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OVERHEATING REDUCTION OF A COLD FORMED STEEL-FRAMED BUILDING USING A HYBRID EVOLUTIONARY ALGORITHM TO OPTIMIZE DIFFERENT PCM SOLUTIONS

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Abstract

Cold formed steel-framed constructions have been strongly disseminated with particular emphasis on the residential sector due to their fast execution, quality control and final cost. However, this construction typology presents a weakness associated with a low thermal inertia and a consequential risk of overheating.

The present research addresses the overheating rate reduction of a cold formed steel-framed building located in the coastal region of mainland Portugal, a particular environment considering the combination of the high outdoor temperature amplitude and the lack of thermal inertia of such building typology. To overcome this weakness, different phase change materials solutions (PCMs) were incorporated into the partition walls and ceilings of south oriented compartments. Thus, thermal energy storage provided by the PCMs solutions play a crucial role in the indoor thermal regulation of the building by minimizing indoor temperature peaks and amplitude improving indoor thermal comfort with lower energy demand.

To optimize the PCM solution in order to reduce the rate of overheating, a hybrid evolutionary algorithm was used in conjunction to the EnergyPlus® simulation engine, adapting a list of parameters. This study was extended to identify the best PCM solution to minimize, in some cases prevent, the overheating risk for different climate applications in Portugal mainland.

The results attained reveal the possibility to reduce the overheating risk by up to 89% in highly glazed south faced compartments and 23% in north orientated compartments. In terms of heating energy demand, a reduction of 17% was also attained, triggered by the PCM storage effect.

Keywords:

Phase Change Materials; Low Inertia; Cold formed steel-framed; Energy Efficiency; Evolutionary Algorithms

1 INTRODUCTION

In the near past (2000 – 2009 period), the energy consumption in EU (European Union) buildings has not changed significantly, however, in South Western European countries the cooling energy demand has increased [1, 2].

In the pursuit of energy savings and thermal comfort, the implementation of new materials and constructive solutions are required in the construction sector. Recent research in this field particularly aimed at cooling demand reduction, is focusing on the following constructions components and strategies that are linked to renewable energy sources: reflective pavements, permeable and water retentive pavements, passive evaporative cooling walls, heat absorbing phase change materials (PCMs), cool roofing materials, green facades and green roofs, night ventilation, ground cooling and floor slab cooling [3-7]. In order to investigate these further, this

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paper explores how the optimization of the building features such as: bypass ventilation air flow capacity; bypass temperature activation; three different window solutions (including double and triple glazing) in combination with thirteen possible PCM solutions with different melting points and latent heat capacity for the partition walls and ceilings of internal compartments south oriented, can be used for overheating reduction.

2 METHODOLOGY

The presented methodology consists in the use of a multi-objective evolutionary algorithm to optimize the building's features with low thermal inertia, with overheating reduction as a goal. To fulfil this goal, dynamic thermal simulation of a cold formed steel-framed detached building was carried out using EnergyPlus® 8.3.0 (EP) software.

The first step starts by a building thermal performance characterization of the original constructive solution (without new features application). In the second step the following features were applied in the model and a thermal characterization was performed and compared with the results attained from the original solution:

- (i) A mechanical ventilation system with heat recovery capacity was specified.
- (ii) Three different windows solutions were tested.
- (iii) Natural ventilation with an air flow rate regulator in h^{-1} was specified.
- (iv) Ventilation by-pass air flow rate was controlled to react to a pre-defined indoor temperature value.

In the third step, thirteen different PCM solutions were combined in the South orientated surfaces and ceiling. In this step the thermal performance was optimized and evaluated and finally, compared with the attained results from the first and second steps.

In the last step the influence of a mix PCM solution combining two PCMs with different melting temperature was evaluated.

3 CASE STUDY: CHARACTERIZATION

The case study building is located in Aveiro at about 5 km from the centre city and 10 km from the Atlantic coast, in North central of Portugal. The building consists of a two-story prefabricated cold formed steel-framed construction with a treated floor area of 148 m^2 and the global percentage of glazing of 16.4% in respect to opaque façade area. The glazing oriented to the Northeast represents a relative percentage of the total glazed area of 32.3%, and 58.7% to Southwest (see Figure 1).

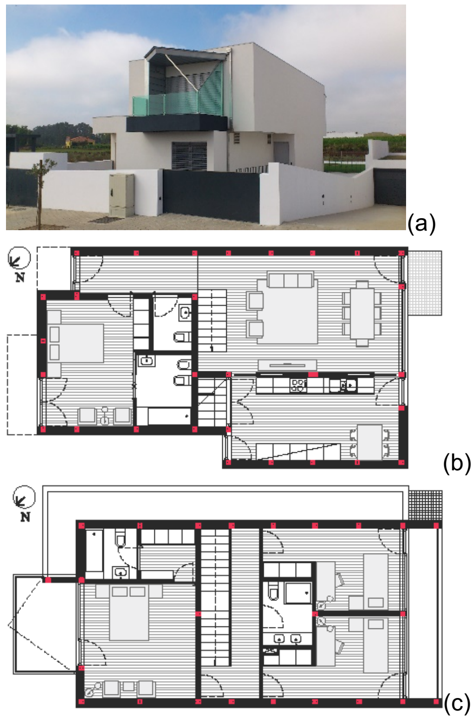

Fig. 1: Architectural blueprints: (a) 3D view; (b) ground floor (c) elevated floor.

The building's external envelope is mainly composed of the followings elements: Ground floor slabs - U_{value} = 0.78 (W/m^2 ºC) and IT (insulation thickness) = 30 (mm); Façade walls - U_{value} = 0.33 (W/m^2 ºC) and IT = 60 (mm); Flat roof - U_{value} = 0.36 (W/m^2 ºC) and IT = 50 (mm).

Windows modelled have a Solar Heat Gain Coefficient (SHGC) of 0.53 and U_{value} of 1.79 (W/m^2 ºC) for the glazing to the Northeast and U_{value} of 1.68 (W/m^2 ºC) to the Southwest.

4 DYNAMIC THERMAL SIMULATION MODEL

Figure 2 shows the SketchUp® model constructed with the OpenStudio plugin, which is a graphical interface used to reproduce the geometry of the model and the thermal zoning division. The annual thermal behaviour of the building was simulated and calculated resourcing to EnergyPlus® software considering the conduction transfer function (CTF) model for the algorithm of surface heat balance calculation. A detached multi-zone model was assembled using eight thermal zones corresponding to the internal compartments of the building (see Figure 2).

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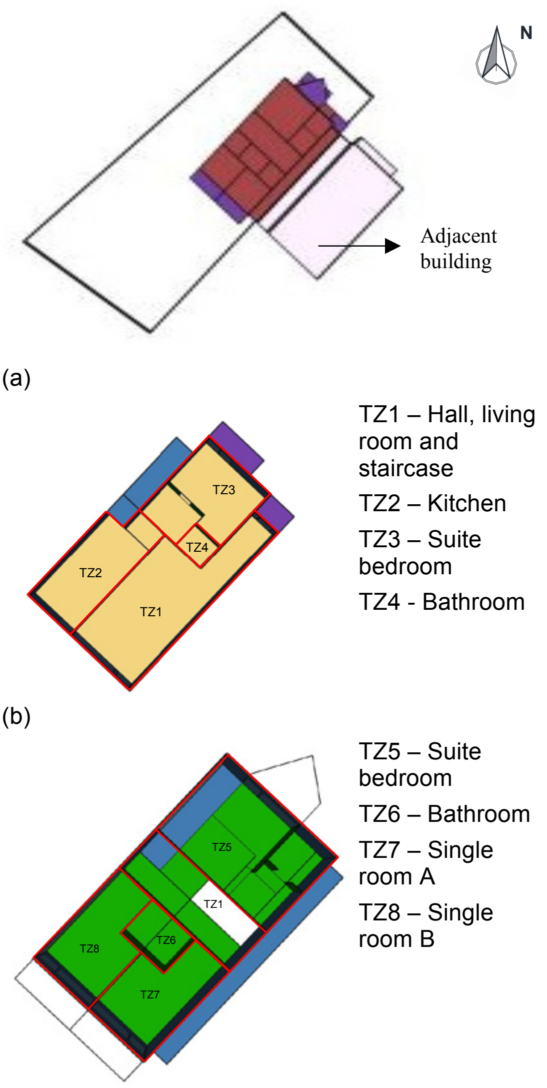

Fig. 2: OpenStudio model geometry: (a) 3D view; (b) Ground floor thermal zones (c) 1st floor thermal zones.

5 RESULTS AND GENERAL DISCUSSION

5.1 Thermal behaviour characterization (1st step)

The original building was simulated considering an ideal air system that meets heating for a setpoint of 20 ºC as minimum indoor temperature to activate the system using an ACR (air change rate) of 0.6 h^{-1}. During the summer season the building characterization was evaluated in terms of an overheating rate considering a mechanical ventilation system with the capacity to provide a constant air flow from the outdoor air of 0.6 h^{-1} without the capacity of air-conditioning.

The results attained were 36.26 (kWh/m^2.a) for heating demand during the heating season and 15.23% of overheating in accordance with the EN 15251 standard during the summer season.

5.2 Thermal behaviour assessment – improvement and optimization (2nd step)

As the original building demands in terms of energy and overheating are important, an optimization process was carried out in order to assess and achieve improved models with a better thermal response.

Passive and hybrid techniques were applied only by changing and optimizing the window solutions, adding a heat recovery air system with capacity to work in by-pass mode increasing the total air flow rate, and by-pass with a temperature control activation based on the indoor air temperature.

The improvements were applied to the model, resorting to an evolutionary algorithm that instructs the software used in the simulations. In the present study (in this step) the parameters used in the optimization process are defined as continuous and discrete variables (see Table 1).

Continuous variables		
Parameter id.	Designation	Box Constraints
x0	Bypass Air flow rate (h^{-1})	0.00 – 2.44
x1	Bypass activation temperature (ºC)	21 - 25
Discrete variables		
x2 (windows North orientated)	Window Solution (W/m^2 °C) ; SHGC	U_{value} = 1.79 SHGC = 0.53
		U_{value} = 0.94 SHGC = 0.61
		U_{value} = 0.70 SHGC = 0.42
x3 (windows South orientated)		U_{value} = 1.68 SHGC = 0.53
		U_{value} = 0.90 SHGC = 0.61
		U_{value} = 0.65 SHGC = 0.42

Table 1: List of parameters.

As objective functions, heating demand and overheating rate were chosen to be minimized by the optimizer. Overheating rate was defined in EP in accordance with EN 15251(category II) [8] and resourcing to Energy Management System (EMS) feature in EP that provides a way to develop custom control and modelling routines.

With this optimization (using the parameters defined in Table 1), higher reductions in heating demand and a significant reduction in the discomfort rate were achieved, when compared to the original solution. The energy and discomfort limits assigned in the plot are indicators of a building with high energy efficiency

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in accordance with the PH (Passive House) standard.

From Figure 3 it is possible to depict the improvement attained in respect to the discomfort rate and heating demand reduction.

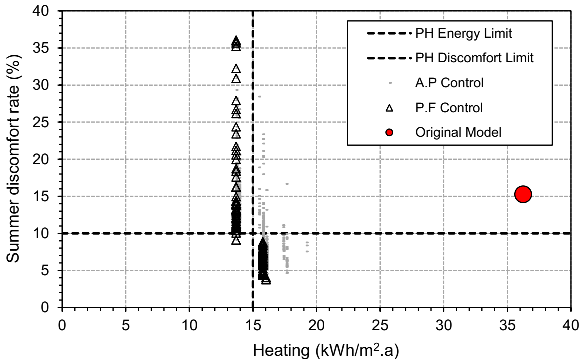

Fig. 3: Optimized results: 1st and 2nd step (A.P- All Points; P.F - Pareto Front).

5.3 Thermal behaviour assessment – PCM solutions and optimization (3rd step)

In this part of this study the initial priority was to prevent overheating during the summer period attaining simultaneously higher thermal comfort levels also using PCM in the constructive solutions.

A layer of PCM was incorporated into the partition walls and ceiling (positioned after the first layer in the wall solution) in the compartments with Southwest orientation (TZ1; TZ2; TZ7; TZ8). The following thirteen PCM solutions were implemented and tested:

(i) Micronal® DS 5001 with a melting point of 21 ºC and an overall enthalpy capacity of 244960 (J/kg) [9];

(ii) BioPCM® series M27 with 21, 23, 25 and 27 different melting point and 289545, 300420, 322285, 322093 overall enthalpy capacity respectively [10];

(iii) BioPCM® series M51 [10];

(iv) BioPCM® series M91 [10].

The results presented in Figure 4 contain the points of the Pareto front (black triangles and black circular shapes markers) which represent a set of optimal solutions.

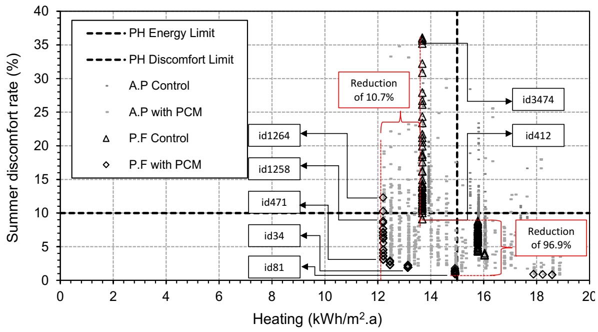

Fig. 4: Optimized results: 3rd step

Through the results, shown in Figure 4, it was observed that the use of PCM solutions has a significant impact during the summer season in the overall overheating reduction (67.1% of reduction). During the heating season, the PCM effect resulted in a heating demand reduction of 10.7%.

Tables 2 and 3 list some of the best solutions after optimization analysis. From Table 2 the main conclusion is the direct relationship between the bypass air flow rate and activation temperature with the summer discomfort rate. A bypass system that works in anticipation (reacting to lower temperature) is a good solution for overheating reduction. Table 3 shows that the best solution in terms of overheating reduction requires the bypass air flow rate at its maximum capacity with a temperature activation of 20.54 ºC using BioPCM type M91 with a melting point of 25 ºC. Other important conclusions are related with the windows solutions. When the main concern is the summer discomfort rate reduction, windows with low U_{value} and SHGC are required for south orientation. For the north orientation this requirement is more permissible to use higher U_{values}.

5.4 Thermal behaviour assessment – Mix PCM solutions and optimization (4th step)

Focusing on the issue of overheating risk and the fact that the PCM is not totally discharged (in a daily cycle), an additional analyse was carried out using a new constructive solution incorporating a mix of two PCMs with different melting points.

Figure 5 presents the results from the optimization.

Optimizer. id#	Bypass Air flow rate (h^{-1})	Bypass activation (°C)	Windows solution north ($W/(m^2\ °C)$)	Windows solution south ($W/(m^2\ °C)$)	Heating demand (kWh/m^2a)	Summer discomfort rate (%)
Id3474	0.10	24.66	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	13.67	35.95
Id412	2.13	20.15	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	13.67	10.03

Table 2: List of solutions in the models without PCM use.

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Optimizer. id#	Bypass Air flow rate (h^{-1})	Bypass activation (ºC)	Windows solution north (W/(m^2 °C))	Windows solution south (W/(m^2 °C))	PCM type	Heating demand (kWh/m^2 a)	Summer discomfort rate (%)
id1264	1.20	20.07	U_{value} = 0.94 SHGC = 0.61	U_{value} = 1.68 SHGC = 0.53	BioPCM M51/Q21/E0.021*	12.31	12.19
id1258	2.16	22.80	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q21/E0.037*	12.20	8.58
id471	2.44	20.00	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q21/E0.037*	12.21	3.07
id34	2.44	20.07	U_{value} = 0.94 SHGC = 0.61	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q25/E0.037*	13.13	1.94
id81	2.44	20.54	U_{value} =1.79 SHGC =0.53	U_{value} = 0.90 SHGC = 0.61	BioPCM M91/Q25/E0.037*	14.92	1.11

* Nomenclature used: M (Btu thermal energy storage capacity); Q (peak melting temperatures in degrees Celsius); E (thickness).

Table 3: List of solutions in the models with PCM.

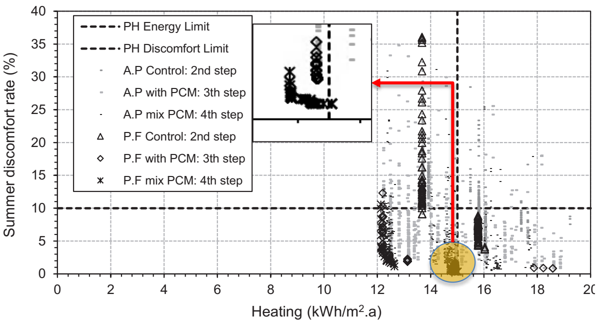

Fig. 5: Optimized results: 4th step.

The use of PCM solutions with different melting points resulted in an improvement in the thermal comfort during the summer season. A reduction of 57% of the discomfort rate was achieved compared to the model with the lowest discomfort rate (0.82% of discomfort rate) from the optimization with PCM solutions with the model that uses a mixed PCM solution (0.35% of discomfort rate).

The optimized solution attained combines the bypass air flow rate of 2.44 h^{-1} with a temperature activation of 20 ºC using windows with U_{value} = 0.70 (W/(m^2 °C)) and SHGC = 0.53 north orientated and U_{value} = 0.65 (W/(m^2 °C)) and SHGC = 0.61 south orientated. This solution was combined with 62% of BioPCM type M91 with a melting point of 23 ºC and 38% of BioPCM type M91 with a melting point of 21 ºC.

6 FINAL REMARKS AND CONCLUSIONS

This study has tackled the overheating reduction issue in low thermal inertia buildings. Different PCM solutions were applied and optimized in the internal partitions and ceiling in the compartments with south orientation.

The main conclusions that can be taken are:

(i) From the work developed, PCM provides a favourable thermal regulation effect with a high reduction in the thermal indoor discomfort rate;

(ii) The selection of the melting point of the PCM is crucial to fully take advantage of the PCM (charging and discharging process on a daily cycle);

(iii) Combining different solutions of PCM with different melting points is advisable since it increases the potential for overheating reduction. The annual overall thermal comfort is improved and cooling energy demand is reduced;

(iv) The ventilation rate is essential to assure the discharging process of the PCM. The charging and discharging processes are only possible due to an effective combination of the PCM melting temperature selection and optimized ventilation rate.

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