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CHARACTERIZATION OF WOOD SAMPLES THROUGH NUMERICAL SIMULATION BASED ON A TEST VALIDATION BENCH PROCEDURE

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Abstract *Nowadays, most of the energy consumption is satisfied through the burning of fossil fuels, which means a great depletion of natural resources with a significant environmental impact. The construction sector in Spain represents more than 30% of the total energy consumption, so building enclosures based on materials with low thermal transmittance are encouraged to be implemented, aiming to reduce energy losses. In this case, the use of wood as a construction material is increasing significantly, due mainly to its insulating properties and relative low environmental impact.*

The setting-up of an experimental prototype through a fully monitored thermal insulated box with a single opening gate, has been designed here to characterize the thermal behavior of specific wood samples, treated with different weather-protection agents. Through a series of tests, with several temperature jumps between the internal and external sides, the thermal performances of such samples were obtained. With all these data, the different hypothesis were properly modeled through the Design builder v 4© software, whose motor Energyplus© is currently fully accepted all over the world for the characterization of buildings.

Finally, taking into account that this material is a relevant part of the whole building enclosure, a further comparative analysis carried out through another numerical model, validated according to the current regulation in Spain (CTE-HE 2013) was finally addressed, whereas former experimental outcomes were used in both models for validation purposes.

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1. INTRODUCTION

Wood is a natural material widely used for a great variety of construction applications, not only due to its mechanical properties but also because of its easy-to-work properties. Wood market is growing up because is easy to transport, transform and install in construction works, but also it is a sustainable raw material. For all of those reasons, wood is becoming one of the most decisive materials for mitigating the greenhouse effect [1-3].
It is also known that it is an environmental friendly material, as it is ecological and renewable. In fact, in the construction field it is demonstrated that wood is a low carbon product, not only as a raw material but also in other elaborated wood products [4-6].
There is also a remarkable tendency towards a green building construction, considering wood as proper material [7]. Although its thermal conductivity is higher than other insulation materials, it presents more thermal resistance than other construction products, like bricks or concrete, used in structures, façades or interior walls. Because of that, it is very common to build wood houses aiming to promote both ecological products and energy savings.
When efficiency in construction is analysed, it is necessary to characterise the thermal resistance of materials in order to promote building energy savings. The R-value of wood has been tested in some works for analysing its thermal behaviour when it is directly exposed to external weather conditions [8, 9]. The thermal resistance value depends on the wood natural properties, specimen and density. The density is difficult to analyse as it is hygroscopic and its inner humidity is variable. Because of that, the regulation establishes the temperature and relative humidity test parameters in order to estimate a suitable value.
The Building Technical Code, based on Spanish normative, distinguishes between softwood and hardwood, but it does not specify specimen [10]. It also provides the wood conductivity value depending on its density, when this is balanced at 20ºC and 65% of relative humidity, including the hygroscopic water.
When wood is exposed to environment it is common to use treated pieces for increasing their life cycle. There are two types of deterioration promoters: biotic and abiotic agents. On the one hand, abiotic agents are those affecting to all material exposed to the environment such as, rain, wind and sun. Wood is a hygroscopic material so it absorbers humidity when it is raining. When this happens, wood swells but when the atmosphere becomes dryer, it retracts originate the cracks. On the other hand, the biotic agents, such as fungus and larval cycle insects eat the material and break down physical and mechanical properties.
Wood protection is not always necessary as depends on wood natural durability and its exposition degree to the exterior. For example, wood in façades or exterior flooring usually requires preservative products; however, depending on wood impregnability it is necessary to use some specific treatments. The impregnability is directly linked not only to the specie but also to the part of the tree it comes from, such as, heartwood or sapwood.
The heartwood is the oldest part of the log, where wood density is higher. Because of that, it presents fewer pores so its absorption is lower. The sapwood, in contrast, is the youngest part of the log so it presents higher absorption rates, which means, it is more impregnable [11]. However, the heartwood has more natural durability, so it has less dependency to protection

substances. In terms of mechanical resistance, the lower the density, the lower the strength, so the heartwood can be considered the strongest part.

It is also known that preservatives, in some cases, can reduce the wood strength, depending on the type of substance such as, CCA (Chromated Copper Arsenate), ACQ (Alkaline Copper Quaternary), Tanalith-E, Wolmanit CX-8 o CDDC (Copper Dimethyl-Ditho-Carbamate) [12]. These chemical products, which are used to protect and enhance the durability of exposed wood, alter its morphology and are responsible of the variation of its physical and mechanical characteristics [13].

Beside the more common chemical preservatives, such as the copper composed ones, there are others in study, based on TiO_2 (titanium dioxide) nanoparticles and clay nanoparticles, both with optimal results against ageing. This opens a clear path towards future implementation of nanomaterials in the wood preservatives field [14].

Another alternative to protect wood is the thermal treatment. That method consists of introducing the wood into an airtight chamber between 190 and 210ºC, depending both on the wood specie and the area it will be exposed, that is, its class use previously mentioned.

The effectiveness of this treatment derives from the extraction of the wood resin. In this way, wood is protected against biotic agents that feed on this substance. However, it is crucial to take into account the variation of physical wood properties, such as strength, hardness and superficial roughness, after treatment [15].

In the Basque country, the most common species are: Radiata pine (Pinus Radiata, D. Don.), Oregon pine (Pseudotsuga Menziesii, Mirbel), European oak (Quercus Robur, L.), Lawson cypress (Chamaecyparis Lawsoniana, A. Murray), and Larch tree (Larix Decidua, Mil.) where more than 70% of forests are property of the county Government, being the main production related to Radiata pine [16], so this specie has been chosen to be characterized with and without preservative substances.

2. MATERIALS AND METHODS

Three samples of Radiata pine were tested in order to evaluate and compare their thermal properties. All samples have been dried until reaching its density in balance at 20°C and 65% of humidity, according to normative requirements on construction products [17].

In order to analyse their thermal behaviour, a test box was built "ad-hoc". This box has insulated faces so the different samples can be placed inside through a small window, as can be seen in Figure 1. The first sample, whose density is 561.42 kg/m^3, has no protection. The second one, whose density is 517.51 kg/m^3, has a treatment based on Cu-HDO, being the chemical name: Bis-(N-cyclohexyldiazeniumdioxy)-copper, and bore. This product is free of chrome and arsenic [14, 18, 19]. The third sample is a thermal treated wood which is specific to outside wood whose density is 501.03 kg/m^3.

Sample slabs dimensions are: 10 cm wide, 30 cm long and 2 cm thickness, the same size as the window they were introduced.

In the interior of the box there is an electric resistance to heat the internal space. The temperature is regulated through a thermostat installed outside. Both interior and exterior temperatures are registered through a data acquisition system.

Figure 1. Detail of the initial construction (left) and final fully monitored test box (right)

The main percentage of heat released by the resistance goes out through the window, as the box thermal resistance is very high, 7.5 $m^2 \cdot °C/W$, as is shown in Figure 2.

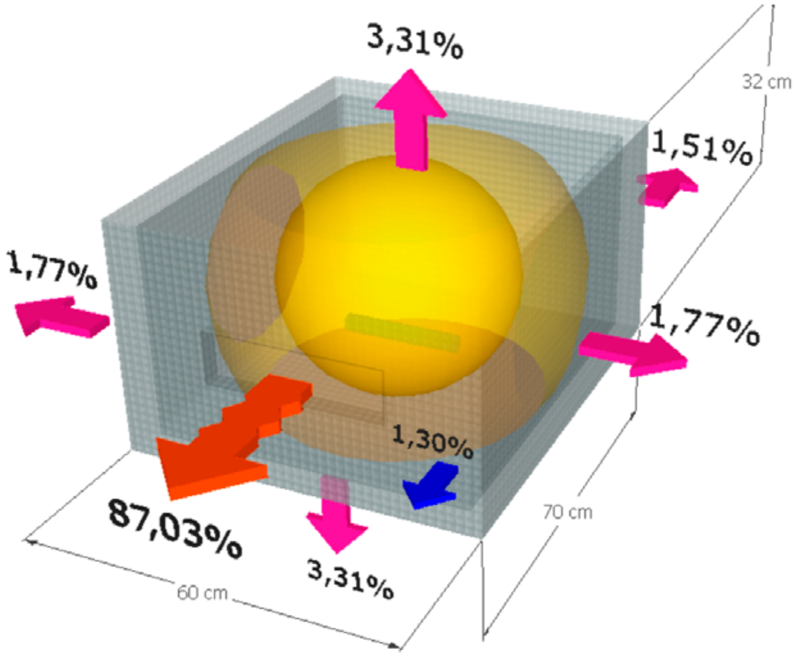


Figure 2. Heat losses estimation through the test box

After the temperature data of internal and external environment were registered, together with the superficial temperature of wood samples, the conductivity value is obtained. In order to define the boundary conditions, both interior and exterior convection coefficients are required. It is considered that natural convection of the air located close to hotter surface exists when in this surface the flux movement is generated due to natural means, flotation. Figure 3 illustrates this phenomenon. In this case, there are no exterior forces as the test box is located inside a laboratory where the air speed is lower than 1m/s.

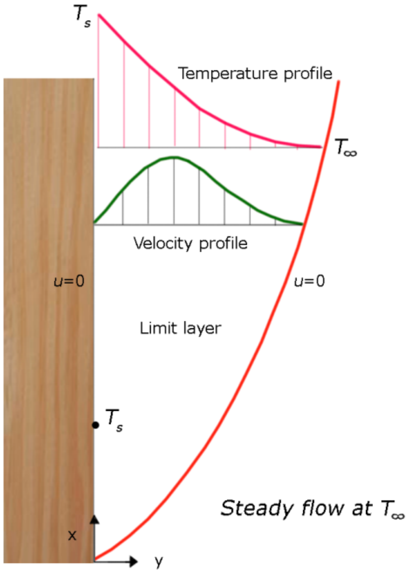


Figure 3. Velocity and temperature profile of natural convection flux in a vertical hot slab

Values are taken from the correlation between the natural convection coefficient and the Nusselt number. There is a correlation between the Rayleigh and Nusselt adimensional numbers, according to Eq. (1).

$$\mathrm{Nu} = \frac{\mathrm{h}_c \cdot \mathrm{L_c}}{\mathrm{k}} = \left\{ 0.825 + \frac{0.387\mathrm{Ra}^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2 \tag{1}$$

Depending on the geometric configuration of the sample and the heat flux, this expression differs. In this particular case where the sample is placed in vertical position, so the heat flux goes through in perpendicular direction, the Rayleigh number is between 10^4 and 10^9, which corresponds to natural convection in laminar flux, in opposition to turbulent flow where the Rayleigh number is between 10^9 and 10^{13} as depicted in Figure 4.

At the same time, the Rayleigh number is linked to Grashof and Prandtl adimensional numbers, as can be seen in Eq. (2):

$$\mathrm{Ra_L} = \mathrm{Gr_L} \cdot \mathrm{Pr} = \frac{\mathrm{g} \cdot \beta \cdot (\mathrm{T_s} - \mathrm{T_\infty}) \cdot \mathrm{L_c}^3}{\mathrm{v}^2} \cdot \mathrm{Pr} \tag{2}$$

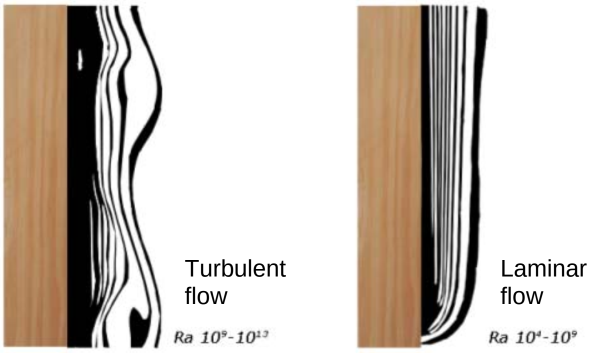


Figure 4. Isotherms on a vertical hot panel; turbulent flow (left) and laminar flow (right)

On the one hand, taking into account that air thermal conductivity (k) at 1 atm and 20°C is 0.02514 W/m·°C, the kinematic viscosity (v) is 1.516 x 10^{-5} m^2/s, and the Prandtl number is 0.7309, it is possible to estimate the convection coefficient corresponding to the exterior face of the box (h_e), which is in contact with the laboratory environment, through the temperature distribution data registered in the tests. In this case, the exterior temperature was around 22°C so an interpolation was made [20].
On the other hand, considering that the heat transfer is released in a linear mode thought the sample, the interior coefficient can be deduced from Eq. (3):

$$h_e \cdot (T_{se} - T_e) = h_i \cdot (T_{si} - T_i) \tag{3}$$

Finally, the superficial resistance of air, exterior or interior, is shown in Eq.(4):

$$R_s = \frac{1}{h} \tag{4}$$

Once the laboratory temperature, the box interior temperature, and the convection coefficients are known, a validation procedure was carried out. In this case, the superficial temperature of the sample was calculated, in order to see that the results coincide.
To validate the data, the THERM v 7.3© software is used [21], which is a two-dimensional finite-element heat-transfer analysis tool. The description of the software is explained next:
THERM's steady-state conduction algorithm, CONRAD [22], is a derivative of the public-domain computer program TOPAZ2D [23, 24]. THERM's radiation view-factor algorithm, VIEWER, is a derivative of the public-domain computer program FACET [25]. THERM contains an automatic mesh generator that uses the Finite Quadtree algorithm [26]. THERM checks solutions for convergence and automatically adapts the mesh as required using an error-estimation algorithm based on the work of Zienkiewicz and Zhu [27, 28].
THERM's calculation routines evaluate conduction and radiation from first principles. Convective heat transfer is approximated through the use of film coefficients obtained from engineering references [29, 30].
On the other side, a CFD (Computational Fluid Dynamics) simulation was proposed through the Design Builder v 4© software in order to model the inner air behaviour. Design Builder combines advanced energy simulation, based on Energy Plus© software [31, 32], with fast

modelling technology. It is an energy analysis and thermal load simulation tool widely used as a collection of many program modules that work together to calculate the energy required for heating and cooling an enclosure using a variety of systems and energy sources. It does this by simulating the enclosure and associated energy systems when they are exposed to different environmental and operating conditions.

3. RESULTS AND DISCUSSION

The acquisition data equipment registered the different temperatures of the system as depicted in Figure 5 for the first sample.

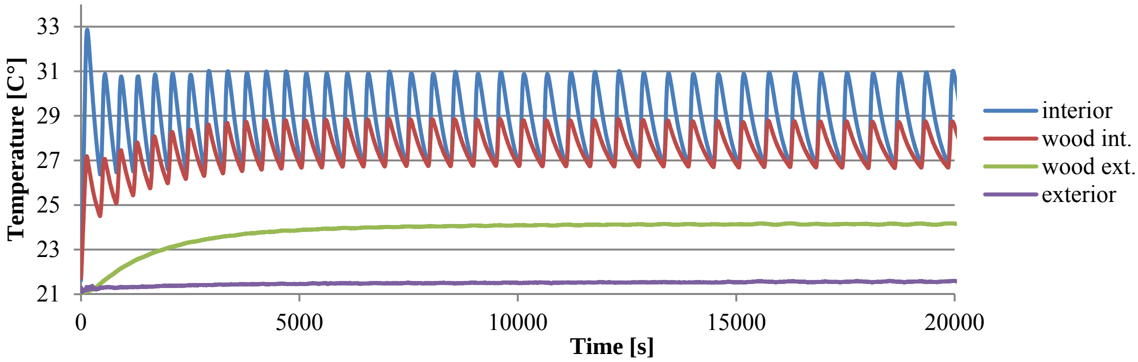


Figure 5. Distribution of temperatures for sample 1

A remarkable oscillation on both superficial and interior temperatures due to the error range of electric resistance and thermostat can be appreciated, although the tendency is finally stabilized in both cases.

A single cycle is taken to estimate the thermal resistance of samples, as depicted in Figure 6. The selected cycle shows constant exterior temperatures, whereas interior temperatures show variation. Because of that, it is calculated the exterior convective coefficient, and then the interior one is deduced through the previously exposed energy conservation principle.

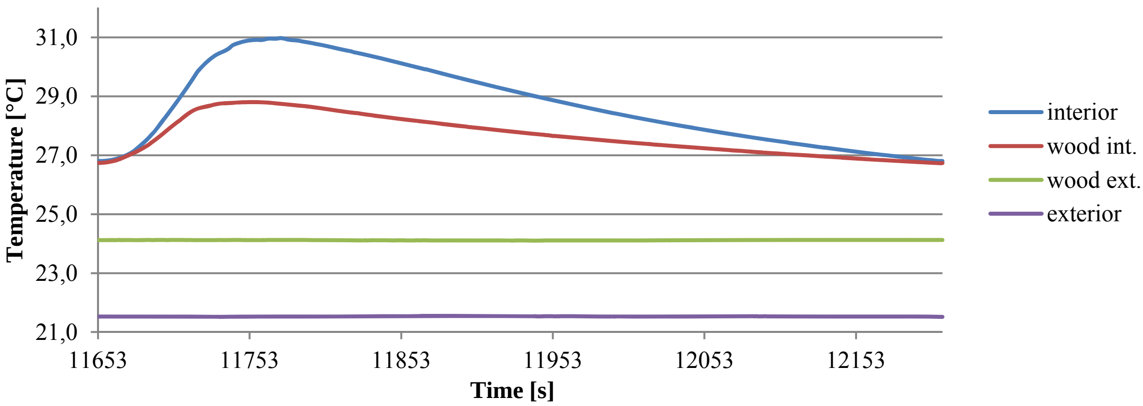


Figure 6. Distribution of temperatures in a stable cycle

Convection coefficients are based on natural convection hypothesis. Coefficients vary along time, so a spreadsheet was fully programmed. Averaged values were validated through THERM v 7.3© software. Both the data registered and the results obtained for each sample are shown in Table 1.

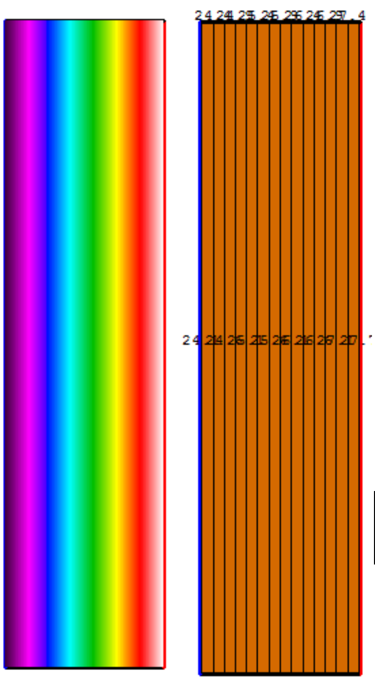
As can be seen, the conductivity of the "Radiata" pine wood is in a range between 0.10 and 0.12 W/m·°C. In this case, four tests were performed for each sample, increasing the interior temperature from 28 to 40°C, in order to analyse the wood behaviour with different temperature gradients. The outcomes are shown in Table 2.

On the one hand, the first sample, which represents the natural wood without preservative treatment, shows the lowest conductivity when the difference of temperature is smaller, that is, when the exterior temperature reaches 21°C and the interior one 28°C.

However, when the difference of temperature among the exterior and the interior environment is higher, 21°C and 40°C respectively, the third sample, thermal treated wood, shows the lowest conductivity.

On the other hand, the test box was finally simulated with Design Builder with the first sample inside for a whole year. In order to estimate the necessary heat consumption at the inner space of the test box, a time was selected, representing the days and hours when the exterior temperature is close to the laboratory temperature considered. It was taking into account both sample conductivity and test temperature to compare data with the 28 °C Test.

The final results are shown in Table 3.



	Sample 1 Test 28°C	Sample 2 Test 28°C	Sample 3 Test 28°C
Data:	T_i: 28.7 T_e: 21.5 λ: 0.103 h_{ci}: 14.54 h_{ce}: 5.93	T_i: 28.6 T_e: 21.9 λ: 0.116 h_{ci}: 14.11 h_{ce}: 6.44	T_i: 28.5 T_e: 22.0 λ: 0.119 h_{ci}: 14.53 h_{ce}: 6.50
Test Temp.:	T_{si}: 27.7 T_{se}: 24.1	T_{si}: 27.5 T_{se}: 24.4	T_{si}: 27.4 T_{se}: 24.6
THERM Results: Max. Temperture →	27.6773	27.4858	27.3684
THERM Results: Min. Temperature →	24.1163	24.354	24.6154

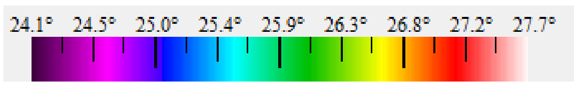


Table 1. Validation of the results with the THERM v 7.3© software

Sample 1	T_i	T_{si}	T_{se}	T_e	λ	h_{ci}	h_{ce}	R_s
	°C	°C	°C	°C	W/m·K	W/m²·K	W/m²·K	m²·K/W
Test 28 °C	28.7319	27.6768	24.1176	21.5308	0.1031	14.5397	5.9308	0.2374
Test 32 °C	32.8870	31.0741	25.7002	21.8231	0.1153	14.0249	6.5578	0.2238
Test 36 °C	36.7870	34.4227	27.1253	21.9374	0.1212	15.4657	7.0481	0.2065
Test 40 °C	40.7096	37.5628	28.0310	21.6339	0.1204	15.1423	7.4485	0.2003
Sample 2	T_i	T_{si}	T_{se}	T_e	λ	h_{ci}	h_{ce}	R_s
Test 28 °C	28.6210	27.4775	24.3723	21.8675	0.1160	12.8301	5.8573	0.2487
Test 32 °C	32.8564	31.0738	26.1137	22.3878	0.1168	13.4783	6.4485	0.2293
Test 36 °C	36.8005	34.3289	27.3721	22.2822	0.1225	14.3883	6.9867	0.2126
Test 40 °C	40.6693	37.5761	28.5766	22.3009	0.1225	14.9055	7.3467	0.2032
Sample 3	T_i	T_{si}	T_{se}	T_e	λ	h_{ci}	h_{ce}	R_s
Test 28 °C	28.5452	27.3705	24.6107	21.9855	0.1194	13.2310	5.9206	0.2445
Test 32 °C	32.8421	30.8691	26.2538	22.2042	0.1189	13.5489	6.6011	0.2253
Test 36 °C	36.7425	33.9787	27.5102	22.0851	0.1215	13.9662	7.1149	0.2122
Test 40 °C	40.6840	37.2003	28.3612	21.3813	0.1223	15.2876	7.6301	0.1965

Table 2. Data registered and results obtained of each sample

Walls	Ceiling	Floor (ext)	Lost	Heating	T_i	T_e
kW	kW	kW	kW	kW	°C	°C
-0.33859	-0.01151	-0.00869	-0.35879	0.35554	28.00	20.49
95.2%	**3.2%**	**2.4%**	**100%**	**0.9% error**		
Lost percentage						

Table 3. Design Builder results for sample S1, at 28°C Test

As it can be seen in the results there is an error between lost and heating results because there have been chosen 287 days whose temperature is similar to the laboratory one, in order to simulate the closest model. If the total year data is considered the lost and heating value is just the opposite, as the system presented is balanced.
Whether results obtained are compared with the test box resistance, it can be appreciated a slight difference, as is shown in Table 4.

Walls	Ceiling	Floor (ext)	Lost	Heating	T_i	T_e
kW	kW	kW	kW	kW	°C	°C
-0.33583	-0.01148	-0.01148	-0.35879	0.35554	28.00	20.49
93.6%	**3.2%**	**3.2%**	**100%**	**0.9% error**		
Thermal resistance distribution			→ See Figure 2			

Table 4. Design Builder results and lost in relation with thermal resistance percentages

In this case, the Design Builder (Table 3) shows that the lost through the ceiling is bigger than through the floor. That represents the behaviour of the air as it changes its density depending on temperature, producing an ascending movement getting the hottest air in the upper level. Because of that the heat lost thought walls is increased and the percentage in Design Builder results is slightly higher than results related to the thermal resistance of the test box.
The convection inside the test box is supposed to be instable, due to the range of temperatures, while the exterior coefficient is kept constant, as the temperature in the laboratory stay constant. In the hypothesis, the interior convective coefficient is estimated from the exterior one, taking into account the superficial temperatures registered in the test together with Equation (3). Figure 5 illustrates the inner air behaviour thought a CFD simulation by using Design Builder software.
Both moisture and heat transfer through a combined Heat and Moisture Finite Element, defined in the Heat Balance Algorithm were analyzed. As a result of that, the superficial air coefficients vary along time and depend on both temperature and mass transfer.
In order to analyse the thermal behaviour of the material it is necessary to know these properties: thickness, conductivity, density and specific heat.

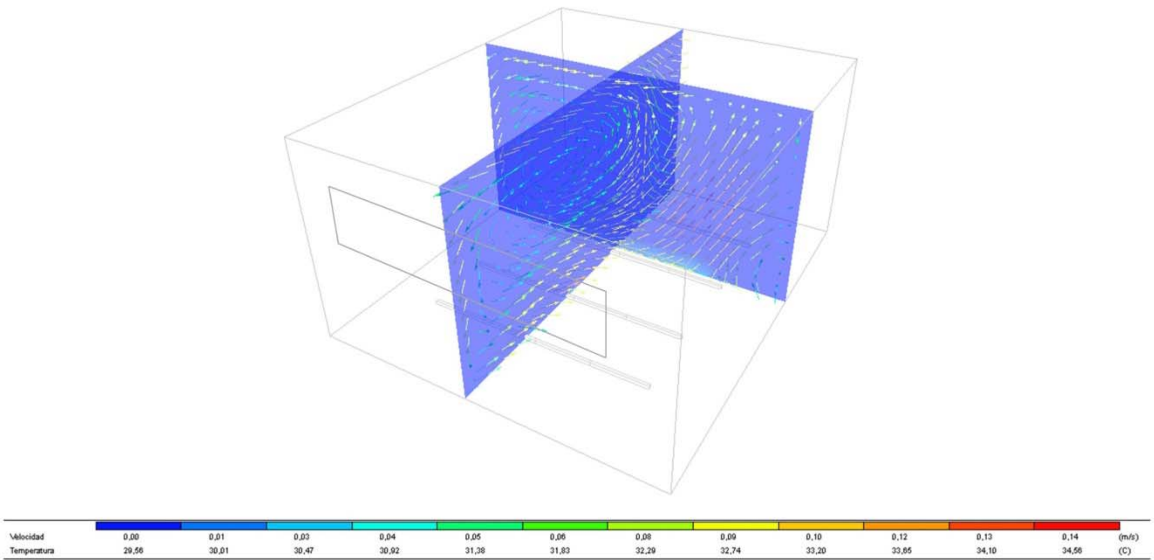


Figure 5. Inner air behaviour thought the CFD model of the box

In this case, the sample properties with the exception of the specific heat are well known. It was supposed a specific heat coefficient for the sample of 1,600 J/kg·K. This value was taken from the Spanish normative, the so called Building Technical code (CTE) [10].

4. CONCLUSIONS

A fully monitored thermal insulated box with a single opening gate, equipped with a thermal resistance inside has been designed and build here to characterize the thermal behavior of specific wood samples, treated with different weather-protection agents. Sample conductivity is measurable and depends on both the difference of temperature from inside to exterior and the type of protection agents applied to samples.

The first sample, natural wood without preserving substances, means the lower conductivity when the difference of temperature is only 7 °C.

The second sample, which was treated with copper salts, implies the less pronounced variation in conductivity.

The higher the difference of temperature between the exterior and the interior environment, the better the third solution is, as its conductivity value decreases. This sample is a thermally treated wood.

On one hand, the climate conditions have strong influence in the selection of the best solution. If the gradient of temperature varies often, the wood treated with copper salts, Wolmanit CX-8, can be the best solution as the most constant conductivity is obtained, whereas the wood without any treatment and the thermal treated one are the best solutions when low and high temperature gradients respectively are reached.

On the other hand, if wood is placed outside, exposed to external climate conditions, it is necessary to use a protection barrier in order to preserve its thermal properties but also incrementing its durability against biotic and abiotic agents, so the first sample is obviously not appropriate at all to exterior uses.

In order to validate the conductivity of samples THERM software was used. In this case, both conductivity and boundary conditions were implemented. To validate the data both exterior and interior surface temperatures were compared with the initial hypothesis.

Finally, the Design Builder software was used for the simulating study. This software presents some limitations both in model size and boundary conditions, as it has been specifically designed for buildings. Due to that fact, a scale model is proposed where the boundary conditions are linked to the on-site data, which cannot be changed from the software, so a careful selection of the data, closer to the test conditions was done.

A comparison between the heat lost in simulation and the thermal resistance of the different parts of the box was addressed. In this particular case, the inner air movement and density makes the heat losses vary as there is a higher percentage of lost detected through the ceiling than through the floor. In general terms, the heat lost represented through the sample according to its thermal resistance is very close to the Design Builder results, as the box is highly insulated.

In short, THERM software to validate wood characterization and Design Builder software to simulate the test procedure are helpful tools to understand the heat transfer procedure involved in this study allowing the characterization of wood samples according to their characteristics.

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NOMENCLATURE

Nu: Nusselt number
h_c: Natural convection coefficient average of the surface [W/m^2·K]
L_c: Characteristic length of the geometric configuration [m]
k: Thermal conductivity of the fluid [W/m·K]
Ra_L: Rayleigh number
Gr_L: Grashof number
Pr: Prandtl number
h: Convection coefficient of air [W/m·K]
T: Temperature of the air [°C]
T_s: Superficial temperature of the material [°C]
R_s: Superficial thermal resistance [m2·K/W]

Greeks
λ: Thermal conductivity [W/m·K]
g: Gravitacional acceleration [m/s2]
β: Volumetric expansion coefficient, 1/K (β = 1/T for ideal gas)
v: Kinematic viscosity of the fluid [m^2/s]

Subscripts
e: Related to external
i: Related to internal

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