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Comparative Study of the Thermal Conductivity of Solid Biomass Fuels

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ABSTRACT: The thermal conductivity of solid biomass fuels is useful information in the investigation of biomass combustion behavior and the development of modeling especially in the context of large scale power generation. There are little published data on the thermal conductivity of certain types of biomass such as wheat straw, miscanthus, and torrefied woods. Much published data on wood is in the context of bulk materials. A method for determining the thermal conductivities of small particles of biomass fuels has been developed using a custom built test apparatus. Fourteen different samples of various solid biomass fuel were processed to form a homogenized pellet for analysis. The thermal conductivities of the pelletized materials were determined and compared against each other and to existing data.

1. INTRODUCTION

Modeling is an important tool in the design and operational control of a plant for biomass thermal conversion processes including combustion, torrefaction, gasification, and liquefaction. It is also important in the context of storage and handling since self-heating of biomass may lead to self-ignition.

Models of the combustion of individual particles of biomass fuel have been developed at a fundamental level,[1,2] and these have been used as submodels for higher level modeling of furnaces using computational fluid dynamics.[3,4] While the power of the modeling tools has increased, the usefulness of the models has been limited by detailed and accurate data on the properties and behavior of biomass fuels. Knowledge of fuel properties is understandably challenging because of the vast variability in materials classed as biomass. In power generation applications, these may include various softwoods, hardwoods, herbaceous energy crops, agricultural residues, and other wastes or industrial byproducts.

To effectively model the heat transfer to and within a biomass particle undergoing pyrolysis or combustion, it is necessary to know the thermal conductivity of the material. The significance of the heat transfer properties of small biomass particles in evaluating the chemical kinetics of pyrolysis and char combustion has been described by Hayhurst.[5] Differences in thermal conductivity affect the internal temperatures and heating rates in the particle which, in turn, affect the reaction kinetics. This is also relevant on the larger scale especially in the phenomenon of self-heating of combustible materials such as the bulk storage of biomass fuel where the risk of self-ignition arising from this is a distinct safety concern.[6] Self-ignition temperatures for biomass materials are dependent on thermal conductivity since this affects the balance between internal heat generation from chemical kinetics and heat dissipation to the external surface.[7] The risk of self-ignition may be predicted through modeling[8] provided reliable data on thermal conductivity and internal heat generation are available.

Published data on thermal conductivity of wood materials are mainly in the context of their use in construction and are generally to inform calculations of building insulation. Well established data from published literature include the *CRC Handbook of Physics and Chemistry*,[9] and the work of Austin and Eastman.[10] Selected examples of published data are summarized in Table 1. Thermal properties of the bulk mass of biomass materials specifically in the context of wood pellet storage and

Table 1. Published Thermal Conductivity Data for Biomass Materials

sample	density, $kg \cdot m^{-3}$	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$	source ref
Group A1: Perpendicular to Fiber Orientation			
sequoia	380	0.082	10
pine	406	0.086	10
white wood	506	0.102	10
cherry	534	0.108	10
gum	559	0.109	10
walnut	609	0.115	10
white oak	615	0.113	10
brown ash	649	0.129	10
red birch	711	0.126	10
sewage sludge	760	0.130	5
balsa	113	0.034	23
balsa	137	0.037	23
softwood	360	0.099	13
pinewood	450	0.110	9
fir	540	0.140	9
spruce	400	0.128	21
maple	710	0.158	21
Group A2: Parallel to Fiber Orientation			
pinewood ‖	450	0.260	9
fir ‖	540	0.350	9
spruce ‖	400	0.279	21
maple ‖	710	0.419	21

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Table 2. Proximate Analysis for Biomass Materials (As Tested)

	moisture, %	volatile matter, %	fixed carbon, %	ash, %	density, kg·m^{-3}
willow a	5.9	73.5	15.6	5.1	530
willow b	4.1	78.7	15.4	1.8	540
wood pellets a	2.7	82.4	14.6	0.3	730
wood pellets b	4.1	79.6	15.3	0.9	650
wood pellets c	5.1	79.6	14.2	1.2	610
wheat straw a	5.5	69.3	18.1	7.1	230
wheat straw b	5.2	72.7	16.1	6.0	350
rape straw	6.1	71.1	15.5	5.8	240
miscanthus a	4.6	74.0	16.7	4.7	700
miscanthus b	3.7	80.4	14.2	1.7	680
olive residue	4.8	70.5	17.5	7.3	1310
torrefied materials					
torrefied pine a	2.4	79.7	17.5	0.4	410
torrefied pine b	1.9	78.1	19.6	0.4	390
black pellet	4.2	72.9	18.9	4.0	1260

using transient heat flow measurement methods have been published by Guo et al.[11] and Sjöström and Blomqvist.[12]

Measurements on thermal properties of softwood particles specifically in the context of combustion applications have also been published. Values for the thermal conductivity and specific heat capacity for samples of softwood, softwood bark, and softwood char are reported by Gupta et al.[13] Similar experiments specifically on pine wood and char samples were also undertaken by Hanklin et al.[14] while properties of larger specimens (300 × 300 × 100 mm^3) of various hardwoods and softwoods were reported by Yu et al.[15] using heat flux sensors with reference to the effects of moisture and temperature.

While the aforementioned published data on some types of wood exist, there are little data on herbaceous materials or other nonwoody biomass fuels. The main reason for this is the difficulty in obtaining a suitably sized uniform sample of material to perform a measurement on. The techniques used for measuring bulk material properties are not practical on a small particle. Both Gupta et al.[13] and Hankalin et al.[14] have used a "Fitch"-type apparatus with samples of wood made into regular discs in the order of a few millimeters thickness. A similar approach can be used for investigating the thermal properties of other biomass materials, but it is clearly not practical to use such a technique on, for instance, raw unprocessed wheat straw. Since biomass is nonhomogeneous and most is distinctly anisotropic, it is difficult to obtain samples which are both large enough for measurement and representative of the material in small particle form.

In an attempt to overcome this issue, an experimental method has been developed in which samples of any solid biomass material can be assessed on a comparative basis. The method requires that the samples are prepared in a consistent way to produce a homogenized disc of material with dimensions and density within a similar range. The test discs are a simple physical form convenient for thermal conductivity measurement. It is important to note that this is not the form in which the fuels are normally utilized. Nevertheless, it is contended that the relative thermal conductivity measurements obtained from the discs are a valid and useful representation of the respective materials. The data may be used to determine the thermal conductivity of various forms of the fuel by applying it to a model of the macrostructure of the material. Modeling of wood by considering the different structural characteristics of different components (solid matter, moisture, and interstitial gas) such as that proposed by Thunman and Leckner[16] is one approach to achieve this.

The objective of this study is to provide thermal conductivity data for accounting for differences between types of biomass fuel in the modeling of thermal conversion, combustion, and self-heating behavior.

2. EXPERIMENT

2.1. Sample Preparation. Samples were received in various forms including pellets, chips, and bales. All samples were milled using a liquid-nitrogen-cooled impact mill until the entire sample was passed through a 90 μm sieve. Since moisture from the original bulk sample is reduced in this process, moisture measurements of the milled samples were obtained using a TA Instruments TA5000 thermogravimetric analyzer subsequently. It is noted that moisture content in the samples ranges from 2 to 6%. A correction, described later, to the measurements based on these values is used to compensate for the variation. All samples were also characterized for volatile content and ash content using standard methods [EN 15148:2009, EN14775:2009]. The average density of particle in the size range 0.5−4 mm was obtained from measurements on single particles in the context of previous experiments.[17] The list of materials tested and the results of proximate analysis are presented in Table 2.

Each material was used to form two test pieces weighing 200 mg (±10%) and 400 mg (±10%), respectively. These were formed using a 13 mm diameter cylindrical steel die in a hydraulic press to a pressure between 360 and 380 MPa. The resulting pellets were weighed on a digital microbalance to a precision of ±1 mg. The thickness of the pellets was measured using a micrometer to a precision of ±0.01 mm.

Additional test samples of unprocessed pine wood were prepared with dimensions similar to the pellets and with fiber orientation either parallel or perpendicular to the heat flow. This was to provide a comparison with the measured thermal conductivity of the pellets and with the published values of other woods (from Table 1).

2.2. Measurement Apparatus. Since the experiment was aimed at small test pieces with relatively low thermal conductivities, it was necessary to design and build a bespoke test apparatus. The design was based on the "split-bar" method which has been used for measuring thermal conductivity of polymers.[18] The arrangement of the apparatus is such that the test piece is sandwiched between two reference components of known thermal conductivity. A heat source is applied to the extremity of one reference piece and a heat sink applied to the opposite end of its counterpart. The axial temperature gradient across the two reference pieces is measured and the heat flow in each determined. The heat flow through the test piece is taken to be the average of that in the two reference pieces. Given the dimensions of the test piece and the measured temperature differential across it, its thermal conductivity is thereby derived.

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The system described was implemented using CZ121 M engineering brass[19] as the reference material having a thermal conductivity of 123 $W{\cdot}m^{-1}{\cdot}K^{-1}$. The diameter of the brass rods was made to be coincident with the test pieces at 13 mm. The lengths of the brass rods were determined mainly by practical considerations of physical support and the required contact area with the heat source and heat sink. The temperature gradient was measured in the sections of each brass rod adjacent to the test piece between 65 and 5 mm away from the contact interface using 0.5 mm diameter mineral-insulated J-type thermocouples. These were inserted into holes drilled radially to the center of each brass rod.

The power requirement of the heat source was estimated for a worst case test with high thermal conductivity (0.5 $W{\cdot}m^{-1}{\cdot}K^{-1}$) and thin test piece (1 mm). Accounting for heat losses along the length of the brass rods, the steady state power requirement was calculated at 3 W. This was provided by a surface-mounted "subminiature proportionally controlled" heater with a nominal rating of 5 W.[20] The heater was mounted on a 50 mm diameter × 50 mm length brass cylinder to act as a heat reservoir. This was in turn mounted on the respective "hot" brass rod. The opposite "cold" brass rod was extended such that it could be immersed in an ice-bath heat sink formed using a vacuum-insulated steel flask. The whole apparatus was mounted vertically and insulation applied to reduce heat loss. A diagram of the assembly is illustrated in Figure 1.

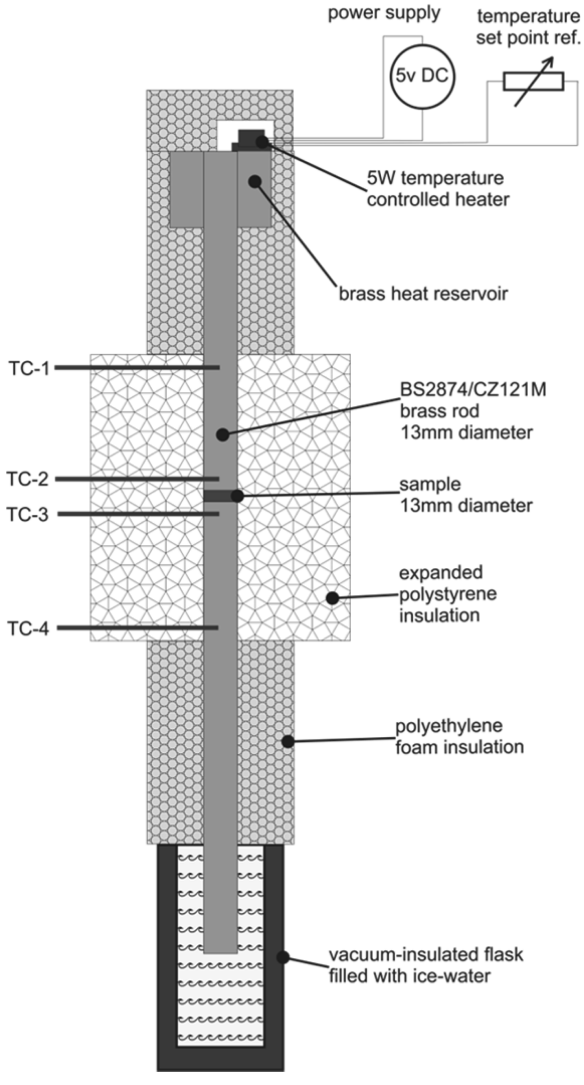

Figure 1. Diagram of test apparatus in cross-section.

A *Picolog* TC-08 thermocouple data acquisition interface and data logging software were used for recording the temperatures.

The test piece was mounted between the two brass rods and held in place by the moderate pressure from the weight of the upper rod. A thermally conductive paste (proprietary product as used for mounting electronic components with λ = 0.19 $W{\cdot}m^{-1}{\cdot}K^{-1}$) was applied to the contact interfaces. Initial measurements omitted this, and significant variations in repeat measurements were noted owing to imperfect surface contact (i.e., air gaps).

With the heater and the heat sink applied, the apparatus was left until the temperatures indicated on the measurement thermocouples had stabilized. The thermocouple measurements were then logged at a rate of one sample per second for a period of at least 30 min. The logged data were checked for stability (i.e., gradient of less than 0.001 $K{\cdot}s^{-1}$) and the mean averages recorded for calculation. At least two measurements were performed on each material.

2.3. Calculation. The axial heat flow in the upper rod is calculated from the ideal heat flow and a correction for the radial heat loss. The calculation is approximated in the expression

$$Q_1 = \frac{\lambda_{brass} A_{CS}(T_1 - T_2)}{L_{TC}} - \left\{\left(\frac{(T_1 - T_2)}{2} - T_{amb}\right)\left(\frac{A_{ins}\lambda_{ins}}{D_{ins}}\right)\right\} \quad (1)$$

where T_1 and T_2 are the temperatures measured by thermocouples TC1 and TC2, respectively; T_{amb} is the ambient temperature (~23 °C); λ_{brass} is the thermal conductivity of brass (123 $W{\cdot}m^{-1}{\cdot}K^{-1}$); A_{CS} is the cross-sectional area of brass rod (133 mm^2); L_{TC} is the axial distance between the two thermocouples TC1 and TC2 (60 mm); A_{ins} is the effective surface area of the insulation layer (5.5×10^{-3} m^2); D_{ins} is the thickness of the insulation layer (40 mm); and λ_{ins} is the thermal conductivity of insulation (0.065 $W{\cdot}m^{-1}{\cdot}K^{-1}$).

The axial heat flow in the lower rod, Q_2, is calculated with a similar expression substituting T_1 and T_2 with T_3 and T_4, respectively.

The axial heat flow through the sample is approximated as the average of the heat flows in the upper and lower brass rods:

$$Q_S = \frac{Q_1 + Q_2}{2} \quad (2)$$

The temperature differential across the sample, ΔT_S, is derived from the difference of T_2 and T_3 with a correction for the 5 mm of brass rod between the thermocouples and interface surface as

$$\Delta T_S = \left(T_2 - \frac{0.005 Q_1}{A_{CS}\lambda_{brass}}\right) - \left(T_3 + \frac{0.005 Q_2}{A_{CS}\lambda_{brass}}\right) \quad (3)$$

The thermal conductivity of a sample with axial length L_S is then calculated from

$$\lambda_S = \frac{L_S Q_S}{A_{CS}\Delta T_S} \quad (4)$$

A correction to the calculated value of λ_S based on the moisture content can be estimated by assuming the moisture content contributes uniformly to the measured value and the contribution is directly proportional to the moisture content by weight. The corrected (dry basis) thermal conductivity, λ_S' is then

$$\lambda_S' = \frac{\lambda_S - \alpha\lambda_w}{1 - \alpha} \quad (5)$$

where α is the proportion of moisture by weight in the sample and λ_w is the thermal conductivity of water at 300 K, taken as 0.61 $W{\cdot}m^{-1}{\cdot}K^{-1}$.[21]

3. RESULTS

Thermal conductivity and the density of wood are strongly correlated as shown by Austin and Eastman.[10] This correlation is the basis of modeling the thermal properties of woody materials—for example, the model for thermal conductivity

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described by Thunman and Leckner.[16] The relationship is also consistent for bulk quantities of wood pellet as shown in the study by Sjöström and Blomqvist.[12]

Examination of the relationship between material density and thermal conductivity is therefore useful for deriving or validating models of biomass in various applications including single-particle combustion, self-heating in bulk storage, and in dust layer combustion behavior. A plot of density against thermal conductivity is also a useful means of visualizing the similarities and differences between the materials measured in this study.

Before presenting the data for the homogenized biomass pellets, the measurement method should be validated by comparing the measured properties of materials against known published values for similar materials. For this purpose, a set of test pieces made from poly(tetrafluoroethylene) (PTFE) were made and the thermal conductivity was measured in the same manner as that for the biomass samples. The resulting measurements showed an average thermal conductivity within 3% of the published value for PTFE[22] and with a standard deviation of less than 3%. In addition, test samples made of bulk pieces of pinewood were formed both with perpendicular and parallel fiber orientation (cross-grain and parallel grain). The resulting measurements showed strong agreement with the published data for wood with similar density. Figure 2 shows a

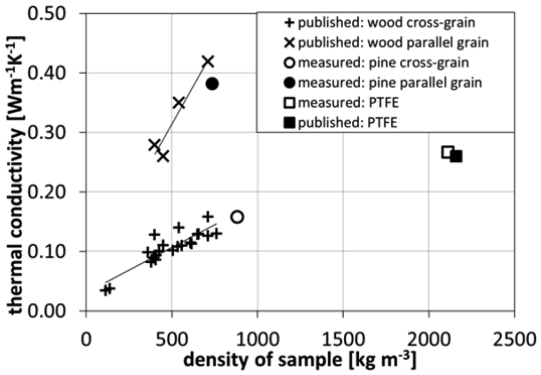

Figure 2. Measured thermal conductivity of cross-grain (open circle) and parallel grain (solid circle) pine samples compared to published values (+ and ×, respectively) for woods [reference Table 1]. Measured thermal conductivity of PTFE samples (open square) compared to published value[22] (solid square).

plot of the measured thermal conductivity versus the material density for the PTFE and pinewood reference samples together with the respective published data for comparison.

Having shown the measurement method to be consistent with published data, the measured values for the homogenized biomass pellets, which fall between the values of the reference materials, can be reported with a high level of confidence. Each material was measured using at least two test samples and at two different heater settings (70 and 60 °C). The calculated standard deviation of the data obtained for each material was, on average, only 3.5%. This value is close to that evaluated for the reference measurements for the PTFE test pieces.

The measured thermal conductivity of the materials tested is presented in Table 3. These data, plotted against sample density, are presented in Figure 3. The plot in Figure 3a also includes the published data from selected biomass materials as listed in Table 1 for comparison. Figure 3b shows the data for

Table 3. Measured Thermal Conductivity Values for Homogenized-Densified Biomass Pellets (Dry Basis)

	density, $kg \cdot m^{-3}$	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
willow a	1179	0.159
willow b	1139	0.184
wood pellets a	1179	0.177
wood pellets b	1128	0.210
wood pellets c	1137	0.189
wheat straw a	1149	0.155
wheat straw b	1165	0.157
rape straw	1192	0.185
miscanthus a	1137	0.157
miscanthus b	1172	0.150
olive residue	1137	0.207
torrefied materials		
torrefied pine a	1203	0.285
torrefied pine b	1179	0.287
black pellet	1261	0.239

the homogenized biomass in more detail along with indications of the type of biomass for each data point.

4. DISCUSSION

Key differences between the various biomass material types can be identified from the data presented in Figure 3. It is clear from this plot that the torrefied materials (torrefied pine and black pellet) have a significantly higher thermal conductivity compared to the natural wood materials. There is less of a difference between the woody and herbaceous materials although, on average, the latter show slightly lower thermal conductivities than the former. Olive residue has a slightly higher conductivity than the woody and herbaceous materials but not as high as the torrefied materials.

Examination of the results of the experiment show that the expected relationship between density and thermal conductivity for wood conforms to a linear function. Considering the wood pellet data alone, the average measured thermal conductivity for the three samples is 0.184 $W \cdot m^{-1} \cdot K^{-1}$ and their average density (ρ) is 1152 $kg \cdot m^{-3}$. A linear regression function for the cross-grain thermal conductivity−density relations can be derived from the published data for wood (Figure 3a) as

$$\lambda_s = 0.00013\rho + 0.037 \quad (6)$$

Evaluating this for the average wood pellet properties gives a thermal conductivity value of 0.187 $W \cdot m^{-1} \cdot K^{-1}$: less than 3% difference from the average measured value. This suggests that the thermal conductivity of the homogenized pellets is directly related to that of the bulk wood perpendicular to the fiber orientation (i.e., cross-grain). Since this relationship is confirmed by the measurements, it is not unreasonable to assume that the other biomass materials examined also show a linear relationship with respect to density. A simple model can therefore be proposed whereby the coefficients in eq 6 are determined for each material type from the data points plotted in Figure 3b. This would allow a thermal conductivity value to be derived for a lower density sample. To illustrate this, Figure 4 shows a plot of the thermal conductivity of each of the tested samples recalculated according to the density of the original material (see Table 2).

The following observations are made concerning the thermal conductivity of these materials in their original form. Both olive residue and black pellet, having high "as-received" densities

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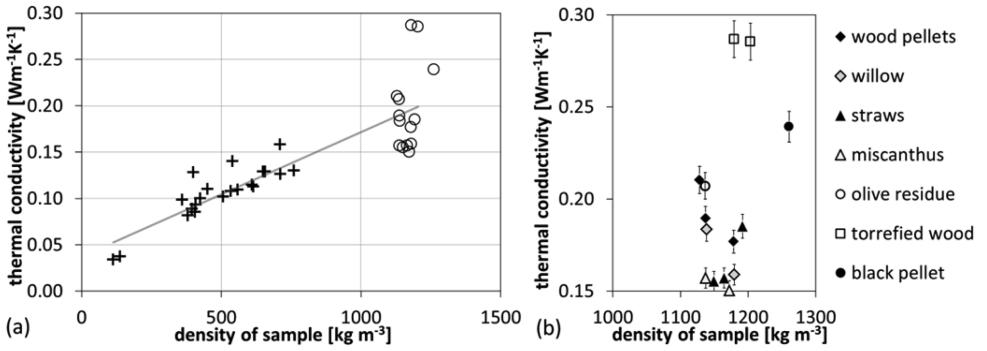

Figure 3. Measured thermal conductivity of homogenized-densified biomass plotted against density: (a) measurements (open circles) compared with published values (+) for cross-grain thermal conductivities of wood; (b) measurements with indication of type of biomass (error bars indicate ±1 SD in measurements).

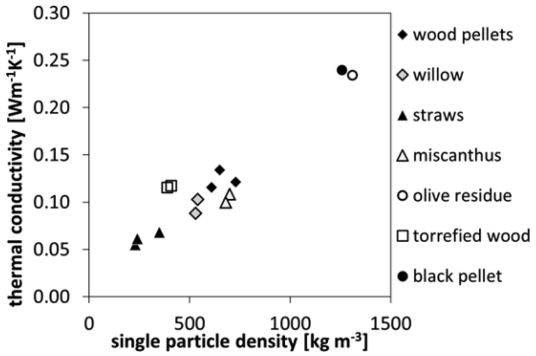

Figure 4. Thermal conductivity of single particles of biomass materials derived from measurements.

(similar to that of the test samples) show values of 0.25 and 0.23 $W \cdot m^{-1} \cdot K^{-1}$, respectively. Wood pellets show a value of between 0.11 and 0.12 $W \cdot m^{-1} \cdot K^{-1}$. Miscanthus and willow are slightly lower at 0.11 and 0.10 $W \cdot m^{-1} \cdot K^{-1}$, respectively, while wheat straw and rape straws can be as low as 0.05 $W \cdot m^{-1} \cdot K^{-1}$. Interestingly, torrefied wood shows a high value in the compressed pellet form but an uncompressed torrefied wood particle has a value similar to that of an uncompressed, untorrefied wood particle —the increase in conductivity of the solid matter is compensated for by reduction in density of the structure.

It should be noted that these derived values apply to the conductivity in the direction perpendicular to the fiber orientation of fibrous materials. As shown in Figure 2, the conductivity parallel to fiber orientation may be 2.5−3 times higher than the perpendicular direction. While the measurement method does not allow verification of this for herbaceous materials, for the purposes of modeling, this multiplier may be assumed to account for the anisotropy of straw and miscanthus in the same way as for woods. This does not apply to olive residue and black pellet since their structure is more isotropic.

5. CONCLUSIONS

A measurement method for determining the relative thermal conductivity of various biomass fuels has been presented. The method has been shown to be effective by comparison with existing published data. The experiment has provided data on the thermal properties of small particles of both woody biomass, herbaceous and other nonwoody biomass, and also torrefied biomass. While there are a considerable amount of published data on thermal properties of wood, there are little, if any, comparable data available for the other materials investigated.

Analysis of the data has confirmed that woody biomass fuels conform to a general relationship between material density and thermal conductivity. The compressed solid matter in torrefied wood was shown to have a significantly higher thermal conductivity than untorrefied wood. Olive residue pellets and black pellet are shown to have higher thermal conductivities than wood while herbaceous materials tend to have lower values than wood.

A means of deriving useful values of thermal conductivity from the measured data for the purposes of modeling biomass thermal processing and single particle combustion has been presented. Further investigation on herbaceous materials would be required to validate the assumption that particles of such materials show thermal anisotropy similar to that of wood.

The data are also useful in the assessment of the self-ignition risk in bulk storage of biomass. Further investigations utilizing measured thermal conductivity together with additional experimental data[6] may be used to develop and validate self-ignition modeling for different biomass materials.

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Notes

The authors declare no competing financial interest.

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