Heat and moisture transfer behaviour in *Phyllostachys edulis* (Moso bamboo) based panels

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Abstract

This study focuses on the heat and moisture transfer behaviours in the *Phyllostachys edulis* (Moso bamboo) panels at various temperature and relative humidity (RH) conditions. Moso bamboo panels with different lamination methods were prepared by assembling bamboo strips from different layers of the bamboo culm wall. Dynamic coupled heat and moisture transfer experiments were conducted. Unsteady state numerical modelling was conducted by COMSOL Multiphysics™. A rigorous approach was adopted in this paper. A series of parametric studies of numerical simulation are firstly presented in this paper and then validated by the experiments. Both experimental and simulation results appear to be consistent with the results of measurements of the basic hygrothermal parameters, which demonstrates the robustness of the results. The temperature and RH results indicated that although the panel made from layers of the internal part of bamboo culm wall can provide good insulation performance, its ability to resist high RH variation is inferior to the layer from the external part of bamboo culm wall. The parametric study found that density is the most critical parameters to influence the temperature distributions in the transient state. The thermal conductivity dominates the temperature variation in the steady state. The water vapour diffusion resistance factor is the key parameter which influences the RH simulation results. Numerical simulation with moisture transfer shows better consistency than the simulation without moisture in both equilibrium and transient states. The results of this study demonstrated that the external part of the bamboo culm wall can be utilised to minimise the RH variation of the panel while the internal part is suitable for increasing the thermal insulation performance of the panel.

Keywords: Moso Bamboo; Heat and moisture transfer; modelling and experimental study; parametric study.

1. Introduction

The implementation of bamboo in the building industry has been regarded as an effective strategy to reduce energy consumption. The advantages of bamboo as a biological building material have been mentioned by many researches (Van Der Lugt et al. 2006, Flander and Rovers 2009, Majumdar *et al.* 2010). To evaluate the potential of bamboo as a biological building envelope material, the temperature and relative humidity (RH) are two essential factors which directly influence the performance of the volume stability, service life and building energy saving. Hence the knowledge of heat and moisture transfer behaviour in bamboo is critically important.

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However, studies of heat and moisture transport in raw bamboo are still under development. The challenges in making these measurements include the following:

A bamboo culm can be approximated as a hollow tube with relatively small thickness.

Direct measurement of the hygrothermal properties, for example, density, porosity, thermal conductivity, specific heat capacity and vapour permeability, is restricted by the curved shape of bamboo.

The size of the temperature and RH sensors needs to be relatively small to meet the contact requirement.

The time consumed in carrying out the moisture related experiments, such as hygroscopic isotherm or vapour permeability measurement, is significant (Latif *et al.* 2015).

Related hygrothermal research on wood was published earlier than the research on bamboo. A heat and moisture transfer model has been utilised to simulate wood drying process (Plumb *et al.* 1985). Younsi *et al.* (2006) presented a three-dimensional simulation of heat and moisture transfer in wood which is based on the theory of coupled heat and mass transfer in capillary porous media from Luikov (1966). Li *et al.* (2010) investigated heat and moisture transfer behaviour of the bamboo plywood wall and bamboo plywood concrete wall. The study focused on the temperature and water content variation of entire composite wall rather than bamboo layers.

The aforementioned reviews indicated that partial differential equations (PDEs) have been broadly utilised in building physics field to describe the transient heat and moisture transfer mechanism of building materials. Due to the complexity of the PDEs, large numbers of mathematical tools were developed to provide the numerical solutions for the PDEs. To assess the accuracy of the current model for hygrothermal modelling, a British standard provided a benchmark example (BS EN 15026 2007) for calibration. Studies from Portal (2011) and Nusser and Teibinger (2012) proved that simulation tool from the theory of Portal *et al.* (2014) and the balance PDEs of WUFI software can meet the requirements of the benchmark. Delgado *et al.* (2012) reviewed 14 hygrothermal modelling tools and suggested that versatility, visibility, renewability and user-friendliness are the features of successful hygrothermal modelling tools.

This study focuses on the heat and moisture transfer behaviours of *Phyllostachys edulis* (Moso bamboo) panels at various temperature and relative humidity conditions. To prepare for this study, a number of experiments were conducted to acquire the data of density, specific heat capacity, thermal conductivity, water diffusivity, water vapour permeability and isotherm curve of Moso bamboo (Huang *et al.* 2014 and Huang *et al.* 2015). These experiments indicated that Moso bamboo demonstrated non-homogeneous hygrothermal properties in different directions. Especially in the radial direction, the content of vascular bundle tissue is obviously higher at the external side of bamboo culm wall (Figure 1). To quantify the influence of the non-homogeneous hygrothermal properties on heat and moisture transfer, both experimental studies and simulation prediction works are included in this paper. The Computational Fluid Dynamics (CFD) simulation allows predictions of the temperature and RH distributions in the bamboo specimens. Furthermore, the speculated values and hygrothermal properties can be adjusted to specify the heat and moisture transfer resistances in the parametric studies of CFD. The heat and moisture transfer experiments can be utilised to not only validate the simulation results but also to identify the temperature and RH response of Moso bamboo in the actual situation.

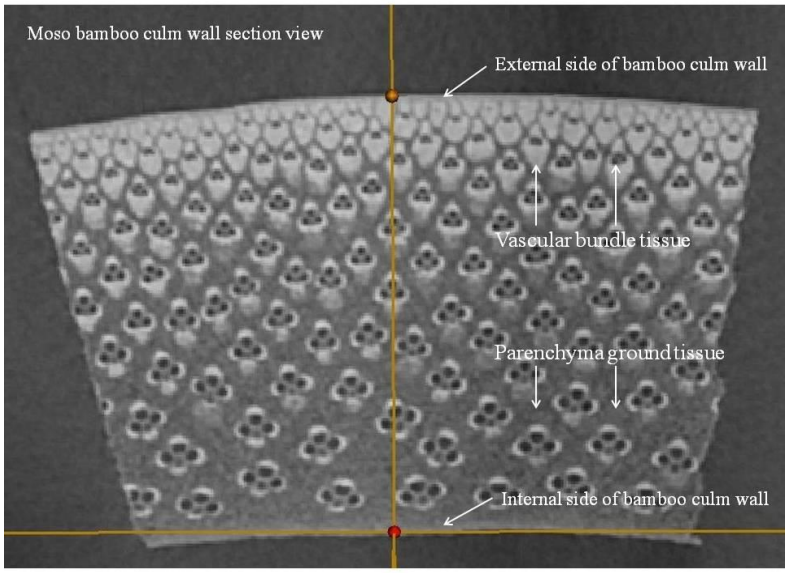

Fig 1. Section view of a Moso bamboo culm wall

Little research has been done on the non-homogeneous hygrothermal properties and their influence on the transient heat and moisture transfer behaviour of Moso bamboo. The results of this study can provide guidance for manufacturing bamboo panels with good thermal performance by integrating external, middle, and internal parts of bamboo culm wall.

2. Methodology

2.1 Heat and moisture transfer experiment design

Four Moso bamboo panels were prepared for heat and moisture transfer experiments. The bamboo was originally imported from Hunan province in China. The age of the bamboo was 4.5-5 years. All panels were laminated from Moso bamboo strips. The cutting position of the bamboo strips is illustrated by Fig 2. Panel 1 was laminated from the strips cut from the external surface of bamboo culm wall. Panel 2 was made by the strips cut from the internal surface. These two panels were utilised to specify the variation in the hygrothermal performance caused by the cutting position. Panel 3 and panel 4 were laminated from three types of bamboo strips. Both two panels have the same middle layer. Panel 3 utilised the external strips as the outdoor surface while Panel 4 utilised the internal surface as the outdoor surface. These two panels were prepared to demonstrate variation of the hygrothermal performance caused by the direction of lamination.

In the radial direction, bamboo culms demonstrated obvious non-homogeneous features in terms of hygrothermal performance. The minimum amount of glue was used in the lamination method. The glue consisted of two components, the 1711 Cascosinol Phenol Rescorcinol Adhesive and the 2520 hardener. The manufacturing method is simple and it is easy for mass production.

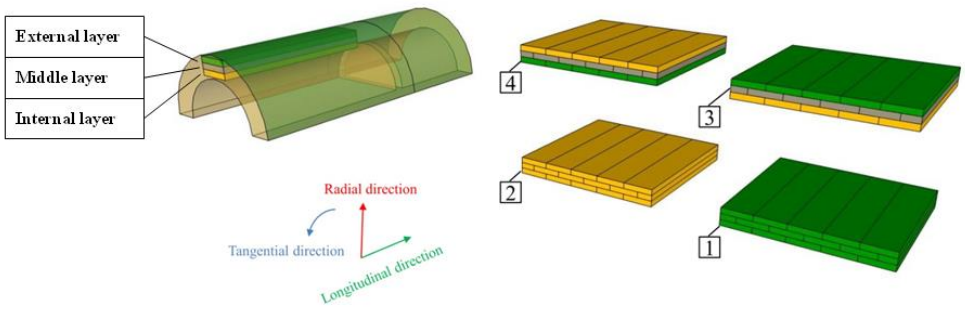

Fig 2. Four types of bamboo laminated panels

The dimension of the panel are illustrated by Fig 3. Grooves were milled on the bamboo strips. The temperature and RH sensors were embedded in the middle point of every layer of the bamboo strip. The monitor points were nominated as No.1, No.2, and No.3 from left to right (See Fig 4). Two extra bamboo strips were utilised to fill the gap and fix the sensors in-between two grooves. The side surfaces of the bamboo panel were insulated with wax to avoid undesired heat and moisture losses. Four panels were assembled using the same method. Each panel used three groups of temperature and RH sensors.

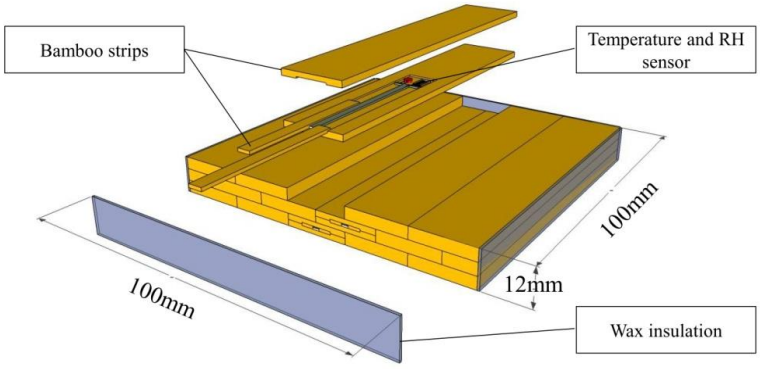

Fig 3. The assembling of the bamboo panel with the temperature and RH sensor

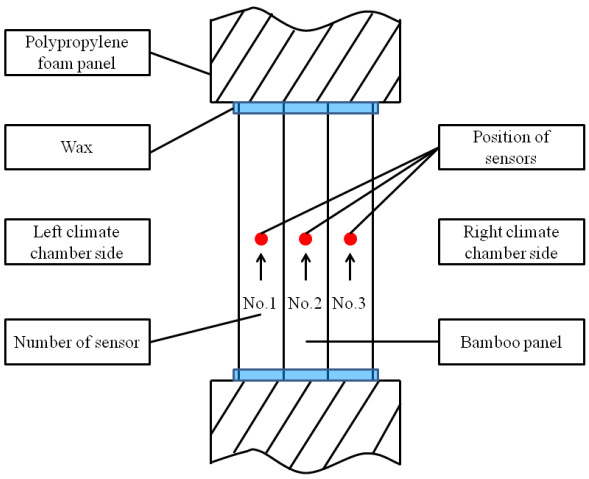

Fig 4. The edge section of bamboo panels with the position of the temperature and RH sensors

The bamboo panels were fixed in a polypropylene foam panel. The external surface of the polypropylene foam panel was covered by aluminium foil tapes. (See Fig 5) The polypropylene foam

panel was placed between two climate chambers. The left climate chamber was utilised to simulate the outdoor temperature and RH conditions. The right climate chamber remained at constant temperature and RH. The polypropylene foam and wax insulation ensured that the heat and moisture flow were perpendicular to the surface with the largest area of bamboo panel.

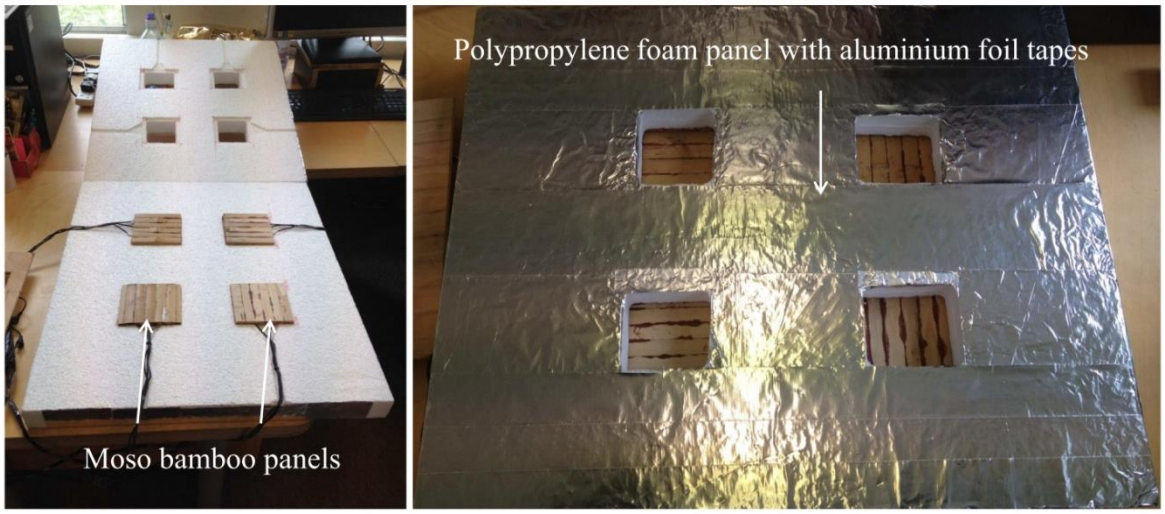

Fig 5. Bamboo panels in a special designed polypropylene foam panel

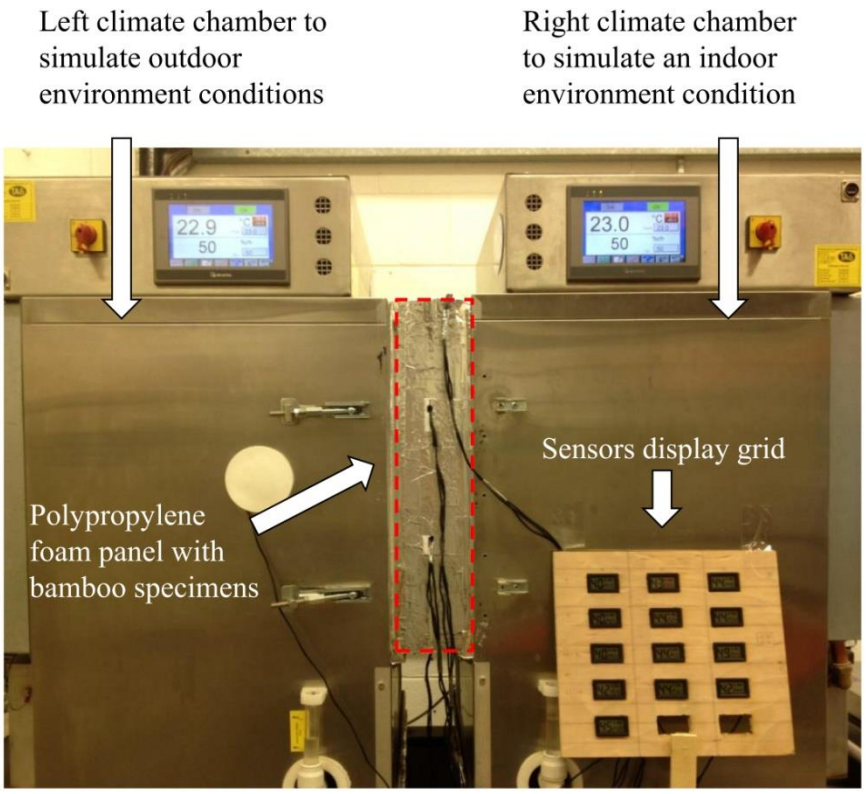

Fig 6. Twin climate chambers for heat and moisture transfer study

The climate chambers can provide wide temperature conditions ranging from -40 °C to 100 °C. The RH conditions can range from 10% to 98%. The temperature and RH fluctuation range are ±10 °C and ±40%

respectively in this study. This scheme can provide representative climate conditions while avoiding deformation caused by volume change and undesired condensation. The temperature and RH conditions are summarised in table 1.

Table 1. The temperature condition plan of two climate chambers

Step number	Time	Left climate chamber condition		Right climate chamber condition	
1	0-Day 1	25°C	50% RH	25°C	50% RH
2	Day 1 – Day 4	15°C	90% RH		
3	Day 4 – Day 8	25°C	50% RH		
4	Day 8 – Day 11	35°C	10% RH		
5	Day 11 – Day 15	25°C	50% RH		

All bamboo panels were stored in the right climate chamber until the temperature and RH were uniform. Then, the panels were sealed between two climate chambers with same initial condition for 24 hours (See Fig 6). A relatively cold and moist climate condition was set for the left climate chamber for 3 days at first. The temperature and RH condition of the left climate chamber were reset to the same condition with the right climate chamber for 4 days. The left climate chamber was set to provide a relatively hot and dry climate condition for 3 days. The experiments were terminated after both chambers had maintained the same condition for 4 days. The temperature and RH data were recorded every 5 minutes.

2.2 Heat and moisture transfer simulation

The governing equations for coupled modelling of heat and moisture transfer in this study are shown in equations 1 and 2. The PDEs were also utilised in MOISTURE-EXPERT and WUFI software (Kunzel and Kiessl 1996, Delgado *et al*. 2012 and Nusser and Teibinger 2012). The hygrothermal properties were inputted as a series of variables and conditional parameters in this study. To satisfy these specific and flexible requirements, COMSOL Multiphysics™ was utilised to conduct the numerical simulation in this study.

$$(\partial H/\partial T)(\partial T/\partial t) = \nabla(\lambda \nabla T) + h_v \nabla[\delta_p \nabla(\varphi P_{sat})] \qquad \text{Equation 1}$$

$$(\partial w/\partial \varphi)(\partial \varphi/\partial t) = \nabla[(D_l \nabla \varphi + \delta_p \nabla(\varphi P_{sat})) \qquad \text{Equation 2}$$

$(\partial H/\partial T)$ Heat storage capacity (J/m^3·K)

T Temperature (K)

t Time (s)

λ Thermal conductivity (W/m·K)

h_v Evaporation enthalpy of water (J/kg)

δ_p Water vapour permeability (kg/m·s·Pa)

φ Relative humidity

P_{sat} Saturated pressure of water vapour (Pa)

W Water content of the bamboo substance (kg/m^3)

$(\partial w/\partial \varphi)$ Moisture capacity

D_l Liquid water diffusivity (m^2/s)

To solve the PDEs, at least 6 input parameters, temperature and RH initial and boundary conditions must be specified.

The average density data of Moso bamboo were obtained by a computed tomography (CT) method. The thermal diffusivity values of Moso bamboo were measured by a flash tube method. The thermal diffusivity values can be used to calculate the thermal conductivity.

The thermal conductivity was calculated by equation 3 (Fourier 1878).

$$\lambda_b = \alpha \rho C_p \qquad \text{Equation 3}$$

λ_b Thermal conductivity of bamboo solid phase (W/m·K)
α Thermal diffusivity (m^2/s)
ρ Density (kg/m^3)
C_p Specific heat capacity (J/kg·K)

The average specific heat capacity of Moso bamboo was measured using a TA instruments Q200 modulated differential scanning calorimeter with a scan rate of 3 °C/min, a modulation of ±1 °C per 100 s, and an oxygen-free nitrogen gas flow rate of 25 ml/min. The results are illustrated by Fig 6. The specific heat capacity values vary as a function of temperature. Therefore, the thermal conductivity data, calculated by equation 3, are also a function of temperature (See Fig 7).

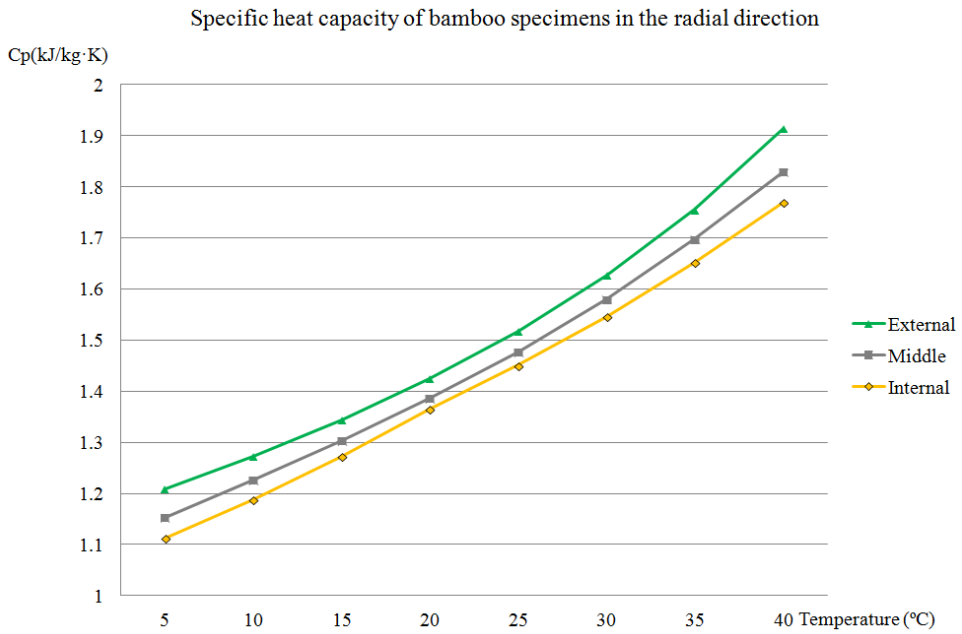

Fig 7. The average specific heat capacity results of bamboo specimens

The liquid water diffusivity of Moso bamboo was estimated by a method considering the porosity and density of the material (Zillig *et al.* 2006). The water vapour permeability of Moso bamboo was measured by a dry cup method.

The water vapour permeable capability of a construction material is often expressed by the water vapour diffusion resistance factor. The water vapour diffusion resistance factor was calculated by equation 4 (BS EN 12086 2013).

$$\mu = \delta_{air}/\delta_p \qquad \text{Equation 4}$$

μ Water vapour diffusion resistance factor (dimensionless)
δ_{air} Water vapour permeability of air (kg/m·s·Pa)
δ_p Water vapour permeability of the specimen (kg/m·s·Pa)
The water vapour permeability of air can be calculated by equation 5 (BS EN 12086 2013).

$$\delta_{air} = (2.306 \cdot 10^{-5} \cdot P_0/R_v \cdot T \cdot P_a)(T/273.13)^{1.81} \qquad \text{Equation 5}$$

δ_{air} Water vapour permeability of air (kg/m·s·Pa)
P_0 Standard atmospheric pressure (101325 Pa)
R_v Gas constant for water (461.5 J/K·kg)
T The temperature (K)
P_a Ambient air pressure (Pa)

The values of water vapour permeability of bamboo (δ_p) need to be inputted in the PDEs for calculation. These values are varied with the temperature because the water vapour permeability of the air (δ_{air}) is a function of temperature.

The moisture capacity values of Moso bamboo were calculated by equation 6 (Times 1998). To calculate the moisture capacity values, the isotherm curves of bamboo specimens of three different layers are necessary. The isotherm curves were measured by a desiccator method. The sorption curves were utilised for the step numbers 1, 2 and 5 whilst the desorption curves were utilised for step number 3 and 4 (See table 1).

$$(\partial w/\partial \varphi) = \xi \qquad \text{Equation 6}$$

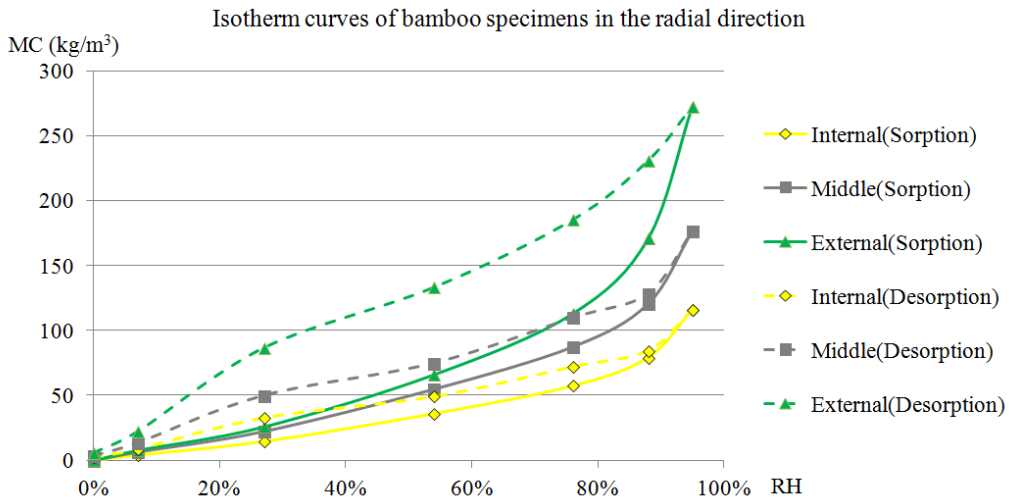

Figure 8. Isotherm curves of the Moso bamboo in the radial direction

To study the influence of the moisture content on thermal properties, the equivalent thermal conductivity of a bamboo strip can be described by equation 7 (Luikov 1966).

$$\lambda = \lambda_b + u''\lambda_w \qquad \text{Equation 7}$$

λ Total or the equivalent thermal conductivity of a bamboo (W/m·K)
λ_b Thermal conductivity of bamboo solid phase (W/m·K)

u'' The ratio of water substance to dry wood substance, dimensionless
λ_w Thermal conductivity of water phase (W/m·K)

Similarly, the heat storage capacity can be described by the equation 8 (Luikov 1966):

$$(\partial H/\partial T) = (C_s + (1/\rho_s)\, C_w W)\rho_s \qquad \text{Equation 8}$$

C_s Specific heat capacity of dry material (J/kg·K)
ρ_s Bulk density of the dry material
C_w Specific heat capacity of water (J/kg·K)

The data of 6 input parameters are summarised by table 2.

Table 2. The essential parameters for heat and moisture transfer PDEs

Input parameters	External	Middle	Internal	Method of measurement
Density (kg/m^3)	1157	723	474	CT (Huang *et al.*2015)
Thermal diffusivity (m^2/s)	6.36×10^{-7}	1.74×10^{-7}	1.28×10^{-7}	Flash tube (Huang *et al.*2017)
Specific heat capacity	See fig 6			DSC (Huang *et al.*2016)
Thermal conductivity at 25°C (W/m·K)	1.12	0.19	0.09	Calculated by Equation 3
Water liquid diffusivity (m^2/s)	6.15×10^{-10}	2.65×10^{-12}	2.95×10^{-13}	(Zillig *et al.* 2006)
Water vapour diffusion resistance factor	57	42	38	Dry cup (Huang *et al.*2016)
Hygroscopic isotherm	See fig 8			Desiccator and DVS

2.3 Boundary conditions

The thermal boundary condition of this study is classified as the Robin condition. The two surfaces, which are exposed to the two climate chambers, are regarded as the convective surfaces. Therefore, the heat flux density and moisture flux density of two convective surfaces can be described by Equations 9 and 10 (Luikov 1966).

$$q = h_T(T_a - T_b) \qquad \text{Equation 9}$$

q Heat flux density (W/m^2)
h_T Heat transfer coefficient (W/m^2·K)
T_a Temperature of the ambient air (K)
T_b Temperature of the bamboo surface (K)

$$\dot{m} = h_m(\rho_a - \rho_b) \qquad \text{Equation 10}$$

$\dot{m}$ Water vapour flux density (kg/m^2·s)
h_m Water vapour transfer coefficient driven by the density difference of water vapour (m/s)
ρ_a Density of the water vapour in the ambient air (kg/m^3)
ρ_b Density of the water vapour in the bamboo surface (kg/m^3)

In this study, the water vapour flux density needs to be calculated by the relative humidity. Therefore, Equation 10 can be changed to Equation 11.

$$\dot{m} = h_{mRH}(\varphi_a - \varphi_b) \qquad \text{Equation 11}$$

$\dot{m}$ Water vapour flux density (kg/m^2·s)
h_{mRH} Water vapour transfer coefficient driven by the difference of RH (kg/m^2·s)

φ_a RH of the water vapour in the ambient air (kg/m^3)
φ_b RH of the water vapour in the bamboo surface (kg/m^3)

The RH can be expressed by the ratio of the density of the water vapour in a medium to the saturated density of the water vapour. See Equation 12 and 13 (BS EN 12086 2013).

$$\varphi_a = (\rho_a/\rho_{sat}) \quad \text{Equation 12}$$
$$\varphi_b = (\rho_b/\rho_{sat}) \quad \text{Equation 13}$$

ρ_a Density of the water vapour in the ambient air (kg/m^3)
ρ_b Density of the water vapour at the bamboo surface (kg/m^3)
ρ_{sat} Saturated density of the water vapour (kg/m^3)
Therefore, the water vapour transfer coefficient in this study can be calculated by equation 14. This coefficient is a variable of temperature because the saturated density of the water vapour varies with temperature.

$$h_{mRH} = \rho_{sat} h_m \quad \text{Equation 14}$$

h_{mRH} Water vapour transfer coefficient driven by the difference of RH (kg/m^2·s)
h_m Water vapour transfer coefficient driven by the difference of water vapour density (m/s)
ρ_{sat} Saturated density of the water vapour

2.4 Assumptions

The heat and moisture transfer behaviour of biological material is fairly complex. This study examines the influence of basic hygrothermal properties on the heat and moisture transfer behaviour of Moso bamboo. A number of assumptions were made to simplify the numerical model:
• The temperature, RH, and velocity of the air in the climate chambers were regarded as constant parameters in this study.
•The heat and moisture lose from the wax insulation and polypropylene foam panel was neglected.
•The heat and moisture transfer of four bamboo panels was one dimensional.
•The expansion of bamboo panels is negligible in this study.

2.5 Model validation

The heat and moisture transfer models were solved by COMSOL Multiphysics™. This model was validated by the benchmark example in a British standard (BS EN 15026: 2007). The results are illustrated by Figs 9 and 10. Solid lines describe the maximum and minimum values of the benchmark material. Dashed lines are the simulation results of the model applied in this study. Both temperature and moisture content results indicated that the model is reliable for the heat and moisture transfer simulation of the building material. Similar validation works has been done by other heat and moisture transfer researches on building materials. (Nusser and Teibinger 2011, and Portal *et al.* 2014)

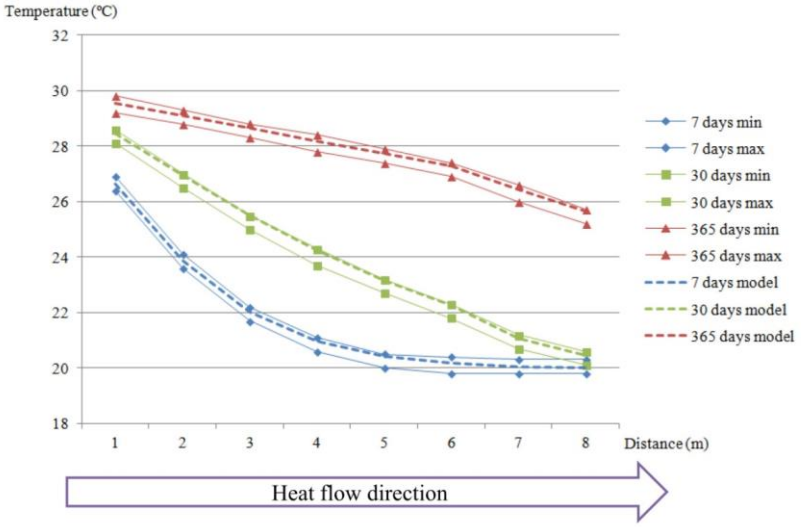

Fig 9. The benchmark validation results for temperature

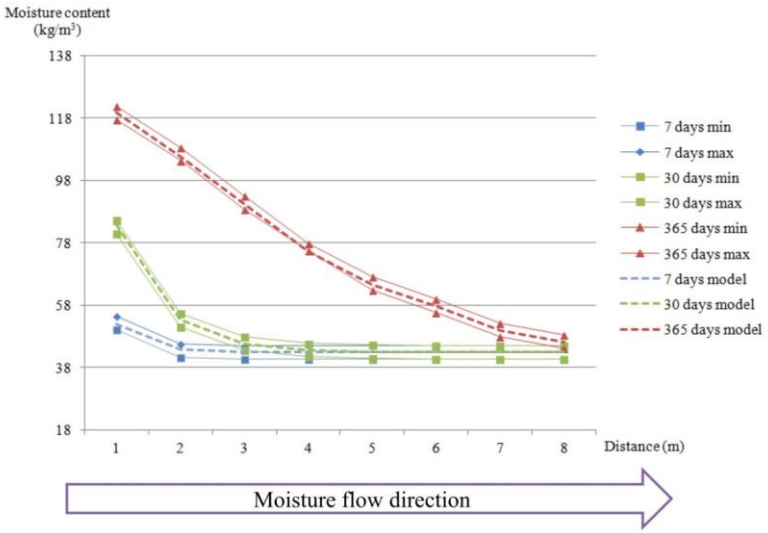

Fig 10. The benchmark validation results for moisture content

3. Results and discussion

The temperature results are illustrated in Fig 11. The red dashed line represents the set temperature. The other dashed lines are the simulation results for three monitor points. The solid lines represent the results from experimental measurements.

It can be seen that less difference between monitoring points No.1, No.2, and No.3 was observed for panel 1 while a greater difference between monitoring points No.1, No.2 and No.3 was found from the results of panel 2. The temperature at sensor No.3 of panel 2 is closer to the right climate chamber than the temperature at No.3 of panel 1. The results from panel 1 and panel 2 clearly indicated that bamboo internal strips have lower thermal conductivity than bamboo external strips when the heat transfer achieves equilibrium state. Similarly, the temperature at No.2 position is closer to the temperature at No.1 position for panel 3. The temperature at No.2 position is closed to the temperature at No.3 position for panel 4. The reason of this phenomenon is caused by the thermal conductivity difference of the first

layers and last layers between the panel 3 and panel 4. The first layer of panel 3 is the bamboo external part and the first layer of panel 4 is the bamboo internal part. The results are consonant with the measured results from the thermal diffusivity and thermal conductivity calculation.

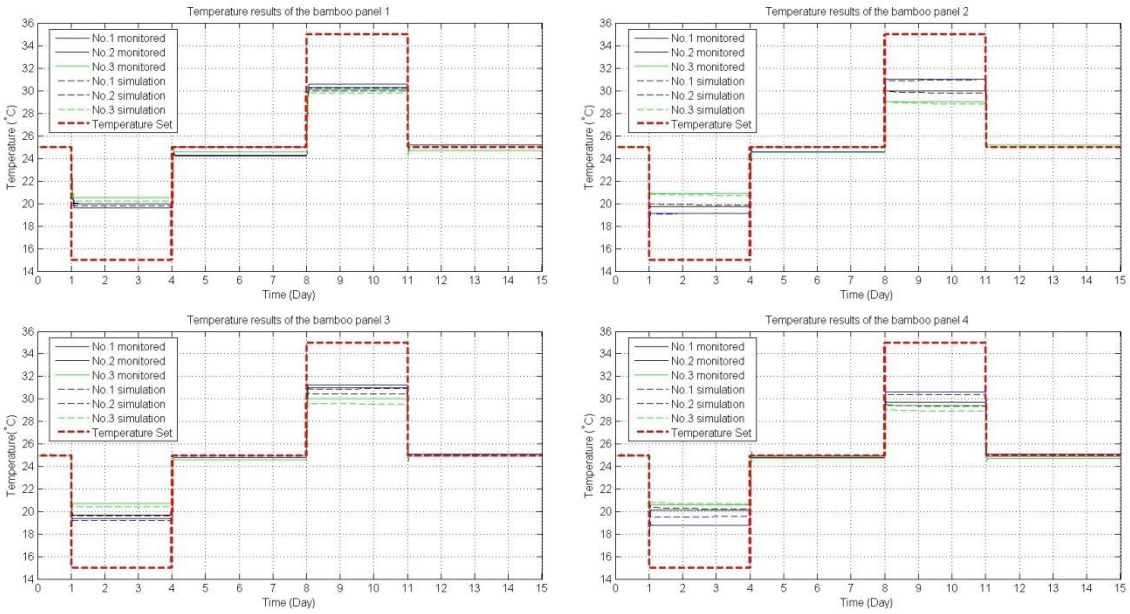

Fig 11. Temperature results for four panels

The relative humidity results are shown in Fig 12. The results indicated that the RH values of the four panels needs much more time to approach equilibrium state than the temperature values. The lowest RH peak value and relative slow RH response can be found from the results of panel 1. The highest peak RH value and relative quick RH response can be found from the results of panel 2. The RH response speed of the panel 3 and panel 4 are between the results from panel 1 and panel 2. The results from the panel 3 are similar to the results of the panel 1. The results from the panel 4 are similar to the results of the panel 2. High water vapour diffusion resistance factor and high moisture capacity were found in the external bamboo culms. Internal bamboo culms demonstrated low water vapour diffusion resistance factor and low moisture capacity. These results also appear to be consistent with the results of isotherm and water vapour diffusion resistance measurements.

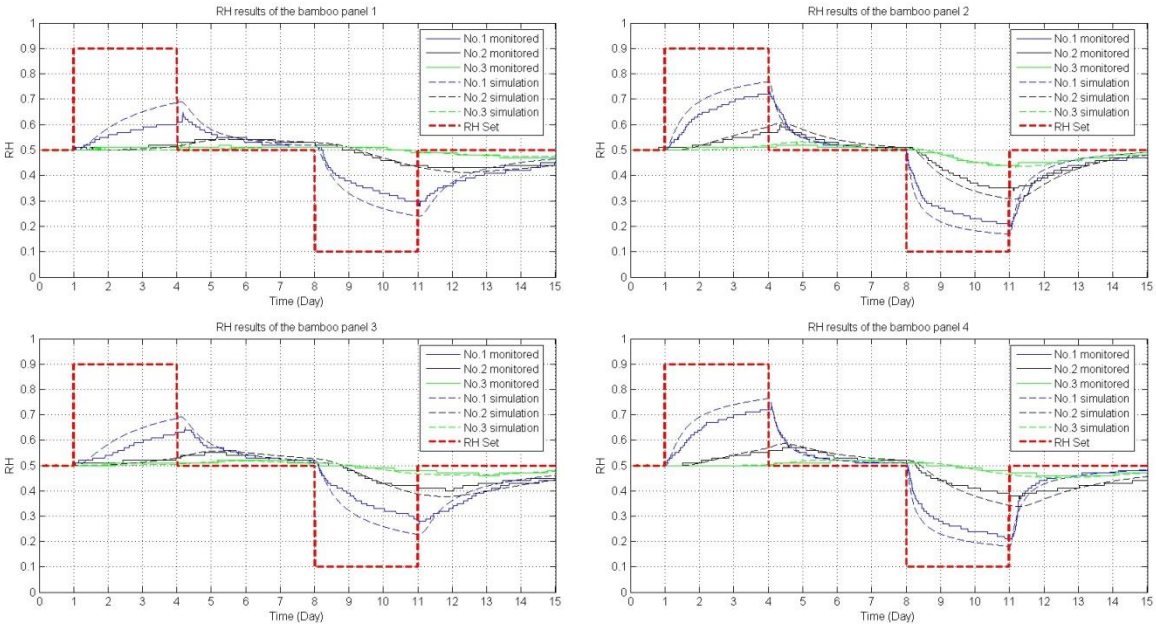

Fig 12. The RH results of four panels

The temperature and RH results indicated that although the layer of panel made by the internal part of bamboo culm wall can provide good insulation performance, its ability to resist the high RH variation is inferior to the layer from the external part of bamboo culm wall. An external part of bamboo culm wall can provide a barrier to the unsteady RH conditions. The internal part of bamboo culm wall can be utilised to increase the thermal resistance of a panel.

The difference between simulation results and measured results for all panels is less than 0.5 ºC in the equilibrium state. The difference of the RH between simulation results and monitored results from experiment measurements is higher than the difference of the temperature results. The results are compliant with the aforementioned assumptions (Section 2.4).

4 Parametric studies

4.1 Results

The parametric study aims to find the parameter which has the greatest influence on the temperature or RH results. The value of each parameter was set to vary from 80% to 120% of the original simulation input. The increment is 20%. The reason for using this range is that the variation of the measured parameters is less than 20% at the same point of measurement. Furthermore, the variation needs to be from both positive and negative directions to make sure the results vary consistently.

The temperature results of the parametric study are shown by Fig. 13. The results indicated that variation of parameters by 20% causes little changes on the simulation results at the equilibrium stage. The time consumption for temperature change is less than 2 hours at the transient stage. Therefore, the temperature variation in this short time period is invisible in Fig. 13.

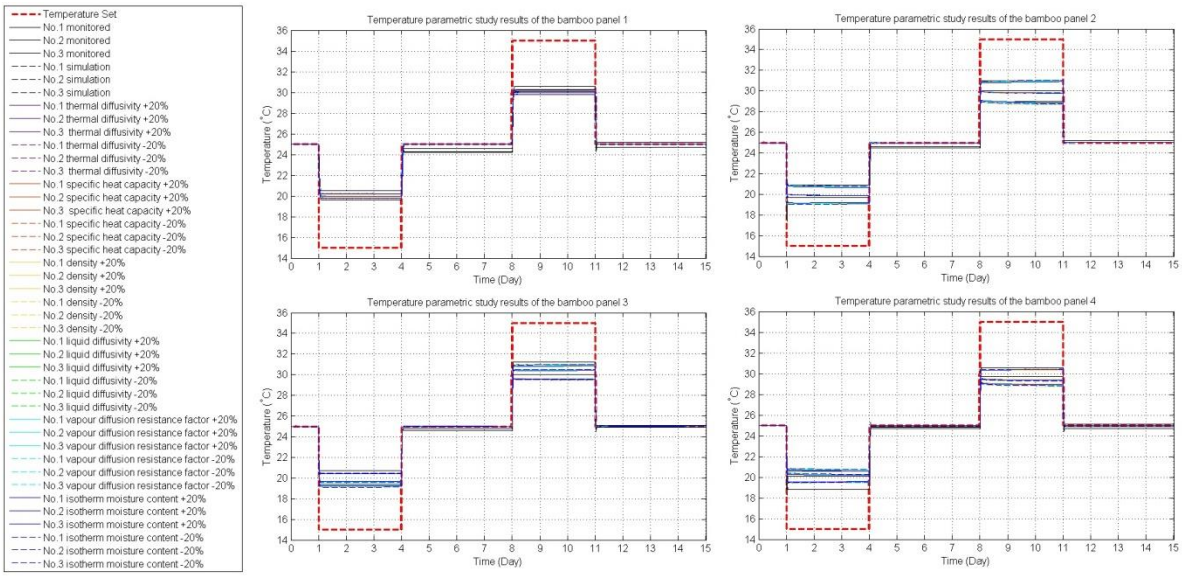

Fig 13. The parametric study results of temperature of four panels

Fig. 14 illustrated the transient temperature change of four panels within 8 hours from the temperature change time point to the time of approaching the equilibrium stage. Although, the adjustments of each parameter demonstrate little changes in the simulation results, the influence of density can be seen. The temperature variation caused by density adjustments are illustrated by the yellow solid line and yellow dash lines. These two lines deviate the most from the original simulation results. Therefore, density can be regarded as the most sensible parameter to influence the temperature simulation results. The results of panel 1 indicated that higher density input can lead to simulation results closer to the experiment results. This trend is not obvious for the other panels.

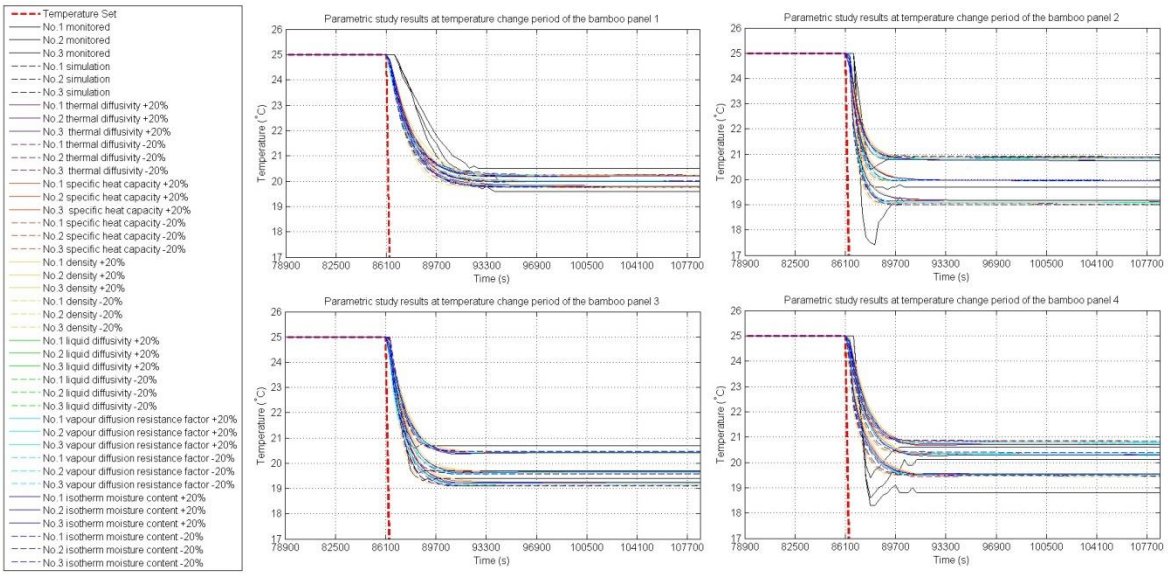

Fig 14. Parametric study results at a temperature change period

To further examine the influence of density, a second parametric study was conducted. The results are shown in Fig. 15. The input density values were set to increase by 50% and 100% respectively. The results indicated that the simulation results at the transient stage are closer to the experimental results by increasing 100% density value for panel 1. However, for other panels, the original simulation results are more accurate. At the equilibrium stage, the original simulation results are closer to the experiment results.

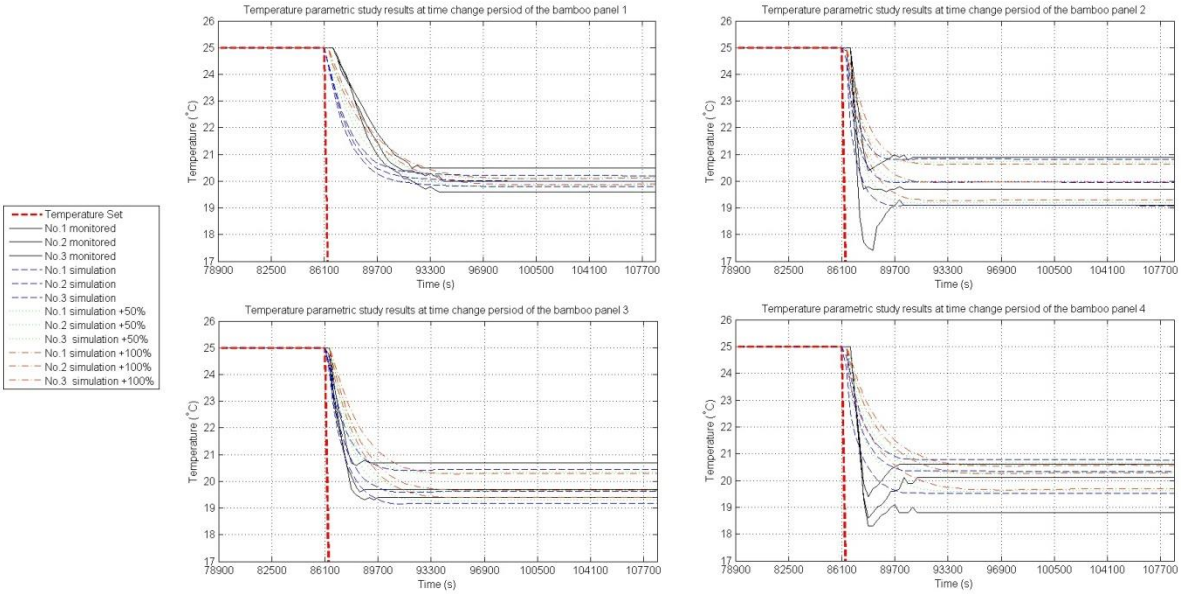

Fig 15. Parametric study results of enlarged density values at a temperature change period

The RH results of the parametric study are shown in Fig. 16. The results indicated that variation by 20% of both vapour diffusion resistance and cause relatively higher influence than other parameters. The 120% lines of these two parameters are closer to the experiment results at No.1 monitor point. Two solid lines are highly overlapped.

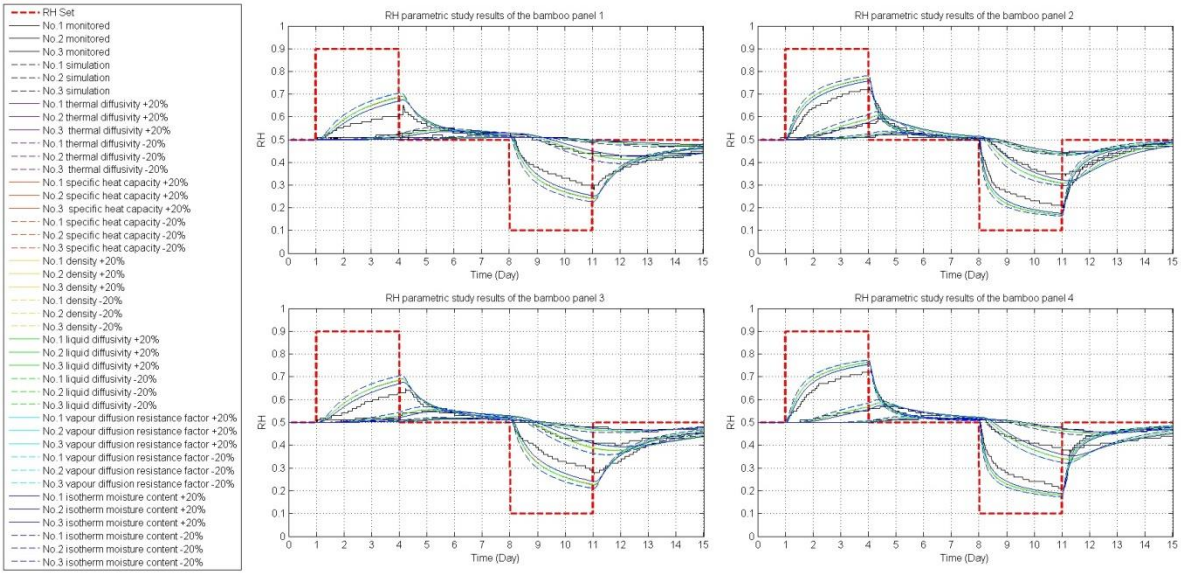

Fig 16. The parametric study results of RH of four panels

The influence of the isotherm moisture content and water vapour diffusion resistance factor μ were considered in a further parametric study. The original values of the parametric study were set to increase by 50% and 100% for a new simulation. The results are shown in Figs 17 and 18.

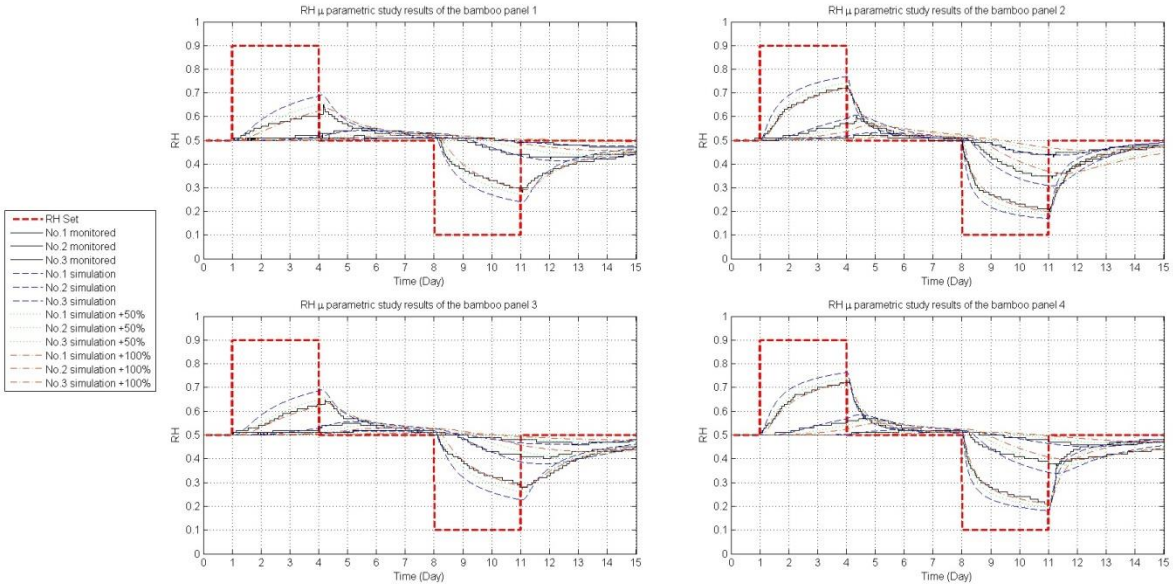

Fig 17. The parametric study results for the RH generated by increasing the μ

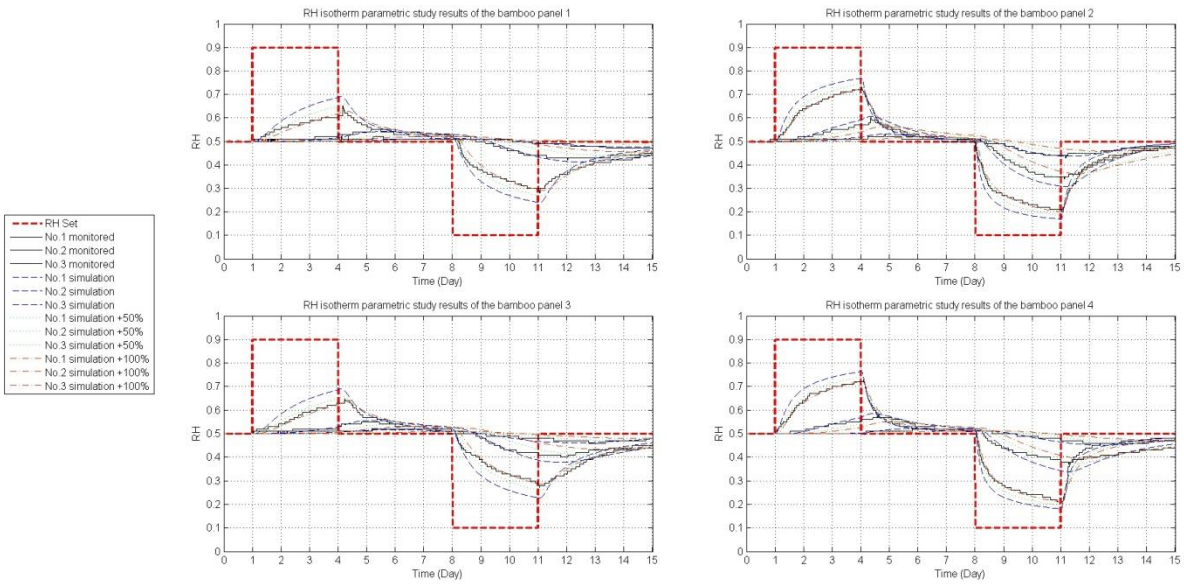

Fig 18. The parametric study results for the RH generated by increasing the moisture content of isotherm

The results indicated that better fitting can be found at the No.1 position of all panels after the parametric adjustment. However, the original simulation results of No.2 and No.3 demonstrated better fitting trend than results of parametric study. Therefore, the parametric study can further focus on the individual adjustment for each layer.

The further parametric study firstly increase water vapour diffusion resistance factor of the No.1 position for all panels. The effect is obvious on results of the No.1 position. However, concomitant values increasing can also be found at No.2 and No.3 positions. To neutralise the undesired increasing values from these two positions, the water vapour diffusion resistance factors of the No.2 position were set to decrease by a trial range. Another method was to increase the water vapour diffusion resistance factors of both No.1 and No.2 positions. This method is not as sensitive as the initial method. After a

number of trials, an acceptable adjustment scheme was utilised on the individual adjustment for each layer. See table 3.

Table 3. The adjustment of water vapour diffusion resistance factors for individual layer

	No.1	No.2	No.3
Panel 1	+50%	-50%	0%
Panel 2	+50%	-20%	0%
Panel 3	+50%	-20%	0%
Panel 4	+50%	-20%	0%

The results are shown by Fig 19. The adjustment of water vapour diffusion resistance factors can lead to a relatively closer simulation results, better than the original simulation results.

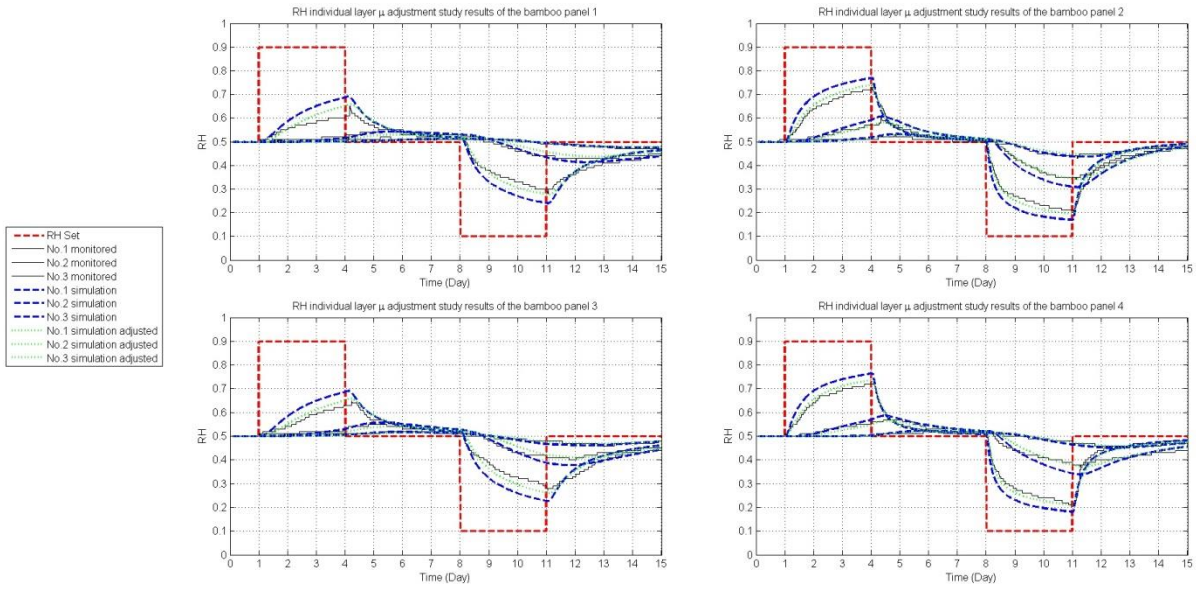

Fig 19. The RH results of individual layer μ adjustment

The same scheme in table 3 was utilised for isotherm moisture content adjustment, the results of the isotherm adjustment are compared with the results of μ adjustment in Fig 20. The comparison indicated that results of μ adjustment are closer to the experimental results. That means, in this scheme, the water vapour diffusion resistance factor can be regarded as a more sensitive factor than the isotherm. Isotherm adjustment may need further variation to approach the same results.

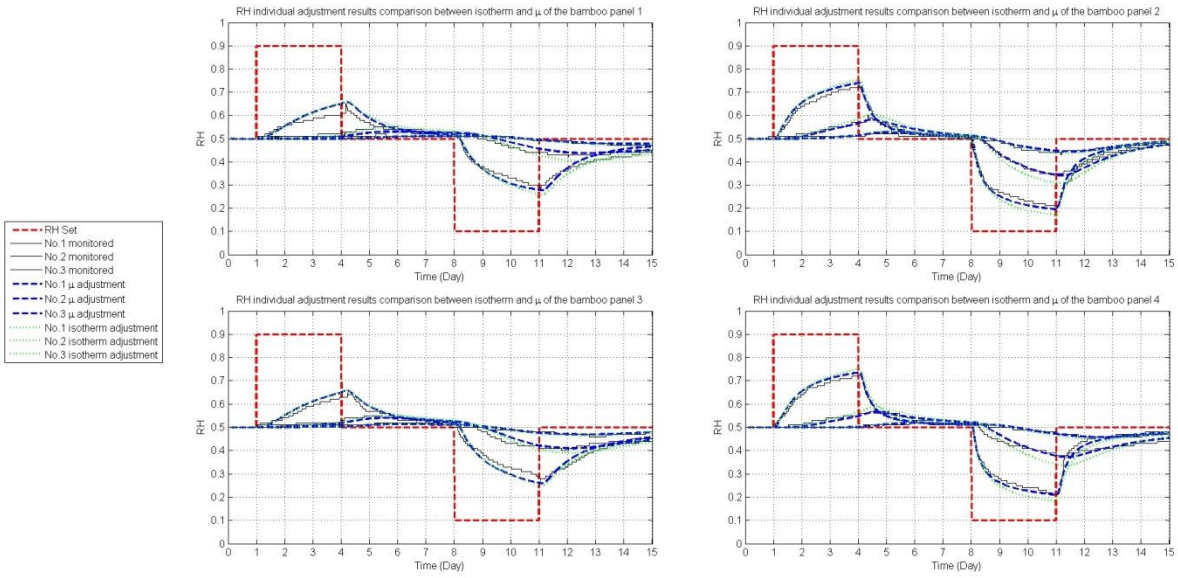

Fig 20. The RH results of individual layer μ adjustment and isotherm adjustment

The liquid water diffusivity was estimated by a method which was presented in the research of Zillig (2006). In this study, the impact of the existence of liquid water diffusivity in the simulation results was evaluated. Fig 21 showed that the RH difference between the simulation results with liquid water diffusivity and the simulation results without liquid water diffusivity may be ignored. The highest difference between the results with liquid water diffusivity and the results without liquid water diffusivity is 0.2% at panel 3. Therefore, simply ignoring the liquid water diffusivity value is acceptable in this study.

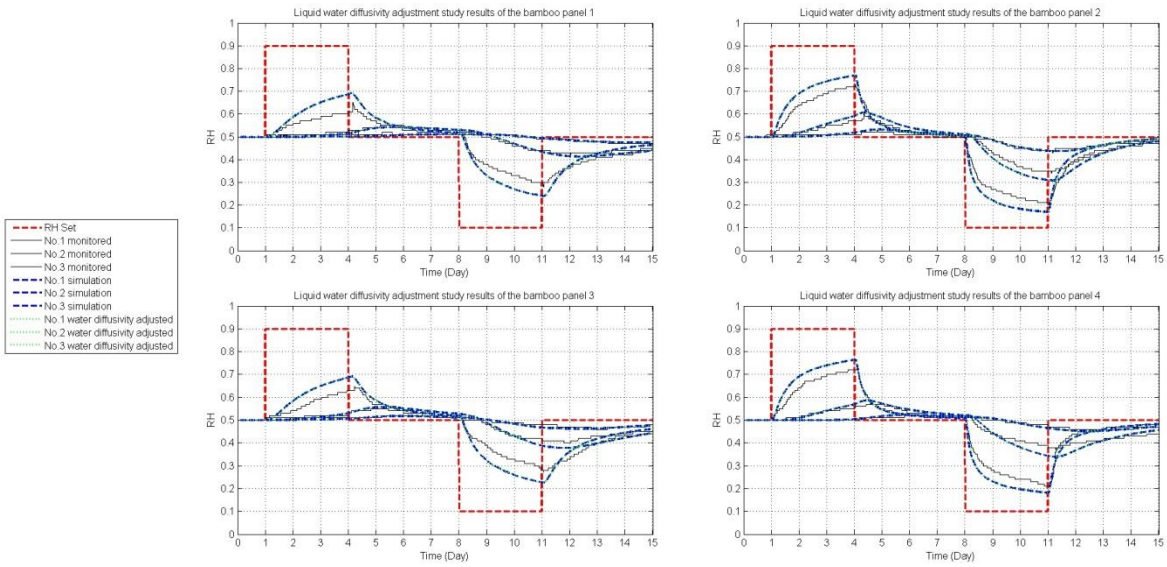

Fig 21 The liquid water diffusivity adjustment result

An extreme case, which could be shown in the parametric study, is the influence of moisture on the temperature results. Fig 22 compares the results among the experiments, the initial simulation, and a simulation without involving any moisture. The results indicated that the simulation with moisture is more accurate than the simulation without moisture in both the equilibrium and transient states. The

results also imply that the existence of moisture could increase the heat capacity and reduce the thermal conductivity. The slower response at the transient state is obvious at panel 1 and narrower temperature distribution can be found at panel 2.

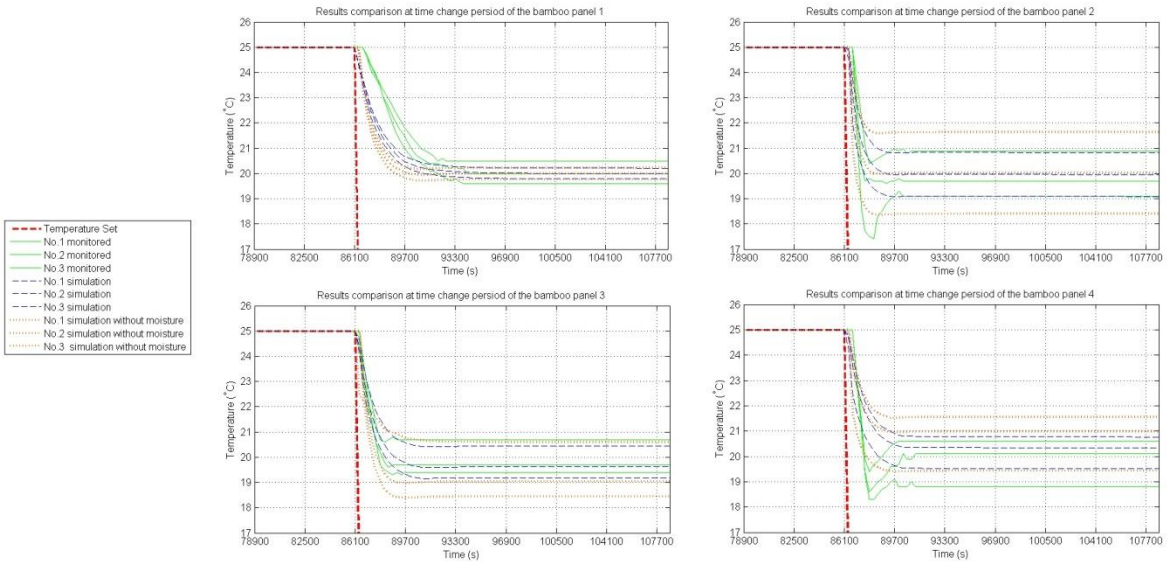

Fig 22. The simulation results with and without moisture content

4.2 Discussion

The parametric study found that density can be regarded as the most critical parameters to influence the temperature simulation results at the transient state. The thermal conductivity dominates the temperature variation at the steady state. The water vapour diffusion resistance factor can be regarded as the most sensitive parameter to influence the RH simulation results. The liquid water diffusion is negligible in the conditions of this study. The parametric study results indicated that the simulation with moisture is more accurate than the simulation without moisture in both equilibrium and transient states. The results also imply that the existence of moisture could increase the heat capacity and reduce the thermal conductivity. The aforementioned assumptions are acceptable in this study.

In addition, temperature results for all panels show a rebound trend after the lowest temperature point. See Figs 14, 15 and 21. The rebound trend is more obvious for panel 2 and panel 4 than for panel 1 and panel 3. The condensation of water can be regarded as a reason for this rebound trend. Low temperature may cause water condensation which can release heat. Panel 2 and panel 4 have a low density layer opposite to the left climate chamber. This layer also demonstrates high vapour permeability and low moisture capacity. A higher content of water vapour can be passed but cannot be stored in this layer. Therefore, the extent of temperature rebound trend is higher at panel 2 and panel 4 than at panel 1 and panel 3.

It should be noticed that the field experiment cannot be replaced by the modelling study. The modelling study was utilised to predict the temperature and RH results. The boundary condition and initial condition are expressed by theoretical values. In real field experiments, these conditions are not the same as the theoretical values. In addition, a modelling study can only predict part of the real phenomenon. The temperature rebound phenomenon is a response which is not predicted by the modelling study. Furthermore, a highly corresponding result from the parametric scheme in this study is just one possible simulation of the real situation. In field experiments, the hygrothermal response may be caused by the effects of multiple factors.

5. Conclusions

This study focuses on the heat and moisture transfer behaviour in *Phyllostachys edulis* (Moso bamboo) panels at various temperature and relative humidity conditions.

Experiments results indicate that panel 2 which was made from internal bamboo strips possessed the best thermal insulation properties of the four panels. Panel 1 which was made from external bamboo strips had the worst thermal insulation properties. The temperature of middle layer of panel 3 is closed to the external side. The temperature of middle layer of panel 4 is close to the internal side. The most significant RH variation is within internal bamboo strips while the minimum RH variation of bamboo layers is within external bamboo strips. Panel 3 showed a similar trend to panel 1 in terms of RH variation of the bamboo layers. Panel 4 showed a similar trend to panel 2 in terms of RH variation of the bamboo layers. The external side of the bamboo culm wall can effectively mitigate variations in the outdoor RH.

Simulations results indicated that the temperature prediction is relatively accurate. The RH prediction is very compliant with the experiment results at the middle and internal layers of the bamboo panels. The accuracy of the simulation for the external layer can be further improved.

Both experimental and simulation results appear to be consistent with the results of measurements of the basic hygro-thermal parameters. The results indicate that although the layer of panel made by the internal part of the bamboo culm wall can provide good insulation performance, its ability to resist the high RH variation is inferior to the layer from the external part of bamboo culm wall. The difference in the RH between predicted simulation results and monitored results from experiment measurements is higher than the difference in the temperature results.

A parametric study found that density can be regarded as the most sensitive parameter to influence the temperature simulation results at the transient state. The thermal conductivity dominates the temperature variation at the steady state. The water vapour diffusion resistance factor can be regarded as the most sensitive parameter to influence the RH simulation results. Liquid water diffusion is negligible in the conditions of this study. The parametric study results indicated that the simulation with moisture is more accurate than the simulation without moisture in both equilibrium and transient states. The results also imply that the existence of moisture could increase the heat capacity and reduce the thermal conductivity. The aforementioned assumptions are acceptable in this study.

The results of this study recommend that the external part of the bamboo culm wall can be utilised to minimise the RH variation of the panel while the internal part of bamboo culm wall is suitable for increasing the thermal insulation performance of the panel. Therefore, a form of high hygrothermal performance bamboo panel can be made from a thin layer of the external part of the bamboo culm wall and thick layers of the internal part of bamboo culm wall.

The newly designed high hygrothermal performance bamboo panel will minimise mould and damp risks for bamboo constructions in humid climate regions and eliminate potential health issues associated with the living environment. The methodology of this study is also applicable to other types of timber building envelopes for which there has been a significant growing demand in the past decade due to the low carbon agenda.

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References

BS EN 12086: 2013. Thermal insulating products for building applications-Determination of water. vapour transmission properties, BSI.

BS EN 15026: 2007. Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation. BSI.

Delgado, J., Barreira, E., Ramos, N. M. and De Freitas, V. P. 2012. *Hygrothermal numerical simulation tools applied to building physics*, Springer Science & Business Media.

Flander K.D, Rovers, R. (2009) One laminated bamboo-frame house per hectare per year. Construction and Building Materials 23(1), pp.210-218.

Fourier, J. B. J. 1878. *The analytical theory of heat*, The University Press.

Huang, P., Chang, WS., Shea, A., Ansell, M. and Lawrence, M. 2014. Non-homogeneous Thermal Properties of Bamboo. In: Aicher, s., Reinhardt, H. W. and Garrecht, H. (eds.) *Materials and Joints in Timber Structures*. Springer Netherlands.

Huang, P., Chang, WS., Ansell, M. P., Chew, Y. M. J. and Shea, A. 2015. Density distribution profile for internodes and nodes of Phyllostachys edulis (Moso bamboo) by computer tomography scanning. *Construction and Building Materials,* 93, pp.197-204.

Huang, P., Zeidler, A., Chang, W.-S., Ansell, M. P., Chew, Y. M. J. and Shea, A. 2016. Specific heat capacity measurement of Phyllostachys edulis (Moso bamboo) by differential scanning calorimetry. *Construction and Building Materials*, 125, pp.821-831.

Huang, P, Simon, GP., Chang, WS., Ansell, M. P., Chew, Y. M. J. and Shea, A. 2017. Thermal diffusivity measurement of Phyllostachys edulis (Moso bamboo) by the flash method. *Holzforschung*. 71(4), pp.349-354.

Kunzel, H. M. and Kiessl, K. 1996. Calculation of heat and moisture transfer in exposed building components. *International Journal of Heat and Mass Transfer,* 40 (1)**,** pp.159-167.

Latif, E., Ciupala, M. A., Tucker, S., Wijeyesekera, D. C. and Newport, D., 2015. Hygrothermal performance of wood-hemp insulation in timber frame wall panels with and without a vapour barrier. *Building and Environment*, 92, pp. 122-134.

Li, N.-P., Long, J.-B., Su, L., Wang, L. and Zhong, S. 2012. Experimental and theoretical study on thermal and moisture characteristics of new-type bamboo structure wall. *Journal of Central South University,* 19, pp.600-608.

Luikov, A. 1966. *Heat and mass transfer in capillary-porous bodies*. 1st ed. London: Pergamon press.

Majumdar, A., Mukhopadhyay, S. and Yadav, R. 2010. Thermal properties of knitted fabrics made from cotton and regenerated bamboo cellulosic fibres. *International Journal of Thermal Sciences,* 49 (10), pp.2042-2048.

Nusser, B. and Teibinger, M. Year. Coupled Heat and Moisture Transfer in Building Components-Implementing WUFI Approaches in COMSOL Multiphysics. *In:* Proceedings of the COMSOL Users Conference 2012 Milan, 2012.

Plumb, O. A., Spolek, G. A. and Olmstead, B. A. 1985. Heat and mass transfer in wood during drying. *International Journal of Heat and Mass Transfer,* 28 (9)**,** pp.1669-1678.

Portal, N. W., Van Schijndel, A. W. M. and Kalagasidis, A. S. 2014. The multiphysics modeling of heat and moisture induced stress and strain of historic building materials and artefacts. *Building Simulation,* 7 (3)**,** pp.217-227.

Portal, N. W., 2011. Evaluation of heat and moisture induced stress and strain of historic building materials and artefacts. Thesis (M.Sc.). Chalmers university of technology, Göteborg.

Time, B. 1998. Hygroscopic moisture, transport in wood, Norwegian University of Science and Technology.

Van Der Lugt, P., Van Den Dobbelsteen, A. a. J. F. and Janssen, J. J. A. 2006. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. *Construction and Building Materials,* 20 (9)**,** pp.648-656.

Younsi, R., Kocaefe, D. and Kocaefe, Y. 2006. Three-dimensional simulation of heat and moisture transfer in wood. *Applied Thermal Engineering,* 26 (11–12)**,** pp.1274-1285.

Zillig, W., Janssen, H., Carmeliet, J. and Derome, D. 2006. Liquid water transport in wood: towards a mesoscopic approach. *Research in Building Physics and Building Engineering*. London: Taylor and Francis Group.