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Application of Cold Radiant Surfaces in the Buildings Development in Summer Conditions

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Abstract

This paper presents a numerical study of sustainable energy application in the buildings construction using cold radiant surfaces in summer conditions. The study is made in a University building and the proposed technology is used to improve the internal thermal comfort conditions in summer conditions. This numerical study uses a software that simulates the whole Building Dynamic Response with complex topology in transient conditions. The numerical model is founded on the balance of energy and mass integral equations. 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 mass balance integral equations, taken into consideration for the water vapor and the air contaminants, are developed for the spaces of the buildings and the solid matrix (opaque and interior bodies). The software is used to assess the human thermal comfort and indoor air quality levels, the cold radiant system, indoor thermal variables, and other parameters. The building analyzed in this work has 107 compartments, of which 33 are for classes. The radiant system is based on the use of subterraneous cold water. Three situations were analyzed: without cold radiant surfaces, with horizontal cold radiant surfaces and with all compartment cold radiant surfaces. The thermal comfort level, using the Predicted Mean Vote (PMV) index, and the indoor air quality, using the carbon dioxide concentration, are evaluated. The results demonstrate that the implemented Heated Ventilation and Air Conditioned system, working in Ventilation and Radiant methodology, with the use of all surfaces equipped with a cold radiant system, allows to guarantee, in the morning, acceptable, and, in the afternoon, near acceptable levels of thermal comfort by PMV index values according to category C of the standard ISO 7730. During occupancy, the indoor air quality levels obtained in the compartments are near the acceptable limit provided by the ASHRAE 62.1 standard.

Introduction

Nowadays, it is common to find the application of radiant heating/cooling systems in new commercial, residential and industrial buildings, due to the comfort advantages and the energy saving opportunities these systems can offer (Olesen, 1997). The use of these kind of radiant systems integrated in walls, floors and ceilings has been studied over the last few years. In the work of Fonseca (2011), the behaviour of the hydronic ceiling system and the interactions with its environment has been experimentally and numerically evaluated. Gao et al. (2017) present a design method of radiant cooling air conditioning system with good results on obtaining human thermal comfort conditions in a building. Krajcik et al. (2013) performed four experiments with different combinations of ventilation systems and radiant heating/cooling systems. They use a mixing ventilation system supplying warm air for space heating or a combination of radiant floor heating and mixing ventilation system for winter conditions. For summer conditions, they use a displacement ventilation system combined with radiant floor cooling. This combination provides good ventilation effectiveness with a draft risk acceptably low (Krajcik et al., 2016). Nemethova et al. (2017) carried out a comparative study about the potential of enhancing thermal comfort and energy consumption created by three different radiant systems, namely, floor heating/cooling, a thermally active ceiling, and a near-surface thermally active ceiling. Ning et al. (2016) proposed a type of cooling radiant ceiling panel whose evaluation showed it has the potential to improve the thermal comfort conditions as well as to provide good indoor environment. Other studies on energy efficiency and/or thermal comfort improvements provided by radiant systems are shown in the works of Oxizidis and Pappadapoulos (2013), for radiant cooling systems, of Yang et al. (2017), for a radiant cooling and displacement ventilation system, and of Conceição and Lúcio (2010).

The indoor thermal comfort level is usually evaluated by the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD) indexes. These indexes were developed by Fanger (1970) for occupied spaces acclimatized by Heated Ventilated and Air Conditioned (HVAC) systems. The PMV index depends on four environmental variables (indoor air temperature, mean radiant temperature, indoor air relative humidity and indoor air velocity) and two personal variables (activity and clothing insulation levels). ISO 7730 (2005) uses these indexes to classify the thermal comfort conditions of indoor occupied spaces according to three categories:

A (-0.2 ≤ PMV +0.2); B (-0.5 ≤ PMV +0.5); and C (-0.7 ≤ PMV +0.7).

The carbon dioxide (CO_2) concentration can be used, in a large number of cases, to evaluate the indoor air quality and the ventilation system performance (Asif et al., 2015; Cheng et al., 2019; ASHRAE, 2016). The relationship between CO_2 concentration and the ventilation rate, under steady-state conditions, is presented in ASHRAE 62.1 (2016). The human CO_2 generation rates depends on the physical activity, the respiratory level, the height and body mass of the person (Persily and Jonge, 2017). A CO_2 concentration below 1800 mg/m^3 is currently considered an acceptable indoor air quality value (ASHRAE, 2016).

The aim of this numerical study is to evaluate the indoor air quality and the thermal comfort conditions for occupants of a University building provided with a cooling radiant HVAC system. The study was developed for typical summer conditions in the region where the building is located, whose climate is of the Mediterranean type. This study comprises the analysis of three situations:

- without cold radiant surfaces (reference case),
- with horizontal (floor and ceiling) cold radiant surfaces
- with all compartment (walls, floor and ceiling) cold radiant surfaces.

Numerical Models

In this numerical study, it is used a whole building thermal response (WBTR) numerical model, a research software developed and upgraded by the authors over the years. The WBTR is based on a system of balance integral equations of energy and mass, solving by Runge-Kutta-Felberg method with error control, and works in transient conditions.

The energy balance integral equations are taken for the:

- indoor air of the compartments:
- the transparent (windows) bodies of the building;
- the interior bodies located inside the compartments;
- surroundings bodies of the building and the opaque (walls and doors) bodies of the building.

The energy balance integral equations considers the conduction, convection, evaporation/condensation, solar radiations and others phenomena.

The mass balance integral equations are taken into consideration for the:

- water vapor inside the air compartments;
- water vapor inside the solid matrix (opaque and interior bodies);
- air contaminants (including CO_2) inside the
- compartments;
- air contaminants inside the solid matrix (opaque and interior bodies).

The mass balance integral equations considers the convection, diffusions, adsorption/desorption and others.

The geometry of the building, created by a Computer-Aided Design software, is used to developed the energy and mass balance integral equations.

This software is used to assess the:

- air temperature inside the compartments;
- air velocity inside the compartments;
- air relativity humidity inside the compartments;
- Mean Radiant Temperatures of the surroundings surfaces (calculated based in the surrounding surfaces as ceiling, floor and walls) of the compartments;
- average PMV index within each occupied space (used to evaluate the level of thermal comfort for occupants);
- carbon dioxide concentration (used to evaluate indoor air quality);
- among other variables.

Example of the WBTR was applied on studies about the thermal comfort conditions obtained in buildings by using different solar passive and active solutions (Conceição et al., 2010, 2019), and on studies about the assessment of indoor air quality using different ventilation strategies (Conceição et al., 1997, 2012, 2018).

Numerical Methodology

The numerical simulation was done for the whole building (Figure 1) located on a University Campus of southern region of Portugal characterized by a Mediterranean-type climate. This building is constituted mainly by:

- Classrooms;
- Amphitheatres;
- Large auditorium.

The building has:

- 125 transparent surfaces;
- 1550 opaque surfaces;
- 107 compartments distributed between a ground floor and two upper floors, where teaching activities take place.

The cooling radiant HVAC system is only applied to the 33 occupied spaces. The radiant cooling system consists of a circuit of pipes installed on the walls, floor and ceiling of the building's compartments. The pipes are fed with water cooled to 18°C pumped from an underground space and the entire system works in a closed circuit.

This numerical simulation considers that:

- when the compartments are occupied, it was used an airflow rate calculated according to ASHRAE 62.1 (2016);
- When compartments are not occupied, it was used an airflow rate of one air renewal per hour.

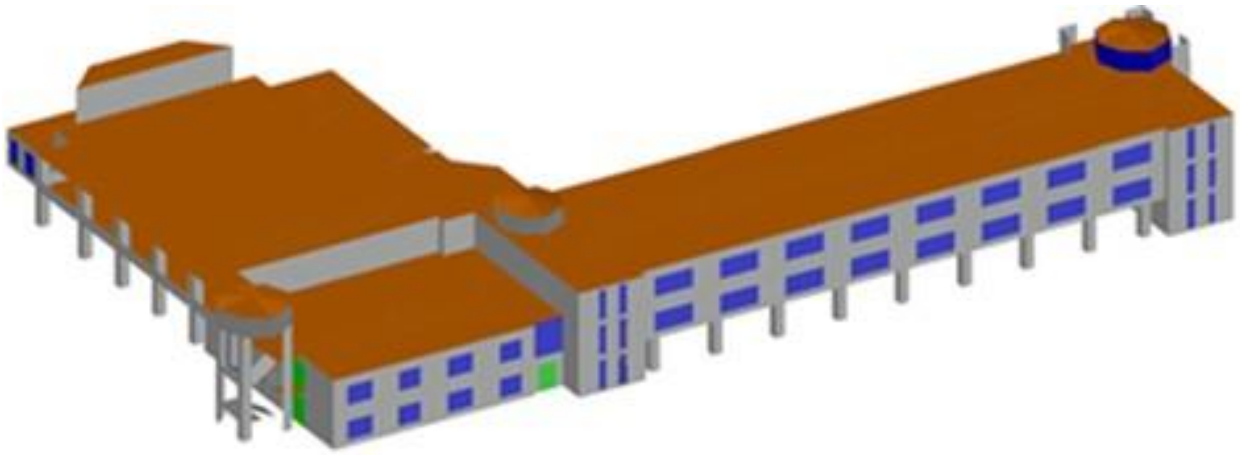
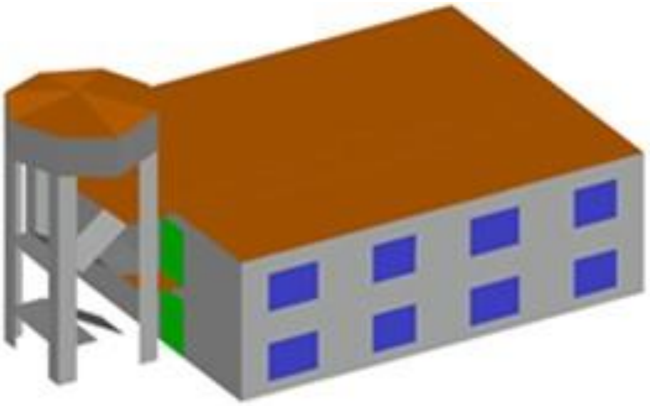
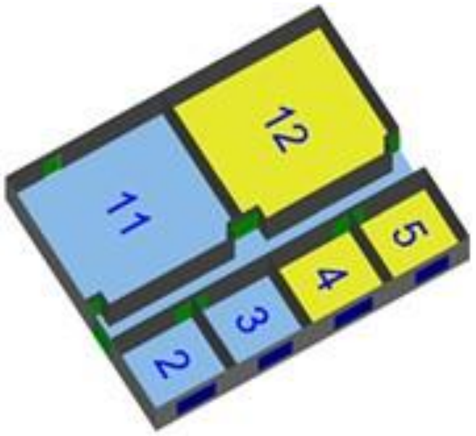


Figure 1: South-east view of the university building used in the numerical simulation.



a)



b)

Figure 2: a) Section of the building in analysis; b) plant view of the ground floor with the analyzed rooms 4, 5 and 12 highlighted in yellow.

For this purpose, the classrooms are occupied, in general, by periods of 90 minutes, with breaks of 15 minutes between periods. The occupancy cycle occurs between 8:00 am and 6:45 pm. The thermal comfort conditions and indoor air quality in all compartments were evaluated by this numerical simulation. However, in this work only the results obtained in classrooms 4 and 5 and in amphitheatre 12 located on the ground floor of the building (whose section and its plant view are shown in Figure 2) are presented. Classrooms 4 and 5 have east-facing windows and amphitheatre 12 has no windows. The average occupancy considered in the classrooms was 20 occupants and in the amphitheatre was 50 occupants. It was considered 1.2 met as the activity level of the occupants (ISO 7730, 2005). Therefore, the estimated clothing insulation level was 0.5 Clo (ISO 7730, 2005).

In this work the implementation of A HVAC system is made. However, this system only works in ventilation and cooling radiation methodology.

Three numerical simulations were done, which are characterized by the use of:

- no cooling radiant surfaces are used;
- only horizontal (floor and ceiling) cooling radiant surfaces are used;
- all (walls, floor and ceiling) cooling radiant surfaces are used. In this Case a uniform radiant system is promote to the occupants.

In this study the accepted thermal comfort conditions, promote to the occupants, in occupied spaces, are in accordance with the category C of the ISO 7730 (2005).

Results and Discussion

At this point, the results obtained for the evolution of indoor air quality level (Figure 3), using CO_2 concentration, of indoor air temperature (Figure 4), of mean radiant temperature (MRT) of indoor surroundings surfaces (Figure 5), and indoor mean thermal comfort level (Figure 6), using PMV index, for two classrooms with east-facing windows (rooms 4 and 5) and one amphitheatre without windows (room 12) are presented.

The results were obtained for the three following situations characterized by the use of: no cooling radiant (NCR) surfaces; horizontal cooling radiant (HCR) surfaces; and all cooling radiant (ACR) surfaces.

In general, during occupancy, the indoor air quality level is not acceptable in the analyzed compartments (ASHRAE, 2016). However, the CO_2 concentration values obtained are close to the acceptable level (1800 mg/m^3). In this case, it is necessary to slightly increase the air renewal rate provided by the ventilation system.

When the radiant cooling system is not used (reference case), during occupancy, the air temperature inside compartments 4, 5 and 12 varies, respectively, between 31.7°C and 37.6°C, between 31.3°C and 37.7°C, and between 27.1°C and 36.6°C. The lowest air temperature values are obtained in the early morning and the highest in the afternoon. The heating of the indoor air in compartments 4 and 5, throughout the day, is essentially due to the incident solar radiation through the windows during the morning and to the accumulation of heat produced by the occupants. In compartment 12, the heating of the indoor air is mainly due to the heat produced by the occupants. When the radiant cooling system on horizontal (floor and ceiling) surfaces is used, the air temperature inside compartments 4, 5 and 12 varies, respectively, between 27.1°C and 34.1°C, between 26.8°C and 34.2°C, and between 24.5°C and 34.5°C. The use of this system makes it possible to lower the temperature of the indoor air in compartments 4, 5 and 12 compared to the reference case by, on average, 3.9°C, 3.8°C and 2.2°C. When the radiant cooling system on all (walls, floor and ceiling) surfaces is used, the air temperature inside compartments 4, 5 and 12 varies, respectively, between 22.6°C and 32.2°C, between 22.5°C and 32.4°C, and between 20.9°C and 32.1°C. The use of this system makes it possible to significantly lower the temperature of the indoor air in compartments 4, 5 and 12 compared to the reference case by, on average, 6.9°C, 6.8°C and 5.0°C.

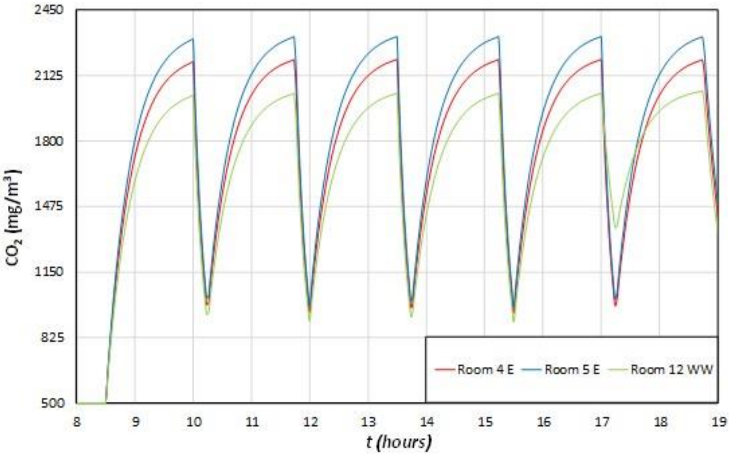


Figure 3: Evolution of CO_2 concentration in the compartments 4, 5 and 12. In the legend, E and WW means, respectively, east-facing windows and without windows.

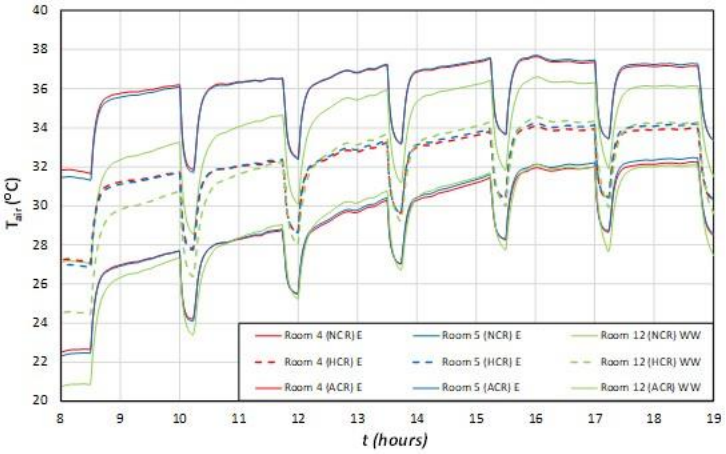


Figure 4: Evolution of indoor air temperature (T_{air}) in the compartments 4, 5 and 12 for the three cases studied: no cooling radiant (NCR) surfaces; horizontal cooling radiant (HCR) surfaces; and all cooling radiant (ACR) surfaces. In the legend, E and WW means, respectively, east-facing windows and without windows.

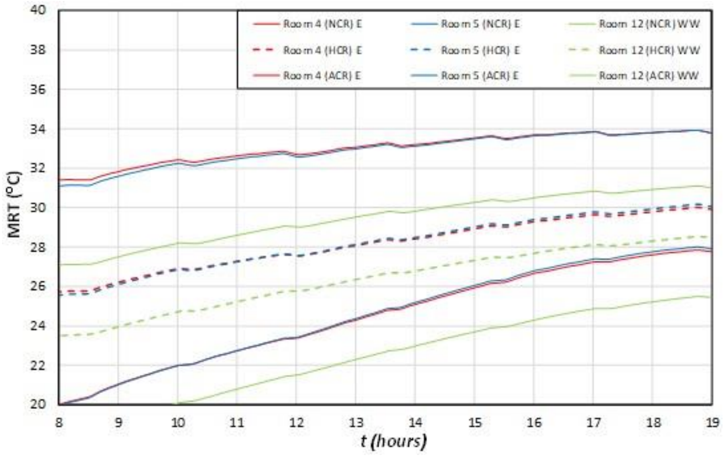


Figure 5: Evolution of mean radiant temperature (MRT) in the compartements 4, 5 and 12 for the three cases studied: no cooling radiant (NCR) surfaces; horizontal cooling radiant (HCR) surfaces; and all cooling radiant (ACR) surfaces. In the legend, E and WW means, respectively, east-facing windows and without windows.

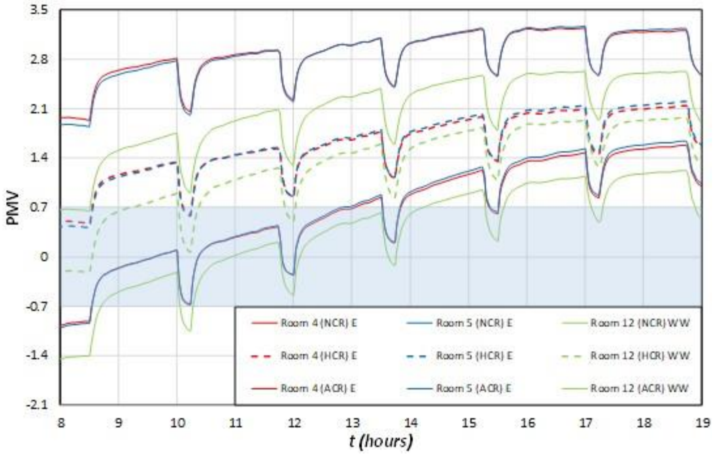


Figure 6: Evolution of PMV index in the compartments 4, 5 and 12 for the three cases studied: no cooling radiant (NCR) surfaces; horizontal cooling radiant (HCR) surfaces; and all cooling radiant (ACR) surfaces. In the legend, E and WW means, respectively, east-facing windows and without windows. The shaded area delimits category C of ISO 7730 (2005).

When the radiant cooling system is not used (reference case), during occupancy, the MRT in compartments 4 and 5 varies between around 31.0°C and 34.0°C, and in compartment 12 varies between around 27.0°C and 31.0°C. The lowest MRT values are obtained in the early morning and the highest in the end of afternoon. The MRT values in compartment 12 are lower than in compartments 4 and 5 because it is not subject to incoming solar radiation, a positive factor in summer conditions. When the radiant cooling system on horizontal (floor and ceiling) surfaces is used, the MRT in compartments 4 and 5 varies between around 26.0°C and 30.0°C, and in compartment 12 varies between around 24.0°C and 28.5°C. The use of this system allows to reduce, on average, the MRT in compartments 4 and 5 of 4.8°C and in compartment 12 of 3.1°C. When the radiant cooling system on all (walls, floor and ceiling) surfaces is used, the MRT in compartments 4 and 5 varies between around 20.5°C and 28.0°C, and in compartment 12 varies between around 19.0°C and 25.5°C. The use of this system allows to significantly reduce, on average, the MRT in compartments 4 and 5 of 8.4°C and in compartment 12 of 7.0°C.

When the radiant cooling system is not used (reference case), during occupancy, the levels of thermal comfort conditions for occupants in compartments 4, 5 and 12 are not acceptable by positive values of PMV index (ISO, 2005). When the radiant cooling system on horizontal (floor and ceiling) surfaces is used, the levels of thermal comfort conditions for occupants in compartments 4, 5 and 12 are still not acceptable for positive values of the PMV index (ISO, 2005). However, the PMV index values improve, on average, about 44% in compartments 4 and 5 and about 37% in compartment 12. The values of the PMV index increase throughout the day following the increase in indoor air temperature and MRT. When the radiant cooling system on all (walls, floor and ceiling) surfaces is used, it is possible to guarantee levels of thermal comfort for the occupants, by values of the PMV index at least within category C (ISO, 2005), in compartments 4 and 5 until around 1 pm and in compartment 12 until shortly after 2 pm. In the afternoon, the thermal comfort levels for the occupants are not acceptable by positive values of the PMV index slightly above the acceptable limit, +0.7, of category C (ISO, 2005). However, this system guarantees significant improvements in thermal comfort levels (approximately 80% on average) for the occupants compared to the reference case. Thus, this system is a relevant constructive option because it is based on a passive and sustainable cooling solution.

Conclusion

In this paper, it was presented a numerical study of sustainable energy application in the buildings construction using cooling radiant surfaces in summer conditions. The study was made in a University building and the proposed technology was used to improve the thermal comfort conditions for the occupants. In the evaluation of the indoor thermal comfort conditions, the PMV index was used. The level of indoor air quality was also evaluated, using the concentration of CO_2, provided by the ventilation system used. Three cases were studied: non-use of cooling radiant surfaces (reference case); use of horizontal (floor and ceiling) cooling radiant surfaces; and use of all (walls, floor and ceiling) cooling radiant surfaces.

From the analysis of the results obtained, it is possible to draw the following conclusions:

- The indoor air quality levels obtained in the compartments are near the acceptable limit provided by the ASHRAE 62.1 standard (2016);
- The use of only horizontal cooling radiant surfaces is not enough to guarantee acceptable thermal comfort levels according to ISO 7730 (2005), although it allows to reduce the indoor air temperature in the analyzed compartments from 2.2°C to 3.9°C, on average, and to improve the thermal comfort levels of the occupants from 37% to 44%, on average;
- The use of all cooling radiant surfaces guarantees acceptable levels of thermal comfort for occupants, by values of the PMV index at least within category C [13], until around 2 pm; however, in the afternoon, near acceptable levels of thermal comfort for occupants, by positive PMV index values, are obtained; it also allows to reduce the indoor air temperature in the analyzed compartments from 5.0°C to 6.9°C, on average.

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