of straw fibers perpendicular to heat flow and 0.0667 W/mK for the case of straw fibers parallel to heat flow. All specimens have a density of 88 kg/m^3.

Shea et al. (2012) put forward a building system utilizing prefabricated timber-framed straw based panels. After a good review of previously reported thermal conductivity values, the authors then tested for the thermal conductivity of their own samples in a heat flow meter. Six wheat straw samples with randomly oriented fibers and densities ranging from 67 kg/m^3 to 112 kg/m^3 were prepared and placed in a controlled in a controlled space of 23°C and 50% RH. At mean sample temperature of 10°, only a modest rise from 0.0594 W/mK to 0.0636 W/mK in thermal conductivity over the corresponding density range was observed. Further, they reported a 15% increase in thermal conductivity when mean sample temperature was increased from 10°C to 30°C.

Vjelien (2012) studied the effect of structural variation on thermal conductivity of straw, which includes orientation: vertical or horizontal and mode of processing of straw: chopped straw, prepared from rotary milling and defibered straw. Further, the work involved use of additives to straw sample such as graphite particles for improving infrared radiation absorption and flax oil for better binding. The measurement of thermal conductivity was carried out in a guarded hot plate apparatus at a mean sample temperature of 10°C and under constant ambient conditions of 23±2°C and 50±5 % RH. Over a density range between 50 kg/m^3 and 120 kg/m^3, the author developed correlations for each of the structurally varying straw samples. It was observed that the horizontal oriented straw showed greater variation with density compared to the remaining samples types. The magnitudes of thermal conductivity for the different samples were found to be in the following order: Defibered straw < Chopped straw < Horizontal oriented straw < Vertical oriented straw

Ashour et al. (2010), citing his thesis, presented thermal conductivity values ranging from 0.0414 W/mK to 0.0486 W/mK for Wheat straw and the same ranging from 0.0353 W/mK to 0.0539 W/mK for Barley straw over different temperatures. The author noted a greater increase in thermal conductivity when temperature was raised from 20.7°C to 34.2°C than when temperature was raised from 10.3°C to 20.7°C.

In referring to previous works, Pruteanu (2010) listed the thermal conductivity results of by McCabe in 1993 and Eisenberg of Oak Ridge National Laboratory (ORNL) in 1998. The former had reported values ranging from 0.0481 W/mK to 0.0578 W/mK for straw bales of density 133 kg/m^3 while the latter had reported thermal resistance ranging from 6.5175 W/m^{2}K to 7.821 W/m^{2}K for a 55 cm thick straw bale which translated to a thermal conductivity range of 0.0703 to 0.0844 W/mK. The author then devised a simple technique to measure the thermal conductivity of straw samples. The first sample having a moisture content of around 6

% and density of 51.06 kg/m^3 had a median thermal conductivity value of 0.0614 W/mK and a second sample of 8.25 % moisture content and 76.40 kg/m^3 density had a median thermal conductivity value of 0.053 W/mK. The median values were calculated from ten trials on each sample.

Other reported results not directly accessed: Beck et al. (2003); DIB; Grelat; Anderson;

We now look in to some indirect methods used by researchers and the corresponding results of thermal conductivity obtained.

On the basis previous literature, Chaussinand et al. (2015) provides a range of thermal conductivity values, as given below, which is exhibited for straw owing to its various influencing factors such as composition, density, moisture content, etc.

$$0.052W/mK \leq \lambda \leq 0.12W/mK$$

Further, the authors have taken up an existing straw bale building named ECO46 located in Switzerland for indirect calculation of thermal properties of straw. Using the fuel consumption data of the building heating system as well as the on-site weather data in a building simulation tool, they arrived at a thermal conductivity value of 0.08 ± 0.005 W/mK for the straw used in the construction of the building.

Design of Experiment

Experimental Procedure

Results and Discussion