Application of indirect evaporative cooling strategies for a warm-humid climate

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Abstract. Energy consumption in buildings for air conditioning has augmented worldwide by the escalation in global warming. The application of passive cooling is a promising approach to mitigate this situation. The aim of this research was to assess and characterize the performance of indirect evaporative cooling strategies combined with other passive cooling techniques, applied in experimental modules, aimed at providing hygrothermal comfort. Results showed that the investigated strategies presented lower temperatures than the external conditions and the control module. The alternative that combined indirect evaporative cooling with thermal mass, solar protection, and night radiative cooling was the most promising, with a temperature reduction of 4.2 K, relative to the mean exterior temperature, and a decrease of 8.3 K of its maximum temperature relative to the maximum exterior temperature. An additional strategy was implemented in this alternative using a phase change material, that further reduced its temperature by 6.3 K, relative to the mean exterior temperature and a reduction of 11.5 K of its maximum temperature compared to the maximum exterior temperature. It is expected that these findings are applicable in actual buildings in warm-humid regions to reduce energy consumption for air conditioning, whilst improving hygrothermal comfort and health of occupants.

1. Introduction

The widespread use of air conditioning (AC) in buildings is directly related to Global Warming (GW) and Climate Change (CC). The rapid rise in ambient temperatures globally implies a greater use of AC in buildings to provide hygrothermal comfort to occupants, which at the same time provokes the unceasing emission of Greenhouse Gasses (GHG), and numerous climate alterations as well as severe health effects on people. A promising approach to mitigate this situation is the implementation of passive cooling in buildings, where the application of indirect evaporative cooling systems (IECS) is a viable and sustainable alternative, particularly in warm-humid regions. This paper presents the results of a research that evaluated and characterized the performance of IECS implemented in experimental modules compared to a control module (CM), and relative to the external ambient conditions of the site selected for this work, the City of Mérida, Yucatán, Mexico, a location with a typical warm-humid climate.
2. Energy consumption relative to the use of air conditioning in buildings

Primary energy consumption worldwide in 2019 increased by 1.3% compared to 2018, from 576.23 ExaJoules (EJ), to 583.90 EJ, coming mainly from fossil fuels [1]. This increase is directly associated to a high-level of Greenhouse Gasses emission (GHG), mainly carbon dioxide (CO₂) to the atmosphere, that is provoking a severe environmental damage.

At present, the growth of GW and the intensification of CC at global level has a direct relationship to the exponential increase in the use of Air Conditioning (AC) in buildings and shows a fast increase, particularly in urban locations. Currently, the use of AC represents almost 20% of the total electricity used in buildings worldwide and 10% of all world electricity consumption [2]. This trend will increase due to factors such as economic and population growth and be evident with greater signals in hot regions as well as in prevailing mild climates during overheating periods. Within the utilization of AC systems, the fastest-growing use of energy in buildings is for space cooling. Total energy use for space cooling in residential and commercial buildings worldwide more than tripled between 1990 and 2016 to reach 2,020-TeraWatt hours (TWh) (Figure 1) [2]. In addition, due to the increase in world population, together with growths in urbanization and the expansion of industrialization, heat waves, such as those that have occurred in Europe and other regions of the planet, more recently in the summer of 2019, more cooling of the buildings will be required in the coming decades. In summary, the increase in the requirements of AC in buildings will generate a massive demand for electrical energy, which mostly comes from fossil fuels, which in turn will cause more pollution and CO₂ emissions, and the consequent deterioration of the environment, aggravating the situation and creating a noxious vicious circle, affecting the ecosystems of the planet, the economy of the building’s occupants, their quality of living, and, more importantly, people’s health.

Figure 1. World Energy Consumption for the Cooling of Spaces in Buildings.
Source: IEA, 2018. http://www.iea.org/publications/free publications/publication/The Future of Cooling

3. Case study: Evaluation and characterization of passive cooling systems.

Methodology and Experimental work

The main objective of this research was to evaluate and characterize various passive cooling systems (PCS) along with Indirect Evaporative Cooling Systems (IECS) in five experimental modules (EM) in their upper cover, aimed at achieving both thermal comfort conditions in buildings in hot-humid climates of Mexico and energy savings. The modules’ geometry, based on previous research [4, 5 and 6], is hexahedral. The Case Study is located in the City of Merida, Yucatan, Mexico, which has a typical warm-humid climate. According to Köppen and Geiger, this climate is classified as BSh. Annual temperature is 27.2 °C; annual mean wind speed: 3.3 m/s; mean global solar irradiation: 5.5 kWh/m² (19.8 MJ/m²); average relative humidity: 72%; and average rainfall: 1,036.9 mm [3].
The EM were designed and built with five different IECS system configurations (M1, M2, M3, M4 and M5), complemented with various PCS, integrating in their upper cover different IECS relative to a control or reference module (CM) (Figures 2, 3 and 4).

Figure 2. Internal view of the Experimental Module

Figure 3. Experimental arrangement during data monitoring of IECS with supplementary passive cooling techniques

Figure 4. Geometry and characteristics of experimental modules. CM: Control Module; M1: indirect evaporative cooling + thermal mass + solar control; M2: thermal mass + thermal insulation; M3: radiative night cooling + thermal mass; M4: indirect evaporative cooling + thermal mass + solar control; M5: indirect evaporative cooling + thermal mass + solar control + radiative night cooling. M3 and M5, Night mode; 18:00-06:00 hrs. Diurnal mode: 06:00-18:00 hrs.
The experimental modules were built with a plywood structure, with dimensions 0.8 meters long by 0.8 meters wide and 0.47 cm thickness, covered inside by a foamular® panel of 0.045 meters thick as thermal insulation to allow adiabatic conditions (Figure 2). This insulation material was made of extruded rigid polystyrene foam with a thermal conductivity value of 0.0288 W/mK (for an average external temperature of 24 °C). The conduction heat transfer of the modules was 1.8072 W/m²K. The “U” value of the module’s envelope was 0.5147 W/m²K. The thermal mass was provided by 54 litres of water introduced into a galvanized metallic tray on top of the modules (Figure 4). The specific heat capacity of water is 4.182 kJ/kgK. Average wind velocity in the location is 3.33 m/s, that provided a suitable air flow rate during the experiments.

The methodology consisted of the evaluation and characterization of IEPCS through the monitoring of the hygrothermal conditions inside the five experimental modules compared with a control module (CM) (Figure 4). These modules integrated different systems on their rooftop cover: Indirect evaporative cooling and solar protection (IEC + SP); thermal mass and thermal insulation (TM + TI); night radiative cooling and thermal mass (NRC + TM); indirect evaporative cooling, thermal mass, and solar protection (IEC + TM + SP); and indirect evaporative cooling, thermal mass, solar protection and night radiative cooling (IEC + TM + SP + NRC).

The initial process included the calibration of sensors and data loggers used in the experiments, and the results obtained indicated a consistency in the recorded values, which validated their use with reliability. The monitoring of dry bulb temperatures (DBT) and relative humidity (RH) values was carried out simultaneously for 30 consecutive days during the prevailing overheating period. In the process of the experimental work and in the modules where the NRC system was implemented (M3 and M5), a variant was included, with respect to the other modules, which consisted of removing the rooftop cover at 18:00 hrs and place it again at 6:00 am period (Figure 4).

4. Analysis and interpretation of the results
During the monitoring period, values of DBT and relative humidity were recorded at ten minutes interval during a typical overheating period in May, when the average exterior temperatures fluctuated from 27 °C to 38 °C. The values obtained were ordered and averaged over a 24-hour cycle. Results indicated that the average temperatures inside the modules decreased with respect to the mean and maximum external temperatures of the nearby Automated Meteorological Station on the location (EMA).

The experimental module M1 showed an average temperature of 29.3 °C, with a maximum of 32.2 °C and a minimum of 26.7 °C, relative to the CM, that showed 31.3 °C, 38.6 °C and 25.6 °C, respectively. These values represented a temperature reduction of 2K, 6.4K and -1.1 K, correspondingly.

The temperature reductions of M1 relative to the external temperatures were 2.5 K, 5.5K and 0.2K, respectively (Figure 5).

The experimental module M3 showed an average temperature of 30.7 °C, with a maximum of 33.4 °C and a minimum of 28.0 °C, relative to the CM, that showed 31.3 °C, 38.6 °C and 25.6 °C, respectively. These values represented a temperature reduction of 0.6K, 5.2K and -2.4 K, correspondingly.

The temperature reductions of M1 relative to the external temperatures were 1.1 K, 4.3 K and 1.1 K, respectively (Figure 5).
Results of the performance inferred that the most promising cooling system investigated was M5, which showed a mean temperature reduction of 4.2 K relative to the mean exterior temperature and a reduction of 8.3 K of its maximum temperature inside the module relative to the maximum exterior temperature (Figure 8). An additional passive cooling technique was implemented in the most promising IECS (Module 5), using a Phase Change Material (PCM) on the rooftop cover by substituting the thermal mass of the water with a polycarbonate shell that encapsulated an organic PCM. This material utilizes the temperature difference between day and night for the storage and release of thermal energy. The monitoring of this passive cooling technique was conducted during the most critical overheating period in the location, with a maximum average temperature of 38.0 °C and a minimum of 26.6 °C. The results were compared with the temperatures in the CM and with the exterior. The average temperature in the CM was 30.2 °C relative with the average temperature in M5 with 25.3 °C, that infers an absolute reduction of 4.9 K (Figure 7). Thus, the average temperature in the M5 was 25.3 °C relative with the exterior average temperature with 31.6 °C (Figure 7).

Therefore, the absolute results within the M5 with this strategy presented a temperature reduction of 6.3 K relative to the mean exterior temperature and a reduction of 11.5 K of its maximum temperature relative to the maximum exterior temperature (Figure 8).
5. Conclusions
The results of this research proved that the IECS have an important energy saving potential by decreasing the use of AC systems during hot periods, whilst achieving thermal comfort for the occupants. The measurements showed that low energy cooling is possible using a combination of enhanced passive cooling systems. Furthermore, this research demonstrated that it is feasible to achieve temperature reductions with the cooling systems investigated and, consequently, resulting in higher levels of comfort without the use of AC. The results also revealed a good potential for energy savings in the systems investigated, from which lessons can be extrapolated and applied in real buildings. Certainly, the envelope of the buildings plays a very important role in the thermal behaviour of such systems and has a huge impact on the AC requirements of the contained spaces [7]. The choice of building materials is of a great importance. In particular, the thermal mass is essential for the reduction of thermal swings. Therefore, the use of thermal mass, with integrated water systems and PCM, as applied in this research, pointed towards an important approach for the cooling of spaces that needs to continue with further research work. In addition, the implementation of these passive cooling systems in buildings, where people cannot afford the purchase of AC equipment and the payment of electricity, may well provide a viable and effective alternative route to providing low energy thermal comfort to many people in a heating world due to the current GW and CC situation. The implementation of these bioclimatic low-energy strategies has also a significant social-economic value and has the potential to generate a virtuous circle in a resilient and more climate-appropriate architecture, aimed at improving the environment and people’s health.

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