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Thermal diffusivity measurement of *Phyllostachys edulis* (Moso bamboo) by flash method

Puxi Huang[1,*], Simon G. Pickering[2], Wen-Shao Chang[1], Martin P. Ansell[1], Y.M. John Chew[3], Andy Shea[1]

1 Dept. Architecture & Civil Eng., University of Bath, UK. Email: P.Huang@bath.ac.uk
2 Dept. Mechanical Eng., University of Bath, UK. Email: S.G.Pickering@bath.ac.uk
3 Dept. Chemical Eng., University of Bath, UK. Email: Y.M.Chew@bath.ac.uk
*Corresponding author

Abstract: The thermal diffusivity of *Phyllostachys edulis* (Moso Bamboo) has been determined in three directions of the cylindrical coordinate system of the culm. A flash tube and an infrared camera system were utilised for this purpose. The results, calculated by the MATLAB programme, serve as a data-base for numerical simulation studies concerning the heat and moisture transfer behaviour of Moso bamboo. The porosity, the complexity of the cellular structure and interconnectivity are the essential parameters influencing the thermal diffusivity of Moso bamboo.

Introduction

Thermal diffusivity (ThD) is a physical property that is expressed as the ratio of the thermal conductivity to the heat capacity of a material. This property is an essential component of the transient heat conduction equation. A larger ThD value means that the material will reach a new equilibrium condition more quickly (Incropera 1981 and Ukrainczyk 2009) as described in the following equations.

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t} \quad \text{Eq. 1;} \quad \alpha = \frac{k}{c_p \rho} \quad \text{Eq. 2}$$

where: α: ThD ($m^2 s^{-1}$); T: temperature (K); t: time (s); k: thermal conductivity (W

m^{-1}K^{-1}); ρ: density (kg m^{-3}); C_p: specific heat capacity (J kg^{-1}K^{-1}).

As illustrated in Fig. 1, density is not the decisive factor for determining the ThD. The pure solid materials have relatively higher ThD values followed by gases and alloys. The ThD of polymers and porous materials is at a relatively lower level (Jams 1968; Blumm and Lindemann 2003; Wilson 2007; Casalegno et al. 2010; Bergman et al. 2011). It was postulated that porosity is an important factor in this regard.

The ThD of Moso bamboo in the longitudinal (L) direction has previously been measured by a laser flash method (Wu *et al.* 2004). Harada *et al.* (1998) applied this method for wood species. The ThD of Moso bamboo veneer board and laminated board has also been measured (Shah et al. 2016). However, the corresponding data in the radial (R) and tangential (T) directions of the Moso bamboo culm are not yet known. ThD measurements in the case of bamboo are challenging because of the heterogenous character of this material both from the anatomical and thermal properties point of view (Huang *et al.* 2014; Huang *et al.* 2015).

ThD of biological materials can be measured by a number of transient methods, such as the transient plate source (TPS) approach or the heat pulse and laser flash approaches (Harada *et al.* 1998; Burgess *et al.* 2001; Dupleix *et al.* 2013). Though all methods are effective, the rapid flash method is most suitable for Moso bamboo, because of its flexibility in terms of the specimen's dimensions. The heat pulse method requires multiple temperature cycles, which is time consuming. The minimum specimen size of the TPS method is restricted by the size of the transient plate sensor.

However, the bamboo specimens must be relatively small if the effects of microstructural variations are of concern. The thickness and the radius of the bamboo are two factors, which restrict the size of specimens in the R and T directions.

Therefore, in the present study the ThD properties in the R, T, and L directions were observed by the flash method. This research is related to thermal insulation of buildings as Moso bamboo-based panels may contribute to this purpose. According to a statistical analysis from UNEP (2014), at least one third of global energy use is attributable to buildings but materials with high insulation performance can minimise energy consumption (Castleton *et al.* 2010). Bamboo panels, as for all bio-based materials, have a favourable life-cycle performance (Hammond and Jones 2008). Bamboo panels still have a considerable optimization potential and the ThD data collected here are expected to contribute to this optimization process concerning the basic heat and moisture transfer properties.

Materials and methods

Specimen preparation: The Moso bamboo culms (*Phyllostachys edulis*) were purchased from UK Bamboo Supplies Limited. The external diameter of the bamboo culms ranged from 70 to 100 mm. The specimens were cut into thin square pieces from these culms. The side length of the square pieces was 10 ±0.5 mm. The thickness of the specimen was 1 ±0.2 mm. The specimens were oven dried at 103°C and stored in a desiccator over $CaCl_2$. Before measurement, all specimens were embedded into acrylic boards to fit the frame of the flash tube heat source (Fig 2).
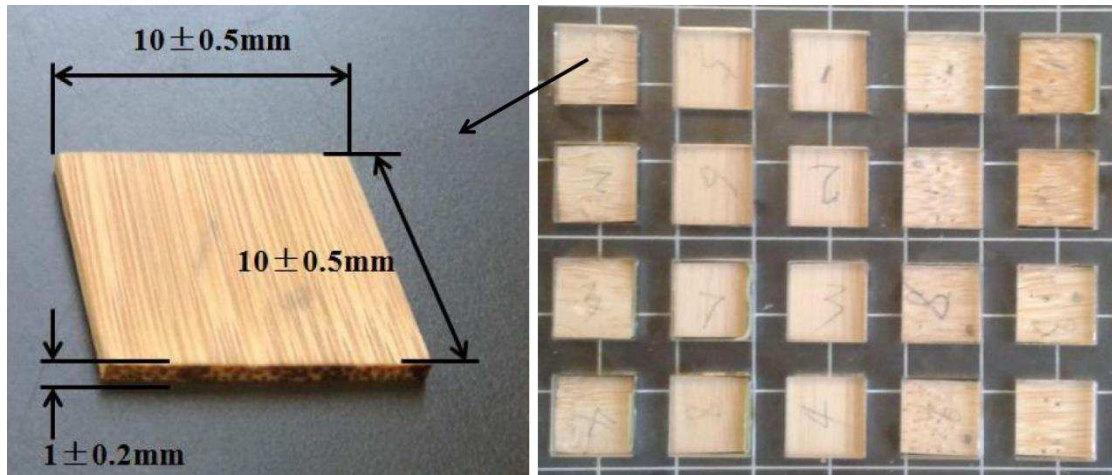
Fig 2 The dimension and fixation of Moso specimens

The specimens were cut in R, T, and L directions from both the internode part and the node part of the culms. In the R direction, specimens were cut from three positions, namely the external surface, middle position, and internal surface of the culm wall. In the T direction, specimens were cut from four positions. The adjacent positions differ in 90° intervals. In the L direction, specimens were cut from three positions. The distance between two adjacent positions is 3 ±1 mm for the node parts and 10 ±1 mm for internode parts, respectively. These distances were determined by the length of the node part and internode part of the culms. Three specimens were prepared at each position for the measurements.

Thermal diffusivity (ThD) measurement by the flash tube method: The ThD was calculated by Eq. 3. The theory was described by Parker *et al*. (1961).

$$\alpha = 1.38 \, (L^2/\pi^2 \, t_{0.5}) \qquad \text{Eq. 3}$$

where, α: ThD (m^2 s^{-1}); L: the thickness of the specimen (m); $t_{0.5}$ the half time for the rear surface reaching peak temperature (s)

The ThD measurement was conducted by means of a flash tube system called thermal waving imaging (TWI) Ecotherm. The system includes a pulse generator, a

flash tube heat source, a mid-wave infrared (MWIR) camera, a controller and data recording PC system (Fig 3). The acrylic board with embedded specimens was fixed in front of the heat source. The temperature of the rear surface of the specimens was monitored by the MWIR camera and the data were saved by PC.
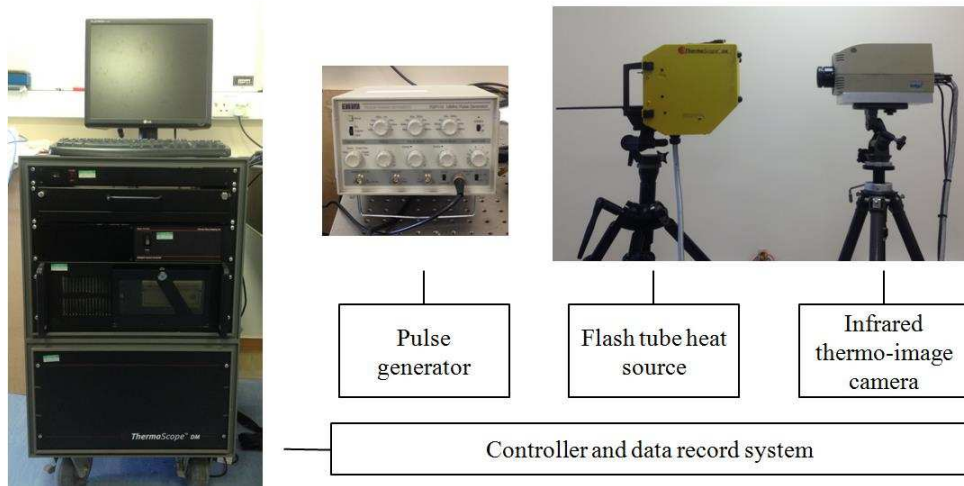

Fig 3 Flash tube system for thermal diffusivity measurement

The database files were processed by a MATLAB programme to identify the flash time and the time, at which the rear surface achieves its peak temperature. After inputting the thickness of the bamboo specimens, the ThD results can be calculated directly by Eq. 3.

Computed tomography (CT) and back-scattered electron (BSE) imaging method: CT and BSE images were utilised to illustrate the relationship between the ThD results and anatomical features of the Moso bamboo. The CT image of the Moso bamboo specimens were captured by the Nikon XT H 225 CT scanner. A JEOL JSM-6480 scanning electron microscope (SEM) was utilised to capture the BSE image of the Moso bamboo specimens in the high vacuum mode. The bulk density and porosity

of the Moso bamboo specimens were calculated by Eq. 4 and Eq. 5. The detailed calculation was described by Huang *et al.* (2016).

$$\rho_{bulk}=40.6Gs-70.4 \quad \text{Eq. 4;} \qquad \phi= (\rho_s- \rho_{bulk})(\rho_s- \rho_a)^{-1} \quad \text{Eq. 5}$$

Where, ρ_{bulk}: Bulk density (kg m^{-3}); Gs: Greyscale; ϕ: Porosity; ρ_s: Bamboo skeletal density (kg m^{-3}); ρ_a: Air density (1.184 kg m^{-3} at 1atm, 25°C).

Results and discussion

The results including average ThD values and standard deviation (StD) in three directions are summarised in Table 1.

Table 1 ThD results

Thermal diffusivity (10^{-7} m^2/s)		Radial direction			Longitudinal direction			Tangential direction			
		External	Middle	Internal	No.1	No.2	No.3	No.1	No.2	No.3	No.4
Internode	Average	6.36	1.74	1.28	2.09	2.12	2.09	1.47	1.48	1.64	1.60
	SD	0.72	0.09	0.004	0.02	0.17	0.08	0.02	0.16	0.04	0.05
Node	Average	7.81	1.61	1.27	2.22	2.14	2.39	1.43	1.47	1.58	1.48
	SD	0.56	0.01	0.02	0.01	0.12	0.02	0.04	0.04	0.09	0.06

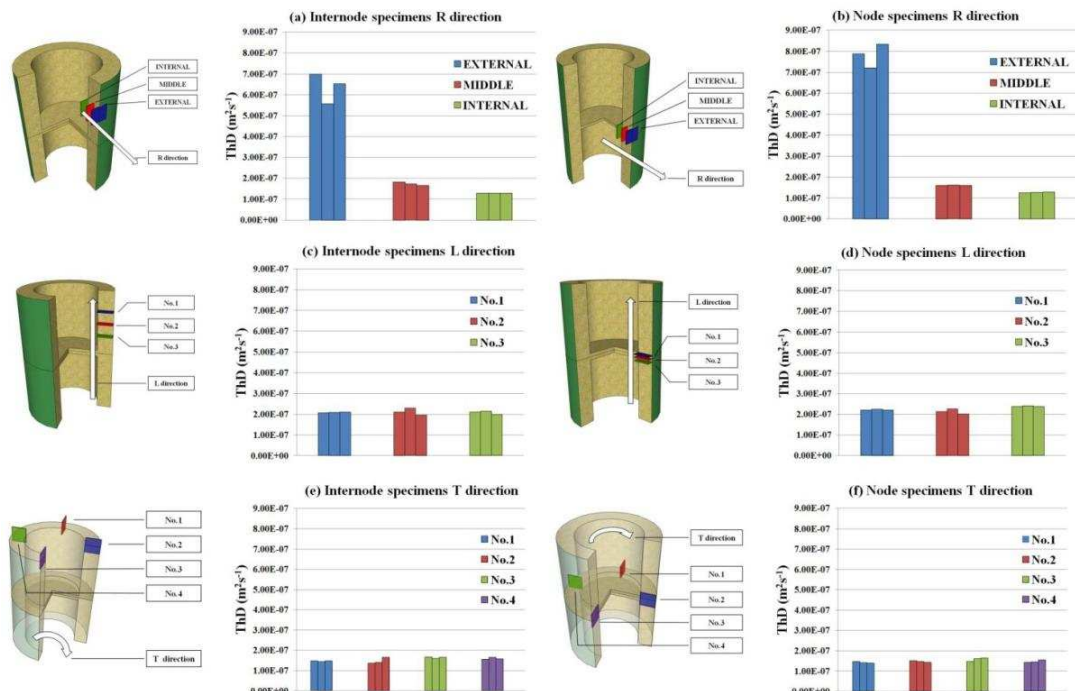The detailed ThD results are illustrated by Fig 4.

Fig 4 ThD results in R, L and T directions

The measurement positions revealed only obvious different data in the R direction in contrast to the T and L directions. This is due to the anatomical characteristics of Moso bamboo. The bulk density data show an increasing trend from the external to the internal surface of the bamboo culm wall (Huang *et al.* 2015).

The density and porosity have been quantified by a previous study. The density of the specimens varies from 588 to 1181 kg m^{-3}. The skeletal density of Moso bamboo varied from 1425 to 1548 kg m^{-3} (Huang *et al.* 2016). The porosity can be calculated by Eq.5 using the average skeletal density value as the input. The relationship between the porosity and the ThD values are illustrated by Fig 5.
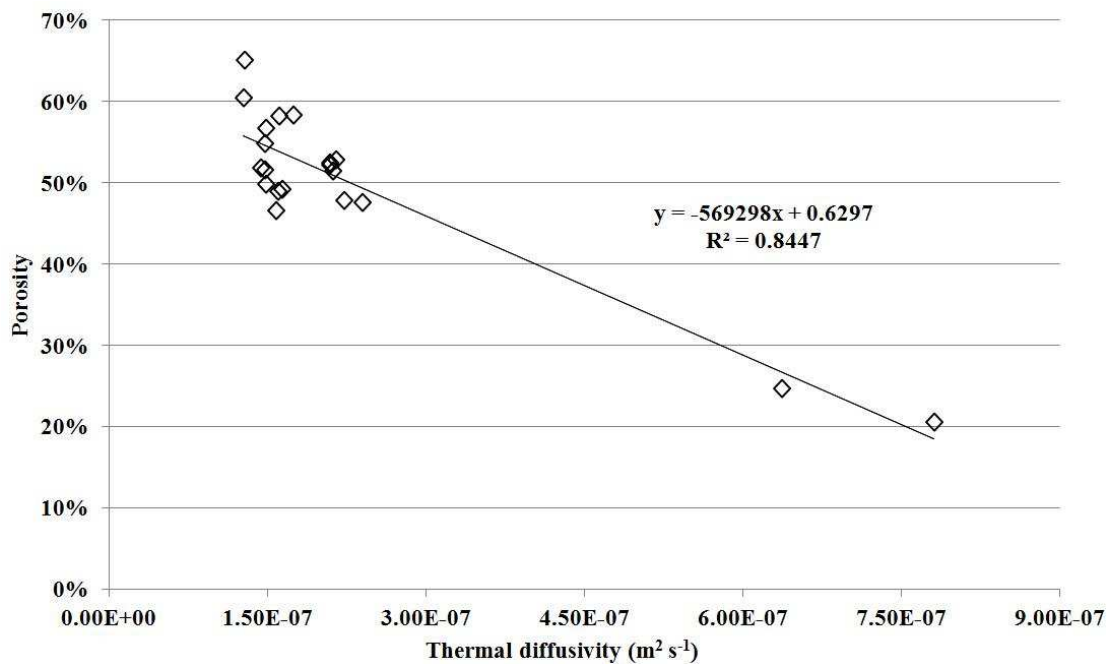

Fig 5 The relationship between porosity and ThD

Porosity can be regarded as a key factor to influence the ThD of the Moso bamboo. Higher porosity can lead to a higher internal surface area which provides a larger area for heat propagation. Increasing porosity could be regarded as a sign of

ThD decreasing. A similar view has been voiced by some previous research on porous materials (Zalameda and Winfree 1990; Thomson 2010). The ThD variation is also attributed to the tissue structure and interconnectivity of pores. The ThD of bread is a typical example of a material with high interconnectivity (Zanoni and Gianotti 1995). Because the water content of the specimens is assumed to be a negligible factor, only two phases exist in bamboo. The gas phase is the air of which ThD ranges from 1.9×10^{-5} to 2.28×10^{-5} m^2 s^{-1} (Wang and Mandelis 1999). The solid phase is the cell wall. The results of this study imply that the ThD of the bamboo cell wall is much less than that of air. If one just considers the fraction ratio, regions/samples with high porosity and high interconnectivity will provide high ThD values. However, the results of this study are not in a good agreement with this assumption. The interconnectivity of Moso bamboo is not large enough to counteract the influence of the high porosity. For Moso bamboo, porosity is more decisive than interconnectivity in terms of the ThD.

Moso bamboo specimens in the L direction have higher ThD values than the specimens in the T directions and the specimens from middle and internal positions in the R direction. The explanation is given in the computed tomography (CT) image and back-scattered electron (BSE) images in Fig. 6. Anatomically, vertically grown fibres provided shorter routes for heat propagation, while the vascular bundle vessels allowed more interconnectivity for air (Fig. 6a and 6c). The Fig. 6b illustrates that the route of heat propagation was though more complex routes in R and T directions than in the L direction.
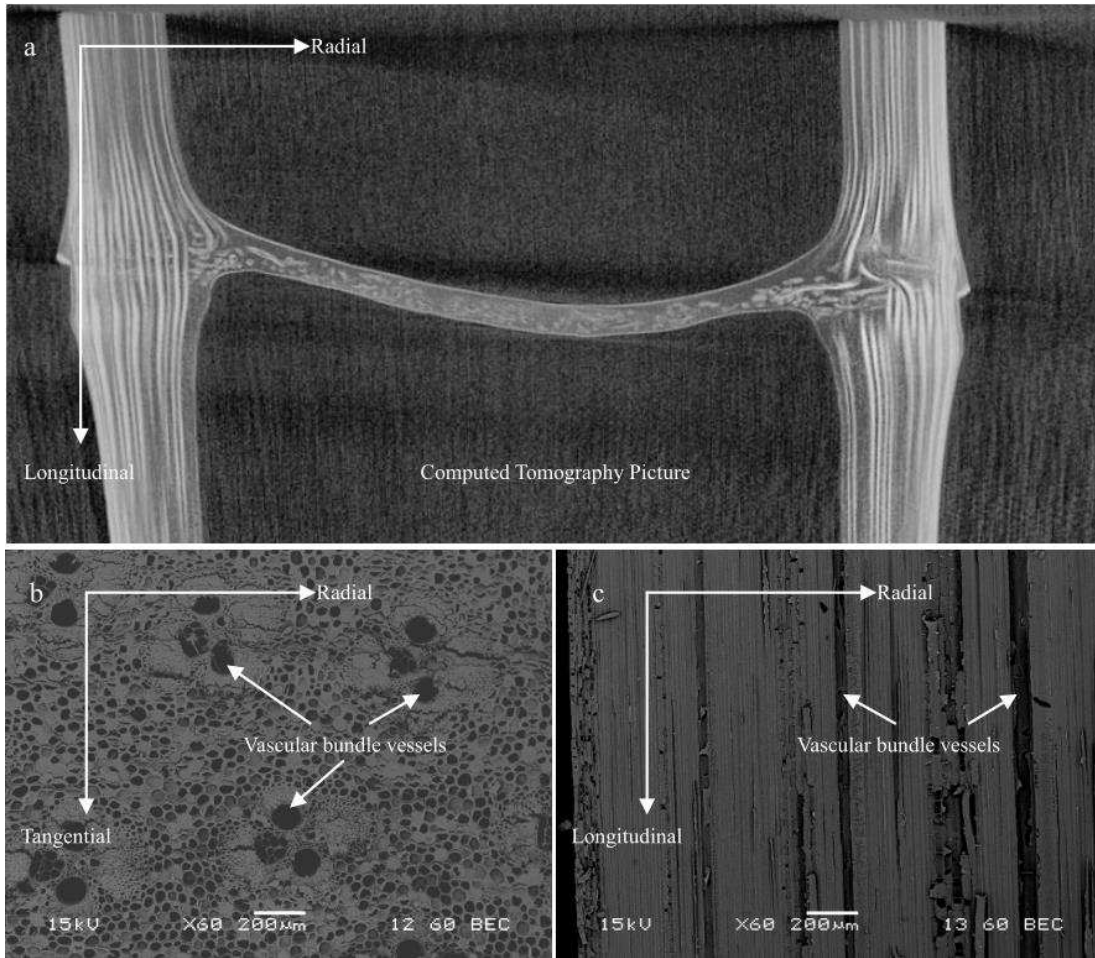
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Fig 6 (a) CT image RL section view (b) BSE image RT section view (c) BSE image

RL section view

Although, the flash method was developed for homogenous materials, its application

for wood and bamboo is also reported (Harada *et al.* 1998 and Wu *et al.* 2004). To

make the specimens effectively homogenous, this study took the following steps:

Firstly, the thickness of the specimen was cut into a relative small size. The thin

thickness minimized the density variation as much as possible. Secondly, the water in

the specimens was eliminated to avoid any undesired influence of water. Thirdly, the

surfaces of the specimens were sanded with very fine sandpaper.

Conclusions

The ThD of the Moso bamboo specimens was measured by a flash tube system. The specimens were measured in all directions of the cylindrical coordinate system at both internode parts and node parts. Obvious difference of ThD results between measurement positions was found in the radial direction. The remarkable differences in porosity and complexity of the heat propagation area in the R direction are regarded as factors which influence the ThD. Higher ThD values were measured for specimens in the longitudinal direction rather than the specimens in the tangential directions and the specimens from middle and internal positions in the radial direction. This phenomenon can be attributed to vertically grown fibres and permeable vascular bundle vessels in the longitudinal direction.

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