In service performance and hygrothermal behavior of thermal renders

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1 Introduction

The rising costs of energy, of thermal comfort requirements by users and the enforcement of increasingly focused laws for the construction of buildings with better energy performance and lower environmental effects, drive demand and the development of new products that will meet to the new requisites of the market: the thermal renders. These are coating products with improved thermal performance: being classified according to EN998-1 (CEN, 2010) into two categories: T1 (≤ 0,1 W/m.°C) and T2 (≤ 0,2 W/m.°C). However, there is a gap of studies on the scope of thermal and hygrothermal performance in service in situ of thermal renders. The study of thermal behavior and hygrothermal of applied thermal renders lead to the present investigation.

One approach (theoretical) to study the performance in service in situ of thermal renders is to run software's or numerical models. These allows the study of several variables and different solutions simultaneously, leading to more specificities regarding the variability of a parameter, thus contributing to a better economic efficiency and reducing risks associated with the presence of moisture (Carmeliet and Zimmermann 2011).

This paper begins by presenting an in situ experimental campaign on applied thermal renders. Then a study of the minimum and maximum temperatures and relative humidities recorded within the autonomous fraction under study. Additionally, a study on the quantification of the risk of occurrence of internal and external surface condensation. Finally, an analysis of the estimates for energy needs for different solutions with thermal renders.

2 Experimental in situ campaign

As a case study was chosen a residential building, consisting of 7 elevated floors, which is under the management of Gebalis, located in Lisbon. The experimental campaign took place on July 24 of 2019 and made it possible to analyze two facades with thermal renders applied, with different solar orientations and with different application methods: by trowel and by mechanical projection. Inserted in a purely urban environment and in a region where vandalism is recurrent.

In 2014, with the purpose of studying the effects of the application of thermal renders in buildings, a 4 cm thick layer of a thermal render was applied in one of the gables, this layer having been applied to the trowel - Zone 1 (Figure 1).

In 2015, a new 4 cm layer of a thermal render was applied, this time in a region of the front facade of the building and applied by mechanical projection - Zone 2 (Figure 1).

Figure 1 - Thermal render applied in 2014 (Zone 1) and in 2015 (Zone 2)

When conducting the in situ campaign, a visual inspection technique was combined with several in situ tests, in which two Karsten tubes, two humidimeters, a pendulum sclerometer, two thermographic chambers and a radiation pyrometer were used. Other equipment was also resorted: a rubber hammer, binoculars, photographic camera and thermohygrometer.

A careful visual inspection made it possible to survey most of the anomalies, but none that are considered critical. However, it is recommended to proceed with the repair of spaces with a lack of material, in order to stop the infiltration of water and the loss of adjacent material.

No presence of excessive humidity was detected (humidimeter), often associated with infiltrations or capillary rises. There were also no surfaces detected with excessive water absorption (Karsten tube), often associated with the presence of cracking.

Part of zone 1 (2014 intervention) has a lack of adherence, a conclusion drawn after the impact of a rubber hammer in the areas under study. The combination of a rubber hammer and a sclerometer made it possible to obtain measurements in points with a lack of adherence (lower bounce).

In a space of a few centimeters, the region that has undergone a thermal requalification shows an increase in temperature compared to the non-intervened region, such a fact that highlights the suitability of the solution used to improve the thermal performance of a building. Additionally, when the inspection was carried out, it was possible to receive the opinion of a resident of an autonomous fraction that was thermally requalified, which was very positive and indicated that its application significantly improved the thermal comfort felt inside the autonomous fraction (Figure 2).

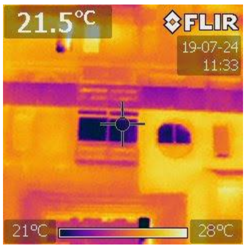


Figure 2 - Thermographic analysis

It is concluded that most of the anomalies manifested (material loss, graffiti's and chalk drawings) are associated with the lack of respect and citizenship on the part of the citizens, more precisely, with vandalism.

It should also be noted that no signs of biological colonization were detected.

3 Simulation

The realization of an in situ campaign in the case of the previous study led to the conclusion that the application of a thermal render improves the hygrothermal performance of a building. Thus, in order to support (or refute) the conclusion of the in situ campaign, it was decided to carry out an analysis of the hygrothermal and energetic impacts of applying a thermal plaster to a case study.

3.1 Case study

The case study selected is an autonomous fraction on a third floor of a residential building compound by eight raised floors. The autonomous fraction has T3 typology and a floor area of 94,4 m^2 and a balcony of 15,1 m^2.

In Figure 3 it can be observed the floor plan with the perimeter of the fraction in question, with the respective thermal surroundings marked. Finally, it should be noted that this fraction is in Lisbon.

The autonomous fraction considered as a case study for the elaboration of the present article was previously studied by Soares (2016), having benefited from a set of files that had been previously developed by Soares (2016). This decision to use already developed files was related to the fact that it is intended to concentrate the available time in the model of evaluation of the hygrothermal behavior of different solutions of thermal renders under different conditions, which had not yet been explored in Soares (2016).

It is noteworthy that the housing fraction under study has a vertical exterior envelope with three distinct solar orientations (North, South and West) and non-useful spaces of common circulation of the building.

Additionally, it is noted that with a horizontal green line (Figure 3) is marked a boundary separating two thermal zones; Zone A from Zone B. The first comprises the two bathrooms, the circulation zone and the two bedrooms with South-facing glazing. As regards Zone B, this covers the lobby area, the kitchen, the living room and a bedroom with solar North orientation. Although Zones A and B are not expected to have very different temperatures and may have been considered to belong to the same thermal zone, it was decided to simulate with different thermal zones, as they are considered to be areas with separate ventilation, meaning that there is an interior door in the interior circulation area delimiting these two separate ventilation sectors, i.e. the existence of a door with an air permeability of less than 12 $m^3/(h.m^2)$ for a pressure difference 100 Pa according to NP 1037-1 2002.

Since treating an autonomous fraction in an intermediate floor and the lower and upper floors are identical, it was considered the pavement and ceiling as adiabatic boundaries, as it is the boundaries that separate heated spaces, similar to the edge of the vertical wrapping marked with a vertical green line of separation between neighboring autonomous fractions belonging to the same building.

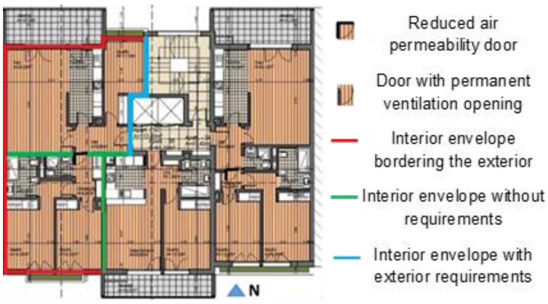


Figure 3 - Delimitation of the thermal boundaries of the case study (Soares, 2016)

Table 1 shows the models characteristics and properties.

Table 1 - Simulation models characteristics

Location	Lisbon (Portugal); latitude: 40,3°; longitude: 8°
Terrain type	Urban
Simulation period	Type year for the city of Lisbon
Glazing	Two South and two North facing glazing
Infiltration	0,6 air renewals per hour
Internal gains	0,05382 persons/m^2 ; lights: 4W/m^2
Paviments	Concrete slabs considered as adiabatic
Interior walls	11cm ceramic brick with 2cm traditional cementitious plaster on both surfaces

3.2 Location and weather data

The case study corresponds to an autonomous fraction that is inserted in a residential building located in Lisbon (Portugal). Thus, the climate file used was “PRT_Lisboa.085360_INETI”, which can be downloaded from the EnergyPlus website. According to the weather file, the average outdoor temperature of the city of Lisbon is 13.58°C and the average relative humidity 73,25%. Thus, the simulations were realized for the type year for the city of Lisbon.

3.3 Fraction simulation software

In the elaboration of this chapter were used files that had been previously developed and explained by Soares (2016). Thus, the need arose to use the same version of EnergyPlus that was used when developing the base file, version 7.1 of EnergyPlus. Soares (2016) used the Google Sketchup program to do the case study modeling (Figure 4) and the OpenStudio Plugin to interconnect the two programs.

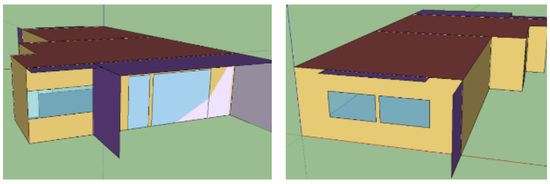


Figure 4 - North and South facing facade view

3.4 Fraction model

No modeling of the whole building was done, but rather the modeling of the autonomous fraction itself and subsequent characterization of the external borders in the EnergyPlus file. The autonomous fraction is composed of two thermal zones: Zone A and Zone B (Figure 5).

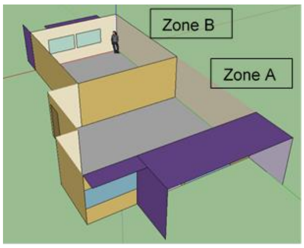


Figure 5 - Interior wall of thermal zone division

3.5 Thermal and hygrothermal models

In the EnergyPlus program models are available that only calculate the heat transfer in the building envelope (thermal-only) and models that also consider the moisture transfer (hygrothermal).

A thermal-only model was used, the “Conduction Transfer Function” (CTF), to calculate the interior temperatures and relative humidities and the energy needs.

In the article published by Tariku *et al*. (2010) it was concluded that the in situ monitored values for indoor temperature and relative humidity match the results reported by the EnergyPlus “Combined Heat and Moisture Finite Elements” (HAMT) hygrothermal model. Thus, in order to calculate the number of hours in which the conditions favorable to the occurrence of internal and external surface condensation occur, the HAMT model was used.

The Energyplus program recommends that the timestep when using the HAMT model be at least 20. Therefore, the timestep was set to 20 for both models (HAMT and CTF).

3.6 Internal gains and schedule

The internal gains associated to the case study influence the interior temperatures and relative humidities and, hence the total energy requirements. The concentration rate of people was considered as 0,05382 people/m^2 and the power of the lights was considered as 4 W/m^2. Additionally, 0,6 air renewals per hour was considered for both thermal zones. Finally, interior shading blinds (collected from 7:30h to 20:00h) were considered.

3.7 Exterior shading tabs

The fact that the case study is an autonomous fraction located in the third of an eight storey residential building, the existence of external shading tabs is an intrinsic feature of the case study, as these correspond to the vertical shading tabs of the balcony’s own fraction and the slab of the upper floor balcony. Thus, the effects of the consideration or not of these elements imply on the interior relative humidity, the risk of condensation and the energy needs were studied. In purple in Figure 4 is illustrated the exterior shading tabs to the case study.

3.8 Materials

Table 2 shows the properties of the materials used when studying the minimum and maximum temperatures and relative humidities recorded inside the case study.

Table 2 - Materials properties used when studying temperatures and relative humidities

Solution	Roughness	Thermal conductivity (W/m.°C)	Density (kg/m^3)	Specific heat (J/kg.°C)
Expanded polystyrene (EPS)	Soft medium	0,037	35	1500
Isodur	Medium rough	0,07	400	700
Aislone	Medium rough	0,05	260	700
Evolution	Medium rough	0,045	360	1000
Fixit 222	Medium rough	0,028	220	700
Hemp	Medium rough	0,102	304	1270
Hollow brick 22cm	Rough	0,336	100	837
Hollow brick 11cm	Rough	0,334	1500	837
Traditional cementitious plaster	Medium rough	1,4	2200	840

In order to quantify the number of hours in which surface condensation occurs and energy needs, two distinct thermal renders were studied. The thermal render used by Barclay *et al.* (2015), also within the scope of the EnergyPlus HAMT model, a lime and natural hemp-based render, which incorporates the advantages of using low carbon renewable materials, with the advantages of using materials with good hygrothermal performance. Another studied render was "*Aislone*", produced by the Weber company, which has incorporated in its constitution EPS aggregates. The characteristics of the thermal renders are shown Table 2.

Regarding the access door to the autonomous fraction was adopted a wooden door with 25 cm thickness, thermal conductivity of 0,15W/m.°C, density of 608 kg/m^3 and specific heat of 1630 J/kg.°C. Table 3 shows the solutions adopted for the glazing and the glass balcony doors.

Table 3 - Windows and glass doors solutions

Solution	Interior glass (mm)	Air cavity (mm)	Exterior glass (mm)
Windows	4	12	4
Doors	4	14	6

Regarding the lower and upper slab that limit the case study, they were considered as adiabatic boundaries and the adopted constructive solution is summarized in Table 4; it is also possible to visualize the constructive solution of the interior walls.

Table 4 - Solutions of adiabatic boundaries

Solution	Material	Roughness	Thickness (mm)	Thermal conductivity (W/m.°C)	Density (kg/m^3)	Specific heat (J/kg.°C)
Interior Wall (Int_ADIA)	Plaster	Rough	30	1,15	2000	837
	Hollow brick	Rough	220	0,336	1000	837
	Plaster	Rough	30	1,15	2000	837
Pavement (inferior slab)	Plaster	Rough	20	1,15	2000	837
	Reinforced concrete	Medium rough	150	1,75	2500	837
	Mortar	Medium rough	30	1,2	2200	837
	Ceramic tile	Rough	8	1,15	1900	837
Ceiling (superior slab)	Ceramic tile	Rough	8	1,15	1900	837
	Mortar	Medium rough	30	1,2	2200	837
	Reinforced concrete	Medium rough	150	1,75	2500	837
	Plaster	Rough	20	1,75	2000	837

3.9 Temperatures and relative humidities

The construction solutions adopted for the case study envelope in order to analyze interior temperatures and relative humidities, without the use of climate control systems, are shown in the flowchart in Figure 6.

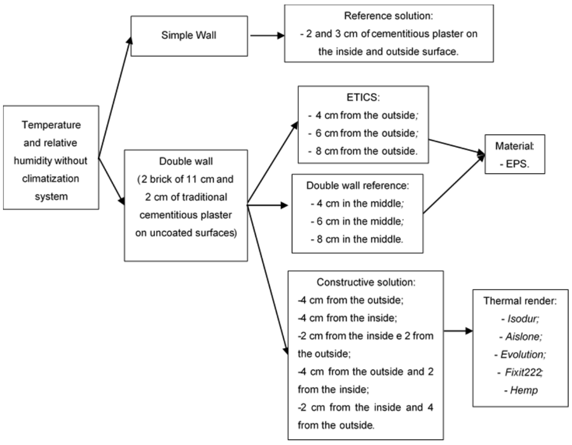


Figure 6 - Flowchart of the studied constructive solutions for temperatures and relative humidity

3.10 Surface condensations risk

3.10.1 Constructive solutions

In the Figure 7 is illustrated a flowchart with the constructive configurations studied to quantify the risk of surface condensation occurrence, without considering climatization systems.

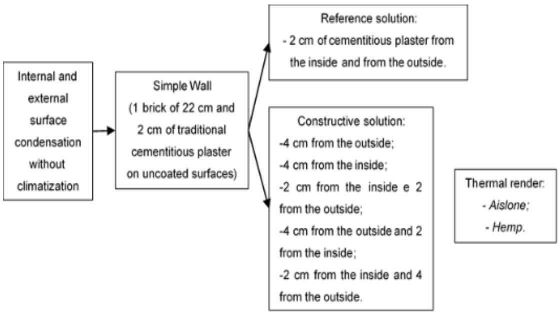


Figure 7 - Studied solutions for condensations

3.10.2 Criteria for quantifying the occurrence of surface condensation

The use of the Energyplus program's HAMT model does not directly quantify the number of hours in which the conditions for surface condensation occur, but rather obtain output parameters (partial water vapor pressure, interior surface temperature, outside dew temperature, outside surface temperature), which when processed and treated allow this quantification to be performed. Thus, the need arose to define criteria in order to study the risk of surface condensation: the potential for outside and inside condensation and the relative humidity equal to 100%.

Concerning the potential for surface condensation outside and inside it is possible to state that the conditions for the occurrence of superficial condensation have been verified when it is positive since this is equal to the difference between the partial pressure of the water vapor in the air and the surface water vapor saturation pressure for interior surfaces and equal to the difference between outdoor dew temperature and outdoor surface temperature for exterior surfaces.

Regarding the second criterion used was to check the number of hours when the relative surface humidity outside or inside was equal to 100% (verified when the air is saturated).

3.11 Energy needs

3.11.1 Constructive solutions

One of the reasons for using the EnergyPlus program was to obtain estimates for the annual, heating and cooling energy needs for various building solutions when considering single or double walls and the presence of shade stabs outside the autonomous fraction.

In Figure 8 it is possible to observe a flowchart with the different constructive solutions analyzed. The thermal renders studied were the same as in the determination of the risk of superficial condensation: “*Aislone*” and “*Hemp*”.

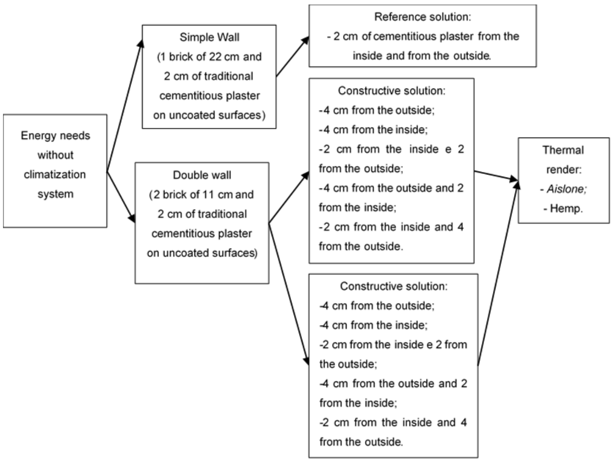


Figure 8 - Studied solutions for energy needs

3.11.2 Comfort temperature ranges

In order to obtain estimates for energy needs, using climate control systems, it was necessary to establish comfort temperature ranges: corresponding to the comfort range suggested by REH (2013), to the minimum temperature in the warm-up period and to the maximum temperature in the cooling period (Table 5).

Table 5 - Considered comfort temperature ranges

	Const_setpoint_year	Const_setpoint_heat	Const_setpoint_cool
Heating setpoint (°)	18	18	10
Cooling setpoint (°)	25	50	25

3.11.3 Schedules

In order to study the effects of calendarization on energy needs, three calendars were defined: annual (1 January to 31 December), heating (1 October to 30 June) and cooling (1 July to 31 September). Each calendar was matched with the respective range of comfort temperatures previously addressed.

4 Discussion and result analysis

4.1 Temperatures and relative humidities

This subchapter has allowed to understand the limits of the thermal comfort range suggested by the REH, 18°C and 25°C, are not respected for all building solutions, when no type of climatization system is used (Figure 9).

The minimum and maximum values of temperatures and relative humidities, throughout the standard year for the city of Lisbon, for each construction solution allowed to conclude that the increase of the thermal render thickness leads to the increase of the minimum values registered for the minimum temperatures, however also leads to the increase in the maximum recorded temperatures. Additionally, it leads to a decrease in the minimum and maximum relative humidities values.

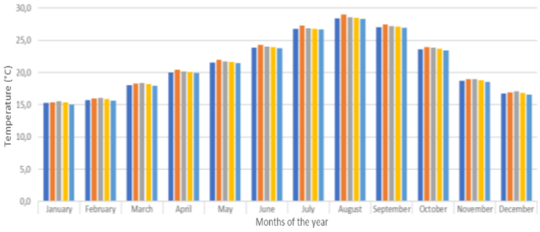
The presence of exterior shading tabs causes a reduction in the minimum and maximum temperatures recorded and an increase in the minimum and maximum relative humidities in the interior environment. Nevertheless, an energy needs study is essential in order to conclude whether shading construction is economically advantageous. It is emphasized that the existence of shading tabs is an intrinsic feature of the case study, since they correspond to the shading tabs of the fraction's own balcony and the slab of the upper floor balcony.

Comparing the temperature results, the application of a 4 cm solution from the inside is advantageous compared to the application of 4 cm from the outside during the warming months, as it allows to increase the minimum recorded temperatures. However, in the cooling months (July, August and September), applying 4 cm from the outside is more advantageous than applying 4 cm from the inside as it reduces the maximum temperatures recorded. In the context of relative humidities, application of 4 cm from the outside or 2 cm from the inside and outside leads to higher values than those when opting for a solution with 4 cm from the inside.

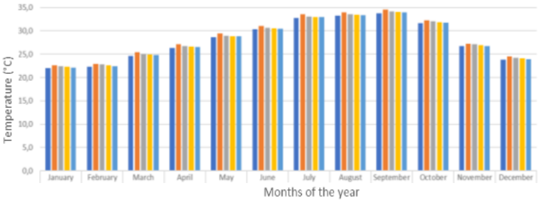
With regard to increasing the thickness of the thermal render over 4 cm, as the increase in thermal comfort is reduced compared to the price increase, these solutions are not interesting for temperature and humidity control without the use of climatization systems, when compared to the application of 4 cm from the inside or outside. It is important to analyze energy needs in order to conclude which constructive solution is most advantageous.

Of the studied thermal renders, the one that presents the best performance in terms of temperatures in the heating period is the "*Fixit 222*", on the other hand the "*Hemp*" presents the best performance in the cooling period. In terms of humidity the best performing thermal render is "*Fixit222*".

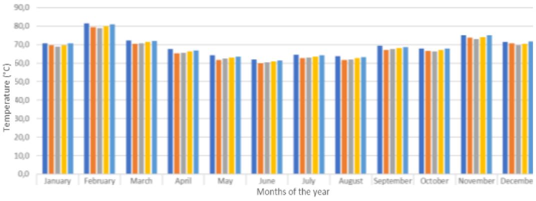
Studying the impacts of each solution on the variables in question, without resorting to climate control systems, is important since, as the cost of living increases, users of the autonomous fractions try to minimize costs by avoiding climate control systems.



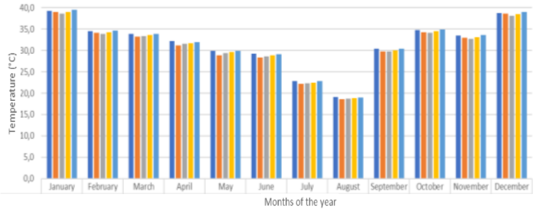
a) Minimum temperatures – Zone A



b) Maximum temperatures – Zone A



c) Minimum relative humidities – Zone A



d) Maximum relative humidities – Zone A

Figure 9 - Interior results for “Isodur” solutions without shading tabs

4.2 Surface condensation risk

Through the analysis of Table 6 a) and b), it was concluded that the criterion adopted for the quantification of condensations, which is to verify the number of hours in which the relative humidity is 100%, is not adequate when quantifying the external condensations in EnergyPlus and that it would be more useful to perform a quantum analysis by relative humidity intervals at the same time.

External shading tabs allows to reduce the number of hours that external surface condensation occurs compared to the values recorded when they don’t exist for North and South oriented surfaces. Although, they increase the risk of external surface condensation on East and West oriented surfaces.

Applying 4 cm of thermal render on the interior surface is preferable in terms of reducing the risk of external surface condensation to applying 4 cm from the outside to West and South oriented surfaces when outside shading tabs are not considered, and also to those oriented North when considering the existence of external shading tabs. Regarding the solar orientation East, the application of 4 cm from the inside presents equal performance to the application of 4 cm from the outside in most cases (null condensation potential), except when opting for the “*Hemp_i4*” constructive solution, presenting better performance. Of all the constructive configurations analyzed the one with the lowest values for the total outer surface condensation potential is the application of 4 cm of thermal insulation on the inner surface. In addition, it can be concluded that it is preferable in terms of exterior surface condensation to apply 2 cm from the outside and 2 cm from the inside than to apply 4 cm from the outside only.

The building solutions with “*Hemp*” thermal render have a lower risk of superficial condensation than “*Aislone*” on North, South and West oriented surfaces. Additionally, they have the same performance on East-facing surfaces, apart from solutions with 4 cm “*Hemp”* from the inside that perform worse than “*Aislone*”. The months with the highest condensing potential were January, February and March, which corresponded to more than 50% of the hours when external surface condensation occurred.

The progressive increase in the thickness of thermal insulation is unfavorable in terms of the increased risk of external surface condensation, as was also concluded by Blaich (1999), the increase in thickness reduces the heat flow from the interior hence reducing the surface temperature of the outer walls.

The HAMT model needs to be refined to consider various moisture transfer mechanisms such as associated with air inlet and outlet and quantification of steam production rate. Because of these limitations, the inner surface condensation potential of all solutions was 0.

4.3 Energy needs

The heating needs of Zone B are on average about five and a half times higher than those of Zone A. However, the cooling needs of Zone B are on average three times lower than those of Zone A. The existence of external shading tabs allows energy savings of 11,54% to 17,35%, favoring its existence in the cooling months and unfavorable in the heating months.

Table 6 - Outer surface condensation (in hours)

a) "ext_REF" and thermal render "*Hemp*"

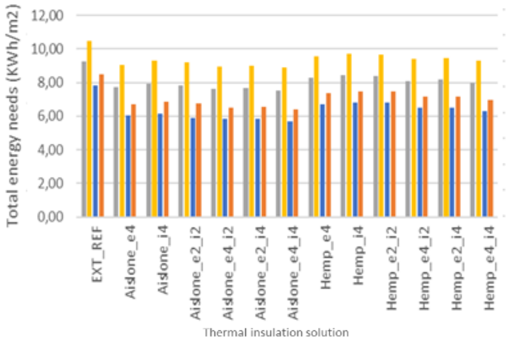
	Solution	Criterion	N	S	E	O
With external shading tabs	ext_REF	φ = 100 %	0	0	0	0
		CP > 0	3,9	0	26,75	7,75
	Hemp_e4	φ = 100 %	0	0	0	0
		CP > 0	0,55	3,30	0	79,25
	Hemp_i4	φ = 100 %	0	0	0	0
		CP > 0	3,60	0	5,65	7,25
	Hemp_e2_i2	φ = 100 %	0	0	0	0
		CP > 0	0,4	0,85	0	21,75
	Hemp_e4_i2	φ = 100 %	0	0	0	0
		CP > 0	0,2	2,8	0	72,90
	Hemp_e2_i4	φ = 100 %	0	0	0	0
		CP > 0	0,75	0,95	0	30,05
	Hemp_e4_i4	φ = 100 %	0	0	0	0
		CP > 0	0,85	3,15	0	84,10
Without external shading tabs	ext_REF	φ = 100 %	0	0	0	0
		CP > 0	11,70	0	23,05	7,50
	Hemp_e4	φ = 100 %	0	0	0	0
		CP > 0	121,05	10,45	0	74,9
	Hemp_i4	φ = 100 %	0	0	0	0
		CP > 0	15,85	0	3,75	7,05
	Hemp_e2_i2	φ = 100 %	0	0	0	0
		CP > 0	54,80	2,20	0	20,25
	Hemp_e4_i2	φ = 100 %	0	0	0	0
		CP > 0	131,5	7,25	0	68,8
	Hemp_e2_i4	φ = 100 %	0	0	0	0
		CP > 0	72,8	2,25	0	26,35
	Hemp_e4_i4	φ = 100 %	0	0	0	0
		CP > 0	162,9	7,50	0	79,60

The application of thermal render "*Aislone*" to the detriment of "*Hemp*" leads to an average reduction of energy consumption from 5,00% to 7,66%. Additionally, all thermal renders lead to significant energy savings.

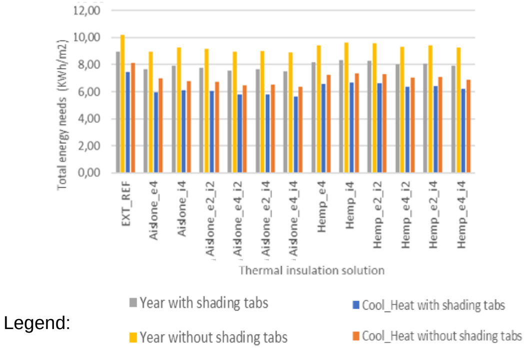
The realization of this subchapter has shown that the use of double walls is an economically more advantageous solution compared to the construction of single wall solutions; a conclusion that meets national construction practices and that the cooling period is more demanding in terms of energy consumption. than the heating period (Figure 10).

In terms of the type of schedule, the schedule that considers separate heating period and heating period leads to lower estimates for annual energy consumption than the consideration of an annual schedule.

The application of 4 cm of thermal render from the outside is the studied constructive configuration that has the highest energy performance for the same thermal insulation thickness. However, the application of 4 cm of thermal render from the inside also allows for excellent thermal performance, however it has the disadvantage of losing interior working area. Additionally, in terms of energy the application solution of 2 cm from the inside and outside is more interesting than the application of 4 cm from the inside. The application of a thicker thermal render leads to lower energy consumption, but with a marginal energy saving that decreases considerably with the thickness increase, being necessary to know the increase of the cost of the solution to draw more conclusions, if the additional cost is easily amortized it is interesting to apply higher thicknesses.



a) Single wall



b) Double wall

Figure 10 - Energy needs for "Aislone" solutions

5 Conclusion

The elaboration of this study allowed to understand that the choice of a constructive solution and the consideration (or not) of shading tabs outside the case study have impacts in the different studied areas (minimum and maximum indoor relative temperatures and humidities, risk of external and internal surface condensation occurring and annual, heating and cooling energy, needs) and that there is no ideal solution, but one that fits better or worse to requirements and needs of each case study and individuals.

Additionally, the studied thermal renders have maintained their integrity and characteristics (after 4 and 5 years in service, that is, subject to real climatic conditions) and that in situ tests are very helpful and can be applied while studying the in situ performance of thermal renders.

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