The Development of Passive Downdraught Evaporative Cooling Systems Using Porous Ceramic Evaporators and their application in residential buildings

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ABSTRACT: This paper seeks to demonstrate that passive evaporative cooling using porous ceramic components can achieve comfort conditions inside residential buildings in hot-dry climates, and that the components can be integrated simply and effectively within existing 60s and 70s housing buildings now due for refurbishment. A case study building in South of Spain (Seville) was investigated in order to performance test different constructional and engineering solutions for the design of the system prototypes to meet different spatial and energy requirements. A performance analysis of the case study building assessed the viability of the proposed system in housing buildings and the related energy and CO₂ savings.

Conference Topic: 2 Design strategies and tools
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INTRODUCTION

The Energy Consumption in residential and commercial European buildings represents 41% of Europe’s energy budget. A proportion of this is used for cooling; this varies by country and building type [1]. The environmental impact of conventional air-conditioning is represented by CO₂ emissions from fossil fuel and, to a lesser degree, by chlorofluorocarbons (CFCs) leaking from compressors. This contributes to the depletion of the ozone layer and consequently increases the greenhouse effect and climate change.

Passive Evaporative Cooling is a cooling method that uses the evaporation of water to cool the air. Its application is based on the availability of water resources and use of draughts into the building. The use of clay and porous ceramic in passive downdraught evaporative cooling has a track record in the vernacular architecture of many hot and dry regions of the world. Wind towers, opening systems, fountains, pools and vegetation were the compositive elements of such cooling systems, used and combined according to different needs and local tradition (Fig. 1).

Nowadays the development of an ‘innovative’ passive evaporative cooling system is required to provide hot-dry countries with a low-tech and passive alternative to conventional air-conditioning; a system which could make full use of the local climatic potential and be easily integrated into modern construction. Desert Coolers are and have been for decades a popular low-cost and compact cooling solution in many hot-dry countries. However, they are not building integrated and their main disadvantages are noise and energy consumption from the fan. Also, the use of wet cellulose pads as porous media can easily promote the growth of harmful bacteria. The use of porous ceramic components in evaporative cooling systems can be potentially combined with more functions, providing comfort conditions and improving the performance of the building envelope at the same time. The advantages of using porous ceramic evaporators as opposed to other spray based direct evaporative systems are: no use of high pressure systems, no water treatment required, and no risk of microbiological contamination (Legionella disease).

An EC funded research (Evapcool) [2] developed porous ceramic components for passive evaporative cooling systems in non-domestic buildings (Fig. 2). It concluded that it is possible to effectively integrate...
modular porous ceramic evaporators in different building components, generating comfort conditions into the indoor space. The research showed that the cooling capacity of the systems is dependent on the ceramic surface area and on the dry to wet bulb temperature depression [3]. A case study project in Iran was performance tested and it was predicted that comfort conditions could be achieved for approximately 90% of the time during the summer [4].

The current doctoral research builds on the EC research project and aims to investigate the application of the Evapcool system in the residential sector with particular reference to a case study building in Seville, South of Spain. This paper focuses on the building integration of the proposed system in apartment blocks and its performance analysis.

Figure 2: Physical model of types of integration of the Evapcool system

2. BUILDING INTEGRATION IN HOUSING

2.1 Housing in Spain

The increasing demand for low cost residential buildings and the scarce availability of land call for a sustainable approach to be adopted in the development and design of high density housing schemes as well as the retrofit of the existing housing stock. Statistical data on the housing stock in Spain show that the majority of buildings are residential [5]. Data on age of the housing stock for Spain [6] shows that in the town of Seville nearly half was built between 1960 and 1980 with 23% built in 1961-70 and 16% in 1971-80. These buildings are often characterised by a very poor quality of the building envelope and a poor performance of the indoor environmental control systems.

It is reported [7] that, although in Spain less than 10% of homes have air-conditioning systems, 71% of the installed capacity is in the residential sector. The EERAC (Energy Efficiency of Room Air-Conditioner) study [8] assessed that the average number of hours of operation of residential air-conditioning in South of Spain (Murcia) was equivalent to 1049 hours/year compared to offices with 1402 hours/year and shops with 2157 hours/year.

2.2 Principles of Integration

The Evapcool system can be integrated in different elements of the building envelope [9]. The most effective option is the wall integrated system where a column of modular porous ceramic evaporators is integrated into a perimeter cavity wall. This is intercepted by a draught of hot-dry air coming from outside via a high level controllable opening. The air in contact with the wet surface of the ceramic evaporators becomes heavier and cooler. It then gets delivered by negative buoyancy into the indoor space via a low level opening (fig. 3a). The use of a room integrated fan might be necessary in still conditions to assure a constant air flow. Another option for integration is the roof system, where banks of ceramic evaporators are integrated in a wind-catcher termination (fig. 3b). The system can be sized, and the number of ceramic modules increased, according to the cooling requirement of the space.

Figure 3: Principles of integration of the system

The Evapcool System can be integrated in any situation where there is a perimeter wall or a roof and it mainly operates at room level. This makes it very versatile and suitable for a wide range of building typologies. However, there are limitations to be taken into account when trying to integrate the Evapcool System (ES) in the building. By looking at the characteristics of existing housing buildings and specifically at the typology of apartment blocks, these limitations can be grouped in the categories of planning, configuration and construction.

In deep plan buildings only the perimeter rooms can adopt the Evapcool wall system. For the core areas, which are usually constituted by corridors, lobbies or general circulation spaces, mitigation techniques and alternative cooling solutions can be found. In apartment blocks the floor level where the perimeter room is located is an important factor in the sizing of the system. The ground floors, usually affected by problems of noise, pollution and often security (Fig. 4) can benefit from the installation of the ES as the ingress of ‘fresh’ air through a wet cavity wall system induces particles and dust to be filtered and noise to be attenuated. In the intermediate floors, as well as in the ground floors, the reduced availability of perimeter space is compensated by reduced envelope gains (solar and conductive) and hence reduced cooling requirements. These are instead higher in the top floor apartments where the roof can be used as an additional surface for the integration of the evaporative system (wind-catcher).
Mitigation techniques, like night time ventilation, solar control and improvement of the building envelope results in a considerable reduction of the cooling loads which can often be absorbed exclusively by the wall integrated ES.

![Figure 4: Strategy of Integration for existing apartment blocks](image)

The type of construction can influence the design and integration of the system. Some adjustments in the specification of the system components and their configuration can be made according to the construction of the building envelope. These relate to the amount of space that the system occupies and its relationship with the perimeter structure. The ceramic modules have been designed mainly to be integrated in a concrete frame construction. This assumes the partial reconstruction of the infill wall masonry and the creation of a new cavity wall where the system can be located (Fig. 5).

![Figure 5: Wall Integration - partial removal](image)

When this is not possible a diaphragm wall can be created on top of the existing perimeter wall (Fig. 6). This will of course reduce the indoor floor area but it does not create any major disruption on the outer façade.

Where a balcony or terrace is available, the cavity wall could be built on the outside with no loss of indoor floor space (Fig. 7). In structural terms, the Evapcool system constitutes approximately 10% of the dead load of a concrete frame structure per linear meter. This implies that for existing buildings a structural check should be undertaken to verify that the structure can absorb the additional load.

![Figure 6: Wall Integration - addition](image)

![Figure 7: Wall Integration - external](image)

3. PERFORMANCE ANALYSIS OF A CASE STUDY BUILDING IN SEVILLE

3.1 Assumptions and methodology

A case study building in the urban context of Seville was identified in order to investigate the building performance of the proposed system. The building is a block of apartments in the housing development of “Barriada Los Diez Mandamientos” designed by the Architect Luis Recasens Mendez-Quipo de Llano in 1958-64 (Fig. 8). The analysis aimed at assessing the performance of the building in winter and summer and the cooling loads in the different rooms. The modelling exercise looked at the original status of the building as designed in 1958 and introduced a series of measures for the improvement of the building envelope and the reduction of the cooling requirements. Amongst those measures, the use of porous ceramic evaporators was tested in order to meet the remaining cooling loads in summer. The performance of the building envelope was also tested to evaluate if the integration of the ceramic
panels could improve the quality of the building fabric and reduce the heating loads in winter.

Figure 8: Case study building, Seville (source: Mosquera Adell, E. et al.)

The performance analysis was undertaken using dynamic thermal simulation [10]. A parametric analysis simulated gradual improvements of the building envelope and the introduction of ventilation and solar control strategies to improve comfort conditions both in summer and winter.

The model specifically looked at the performance of a typical top floor apartment (Flat A) and an intermediate apartment (Flat D). This enabled to appreciate the different cooling requirements due to configuration and orientation.

3.2 Thermal modelling analysis

The simulations were run for a typical hot summer day (day 215 – August 3rd) and a typical winter season (October to April). The results were expressed as temperatures profiles, cooling loads and annual heating demand. The parametric study showed the presence of residual cooling loads not met by the selected mitigation strategies. This constituted a case for the adoption of the proposed passive evaporative cooling system (Evapcool).

The nominal cooling power of the proposed system was first simulated as a cooling system with a set point of 26°C. This simulation modelled the equivalent cooling energy to be met by the Evapcool System in summer to keep a temperature of 26°C. This is an obvious oversimplification but necessary for a preliminary sizing of the system. This assumption was based on the analysis of the weather data [11] of Seville (fig. 9) where the potential delivery temperature of the evaporative system is below 26°C for 95% of the time in summer. The delivery temperature was calculated as 2°C above the wet bulb temperature [12].

Figure 9: Annual weather data for Seville

The results showed that the cooling demand of the top floor was higher than the intermediate floor. However, the effect of high internal gains and large glazing areas induced higher cooling loads in the intermediate floor living room than in the top floor one (Fig. 10). Conversely, the top floor South bedroom had higher cooling demand than the intermediate floor bedroom and this was mainly due to higher conductive gains through the roof.

Figure 10: Predicted cooling loads

The cooling demand of each room was translated into the area of Evapcool system necessary to keep the indoor temperature below 26°C by using the Performance Chart below (Fig. 11).

Figure 11: Specific cooling power of the ES

The chart [13] gives the specific cooling power of different heights of Evapcool Systems expressed as a function of the ambient dry to wet bulb temperature difference. By entering the temperature differential at the peak hour of the analysed typical summer day it is possible to identify the specific cooling power for each height of the system. For example given a target cooling power of 610W for the top floor living room and chosen a system height of 1m the required system’s width is 1.4m. This is derived from the formula:

\[ Q_t [W] = Q_s \times \Delta T \times h \times w [W/K.m^2 \times m \times m] \]

Where \( Q_t \) is the total cooling requirement; \( Q_s \) is the specific cooling power (derived from the chart); \( \Delta T \) is the dry to wet bulb temperature differential (derived from weather data and entered on the x axis of the chart); \( h \) is the height of the Evapcool System and \( w \) is the width of the ES (Fig. 12). Therefore:
$$w \ [m] = \frac{Q_l(Q_s \Delta T \times h)}{W/(W/K.m^2 \times K \times m)}$$

Figure 12: Evapcool Columns

To different heights correspond different widths and they are chosen according to the availability of space and possible types of integration. Figure 13 shows possible ways of integrating the ES in the different rooms.

Figure 13: Top floor plan showing integration of the Evapcool system

A more detailed analysis of the system was performed by modelling the temperature output profile of the system into the indoor spaces. This was done by specifying an hourly ventilation and temperature profile into the modelled room. The temperature profile was based on the hourly variation of the wet bulb temperature. It was created by adding 2degC to the wet bulb temperature. The basic ventilation rate was set to an assumed value corresponding to the ventilation provided by a room integrated low wattage fan. However, the volume flow rate was increased to test the sensitivity on the system performance (fig. 14). The simulation shows that by increasing the volume flow rate to 0.06m$^3$/s (0.07kg/s) the air temperature during occupied hours can be kept below 27degC.

The Heating Loads were also calculated to appreciate the effect of the improved cavity wall in winter (fig. 15). The cavity wall build-up results in an improved U-value of 0.3W/m$^2$.K. This has been applied on the walls of the living rooms where the requirement for a greater area of ceramic panels justifies the substitution of the existing external wall with a new cavity wall. In this instance, the effect of improving the building envelope of the two flats is marginal compared to a full re-cladding but it is still possible to appreciate a drop of the annual heating demand by 12.8% and 10.4% for the top and intermediate apartments respectively.

Figure 15: Annual heating demand for the two flats

3.3 Computational Fluid Dynamics

The performance of the proposed passive evaporative cooling system integrated in the case study building was investigated using 2D computational fluid dynamics [14]. This tested the effect of the Evapcool System in the top floor South facing living room and the bedroom. The analysis took into account different scenarios of integration and related strategies for the positioning of the ventilation and cooling inlets and outlets.

In order to simplify the modelling of the Evapcool System it was assumed that the air delivered at the inlet is 2degC above the wet bulb temperature (i.e. 23degC) and that the air velocity at the inlet is 0.3m/s. The CFD analysis investigated the patterns of air movement, temperatures and comfort in the room assuming that the conditions within the ES cavity wall were given. It tested two types of integration: the wall and the roof system.

Figure 16: Cross section of top floor bedroom showing CFD temperature profiles
The results showed that comfortable conditions can be achieved in the bedroom (Fig. 16) adopting an evaporative cooling system which delivers cool air at a temperature of 23\textdegree C and a rate of 0.045 m$^3$/s and by positioning the inlet at low level and the outlet at high level of the perimeter and rear walls of the room respectively. This lowers the air and mean-radiant temperatures of 6\textdegree C and 1.5\textdegree C respectively with a PPD of 5\% in most of the room. In the living room the performance of wall and roof systems were compared (Fig. 17, 18).

The most efficient strategy resulted to be the cavity wall solution. There two inlets are placed on the perimeter wall (high and low level) and one outlet on the opposite wall. This arrangement coupled with an air flow rate of 0.06 m$^3$/s provides very uniform temperature distribution with an average temperature of 26\textdegree C and a mean radiant temperature of 27\textdegree C. The PPD is also 5\%.

CONCLUSION

An ‘innovative’ passive evaporative cooling system using porous ceramic components can be integrated in residential buildings. This can meet the cooling loads of existing housing apartments. The case study analysis demonstrated that these cooling loads can be met by a wall integrated system (Evapcool). The system can vary in height and length according to the required load. Its integration requires a minimal intervention in order to create appropriate cavity wall where to locate the porous ceramic evaporators. The addition of insulative layers on both sides of the cavity wall can improve the quality of the building fabric and it has been estimated that in winter the heating loads can be reduced by approximately 12\%. The total Annual Energy savings (gas and electricity compared to the use of conventional air conditioning) from the use of the ES are 1.53 MWh and 1.55 MWh for the top and intermediate flats respectively. This translate in a total CO2 saving of 18.5 Tonnes for the whole building.

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REFERENCES

[6] Ditto
[13] Ditto