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TROMBE WALL THERMAL PERFORMANCE FOR A MODULAR FAÇADE SYSTEM IN DIFFERENT PORTUGUESE CLIMATES: LISBON, PORTO, LAJES AND FUNCHAL

Helenice M. Sacht[1], Luis Bragança[1], Manuela Almeida[1] and Rosana Caram[2]
[1]Department of Civil Engineering, University of Minho, Guimarães, Portugal.
[2]Institute of Architecture and Urbanism, University of São Paulo, São Carlos, Brazil.

ABSTRACT

Trombe wall and high performance glazing are the façade system improvements used in this research. This paper reports about an ongoing investigation on a new façade system: "Façade Modules for Eco-Efficient Refurbishment of Buildings", focused on thermal performance of Trombe wall and glazing. Computational simulations were performed with DesignBuilder software for different arrangements of modules, occupancy profile and internal gains according to Portuguese reality. For this research were considered two double-glazing, four climates in Portugal, one and two Trombe walls and four solar orientations. Results show an important energy consumption decrease with use of Trombe walls and double self-cleaning glazing.

INTRODUCTION

Building façades constitute an important component to propose solutions, once they have major influence on the energy consumption in the building and on occupants comfort. Recently, façade systems are increasingly integrating not only sophisticated active system devices, but also passive solutions. Trombe wall is one example of this kind of technology.

Since ancient times, people have used thick walls of adobe or stone to store solar energy captured during the day and release it slowly and evenly at night to heat buildings. Nowadays, low-energy buildings often improve on this ancient technique by integrating a thermal storage and delivery system called "Trombe wall" (Torcellini; Pless, 2004).

Edward Morse, an American was the first to describe the Trombe wall concept on 1881 patent (Morse, 1881). However, the idea was re-patented and popularized by the French engineer Felix Trombe and architect Jacques Michel (Trombe, 1972). Other denominations for Trombe wall is Trombe-Michel wall, solar wall, thermal storage wall, collector storage wall, or simply storage wall.

A typical Trombe wall (TW) consists of a 10 to 40cm thick south oriented wall (northern hemisphere) and faced with a single or double layer of glass. The glass is placed from 2 to 5cm from the massive wall to create a small airspace. To increase the absorptivity of solar radiation, the surface of the massive wall is usually painted using black color (Sun et al., 2011). Heat from sunlight passing through the glass is absorbed by the dark surface, stored in the wall, and conducted slowly inward through the wall. High transmission glass maximizes solar gains to the wall. As an architectural detail, patterned glass can limit the exterior visibility of the dark concrete wall without sacrificing transmissivity. For a 20cm-thick Trombe wall, heat will take about 8 to 10 hours to reach the interior of the building. It means that rooms warm slowly, reducing the need for conventional heating considerably (Torcellini; Pless, 2004).

According to researches, Trombe walls are an effective technology for reducing heating energy, as much as 47% in residential cases (Balcomb, 1992) and, therefore, they can be used as an efficient and durable solar heating method.

The performance of Trombe walls is lower if the interior wall is not open to the interior zones. Based on previous experiences the heat delivered by a Trombe wall in a residence can be reduced by over 40% because kitchen cabinets were placed on the interior of the wall (Balcomb, et al., 1998; Balcomb, et al., 1999).

The apparent amenity of Portugal climate, lead to the non-existence of central heating or cooling systems in most part of the buildings, exceptions made for the service buildings. Gonçalves et al. (1997) developed a research about "Passive Solar Buildings in Portugal: Experiences in the Last 20 years". In this study presented some examples of Trombe wall uses. Vale Rosal (Figure 1) is a residential building that has a Trombe wall whose area is 3,5m² and is located in Charneca da Caparica, Lisbon. The Schäfer Residence (Figure 2) has a Trombe wall whose area is 12m² and is located in Porto Santo, Madeira.

Figure 1. ". Vale Rosal Building (Charneca da Caparica-Lisbon).
Reference: Gonçalves et al., 1997.

Figure 2. Schäfer Residence (Porto Santo-Madeira).
Reference: Gonçalves et al., 1997.

According to Gonçalves et al. (1997), the Trombe walls in Portugal have areas of 2 to 6% of floor area (from 3.5m^2 up to 33m^2), which in some cases amounts to very significant areas in relation to the size of the adjacent space, that usually corresponds to bedrooms but may also be a living room. Wall thickness of 15 to 40cm was found in this research. The majority of the walls do not have any vents. The glazing used in most of them is single. In terms of summer protection, some use movable or fixed shading devices; others do not have any solar protection at all. Figure 3 presents another example of the building with the largest area (33m^2) of Trombe wall in Portugal. It is a school building, nursery and is located in Mertola.

Figure 3. Nursery (Mertola)
Reference: Gonçalves et al., 1997.

In recent decades, façade technologies have undergone to substantial innovations both in quality of materials/components and in the overall design concept of the façade system by integrating specific elements to adapt the mediation of the outside conditions to user requirements. These improvements include passive technologies, such as multi layered glazing, sun protections, ventilation, Trombe walls, etc. (Castrillón, 2009) as shown previously.

In order to test passive solutions and foresee their performance in a more economical and less time-consuming way than with practical experiments, computer simulation offer a variety of tools that can be used.

Ellis (2003) did a validation of EnergyPlus use for unvented Trombe wall model and it performs well compared to experimental data. According to the author, users should not hesitate to use the model for the simulation of passive solar buildings.

In this research, the software used is DesignBuilder v. 1.8, a graphic interface for the EnergyPlus.

The results of "Standard Method of Test for the evaluation of Building Energy Analysis Computer Programs" for DesignBuilder agree with the equivalent results for the EnergyPlus simulation engine. It shows that DesignBuilder is generating correct input data for EnergyPlus, as well as adding to confidence in the absolute accuracy of the results generated by DesignBuilder/ EnergyPlus (ANSI/ASHRAE, 2010). The majority of results for DesignBuilder were found to be identical to the results extracted from the GARD Analytics report for EnergyPlus run in standalone mode, the remainder were showed minimal differences (Gard, 2009).

This kind of tool can be used for the development of new façades system, as well. The ideal goal for new façades system would be the development of a dynamic and flexible system in way to adapt to the climatic changes, to the occupants requirements and, however, to adapt to the building. An improvement would be the development of a suitable system that facilitates the assembly of the façade, containing passive elements, glazing and reception of solar energy. Improve the comfort conditions in agreement with the climatic needs and be mounted in agreement with the solar orientations and wanted functions. This paper presents partial results of an ongoing investigation about glazing modules of a new façade system: "Façade Modules for Eco-efficient Refurbishment of Buildings" on the development (Sacht et al., 2010). The focal point is the thermal performance of Trombe walls and glazing modules.

SIMULATIONS

Computational simulation was carried out applying the DesignBuilder 1.8 software to analyze a case study, which consists of a room (25m^2) with different arrangements of façade modules. Simulations were made considering the following parameters: (i) two different double glazing types (composed by green solar control glass and low-e glass; self-cleaning glass and float clear glass), (ii) one or two Trombe walls; (iii) four solar orientations (north, south, east and west) and (iv) two envelopes: a Portuguese traditional system (double masonry) and a light gauge steel framing system (LGSF).

For validation purposes were compared the heating and cooling energy needs values obtained by thermal simulations with the ones calculated in accordance with the Portuguese thermal regulation for residential buildings, "*Regulamento das Características do Comportamento Térmico dos Edifícios* - RCCTE" (RCCTE, 2006).

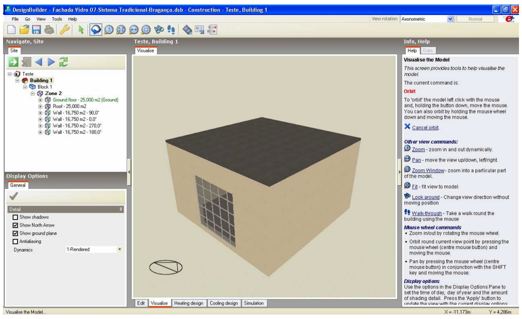
For the thermal performance simulation was analyzed four Portuguese climates, in this case, Lisboa, Porto, Lajes and Funchal (Table 1). Simulations were done for four solar orientations (north, south, east and west), considering the annual period. The use of a façade with one or two set modules of Trombe walls was carried out.

Table 1. Climates for Computational Simulation.

Climates	Climatic Zone		Energy Needs		Duration of Winter (months)
	Winter	Summer	Heating (kWh/m^2.year)	Cooling (kWh/m^2.year)	
Lisboa	I1	V2	56.36	32.00	5.30
Porto	I2	V1	74.66	16.00	6.70
Lajes-Açores	I1	V1	36.42	21.00	4.00
Funchal-Madeira	I1	V1	46.42	23.00	3.89

DesignBuilder

DesignBuilder software is a friendly graphic interface for the program EnergyPlus simulation engine, to the family of software tools for modeling building facades and fenestration systems (Figure 4). Developed for use at all stages of building design, DesignBuilder combines state-of-the-art thermal simulation software with an easy-to-use. This software allows calculating building energy use; evaluating facade options for overheating and visual appearance; visualization of site layouts and solar shading; thermal simulation of naturally ventilated buildings; lighting control systems model savings in electric lighting from daylight; calculating heating and cooling equipment sizes, etc.



Visualise the Model

This screen provides tools to help visualise the model.

The current command is:

Orbit

To 'orbit' the model left click with the mouse and, holding the button down, move the mouse. You can also orbit by holding the mouse wheel down and moving the mouse.

Cancel orbit.

Other view commands:

Zoom - zoom in and out dynamically.

Pan - move the view up/down, left/right.

Zoom Window - zoom into a particular part of the model.

Fit - fit view to model.

Look around - Change view direction without moving position

Walk-through - Take a walk round the building using the mouse

Mouse wheel commands

- Zoom in/out by rotating the mouse wheel.
- Orbit round current view point by pressing the mouse wheel (centre mouse button) and moving the mouse.
- Pan by pressing the mouse wheel (centre mouse button) in conjunction with the SHIFT key and moving the mouse.

Display options

Use the options in the Display Options Pane to set the time of day, day of year and the amount of shading detail. Press the 'Apply' button to update the view with the current display options

Figure 4. DesignBuilder software main screen.

Trombe wall systems can be simulated in DesignBuilder software using an option of inside convection algorithm called "cavity". In this option, the zone is a cavity such as the glazed cavity within Trombe wall or a double facade. This algorithm correctly calculates the convection coefficients for a narrow sealed vertical cavity based on the ISO 15099 standard. The algorithm analyzes the Trombe wall zone to figure out which are the two major surfaces and then sets the coefficients on those surfaces. The other minor surfaces receive negligible convection (DesignBuilder Software, 2008).

As previously mentioned, the EnergyPlus modeling approach for the sealed passive Trombe wall has been validated with experimental data, as previously mentioned (Ellis, 2003).

For a naturally ventilated Trombe wall, there is no built-in algorithm for calculating the correct convection coefficients on the inside of the cavity walls. One option is to use the "Detailed" inside convection algorithm. This algorithm takes into account some natural convection effects but is intended for a normal sized room. It is possible to define holes and vents through the Trombe wall by drawing them on at surface level. Vent openings can be scheduled and controlled by internal temperature (DesignBuilder Software, 2008).

In this research "cavity" and "detailed" inside convection algorithms was tested in DesignBuilder, but as the heating needs values was similar for a small ventilation area (0.10x0.20m^2), was used the cavity inside convection algorithm.

Standard Model Definition

The "standard model" was defined considering a one-storey isolated cell, with regular geometry 5,0 x 5,0 (25m^2), a ceiling height of 2,80m, these dimensions followed the recommendations of the Portuguese Urban Building Regulation "Regulamento Geral das Edificações Urbanas" (RGEU, 2007). A total dimension of 2,5 x 2,5 (6,25 m^2) for the façade modules composition. This isolated cell was simulated considering the implementation of one and two Trombe walls. A set of five Trombe modules makes a complete "Trombe wall" (Figures 5 and 6).

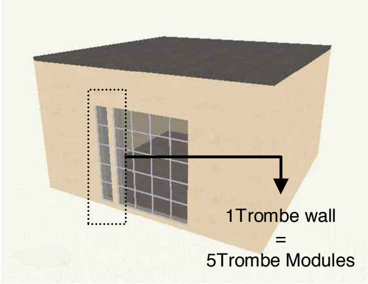


Figure 5. Model: One Trombe wall.

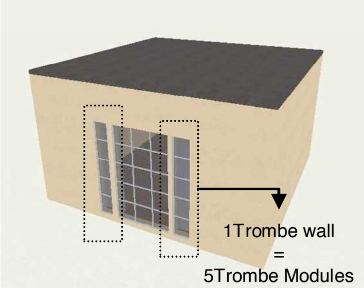


Figure 6. Model: Two Trombe wall.

For Trombe wall module in this façade system was considered the use of a double glazing with high shading coefficient. The double glazing has two panes composed by diamant glass 4mm (Saint-Gobain Glass) and 12mm air space, thus allowing maximum solar radiation penetration. The area of a complete Trombe wall composed of five modules is 0.50 x 2.50m (1.25m²). Higher and lower modules have ventilation openings on the massive wall, whose area is 0.02m² (0.10x0.20m²). The operating time was considered for such openings from 9:00 to 18:00 for the winter. During the summer the openinings remained closed during the day and opened at night.

Envelopes

A Portuguese conventional construction system (double-wall masonry) and a light gauge steel framing system (LGSF) were considered in the model for the opaque envelope. The LGSF envelope composition was based on the research of Santos et al. (2009). The traditional system is composed by lightweight concrete slabs and insulation (stone wool), external walls in double masonry with interior insulation and cement mortar plaster.

The light gauge steel framing system is also composed by lightweight concrete slabs and others insulation components (expanded polystyrene - EPS), and EIFS (External Insulation and Finish System), OSB boards, stone wool and gypsum plasterboard was used in the walls. Table 2 presents the overall heat transfer coefficient values – U -factor (W/m² ºC) for Portuguese conventional construction system and light gauge steel framing system.

Table 2. Overall Heat Transfer Coefficient (W/m² ºC)

Heat Transfer Coefficient (W/m² ºC)		
Element-Envelope	Portuguese Conventional System	
	Total Thickness (cm)	U (W/m²ºC)
External Walls	0.365	0.46
Roof Slab	0.280	0.55
Element-Envelope	Light Gauge Steel Framing System	
	Total Thickness (cm)	U (W/m²ºC)
External Walls	0.200	0.14
Roof Slab	0.333	0.22

Glazing Types

Important factors must be observed in the glazing selection, such as: solar factor (or g-value), solar heat gain coefficient, shading coefficient, and visible transmittance, furthermore U-factor resultant of glazing composition. The glasses selected for the standard façade module simulations are from Saint-Gobain Glass. Table 3 presents the main properties of simple glasses.

Table 3. Glass types.

Glass					
Properties	Cool Lite KNT 155 Green	Bioclean	Planilux	Planitherm Futur Ultra N	Diamant
Thickness (mm)	4 mm	4 mm	4 mm	4 mm	4 mm
Solar Factor	0.45	0.84	0.85	0.63	0.90
Shading Coefficient	0.52	0.97	0.98	0.72	1.04
Visible Transmittance	0.47	0.87	0.90	0.88	0.91
U (W/m²K)	5.75	5.87	5.80	5.73	5.80

These glasses were used in the computational simulations in DesignBuilder software to obtain heating needs to all climates. Furthermore, a 12mm air layer between outermost and inner panes was considered. It should be noted that these values were obtained from Window 6.2.33.0 software (LBNL, 2011). Table 4 presents the glazing compositions based on the glasses types presented in Table 3.

Table 4. Glazing Properties.

Properties	**Glazing**		
	Glazing 04	**Glazing 07**	**Trombe Glazing**
Outermost Pane	Cool Lite KNT 155 Green 4mm	Bioclean 4mm	Diamant 4mm
Inner Pane	Planitherm Futur Ultra N 4mm	Planilux 4mm	Diamant 4mm
U (W/m²K)	1.66	2.69	2.72
Solar Factor	0.28	0.40	0.83
Shading Coefficient	0.33	0.46	0.95
Visible Transmittance (%)	0.42	0.71	0.84
Relative Heat Gain (W/m²)	217.72	311.28	622.90

Cool lite KNT 155 green is a temperable solar control glass; planitherm futur ultra N is a glass with very low emissivity; bioclean is a self-cleaning glass; planilux is a multi-purpose clear float glass and diamant is a clear float glass.

Internal Gains and Reference Temperatures

The Portuguese standard RCCTE (RCCTE, 2006) presents 4W/m² as an average value for the total internal gains (occupation, lighting and equipments). However, due to possibilities and simulation options offered by the software DesignBuilder, the internal gains were separated for the occupation, lighting and equipments (Table 5).

Table 5. Internal Gains (W/m²)

Internal Gains	Values (W/m²)	Details
Occupation	5,6 W/m² (2 people)	70 W per person
Lighting	9,4 W/m²	Illuminance (incidence): 300 lux; Fluorescent lamp (40 W); Efficiency 80 lm/W (40 % delivery efficiency).
Equipments	8 W/m²	Total equipment potency: 200 W.

As RCCTE standard does not have schedules (days of the week, hour and time) of occupation, lighting and equipments use for residential buildings, the values were obtained from Souza (2008). The value 20°C was considered as reference of heating indoor temperature (winter); 25°C for cooling indoor temperature (summer) and the natural ventilation rate was 0.6 air changes per hour, in agreement with RCCTE (RCCTE, 2006).

DISCUSSION AND RESULT ANALYSIS

The heating energy needs for four solar orientations (north, south, east and west), considering the annual period are presented. The analysis of the results is done based on the heating energy needs estimation for Lisbon, Porto, Lajes-Açores e Funchal-Madeira performed according the RCCTE energy calculation method.

Lisbon

All façades with passive solutions analyzed for Lisbon climate presented heating energy needs lower than the one calculated according to RCCTE (56.36 kWh/ m².year) (Figure 7 and 8). The façade solution with Glazing 07 and 1 or 2 Trombe wall presented better results in comparison with the other façade types. It was observed that the heating energy needs are similar for both of the analyzed envelopes. Practically, the results for one or two Trombe walls with the characteristics listed above were identical.

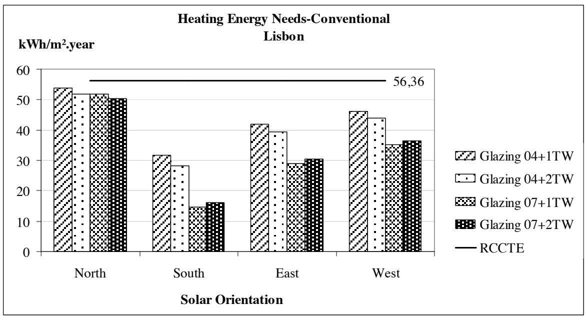


Figure 7. Lisbon: Heating Energy Needs - Conventional System

According to the RCCTE (calculated values) for this model, Lisbon presents the highest cooling needs. Especially in the Lisbon climate, the use of glazing 07 with one and two Trombe walls caused an energy consumption increases by 16-40% (on 32kWh/m².year) for south, east and west solar orientations for double-wall masonry system. This can be reduced, for example, with the use a shading system during the summer.

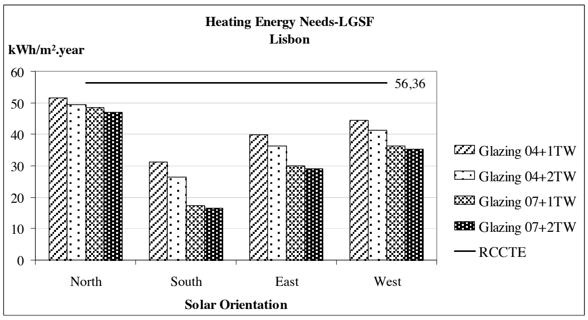


Figure 8. Lisbon: Heating Energy Needs. LGSF System

Porto

Taking into account the results illustrated in Figure 9 and 10, for Porto climate, all analyzed façade types presented heating energy needs lower than the one calculated according to RCCTE (74.66 kWh/ m².year). Glazing 07 and one or two Trombe walls presented better results in comparison with the other façades. For south solar orientation, it was observed an important energy saving with the passive solutions integration. Heating energy needs presented similar values for both envelopes.

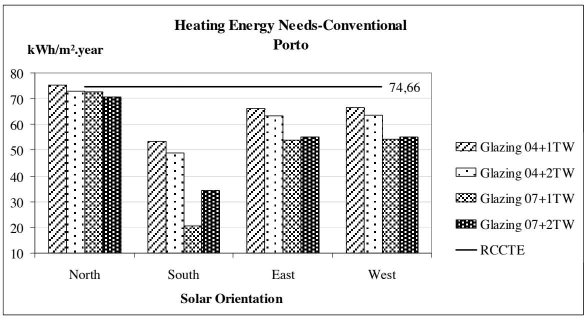


Figure 9. Porto: Heating Energy Needs. Conventional System.

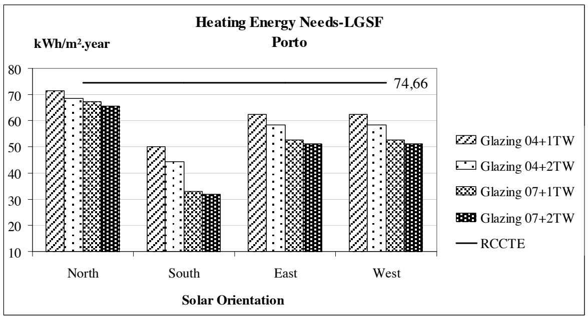


Figure 10. Porto: Heating Energy Needs. LGSF System.

Lajes-Açores

For Lajes-Açores climate, all analyzed façades presented heating energy necessity lower than the one calculated according to RCCTE (36.42 kWh/ m².year) (Figure 11 and 12). Glazing 07 grouped with one or two Trombe wall again presented better results in comparison with the other façades types. Heating energy needs presented lower values for the light gauge steel framing envelope. In general, the results were identical for the use of one or two Trombe walls for glazing 07 results.

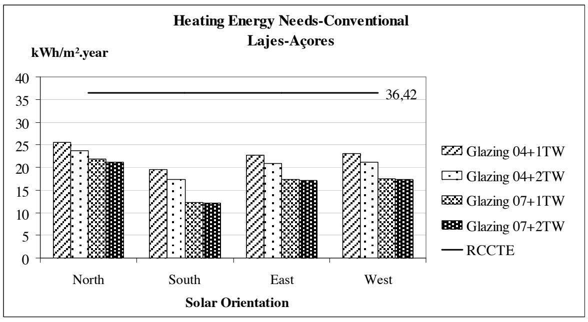


Figure 11. Lajes-Açores: Heating Energy Needs. Conventional System

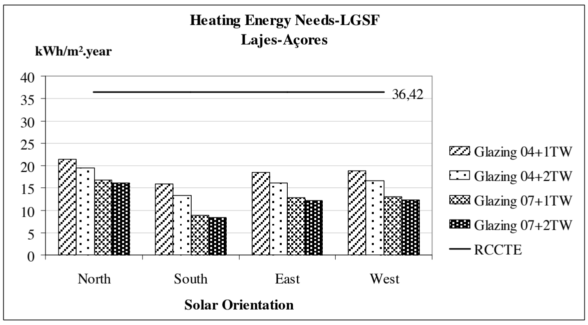


Figure 12. Lajes-Açores: Heating Energy Needs. LGSF System

Funchal-Madeira

All the façade types analyzed for Funchal-Madeira climate presented heating energy needs lower than the one calculated according to RCCTE (46.42 kWh/ m².year) for the analyzed model (Figure 13 and 14). The façade solution Glazing 07 and 1 or 2 Trombe wall presented better results. Heating energy needs presented approximate values for the both analyzed envelopes. For north orientation the solutions variation did not show any significant differences between the results. For south solar orientation, the minimum energy consumption occurred with the passive solutions use.

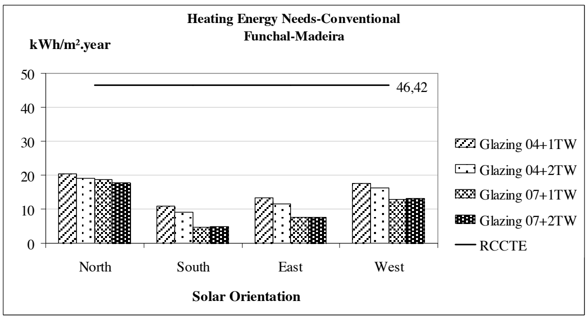


Figure 13. Funchal-Madeira: Heating Energy Needs. Conventional System

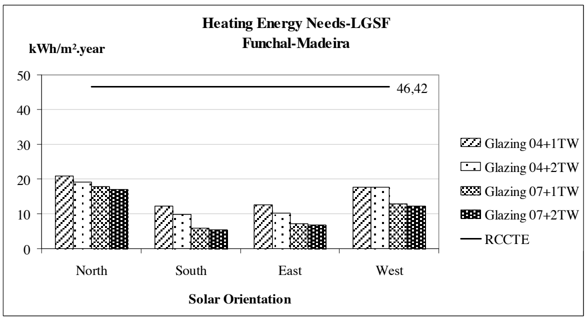


Figure 14. Funchal-Madeira: Heating Energy Needs. LGSF System

CONCLUSION

In this research were performed energy simulations for the two glazing types and Trombe wall for four Portuguese climates. The results showed that all façade types presented heating energy needs lower than the maximum limits according to the Portuguese energy building performance regulation RCCTE. In this case, façades with Glazing 07 (Bioclean 4 mm - Planilux 4 mm) with one or two Trombe walls stood out due to the smallest heating energy need when compared with those others. Heating energy needs were similar to both of the analyzed envelopes. For milder climates, like in Lisbon, Lajes and Funchal, the use of one or two Trombe walls lead to identical results and, therefore, the second Trombe is not needed to achieve the same level of energy savings. For all climates, south solar orientation presented the minimum energy consumption with the passive solutions integration.

According to RCCTE, the period in months of the heating season is for Lisbon 5.3; for Porto 6.7; for Lajes 4 and for Funchal 3.89. It means that, per year, only during these number of months heating is necessary to maintain indoor comfortable conditions.

Based on this and on the achieved results, the integration of passive heating solutions in the façade modules seems to be the adequate strategy proposal to the better performance and to decrease the heating energy needs.

However, it is also very important to consider the cooling energy needs. As an example, Lisbon presents the highest calculated values of cooling needs from RCCTE for this model. Therefore, is important to explain that better façades solution for heating needs caused an energy consumption increases by 16-40% (on 32kWh/m^2.year) in cooling needs. It can be reduced using shading systems during the summer. That kind of module will be foreseen in the façade system.

The integration of the proposed passive solutions in in the façade system concept "Façade Modules for Eco-Efficient Refurbishment of Buildings" can give an important contribution for the energy consumption reduction with heating systems.

Designbuilder software seems adequate to be used for thermal performance simulations of passive systems by the comparison of the results with calculeted heating energy needs according to RCCTE (RCCTE, 2006).

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