Energy Production in Solar Collectors in a University Building Used to Improve the Internal Thermal Conditions in Winter Conditions

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Abstract. In this numerical study the energy production in solar collectors in a University building used to improve the internal thermal conditions is made. Passive and active solutions, using external solar collector and internal thermo-convectors, are used. The numerical simulation, in transient conditions, is done for a winter typical day with clean sky. This numerical study was carried out using a software that simulates the Building Dynamic Response with complex topology in transient conditions. The software evaluates the human thermal comfort and indoor air quality levels that the occupants are subjected, Heated Ventilation and Air Conditioned energy consumption, indoor thermal variables and other parameters. The university building has 107 compartments and is located in a Mediterranean-type environment. External solar water collectors, placed above the building's roof, and internal thermo-convectors of water/air type, using mixing ventilation, are used as passive and active strategies, respectively. The thermal comfort level, using the Predicted Mean Vote index, and the indoor air quality, using the carbon dioxide concentration, are evaluated. The results show that in winter conditions the solar collectors improve the thermal comfort conditions of the occupants. The indoor air quality, in all ventilated spaces, is also guaranteed.

1 Introduction

In Portugal, there has been a significant increase in energy consumption in buildings, driven in part by the intensive use of Heated Ventilation and Air Conditioned (HVAC) system equipment and the dissipative behaviour of the building. In this context, the need to develop HVAC systems that enable thermal comfort levels to be maintained with sustainable low energy consumption becomes imperative.

This study is associated with the development and application of a solar HVAC system. The HVAC system of the building's compartments, in winter conditions, is carried out using solar thermal energy. The objectives are to obtain numerically the level of thermal comfort and the quality of the indoor air to which the occupants of the rooms are exposed. The HVAC system simulated uses solar panels that, through a system of ducts, which will provide the heating of the rooms interior by thermo-convectors.

Several works were developed in the application of thermal solar collectors. In the work of Kalogirou et al. [1] the review of exergy analysis in solar thermal collectors was analysed. In the work of Suman et al. [2] a review performance of solar collectors was made. In the work of Jamar et al. [3] a review of the water heating system for solar energy applications was analysed.

Several parameters are used in the evaluation of the thermal comfort and indoor air quality, namely, Predicted Mean Vote (PMV) index, Predicted Percentage of Dissatisfied (PPD) index and carbon dioxide (CO_2) concentration. CO_2 concentration can be used to evaluate indoor air quality [4-6]. PMV and PPD, see Fanger [7], are applied to determine the thermal comfort conditions in conditioned spaces and they are used by ISO 7730 [8] and ASHRAE 55 [9] to define three thermal comfort categories (A, B, C) requirements.

In this study a software, that simulate the Building Dynamic Response, which evaluates the air temperature distribution, surfaces temperature distribution and energy consumption is used (see the works of Conceição and Lúcio [10,11]). The software considers the evaluation of thermal comfort through the PMV/PPD indexes [12], adaptive thermal comfort [13], and temperature control model [14]. The study of Conceição et al. [12] shows also a control methodology of the HVAC system based on PMV.

This kind of simulation was made by others authors using others numerical models. The wall building thermal performance is study in Balaji et al. [15], a

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review of the building thermal comfort and building energy consumption are presented in Yang et al. [16], and the building energy simulation model of green roof is shown in Sailor [17].

In order to evaluate the occupant thermal comfort level, that each occupant is subjected, and the airflow topology inside each space, the results obtained in this software can be used in others software that consider a coupling of Computer Fluid Dynamics (CFD) and Human Thermal Response (HTR) numerical models. This methodology can be seen in the studies of Conceição and Lúcio [18-20], Conceição [21], and Conceição et al. [22,23].

The thermal comfort is a topic analysed, in the last years, by several authors. Examples can be showed in the works of Ekici [24], Fabbri [25], and Pourshaghaghy and Omidvari [26]. In Ekici [24], a review of thermal comfort and a review method of the application of the Fanger's PMV and PPD equations is analysed. Fabbri [25] used the thermal comfort level in the evaluation of kindergarten spaces comfort conditions is analysed. In this study measurements of PPD and PMV indexes and questionnaire are used. Pourshaghaghy and Omidvari [26] used the PPV and PPD indexes in order to evaluate the thermal comfort in a hospital environment.

In this study, it is used a new methodology to heating the occupied spaces through a natural renewable energy source, particularly, solar energy. The process is based on the application of solar thermal collectors, placed above a university roof area, to heat water which will be used inside the occupied compartments by thermo-convectors. The HVAC system, based on a set of thermo-convectors, will be controlled by a PMV index control system in order to guarantee acceptable thermal comfort levels within category C [8].

The main objective of this work is from a passive solar solution, using solar thermal collectors, and from an active solution, control of the HVAC system, to guarantee acceptable thermal comfort levels within the occupied compartments, keeping the PMV index at least within the category C, and acceptable levels of indoor air quality, keeping the CO_2 concentration below 1800 mg/m^3, for winter conditions. The use of these two solutions will allow to obtain energy gains, in addition to promoting the use of a renewable energy source in the implementation of HVAC systems.

2 Numerical Model

In this numerical simulation, a research software, developed by the authors over the past two decades, was used to evaluate the Building Dynamic Response. The numerical model, that simulate the Building Dynamic Response, can be analysed, for example, in Conceição et al. [27] and Conceição and Lúcio [28]. In these works, all main equations and all main coefficients are presented. These studies presented different applications, however, in both applications the thermal response, the energy consumption and the thermal comfort are analysed in detail. The software used in this work was validated, using school buildings, for winter

conditions in Conceição et al. [29] and for summer conditions in Conceição and Lúcio [30].

The numerical model is based on the balance of mass and energy integral equations. The mass balance integral equations are considering for the water vapour and the air contaminants. These equations are developed for the spaces of the buildings and the solid matrix (opaque and interior bodies). The energy balance integral equations are taken for the indoor air of the compartments, the transparent (windows) bodies of the building, the interior and surroundings bodies of the building and the opaque (walls and doors) bodies of the building. The resolution of the equations system is done by the Runge–Kutta–Felberg method with error control. The outputs of the numerical software are the solar radiation evolution, radiation heat exchange, convection coefficients, indoor air temperature, indoor air velocity, dioxide carbon concentration, PMV and PPD thermal comfort indexes, among others.

This numerical model is used to calculate:

- the temperatures of indoor spaces,
- the temperature of opaque bodies (ceiling, floor, walls and others);
- The temperature of transparent bodies (windows);
- The temperature of the interior bodies.

The numerical model calculates also the:

- Concentration of contaminates (as carbon dioxide concentration);
- Concentration of water vapour.

In the assessment of the indoor air quality, the CO_2 concentration is used. In the evaluation of the level of thermal comfort, the PMV index is used [7]. This index considers the values of the environmental and personal parameters. In the environmental parameters are considered the mean air velocity, mean air temperature, mean air relative humidity and mean radiant temperature. In the personal parameters this index considers the activity level and clothing level. In the monitoring and controlling the HVAC system, it will be used the PMV index [8].

3 Numerical Methodology

The building used in this work is an educational building (Figure 1) constituted essentially by classrooms, amphitheatres and an auditorium. It consists of 125 transparent surfaces, 1550 opaque surfaces and 107 compartments distributed between a ground floor and two upper floors, where teaching activities take place. The HVAC system will only be applied in the 33 occupied compartments.

This numerical simulation considers the internal occupation and ventilation. The selection of the airflow rate took into account the situation of occupation or non-occupation of spaces. When the spaces are occupied, the airflow rate used was calculated according to the Portuguese standard [31]. When spaces are not

occupied, it was used an airflow rate of one air renewal per hour.

In the numerical simulation, it was considered that the classrooms, laboratories and offices are occupied, in general, by periods of 90 minutes. The breaks considered between the occupation periods have a duration of 15 minutes. As the numerical simulation was performed for typical winter conditions, it was defined a clothing level of 1 clo [8]. The level of activity considered was 1.2 met [8].

A numerical simulation was made using 611 solar collectors (with dimensions 2 x 1.1 m^2) installed on the roof of the building (Figure 1) to provide heat to the air conditioning system, in winter conditions [32]. The

collectors are placed together to make up rows. The heated water in the collectors is distributed throughout the building through a system of thermally insulated pipes. The HVAC system, worked as heating system, consider thermo-convectors installed on the ceiling of each occupied spaces. Figure 2 presents a system sketch for the technical system showing connections of the solar collectors to ducts and to internal thermo-convectors. Figure 2 also shows the airflow patterns in the room.
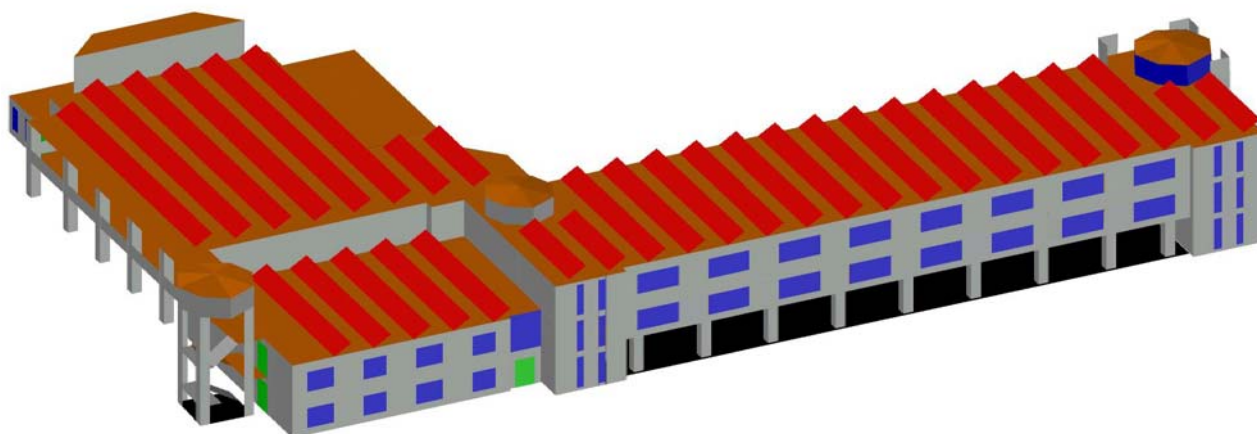
Figure 1. South-east view of the external perspective of the university building with solar collectors (red colour) installed on the roof.
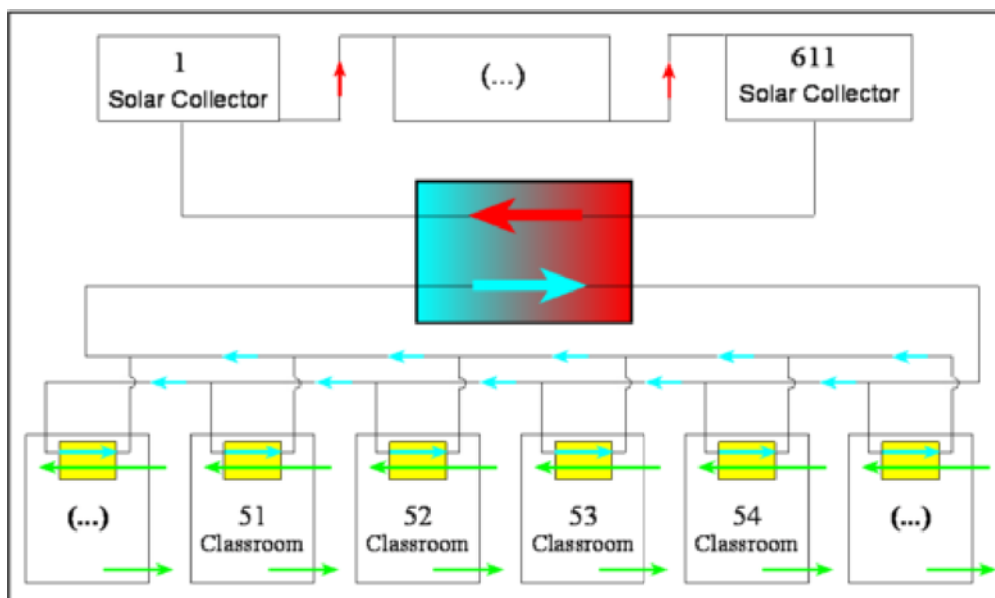
Figure 2. Scheme of circuits between solar collectors, fluid deposit, and classrooms: in red, hot water circuit; in blue, cold water circuit. In addition, it is visible the airflow (green colour) inside of classrooms in contact with a heat exchanger.

4 Results

This section presents the results obtained of the average indoor air temperature (Figure 3), indoor

thermal comfort level (Figure 4), using average PMV index, and indoor air quality level (Figure 5), using CO_2 concentration, for four classrooms with East-facing windows. Figures 3 and 4 also shown, comparatively, the evolution of indoor air temperature and PMV index

without and with the application of a solar renewable energy system. The perception of the thermal comfort of the occupants is given by the PMV index. The PMV index presented corresponds to the average value obtained in the occupied area. This value is obtained according to the average values of the air temperature, the air speed and the relative humidity of the air obtained in the occupied area. The PMV also depends on the average radiant temperature obtained in the center of the occupied area due to the existing radiative exchanges with the surrounding surfaces. In addition to the environmental parameters, the PMV index also considers the personal parameters given by the average level of clothing (1.0 clo in winter conditions) of the occupants and by their level of activity (1.2 met). The perception of indoor air quality is given by the average concentration of CO_2 in the occupation area.

The results show that the use of the solar HVAC system allows to increase, on average, the indoor air temperature of the classrooms by 4ºC to a value around 20ºC. However, the behaviour of this system is not so significant in the morning because there is not enough energy available.

When the space is occupied and the solar HVAC system is used, the control of this system through the PMV index allows to guarantee acceptable levels of thermal comfort within category C (PMV between -0.7 and +0.7) of ISO 7730 [8] by negative values of PMV index. The HVAC solar heating system is connected when the PMV value is lower than -0.7 and disconnected when the PMV value is higher than -0.7.

Finally, the ventilation topology used guarantees acceptable indoor air quality according to the ASHRAE 62.1 standard [4].

The results of the simulation, carried out for winter conditions, show that the solar HVAC system produces enough energy to provide acceptable levels of thermal comfort and indoor air quality in all rooms throughout the occupation regime.
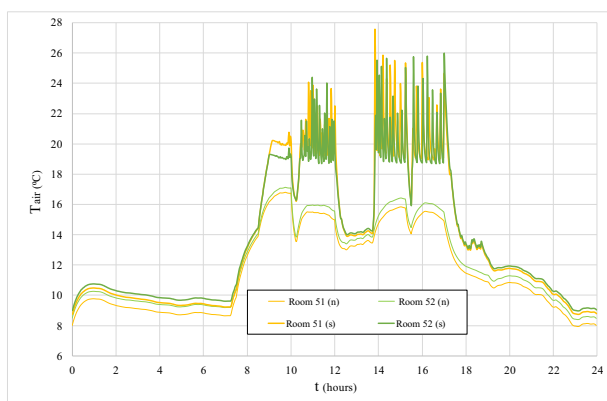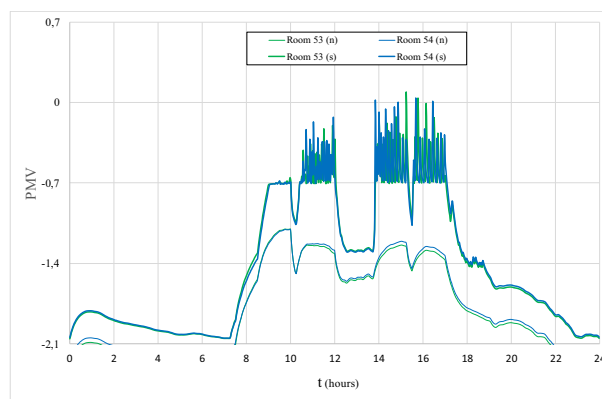

Figure 3. Evolution of air temperature (T_{air}) on the rooms, in the East side building, in winter conditions, the classrooms 51 and 52, where the thin line is associated with none (n) solar renewable energy system, while the thick line is associated with (s) solar renewable energy system.
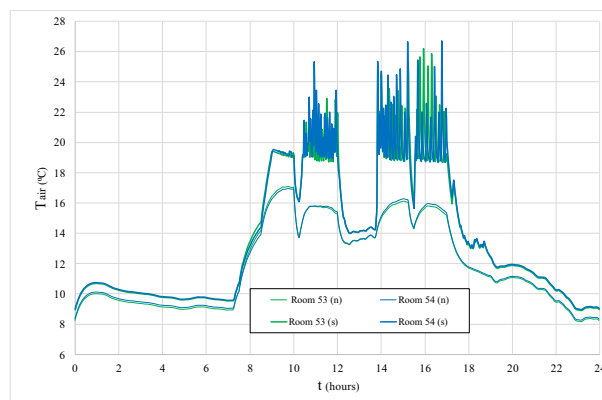
Figure 4. Evolution of air temperature (T_{air}) on the rooms, in the East side building, in winter conditions, the classrooms 53 and 54. The thin line is associated with none (n) solar renewable energy system, while the thick line is associated with (s) solar renewable energy system.
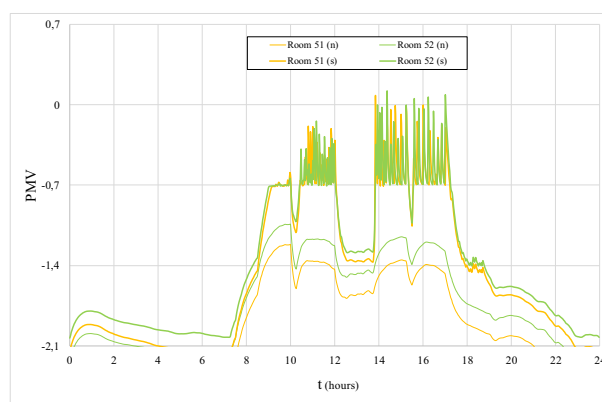

Figure 5. Evolution of PMV index on the rooms, in the East side building, in winter conditions, the classrooms 51 and 52, whereas the thin line is associated with none (n) solar renewable energy system, while the thick line is associated with (s) solar renewable energy system.


Figure 6. Evolution of PMV index on the rooms, in the East side building, in winter conditions, the classrooms 53 and 54, whereas the thin line is associated with none (n) solar renewable energy system, while the thick line is associated with (s) solar renewable energy system.
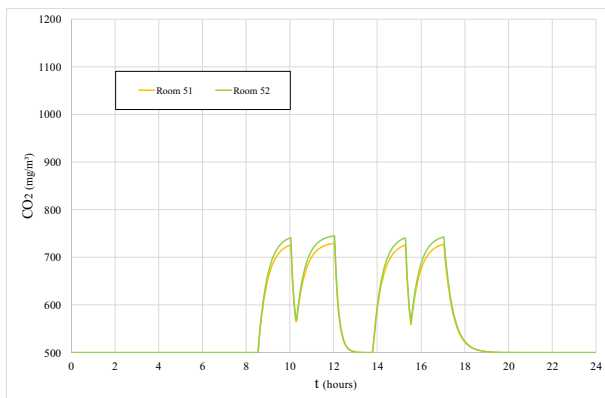
Figure 7. Evolution of CO_2 concentration in the rooms, in the East side building, in winter conditions, the classrooms 51 and 52.
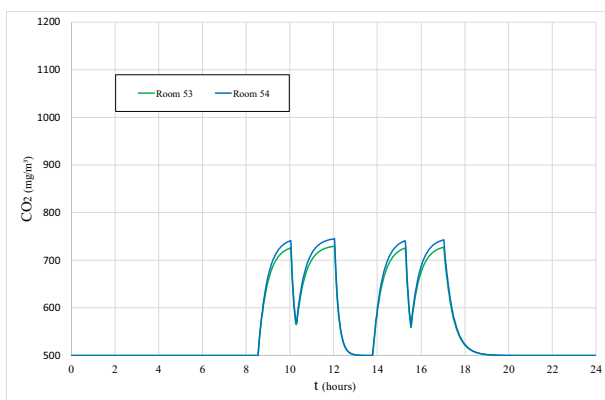
Figure 8. Evolution of CO_2 concentration in the rooms, in the East side building, in winter conditions, the classrooms 53 and 54.

5 Conclusion

This work presented an analysis of the energy production in solar collectors in a university building used to improve the internal thermal conditions in winter conditions. The numerical study was developed through a Building Dynamic Response software. In this study a HVAC system, based on the use of solar energy produced in collectors and with control of the PMV index, were developed.

The use of the solar HVAC system, with control of the PMV index, makes it possible to guarantee acceptable levels of thermal comfort for occupants within category C [8]. The air temperature inside these four compartments rises to around 20ºC. The indoor ventilation topology guarantees also acceptable levels of indoor air quality.

In a future work the solar HVAC system will be applied to improve the thermal conditions of all occupied rooms in the building. It will be assessed whether the energy production will be sufficient to guarantee acceptable levels of thermal comfort in winter conditions.

Acknowledgement

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