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IN-DEPTH TEMPERATURE MEASUREMENTS OF TIMBER IN FIRES

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ABSTRACT

Modern construction relies more and more on metallic connectors. Their failure during fires is related to the glass transition of the lignin matrix at around 100°C. Based on this information, a series of tests were carried out exposing a wood specimen to various heat fluxes in a Cone Calorimeter. The aim of this research is to develop a sound temperature measurement methodology in wood samples exposed to high heat fluxes and to build a data-base in order to evaluate different wood pyrolysis models. The experiments yielded highly repeatable results that are seldom achieved with wood.

1. INTRODUCTION

Fire resistance of timber has been the subject of numerous studies and a number of guidelines have been proposed for the design of wooden structures on the basis of their resistance to fire^{[1][2]}. The effect of fire on timber is separated in two distinctive processes, the loss of section due to burning and charring and the loss of strength of the un-charred section. This paper deals with the latter phenomenon, which has become an important issue in modern timber building design.

The physical properties of each of the polymers that make up wood evolve with temperature, being lignin the one that shows the most significant mechanical property changes at the lowest temperatures. Lignin is an amorphous polymer that cements the cells together, thus providing resistance to compression and shear^{[3][4]}. Lignin attains its glass transition at temperatures as low as 60°C when saturated with water^[5], leading to a loss of binding strength between the fibres. The attainment of the glass transition has important effects on the modulus of elasticity and on thus on the mechanical behaviour of wood^{[5][6]}. Previous research^{[6][7]} has shown that lignin experiences a significant loss of its mechanical strength around 100°C. Despite the uncertainty of the glass transition temperatures, it is clear

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that they are lower than the temperatures affecting other processes linked to strength reduction, like charring, which occurs on the vicinity of 300°C^[8]. Another important characteristic of the process of lignin vitrification is that the heat required for this endothermic process is low compared to the latent heat of evaporation of water; Irvine reports changes in the specific heat of lignin of around 0.3 – 0.36 J/g·K during the process. This transition is therefore relatively weak, and can be blurred by any loss of moisture^[5].

Metallic connectors have a widespread use in modern timber construction. Their presence leads to an increase in the impact of the role of shear stress in the failure of timber structures during fires. Failure by shear stress is generally not related to fibre strength or loss of cross section, but mostly to the failure of the lignin matrix^[4]. Thus, the performance of metallic connectors will be affected by property changes of this nature.

When a timber element is exposed to the heat-flux from a fire, it gradually heats up creating a temperature gradient within the wood. The in-depth propagation of the heat by conduction ultimately dictates the failure mode of the element. Thus, the analysis of the timber failure in fires requires a proper prediction of the transient in-depth temperature distributions.

Numerous models and experiments have been carried out in the past to understand and predict the behaviour of wood subjected to high heat fluxes^{[9][10][11]}, but they have been mainly centred on addressing the problems of its ignition and pyrolysis. Low temperature loss of strength has been considered only as a correction^{[2][12]}. In-depth temperature measurements on wood have been carried out, exposing samples to constant heat fluxes or to furnace tests^{[4][11][13][14][15][16][17][18][19][20]}. The former have been used mainly to validate mathematical models, while the latter have been largely employed to generate equations that predict temperature as a function of depth.

The limitations of standard furnace testing are described by Drysdale^[21], and include furnace-dependent results and variable imposed heat fluxes which are difficult to quantify. The temperature-depth equations^{[12][16][18]} also have some weaknesses, like the fact that some of them only account for the non-charred part of the wood, use fixed charring rates or are independent of the imposed heat flux (they assume a standard furnace exposure): Nevertheless, they are valid and useful tools and were applied as a background for the development of design methods in Eurocode 5^{[16][18]}:

$$T(x) = T_i + (T_p - T_i) \cdot \left(1 - \frac{x}{a}\right)^2 \quad (1)$$

where

T = wood temperature [°C]

T_i = initial wood temperature [°C]

T_p = char front temperature, generally assumed to be 300°C

x = depth measured from the char front [mm]

a = thermal penetration depth, usually taken as 40 mm

The use of a standard furnace represents a significant limitation to the definition of these in-depth temperature profiles. The main reason is that the imposed heat flux does not only vary with time but is also difficult to define because it will be the result of the overall thermal conductivity of the sample. Therefore, generalization of these in-depth temperature distributions to realistic fires to assess performance under fire might induce errors that have yet to be quantified.

This paper reports on a series of measurements of in-depth temperatures on wood specimens subjected to constant heat fluxes. The use of constant heat fluxes provides a thermal boundary condition on the samples that can be quantified with greater precision, thus

facilitating the validation of analytical and numerical models. The aim of this research is to develop a methodology for reliable measurement of temperature distributions in wood samples exposed to fire-like heat fluxes and to build a sound data-base of temperature measurements in order to evaluate different models that predict the evolution of these temperature profiles. Surprisingly, these measurements cannot be found in the literature.

2. EXPERIMENTAL PROCEDURE

A series of tests were carried out in a Cone Calorimeter exposing a wood specimen to heat fluxes between 10 and 60 kW/m². The experiments carried out were performed in two stages. The initial stage consisted of measuring the temperature profiles of wood samples exposed to various heat fluxes, while during the next step mass loss measurements were done using the same heat fluxes as in the previous phase. This was done to avoid interference of the thermocouples in the mass loss rate measurements. However, this report only presents the results of the first stage of the research.

The specimen was tested in a vertical configuration (i.e. the exposed face is in a vertical position), with no piloted ignition source. The type of wood used during the experiments was Redwood Pine (*Pinus sylvestris*). The sample dimensions were ~100 x 97 x 67 mm. The selected heat fluxes were 10, 18, 25, 40 and 60 kW/m². These heat fluxes represent a wide set of exposures that is unusual for structural type analyses, nevertheless given the low temperature of the lignin glass transition it was deemed necessary to study exposures typical of the early stages of fire growth.

In each experiment, five thermocouples were placed in 2 mm diameter holes drilled perpendicular to the exposed surface, from the back (unexposed) side of the specimen. One hole was drilled on the centre of the sample face, while the remaining four holes were drilled on a 20 mm radius circle around the first hole. The thermocouple junctions were placed at depths of 5, 10, 15, 20, 25, 30, 35 and 40 mm from the exposed surface. The thermocouples utilised were N-type with fibreglass insulation. The fibreglass insulation allows the thermocouple to reach temperatures as high as 540°C without sustaining considerable damage. The tip of the thermocouples was cut off after each test and a new junction was welded in order to ensure the total integrity of the device.

An aluminium block (31 mm thick) was attached to the back of the sample as a means of providing a well defined back-end boundary condition. For all tests an extra thermocouple was fitted at the interface between the sample and the aluminium block to track the evolution of its temperature. Measurements showed that the aluminium block had a constant temperature along its depth. Each experimental condition (i.e. heat flux and thermocouple depth) was repeated three times, with a total of 120 tests carried out.

The specimens were acquired kiln dried, and they were kept in a room where the maximum and minimum temperature and relative humidity were recorded each day for about a month before the experiments commenced. It was found that the temperature and humidity variations were not significant, with less than 10°C difference between the highest and lowest recorded temperatures in 82 days, and a variation in the moisture content of air always lower than 35% RH in the same period. The average moisture content of the samples was of about 11%. Prior to each experiment, the specimen was weighed and its dimensions measured.

During the first series of tests only the temperatures were recorded, with no mass loss measurements or gas analysis performed. Measurement of the ambient temperature in the Cone Calorimeter was also carried out. A few tests with mass loss and temperature measurements were conducted to demonstrate consistency. Mass loss measurements were discarded for those experiments.

The duration of the tests was determined by the temperature of the back of the sample. The experiments would continue until the heat losses at the back of the specimen were significant (i.e. greater than 10%) compared to the incoming heat flux from the Cone Calorimeter.

3. EXPERIMENTAL RESULTS

The experiments yielded highly repeatable results that are seldom achieved with wood. The results were averaged for each thermocouple depth and heat flux. In most of these averaged results, a plateau is unmistakably identified in the vicinity of 100°C, clearly showing the effect of the evaporation of the moisture contained within the wood. No plateau is observed that can be attributed to the glass transition of lignin.

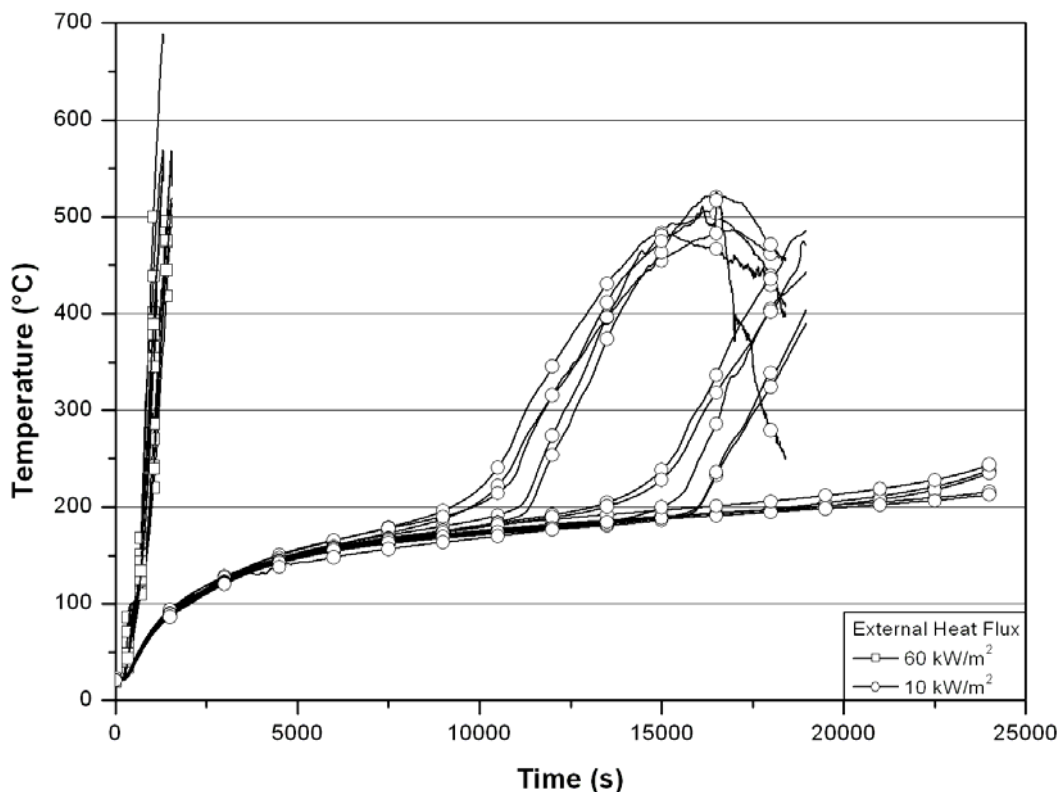


Fig. 1 – Raw thermocouple readings for two different heat fluxes, 10 and 60 kW/m² at a depth of 15 mm.

A weaker repeatability was found in the lower heat fluxes, with some tests showing faster heating rates than others. Figure 1 shows all the thermocouple readings taken at a depth of 15 mm from the exposed surface for imposed heat fluxes of 10 and 60 kW/m². While all the measurements for the 60 kW/m² case follow a general trend, the three repetitions done at 10 kW/m² show different heating patterns. The samples reached 200°C all at different times, with a difference of about 10,000 seconds between the extreme cases.

A sample of the averaged results is presented in Figure 2. As it can be seen, Figure 2 shows the average temperature histories for 8 thermocouples. All thermocouples show the presence of a plateau at approximately 100°C. This plateau becomes less obvious for deeper thermocouples. Temperatures have all been truncated at the point where the regression front

reached the thermocouple. This point is generally characterized by very unstable measurements obtained from the thermocouple. The data obtained beyond this point was deemed to be unusable.

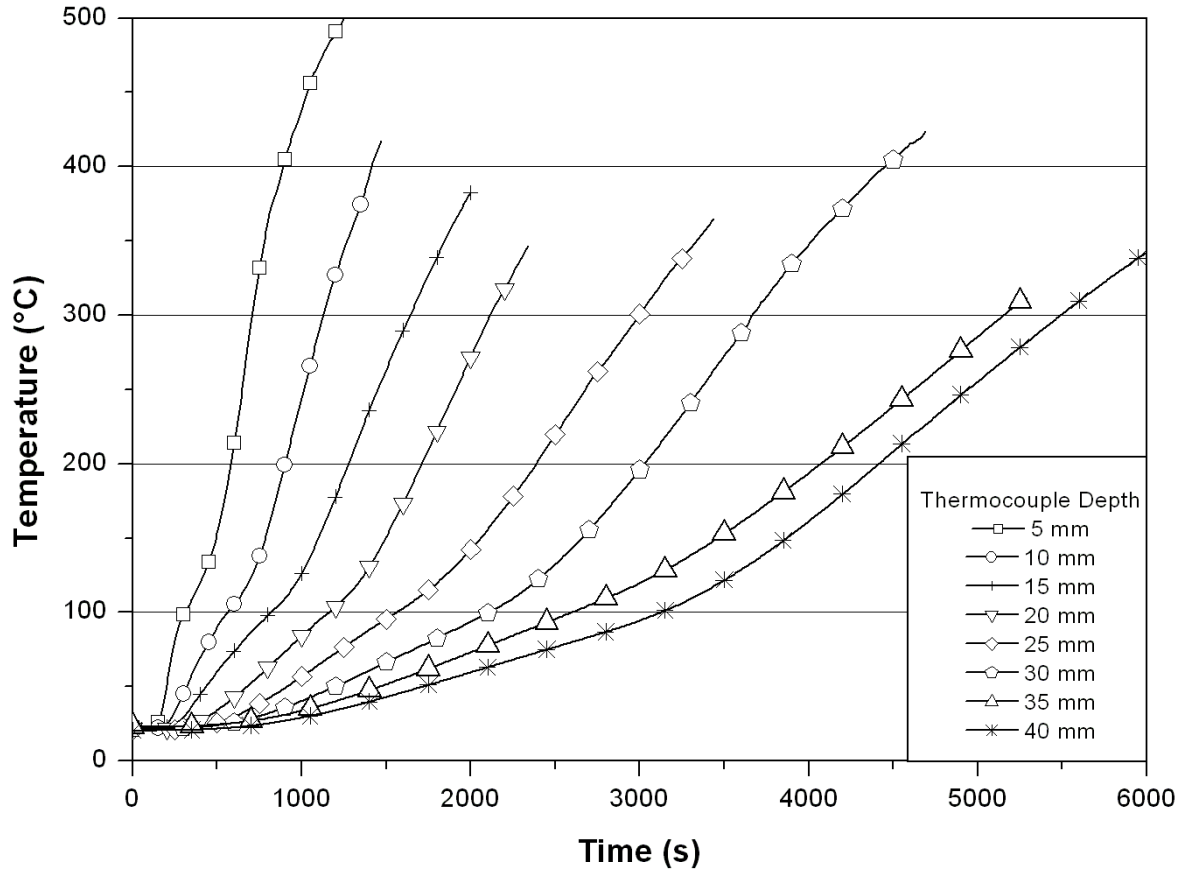


Fig. 2 – Average temperature readings for an imposed heat flux of 25 kW/m² for various thermocouple depths.

4. SIMPLIFIED HEAT TRANSFER MODEL

A semi-infinite heat transfer model that treats the material as an inert solid was used to establish characteristic values for the different parameters of the problem^[22]. These characteristic values were used to non-dimensionalize time, depth and temperatures. This analysis was done as a baseline exercise to establish departures from an inert heating solution. The non-dimensional variables are the following:

$$t^* = \frac{t}{t_C} \quad (2)$$

$$x^* = \frac{x}{x_C} \quad (3)$$

$$\theta^* = \frac{T - T_\infty}{T_C - T_\infty} \quad (4)$$

The characteristic variables are showed below:

$$T_C = \frac{a\dot{q}_e''}{h_{TOT}} \quad (5)$$

$$x_C = \frac{k}{h_{TOT}} \quad (6)$$

$$t_C = \frac{k \cdot \rho \cdot c}{h_{TOT}^2} \quad (7)$$

where

t = time [s]

x = depth from exposed surface [m]

T = wood temperature [°C]

T_∞ = initial wood temperature [20°C]

a = wood absorptivity [0.88]

\dot{q}_e'' = external (imposed) heat flux [W/m²]

h_{TOT} = total heat transfer coefficient (convection and radiation) [35 W/m²·K]

k = thermal conductivity of wood [0.105 W/m·K]

ρ = wood density [524.21 kg/m³]

c = wood specific heat [2200 J/kg·K]

The temperature distribution for the heating of an inert solid with constant heat flux is given by the following expression:

$$\theta(x,t) = T_C \cdot \left[\operatorname{erfc}\left(\frac{n}{\sqrt{4t}}\right) - e^{(mn+m^2t)} \cdot \operatorname{erfc}\left(m\sqrt{t} + \frac{n}{\sqrt{4t}}\right) \right] \quad (8)$$

with

$$\theta = T - T_\infty \quad (9)$$

$$n = \frac{x}{\sqrt{\alpha}} \quad (10)$$

$$m = \frac{h_{TOT}}{\sqrt{k \cdot \rho \cdot c}} \quad (11)$$

$$\alpha = \frac{k}{\rho \cdot c} \quad (12)$$

5. ANALYSIS OF RESULTS

Figure 3 represents the non-dimensional temperature distribution for thermocouples placed at 5 mm from the surface for heat fluxes of 10, 25 and 60 kW/m². Also included is the inert heating temperature history per equation (8). This corresponds to the inert heating case, and a comparison of this curve with the other temperature profiles establishes how much they depart from this behaviour. It can be stated that the initial behaviour of wood is inert. The samples subjected to higher heat fluxes depart in the first place from the non-burning behaviour (for the 60 kW/m² case, this occurs at a non-dimensional time of around 2.0; for 25 kW/m² this happens at around 2.6). This departure is originated by the commencement of the evaporation of the moisture contained in the wood, which due to its endothermic nature, slows down the heating. Since the samples subjected to lower heat fluxes have been heated for a “longer” non-dimensional time without any fall in the intensity of the heat flux, their non-dimensional temperatures continue to rise above the temperatures of the samples in which the loss of water has already started. The higher heat fluxes later catch-up with the other samples, because the heating rate of latter has already been hindered by the onset of the moisture evaporation. Another retard in the heating rate occurs when the samples reach the temperatures that mark the beginning of the process of pyrolysis (another endothermic reaction). This happens at a non-dimensional time of about 3.5 for 60 kW/m² and at around 6.0 for 25 kW/m². The fact that the non-dimensional temperature of the 60 kW/m² sample does not rise above that of the 25 kW/m² one is attributed to the non-dimensionalisation: the real temperatures are divided by $T_C - T_\infty$, and the terms in T_C are the same for all the heating scenarios, except for the value of the imposed heat flux.

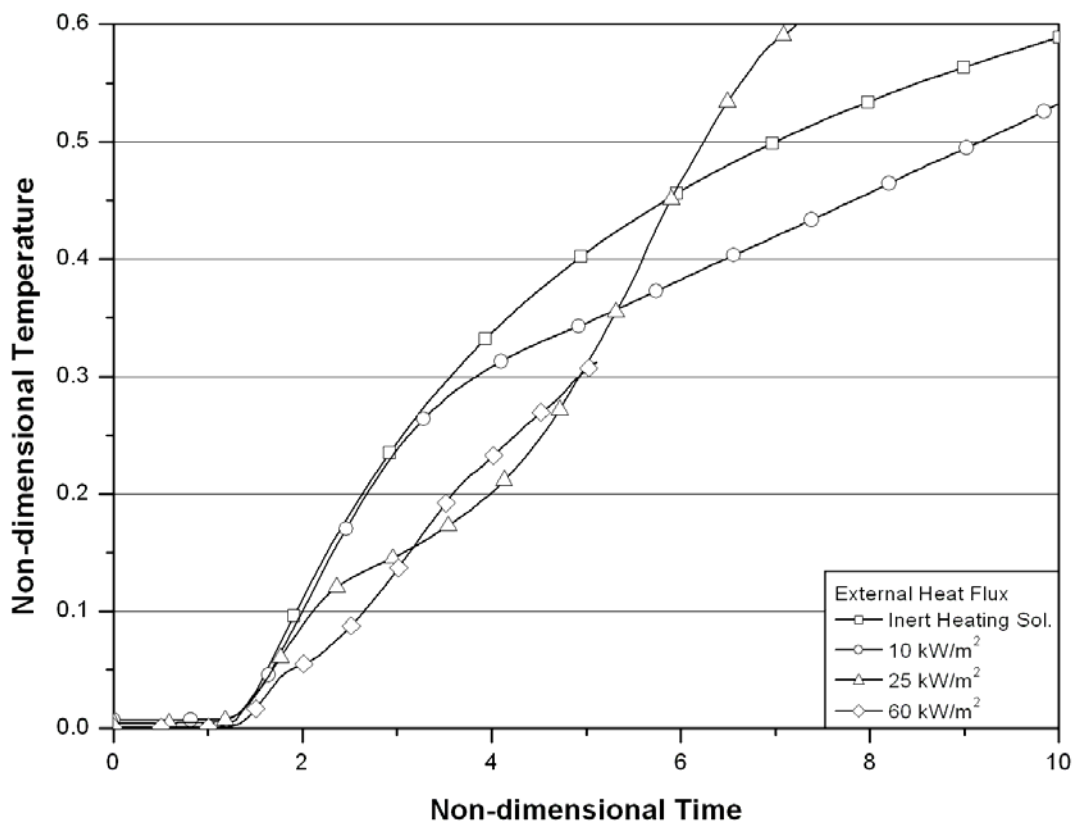


Fig. 3 – Non-dimensional temperature curves for various heat fluxes at a thermocouple depth of 5 mm.

It is interesting to note that for the heat fluxes below the accepted critical heat flux for ignition of wood (12 kW/m^2 [21]), the wood behaved very much like an inert material. No 100°C plateau was observed in those cases, probably due to the fact that the heating was slower than the migration of the moisture into deeper parts of the specimen. However, the curve does depart from the inert solution when this temperature is reached (occurring at a non-dimensional time of 5.00 for 10 kW/m^2 ; see Figure 3). This indicates the onset of endothermic reactions at approximately 10 kW/m^2 .

In the deeper regions, the heating rate is slower than at shallower regions. This is because the incoming heat flux to the deeper regions is attenuated by the diffusion of the heat through the solid. Figure 4 shows the non-dimensional temperature curves for a depth of 30 mm. A change in the gradient is observed for 60 and 25 kW/m^2 when the sample reaches a temperature of 100°C , at non-dimensional times of 12.6 and 18.6 respectively. For 10 kW/m^2 , this occurs at a time of 80.6, falling off the scale of the graph. The evaporation of the moisture is not associated with a temperature plateau in this case, but with a steep increase in the heating rate. The difference between the three different curves is reduced as the thermocouple depth increases. The 60 kW/m^2 curve quickly becomes the one with the highest non-dimensional temperature, due to the effect of the increased imposed heat flux caused by the burning of the sample. At a non-dimensional time of 18.9, the 60 kW/m^2 specimen reaches the pyrolysis temperature; this can be observed in the graph as a slight change in the gradient.

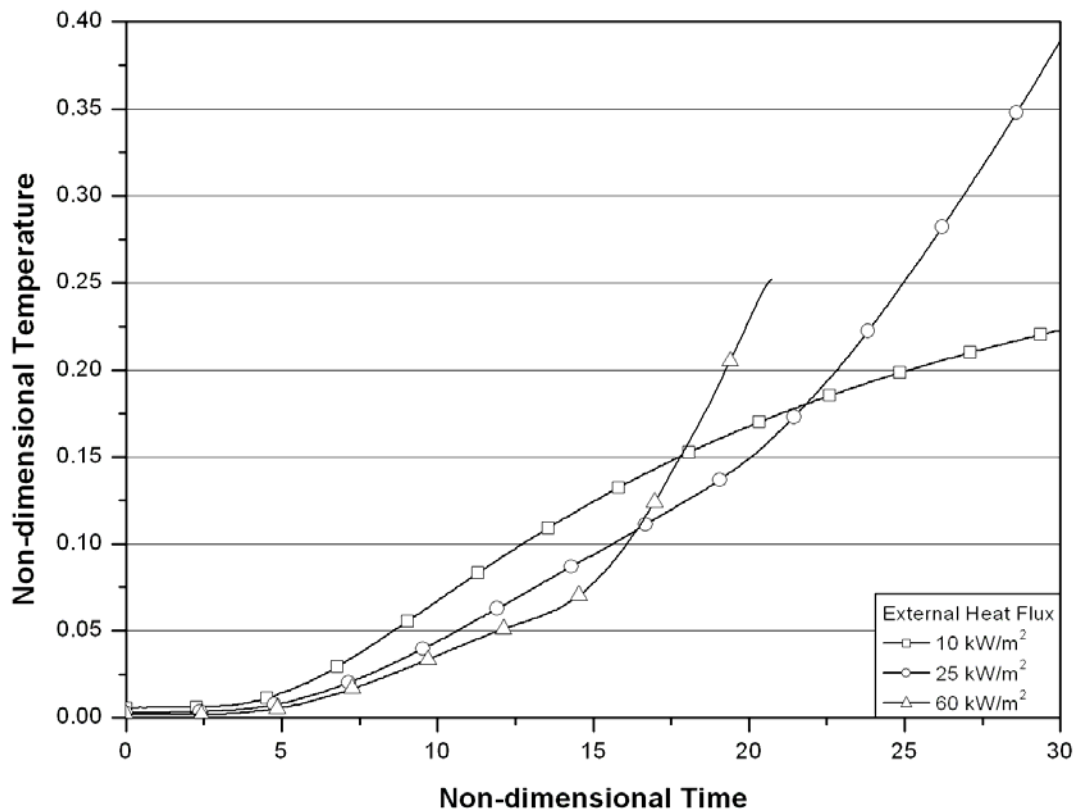


Fig. 4 – Non-dimensional temperature curves for various heat fluxes at a thermocouple depth of 30 mm.

6. CONCLUSIONS

Temperature measurements carried out in wood specimens subjected to various fixed heat fluxes yielded results that are highly repeatable, something seldom achieved with wood. A reliable methodology for measuring these temperatures was developed, and a considerable data-base of temperature profiles was built. The results show the effect of the evaporation of the moisture contained in the sample, but showed no clear consequence of the vitrification of lignin, confirming that this process does not require much heat input to take place. The start of the pyrolysis reactions is also marked by a change of gradient in the temperature-time curves. Weaker repeatability was observed for the lower heat fluxes.

An analysis was carried out to determine the departures in the behaviour of the samples exposed to different heat fluxes from that of an inert solid. This analysis established that wood behaves almost like an inert material when heated with low heat fluxes. The onset of the pyrolytic behaviour is at about 10 kW/m^2 . The differences between the curves of samples heated at different imposed heat fluxes diminish as the depth increases, but there is still a marked distinction between the lower and higher heat fluxes.

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