An exploration of the application of an innovative wall integrated passive evaporative cooling system in the context of Seville as well as Spanish and European energy performance standards.

Environmental retrofit: building integrated passive cooling in housing

Rosa Schiano-Phan

As the existing housing stock ages throughout Europe, retrofitting offers many opportunities for the substantial improvement of the energy performance of residential buildings and the provision of sustainable alternatives to conventional heating and cooling. The effect of global warming is leading to a widespread use of air conditioning in existing and new residential buildings. This potentially implies an increase in cooling energy and adverse environmental effects on an unprecedented scale. In the hot and dry climate of many south European cities, this could be avoided with the use of an innovative wall integrated passive evaporative cooling system, which harnesses air, water and porous ceramic to provide comfortable indoor conditions. Dr Rosa Schiano-Phan discusses the applicability of such a system to the urban context of Seville in the light of the current Spanish regulatory framework and recent developments of European energy performance standards.

In June 2003, Italy suffered a country-wide loss of electrical power experienced by 58 million people. Across the Atlantic, in eastern and central US and Canada, later on that summer, a similar number of people was involved in a two day loss of electrical power, with an economic cost estimated to run into billions of dollars. Both these two episodes were directly related to a demand for air conditioning which exceeded generating capacity. During the same summer, in France and the UK, the toll of excess deaths raised to tens of thousands due to unprecedented high temperatures and obvious inadequacy of cooling provisions. With the market for room air conditioning steadily increasing across Europe and the developing countries, and with the established evidence of global warming, these extremes can become even more frequent worldwide. Also, the periodic rise in the cost of crude oil has reopened the energy crisis and naturally creates more incentives for energy savings and efficiency. Additionally, the environmental impact of air conditioning such as their global warming potential (GWP) is still high even in those using so-called 'green' refrigerants like the HFCs and this calls for a fast and effective shift towards passive and refrigerant free forms of cooling.

In recent years, both research and applications of passive downdraught evaporative cooling (PDEC) in buildings have been carried out worldwide. Two previous arq articles by Professor Brian Ford report on various aspects of PDEC design.[1] We are now at a stage where a substantial technical knowledge has been generated on PDEC and a few pioneering buildings effectively showcase the use of such system and design approach, as an alternative to mechanical cooling. However, PDEC mainly caters for the non-domestic sector and it is desirable to adopt low-cost and simpler alternatives suitable for the residential market.

The heritage of the recent past: apartment buildings in Seville

With almost 700,000 inhabitants, Seville (37.43°, -6.04°) counts for one quarter of the population of Andalusia and, with its metropolitan area, covers about one fifth of its territory. Residential buildings in Seville represent 93% of the existing stock[2] and of this, the majority are apartments[3] built between 1960 and 1980.[4]

A typical 1960s apartment block is of concrete-frame construction with block infill. On the perimeter walls, this creates extensive thermal bridges and consequent problems of condensation and possibly leakage. Infill walls are usually uninsulated and made of perforated blocks with a depth varying between 300 mm and 400 mm. Cavity walls can be found, but these are often unvented and without insulation. Where applied, insulation is generally in the form of 30–40 mm polystyrene sheets placed in the cavity or on the inside of the walls, with U-values typically ranging from 0.65 to 0.46 W/m^{2}K, until the recent revision of the insulation levels in Spain (CTE: Código Técnico de la Edificación, RD 314/2006 and RD 47/2007). Internal insulation allows rooms to heat up more quickly during the winter and is, therefore, suited to dwellings which are heated intermittently. This form of insulation, however, can prevent the exposure of thermal mass and consequently reduce its stabilising

https://doi.org/10.1017/S1359135510000758

effect on air temperatures in summer. In many cases, this does not happen because many concrete-frame apartment buildings show virtually un-insulated and exposed concrete beams, columns and slabs. Although exposed concrete is desirable in summer, insulation should be provided on the outside to avoid heat bridges in summer and condensation and heat losses in winter.

At present, the main activity of the construction industry in Europe is focused around the retrofit of existing buildings. This is due to a drop in new construction and the need to upgrade the poor quality construction of 1950s' and 1960s' buildings to new environmental and energy legislation and desired comfort levels of the occupants. In the case of Seville, the majority of residential buildings were built between the 1940s and 1970s and are now due for refurbishment. Spain also has the highest proportion of owner-occupied buildings (88%) in Europe. This gives more scope for the development of passive cooling solutions which can be integrated into the fabric of buildings and which can improve energy performance and comfort standards with a low environmental impact.

Cooling in residential buildings

Residential buildings are, together with the tertiary sector, responsible for 41% of Europe's end-use energy consumption. Overall, cooling in European buildings contributed to a 90% increase in the electricity consumption between 1990 and 1996 with a predicted 200% increase by the year 2010. This implies that, without any major low energy strategy, in 2010 the CO_2 emissions in the atmosphere would be twenty times greater than in 1990 due to mechanical cooling alone.[5]

In commercial buildings the proportion of energy used for cooling is around 4% (European Commission, 2004). This, however, does not include the energy required to drive fans and pumps which can account for 30–40% of the electric energy consumption. The exact contribution of cooling to the energy use of residential buildings is not known. In residential buildings across Europe a large proportion of the energy is used for space heating (57%), followed by water heating (25%) and electric appliances (11%).[6] In Spain, the energy consumption in the residential and commercial sectors represents 14% and 7% of the country's total consumption respectively.[7] The distribution of energy use in the Spanish residential sector follows the European trend, with electric appliances representing 12% of the energy consumption,[8] some of which will be for cooling. From data on the air-conditioning market in western Europe,[9] it is apparent that south European countries such as Italy and Spain are responsible for the majority of the room air-conditioning market (sales and installations).

Apart from the energy issue, the environmental impact of the increased use of air-conditioning units also lies in the risk of refrigerant leakage from compressors. This is particularly high in old and obsolete equipment, which still use the type of refrigerants now outlawed. These refrigerants, like CFCs and HCFCs, are highly damaging due to their ozone depleting and global warming effects. The new generation of 'green' refrigerants[10] are created from a blend of different gases. Although they have a zero ozone depletion potential (ODP), they also have a substantial global warming potential (GWP).[11] It is, in fact, illegal to air even green refrigerants in the atmosphere, as their particles are highly polluting and contribute to the greenhouse effect. From this perspective, it is difficult to appreciate the amount of refrigerants actually released into the atmosphere, as it is likely that this happens every time compressors are overcharged and leaks occur. Many of these refrigerant blends are used at high pressure becoming inflammable and toxic at high temperatures. In spite of old generation refrigerants now having been banned, there are still many a/c units in use which are likely to be faulty and obsolete. This can be the cause of high energy consumptions and substantial leaks of refrigerants into the atmosphere.

There are a number of passive and hybrid alternatives to conventional air conditioning in residential buildings, which can be effective in achieving the comfort and energy consumption levels demanded by the recent voluntary standards and mandatory legislation of many south European countries. These passive cooling strategies can be grouped according to the heat sinks by which they are generated: night ventilation, night sky radiant cooling, ground cooling and evaporation of water. Their applicability varies depending on the local climate and context and a comprehensive review of their technical applicability is offered by Santamouris.[12]

The regulatory framework in Spain and the Passivhaus standard

New mandatory standards for the energy performance of buildings, in compliance with the European Directives, were introduced in Spain between 2006 and 2007 (RD 314/2006 and RD 47/2007). In the light of the European directive 2002/91/EC, a major revision of the national legislation on energy performance of new and existing buildings was undertaken. The directive applies to new buildings as well as those undergoing major renovation. It is evident that such legislation is particularly relevant to apartment blocks in many southern European towns like Seville, where major refurbishment of the stock is required and where measures to improve thermal performance of the buildings must be taken.

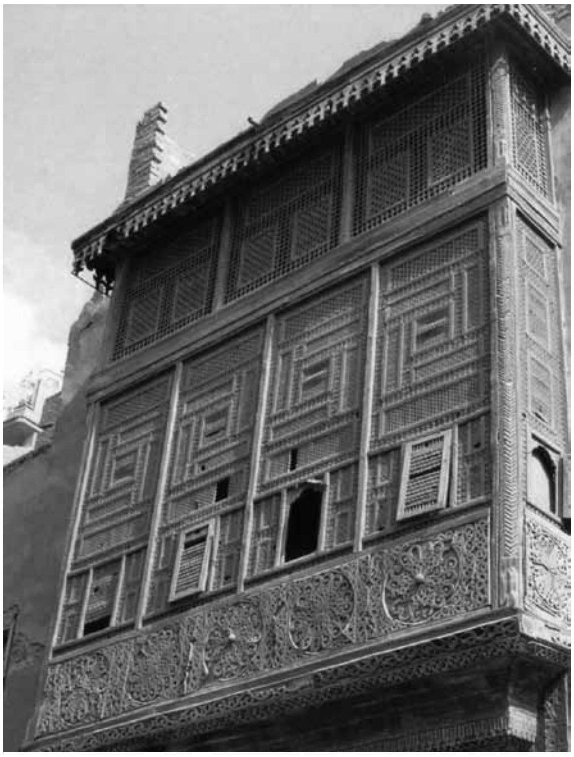
The Spanish buildings' energy certification has been based on energy performance indicators such the overall CO_2 emissions and primary energy consumptions. Additionally the complementary indicators are heating and cooling requirements and heating primary energy consumption. The building energy rating is based on a classification which takes into account climatic factors as well as age, use, typology etc. The classes vary from A, most efficient/best performing, to E, worst performing, and are applicable to both new and existing buildings. For Seville a class A residential building corresponds to an annual primary energy consumption of less than 10.7 kWh/m², whereas class E to a consumption greater than 42.1 kWh/m².

A recent review of the applicability of the German Passivhaus standard to affordable Spanish residential buildings[13] suggested that, in Seville, a 100 m² typical three-bedroom house built according to the 2007 Building Technical Code and improved to increase performance, could achieve a cooling demand of 21.7kWh/m² per annum and a heating demand of 2.8kWh/m² per annum. In the Spanish energy labelling classification this corresponds to a B rating for cooling and an A rating for heating. The total energy saving compared with a conventional alternative is approximately of 57% but cooling clearly represents the most significant load.

Passive evaporative cooling: the use of porous ceramic in the tradition

Traditionally, buildings in hot-dry regions of the world have achieved comfort conditions using direct evaporative cooling coupled with high thermal mass, shading and other strategies aimed at reducing the cooling loads of the building. The use of fountains and outdoor water features is part of an Islamic tradition which stretches from the Moghul's architecture of India to the Moorish examples of southern Europe and is often applied to residential buildings. The application of these systems is strictly related to the building typology and the architectural and urban tradition of the region in which they are used. Wind towers, opening systems, fountains, pools and vegetation are the compositive


1

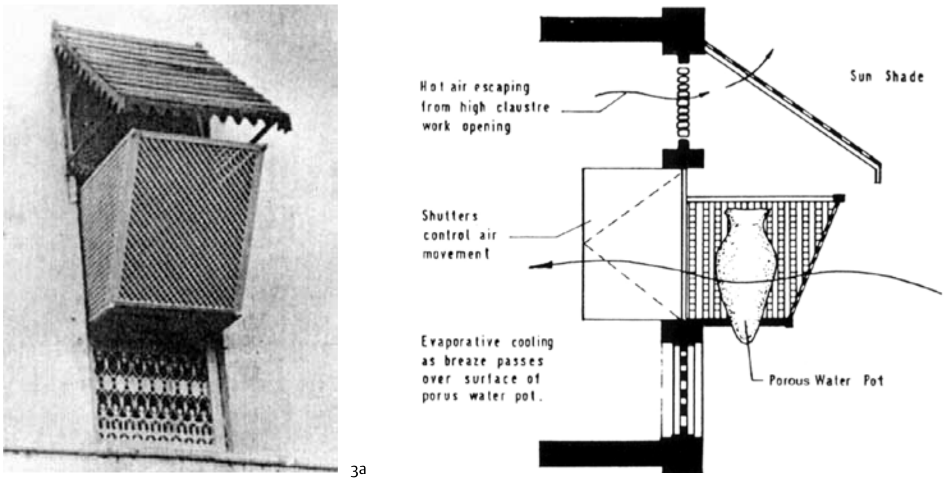

2a


2b

1 Salsabil fountain in La Ziza Palace, Palermo, Sicily

2 Largest surviving medieval Mashrabiya in Cairo (*a*) and in Sicily (*b*)

3 Muscatese Window System



3a

3b

elements of such cooling systems and they are used and combined according to different needs and local tradition. Most of the examples highlight indigenous technologies based on low and local use of energy, and resources that work in harmony with the natural environment and which have been ignored, if not actually suppressed, during the rapid growth of the industrialised world.[14]

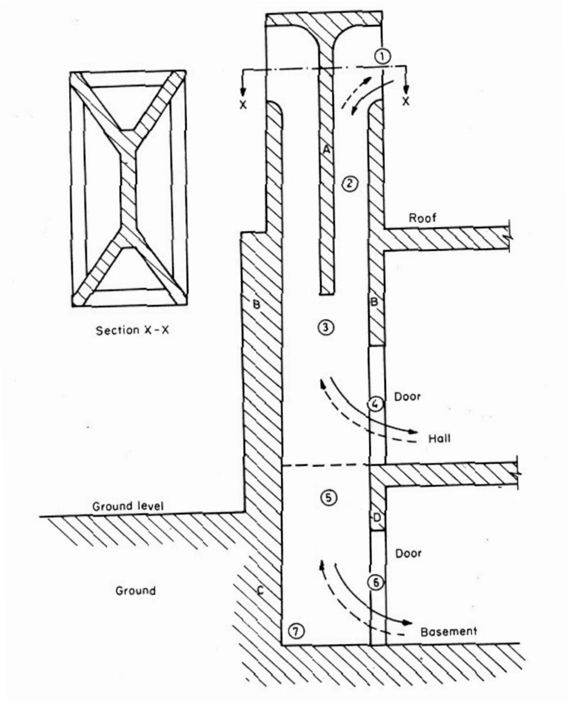
Among the typology of fountains and outdoor water features, the *salsabil* is a marble fountain used in medieval Arabic and Moghul architecture. Earliest existing examples come from across many diverse places such as Afghanistan, Algeria, Egypt and India and date back to the eleventh century. One of the best preserved and finest existing examples in Europe is probably in La Ziza Palace in Palermo, Sicily which dates back to the twelfth century *[*1*]*. This consists of a water spout in the back wall, usually located under a portico looking over the courtyard, flowing onto a carved marble slab tilted towards a little channel or intermediary pool before ending in a central pool in the middle of the courtyard. The movement of water associated with a large evaporative surface enhanced the cooling effect on the courtyard's microclimate. It was used in religious buildings as well as palaces, and its aesthetic and spiritual meanings in the Arabic medieval culture were very strong. In the Koran it was referred to as 'the fountain of paradise' from where the enlightened drink. The sequence of moving and still water, apart from producing sensory pleasure, are a reminder of the power of nature and God.[15]

Porous ceramic media are often found in traditional examples of passive evaporative cooling systems integrated into building elements or components such as clay water jars in wooden windows or at the bottom of wind towers. The *mashrabiya [*2a, 2b*]* is an opening with a wooden lattice screen, which performs different functions so as to provide privacy, ventilation, solar control, glare reduction, and to cool the air by evaporation, consequently increasing the relative humidity of the indoor spaces. Its name is derived from Arabic and means drinking place. This was a cantilevered space with a lattice opening, where small ceramic water jars were placed, so as to be cooled by evaporation as air moved through the opening.[16]

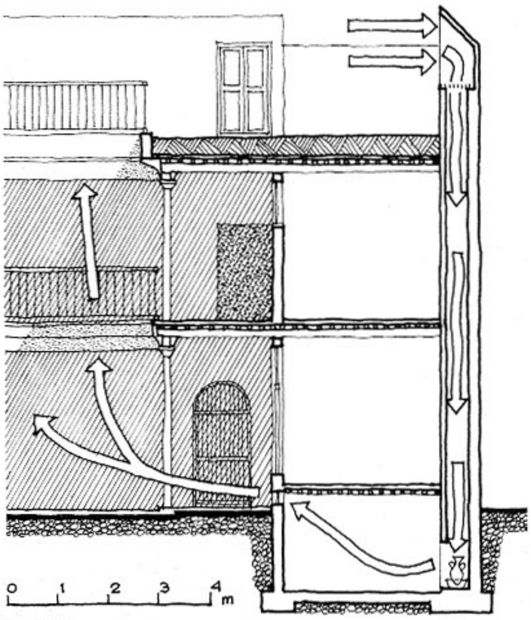
A variant of the *mashrabiya* found in Muscat, Oman was reported in the mid 1970s *[*3a, 3b*]*.[17] The window is made of three parts: a lower part where a lattice screen allows an uncontrolled air flow, a middle part where a cantilevered lattice structure holds a porous ceramic water jar and internally shutters are placed to control air movement, and an upper part where a shaded lattice work allows hot air to escape. Water seeps through the water-filled jar and keeps the outer surface of the jar permanently moist. Air passing over the surface causes the water to evaporate and absorbs heat energy, thus cooling the air and providing a supply of cool water for drinking. The window provides cooling, air movement and solar control in one system, just as a modern air-conditioning unit would do. Whereas an air-conditioning unit would require electrical energy and a control system to operate, the Muscatese window is a complete self-regulating system that relies only on the provision of sufficient air movement and the availability of a small quantity of water.

The Iranian wind towers or *baud-geers* are designed to provide natural circulation and cooling of the ambient air through the building *[*4*]*. Iranian wind towers have openings on the top facing all directions or, in some cases, only in the direction from which the wind is predominant. There are many wind tower types; these can vary for tower heights, openings and different cross-sections for airflow passages. The designs vary according to the desired airflow rate, heat transfer area, sensible heat storage capacity and evaporative cooling surfaces.[18]

Similarly, as with the Iranian wind tower system, the courtyard houses of Iraq[19] have a series of wind catchers placed on the roof to provide natural ventilation for a basement room where the residents normally take their summer afternoon siesta. Each catcher is connected to the basement by a duct contained between the two skins of a party-wall, which is cooled during the night by natural ventilation. Due to their not receiving any direct solar radiation and also because of their thickness, the surfaces of the internal party-wall remain at a



4



5

4 Traditional Iranian Wind Tower

5 Iraqi Wind-catcher using a water jar

6 Principle of operation of the Evapcool System

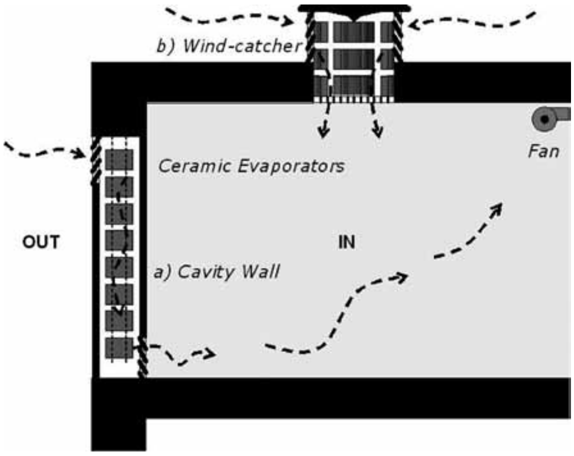
lower temperature than the rest of the interior throughout the day. The incoming air is cooled by conduction when it comes into contact with the cold inner surfaces of the duct walls, and its absolute humidity is increased as it passes over porous water jugs just before being discharged into the basement *[5]*. After passing through the basement, the air flows into the courtyard, helping to ventilate this area during the daytime. The same evaporative cooling system using porous water jars can be found in the Sind region of Pakistan[20] and in the Egyptian counterpart from the examples of Hassan Fathy's architecture.[21]

Recent innovations and contemporary applications

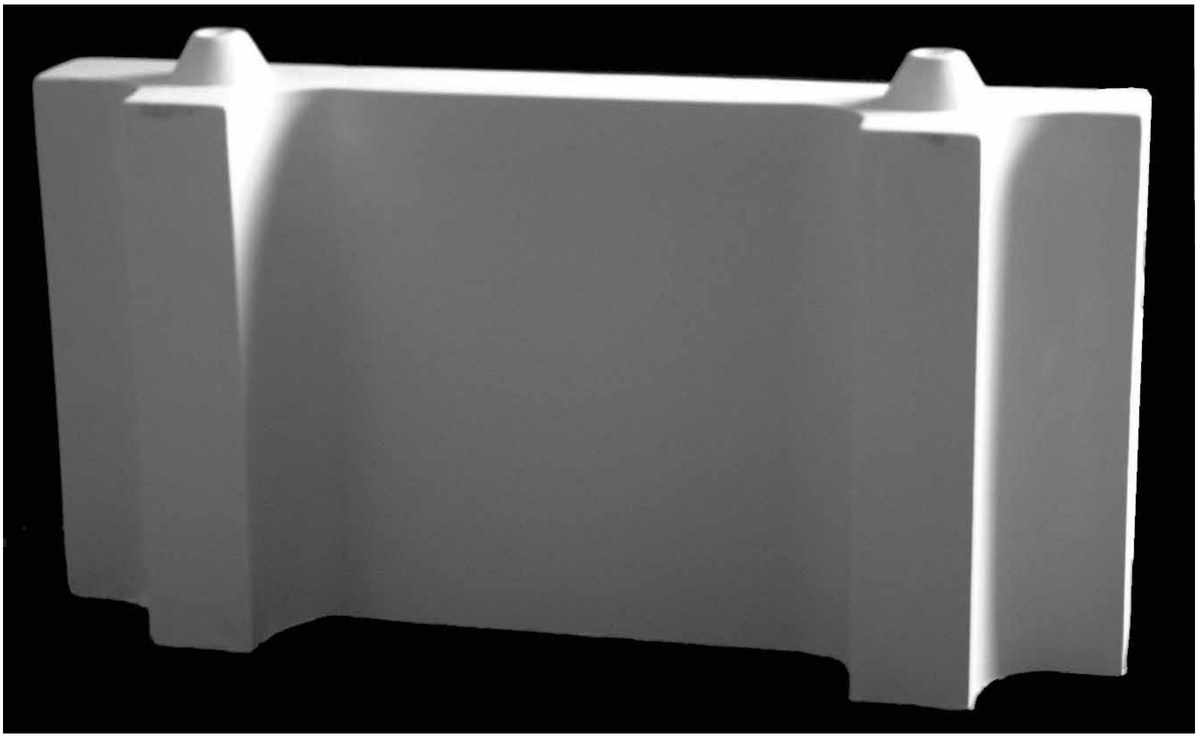
Conventional cooling solutions such as refrigerant based room air conditioners as well as evaporative desert coolers, present problems of noise, risk of microbiological contamination and risk of poor efficiency, if adequate and regular maintenance is not performed. Furthermore, the environmental impact of refrigerant-based units, including those branded as 'green', is not negligible and is manifest in high global warming potentials. Conventional desert coolers do avoid the use of refrigerants and consume 25% less energy, but are not building-integrated and are often unsightly, being attached to the outside of buildings.

Research on innovative passive evaporative cooling has mainly concentrated on developing systems, such as passive downdraught evaporative cooling systems (PDEC), which can effectively cool large volumes of space relying on high air change rates; however, these do not affect the building envelope and cannot be used directly in cellular spaces (for a review of the latest developments in PDEC systems consult Ford and others).[22] Modular porous ceramic evaporators are the modern transposition of the traditional concept of the water jar integrated into the building. They can be considered a type of PDEC system but their main advantage is to be an integral part of the building fabric and, thus, they avoid the risk of microbiological contamination as the water is contained in the ceramic evaporators, located in a diaphragm wall, and cannot get into direct contact with the occupants.

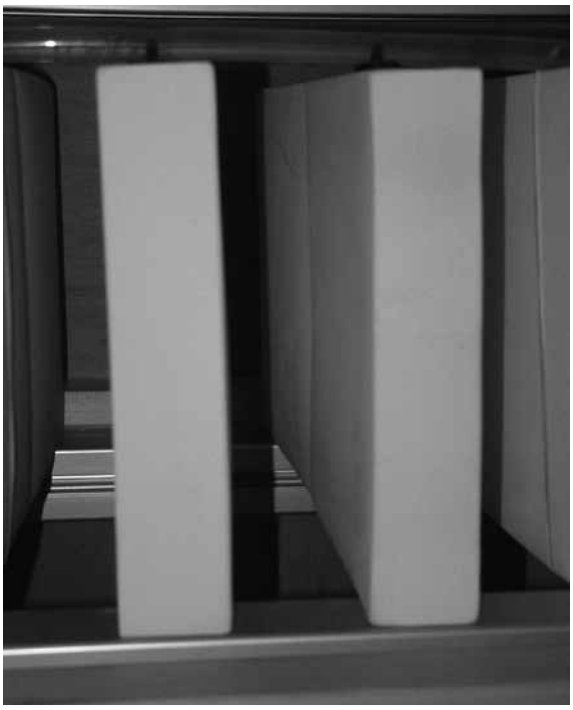
Research into the development of modular evaporators for cooling of non-domestic buildings was initiated in 2001 by Brian Ford and others.[23] in an EC funded research project (Evapcool), which demonstrated the feasibility of a direct evaporative cooling system using porous ceramic in non-domestic buildings *[6, 7a, 7b, 8a, 8b]*. The EC research project left a few unexplored issues, such as installation, effective water supply and distribution, maintenance and control. Moreover, the performance analysis highlighted that the ceramic area required to meet the typical cooling loads of a non-domestic building is very large, to the point of potentially compromising the cost effectiveness of the proposed system, and with implications for their



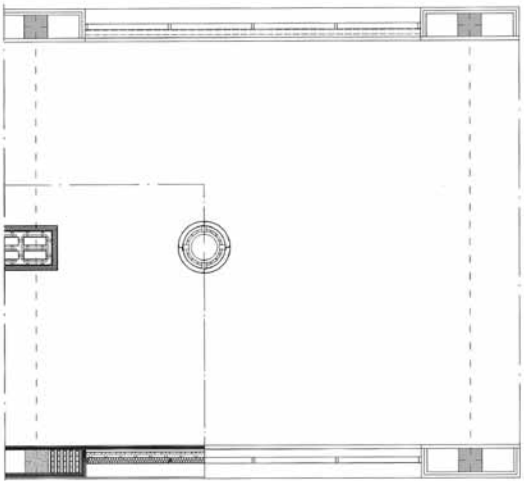
6



7a



7b



8a

7 *a–b* **Stacking Ceramic Prototype (*a*) and Shelved Ceramic Prototype (*b*)**

8 **Typical concrete frame office used for the Evapcool EC project (*a*) and Physical model of Evapcool systems integrated in a top floor office (*b*)**

9 **Spanish Pavillion at Zaragoza Expo 2008**

10 **Green Office, Teheran**

8b

9a

9b

10

architectural integration. Additionally, the reduction of floor area can be a limiting factor in office building applications, especially in urban areas where the cost of renting is very high. An outcome of the research was also that application of porous ceramic evaporators is much more suitable to the residential sector, especially because of the lower cooling loads, which can be met in a more cost effective manner.

To date there are some but very few known examples of porous ceramic applications to non-domestic buildings. Francisco Mangado's Spanish Pavilion at the 2008 Zaragoza Expo featured an array of 750 clay columns, supporting the roof's shading canopy. The columns rise from shallow pools and are occasionally interrupted by glazed exhibition space. The original design strategy was intended to create a passive evaporative cooling effect of the semi-open space from the ceramic columns wetted by osmosis. However, as also the architect admits, this process is interrupted by the sand and cement mortar joining the ceramic cylinders. This could have been easily avoided if a lime-based mortar was used maintaining the porous continuity of the tubes. In any case, the building has been widely acclaimed as critics[24] and visitors alike appreciated the fitting reference to the

Expo's theme of Water and Sustainable Development and the visually fascinating result *[9]*.

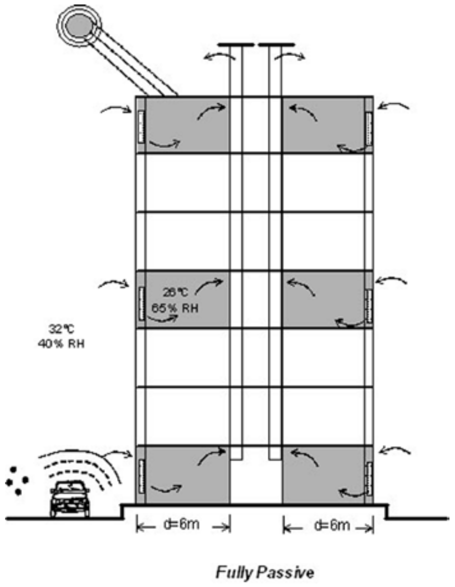
A slightly more low-tech application of the concept of porous ceramic for passive evaporative cooling in buildings is represented by the Tehran mayor's 'Green Office' completed in 2008.[25] The architects, Golzari and Saberi, adapted the concept of the porous ceramic wall, developed by Brian Ford and Rosa Schiano-Phan, to suit the limited budget and unavailability of the modular porous ceramic evaporator, and transposed the principle of a wet wall to an ordinary brick wall wetted from the top by irrigation pipes. The wall sits behind a glass panel in the reception area of the mayor's office *[10]* and its purpose is clearly more illustrative than effective in cooling an interior, whose design unfortunately did not benefit from an equal level of sustainable, passive design measures, as the conventional suspended ceiling and luminaires suggest.

Building integration of porous ceramic systems in residential buildings

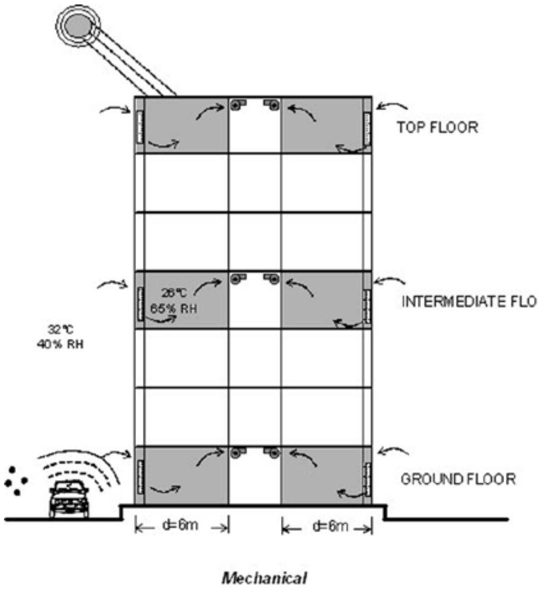
The passive evaporative cooling system using porous ceramic evaporators in residential buildings was the subject of a Ph.D. research[26] investigating the development of a system intended for cellular room operation (porous ceramic system (PCS).

In order to cool the hot and dry air coming from outdoors, the system needs to be placed adjacent to the perimeter walls or, alternatively, in contact with the roof. This is generally possible in shallow plan buildings; however, in deep plan buildings, only the rooms with direct access to external walls can use this technique. Mitigation techniques and alternative cooling solutions must be adopted for core areas such as corridors, lobbies or general circulation spaces. In apartment blocks the floor level also has an impact on the sizing of the PCS. The ground floors, usually affected by problems of noise, pollution and often security, can greatly benefit from the installation of a PCS. 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 PCS. Mitigation techniques, such as night-time ventilation, solar control and improvement of the building envelope result in a considerable reduction of the cooling loads which can be lowered to as little as 23kWh/m^2 (corresponding to a B rating in the Spanish Energy Performance Building Classification and very close to the Spanish Passivhaus performance review of about 22kWh/m^2).[27] The wall integrated ceramic system is capable of fully meeting this residual cooling load.

The system's ventilation regime can be implemented in several ways depending on the opportunities and constraints that the refurbishment project offers. The possible main strategies *[11]* vary from a purely passive mode, where the air movement relies entirely upon a natural ventilation strategy, to a mechanical mode, where the outdoor air is pulled through the wet cavity via a low wattage extractor fan. A mixed mode could offer a suitable compromise where air movement is mainly provided by natural buoyancy using stack effect, provided by a central atrium space (e.g. staircases). When this is not sufficient, or when extra ventilation is required (e.g. to counteract negative pressure), the extractor fan can be used as back-up system.



11a



11b

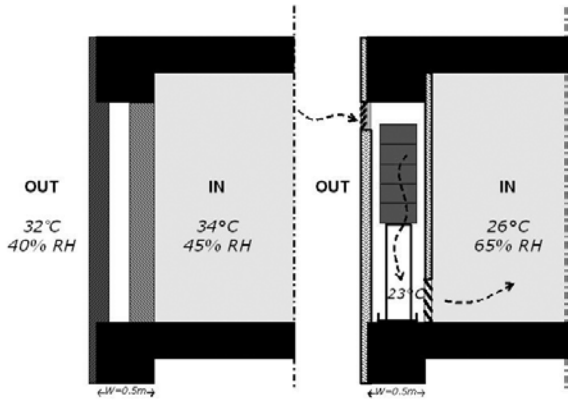
11 Building strategies

12 Diagrams showing integration of Ceramic System with substitution of existing perimeter wall (before – left and after – right)

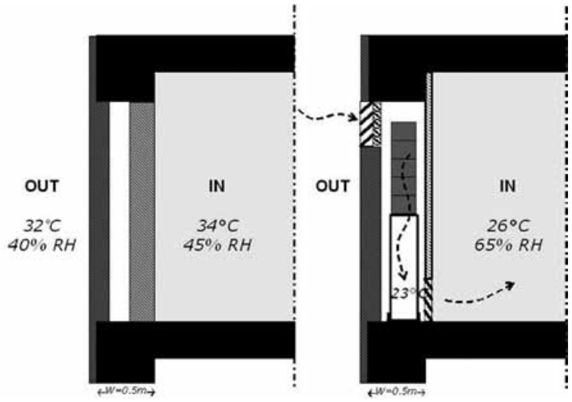
13 Diagram of Ceramic System showing add-on diaphragm wall integration (before and after)

14 Outdoor diaphragm wall integration (before and after)

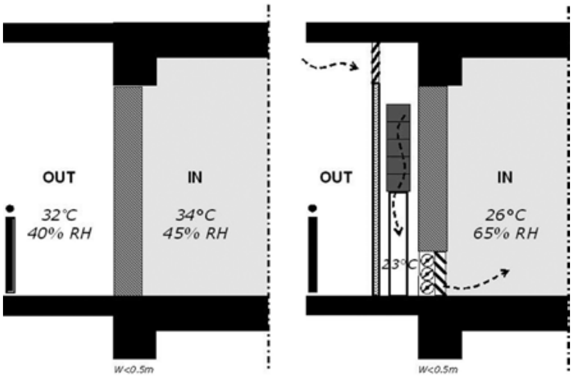
The type of wall construction can clearly influence the design and integration of the system. Some



12



13



14

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 and components. In existing buildings of concrete-frame construction there are two main scenarios for the integration of the PCS. One is represented by a full substitution of the existing perimeter wall *[12]*; the other is to retain part of the existing wall *[13]*. These two scenarios depend on many factors, often related to the age of the building and its condition; however, they both have implications for the detailed integration of the system and its relationship with the other building components. Additional options for smaller cooling requirements are the window sill and bulkhead options *[15a, 15b]*.

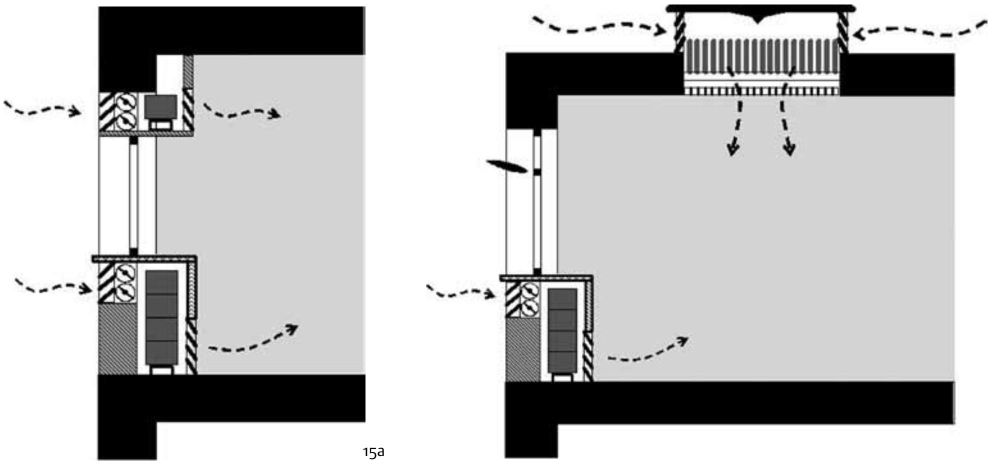
Additional components required for the full installation and correct operation of the system are the supporting structure and the water supply system. Although galvanised steel is the lighter option and allows a degree of prefabrication, which can undoubtedly be desirable especially in the minor interventions, the use of masonry (corbelled bricks) can be an easier and cheaper alternative. The water supply and distribution system is preferably made of gravity-fed rainwater, distributed in standard pressure pipes and controlled by a float valve. This has the advantage of creating a self-regulating system where the water supplied is equivalent to the water evaporated. Furthermore, rainwater represents an ideal solution to the potential problem of scale deposition for its low calcium content. The impact of controls on the design and installation depends on the required degree of complexity, compatible with the context and building application (e.g. high spec apartments or social housing). A basic specification requires manual controls of the inlet and outlet openings and a gravity-fed rainwater supply system, which will considerably reduce both the cost and environmental impacts.

Technical applicability and performance

There are two fundamental criteria for the technical applicability of the PCS: 'climatic applicability' and 'geometric applicability'. Climatic applicability tests the existence of the appropriate climatic conditions for the integration of passive evaporative cooling into the chosen location. Evaporative cooling can only be applied in hot and dry climates. To assess the general viability of evaporative cooling in a specific location, monthly climate data can be plotted on a psychrometric chart. A more detailed assessment can be done by analysing the hourly weather data for a typical year and verifying that: a) the ambient wet bulb temperature is above 24°C for no more than 100hrs during the cooling season; b) there is a relatively high (typically around 10K) wet bulb temperature depression (i.e. the difference between ambient dry and wet bulb temperature). This last criterion has some important implications in the choice of the typical hot day to design for. The preferred approach to the design of the porous ceramic system is to size it for one typical hot day rather than for the absolute summer peak condition. By designing for conditions which are representative of hot summer days, one avoids the risk of over-sizing the system, which would be more likely if designing for absolute peak conditions.

For 'geometric applicability' it is intended the potential for application of the proposed system gauged against geometric parameters (e.g. perimeter walls, exposed roof, etc.). The porous ceramic system as defined above can be assumed to be always applicable in residential buildings by being a system fully integral to the building envelope. Theoretically speaking, the porous ceramic system can be integrated wherever there is an exposed wall; however, there are a series of limitations which might jeopardise its full integration, beginning with the size of the system required to offset the typical cooling loads of the room or the dwelling in consideration.

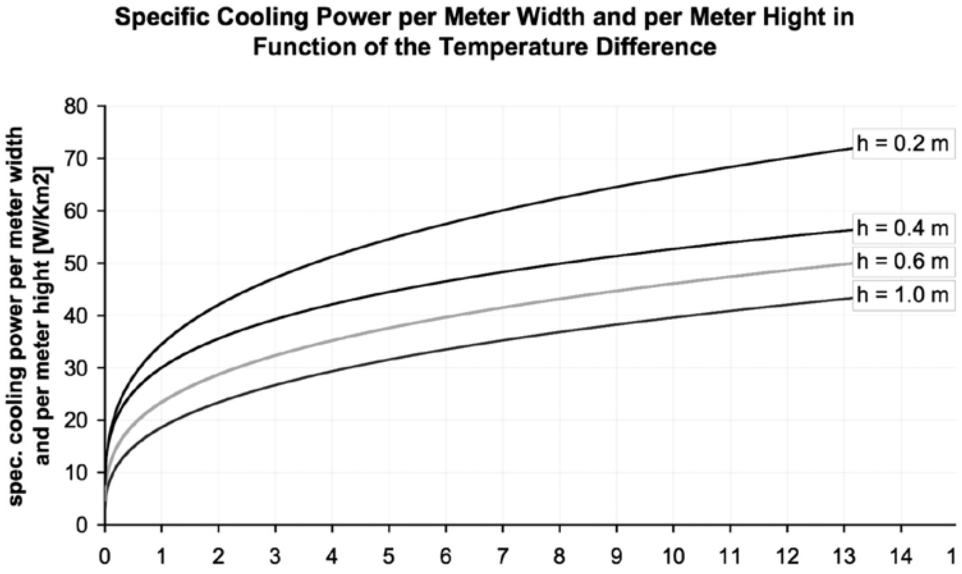
15 **Bulkhead and window sill, Wind-catcher and window sill**



15a

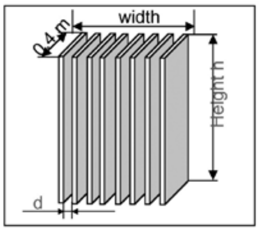
15b

16 **Performance Chart**



16

17 **Porous Ceramic System and Formula characterising the cooling output of the PCS system**



$Qt = Qs \times \Delta T \times h \times w$;
Where:

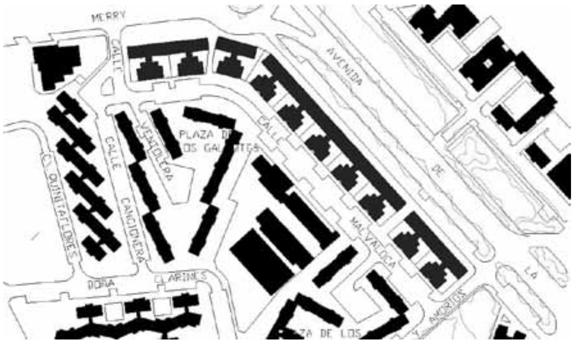
- Qt is the total cooling requirement in Watts.
- Qs is the specific cooling power in W/m^2K (derived from the chart).
- ΔT is the Wet Bulb Temperature Depression in Kelvin (derived from weather data and entered on the x axis of the chart);
- h is the height of the Porous Ceramic System in m.
- w is the width of the PCS.

17

Given the appropriate climatic conditions, the technical applicability of the proposed porous ceramic system in 1960s residential buildings is dependent on the ratio between useful perimeter walls and required width of the PCS. It is on this ratio that the degree of applicability is defined, and this goes from an integration requiring radical interventions, such as substitution of the perimeter walls, to a system integration requiring the simple add-on of a diaphragm wall on the inside of the building.

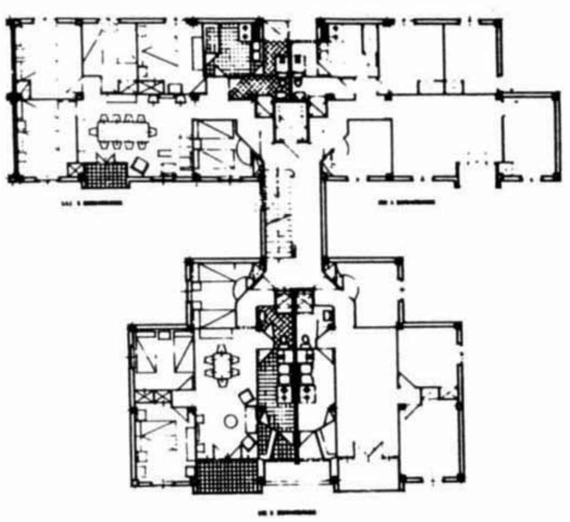
The size of PCS required to meet the space cooling demand can be obtained from the performance chart [16] developed as part of the Evapcool project.[28] The chart gives the specific cooling power of different heights of the PCS expressed as a function of the ambient wet bulb temperature depression. By entering the temperature depression at the peak hour of a typical summer day, it is possible to identify the system's specific cooling power for each system's heights. From the specific cooling power it is possible to derive, by inverse formula, the width of the PCS [17] to be integrated into the building envelope.[29] For instance, for a wet-dry bulb temperature depression of 10K, the specific cooling power of the system ranges between 40 and 68W per square metre of

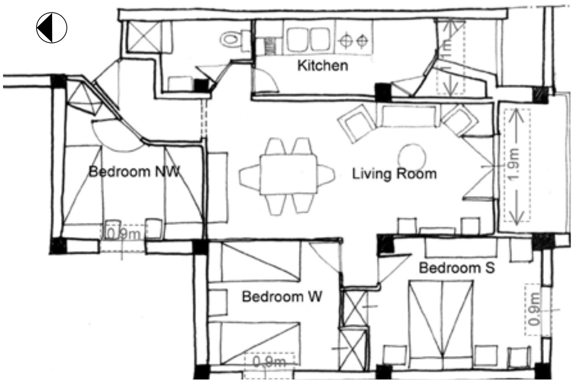

18a



18b


18c


18d



18e

18 Case study Building: Housing Development 'Barriada Los Diez Mandamiento', Calle General Merry y Malvaloca, Seville. Arch. Luis Recasens Mendez-Quipo de Llano, 1958–64
a Arial photograph of the development (OPS, 2003)
b Noli plan from 1:5000 map of Seville
c The development in 1964 (Mosquera Adell, 1992)
d Plan (Mosquera Adell, 1992)
e Diagram of Porous Ceramic System integration in Top Floor Apartment

ceramic surface area and temperature differential K. The variation in specific cooling output depends on the height of the system. Shorter systems (h=0.2 m) offer greater specific cooling power due to increased efficiency; however, a greater width may be necessary to obtain the total cooling capacity required. On the other hand, higher systems (h=1 m), which offer smaller efficiency since the evaporative cooling effect is diminished by the saturation of the air along the system's height, can provide the required total cooling capacity with smaller widths, easier to integrate into the envelope. For example, a PCS of 2 m x 0.6 m (W x H) can meet the cooling demand of a regular living room (36W/m^2 of floor area). Dynamic thermal modelling and CFD analysis for a case study apartment in Seville *[18]* suggested that the system can provide temperatures below 28°C for 75% of the occupied time of the year. This is considerably lower than the outdoor temperatures (32°C) but can only be achieved as a result of an integrated passive design approach and in conjunction with a series of thermally mitigating passive strategies such as solar control, exposed thermal mass and night-time natural ventilation.

A potential problem, associated with the application of the PCS and direct evaporative cooling in general, which can affect comfort in the indoor environment, is the risk of high humidity levels, especially if manual controls are not operated correctly, allowing humid air to enter the indoor space when not required. This risk, however, is minimised by the fact that the system is intrinsically self-regulating as the evaporation of water, and the subsequent cooling effect, does not take place unless the environmental conditions of high temperature and low humidity are met. When the cold more humid air enters the occupied space, it is quickly mixed with the dry air improving comfort. The risk of high humidity levels is avoided if the inlet opening is controlled automatically with both temperature and RH sensors.

A pilot study, looking at the geometrical applicability of the system onto a small group of case study apartment buildings in Seville, showed that the system is fully applicable to 70% of the buildings observed. This means that, in 70% of the buildings, the system can meet the entire typical cooling loads. For the remaining 30%, the system cannot entirely remove the apartments' cooling loads. On these assumptions and assuming an average energy saving of 31kWh/m^2 from the application of the PCS, the average CO_2 saving is estimated to be 9 kg/m^{2}yr. Assuming that this result is applicable to the proportion of apartment blocks from 1940 and 1970 in Seville (48%), the PCS system could potentially save 0.58 million tonnes of CO_2 per year. Other factors, however, which could impinge on the technically achievable CO_2 reductions include consumer attitude; competition from other products; availability; know-how and cost.

Life cycle and capital costs

The average cost of a PCS diaphragm wall of dimensions 1 m (width) by 2.7 m (height) is estimated to be £1,368 in 2005. This includes the cost of the supporting structure, openings and partitions. The porous ceramic array is 1 m wide by 0.6 m high. Such a system has a peak cooling output of 0.5kW and can keep an average sized kitchen in comfortable conditions for most of the summer in Seville. Four variants corresponding to a different degree of technical complexity and market such as 'Vernacular', 'Low-tech', 'Medium-tech' and 'High-tech' would result in a cost range of £500 to £1,780. Life cycle costing comparing the proposed system with that of a conventional room air-conditioning unit of 2kW cooling power and costing £1,100 (year 2005) showed that, despite an initial capital cost greater for the PCS, the cost of the air-conditioning unit over a period of 25 years is nearly double the cost of the porous ceramic system. This demonstrates that the system is an economically viable cooling solution compared with conventional air conditioning.

Apart from costs and applicability there are other factors which influence consumer choice between a conventional cooling system and an innovative passive system. These are lack of confidence, both from the building owner and the builders/installers, in new energy technologies. Furthermore, the long lifespan of buildings and the long gaps between refurbishment cycles hinder application, as the proposed system and many of the proposed energy efficient measures are only cost-effective or practically feasible to the building owner if installed at the time of initial construction or refurbishment. Clear and impartial advice on the energy-efficient options and concrete evidence of their benefits, based on operating experience in the field, often do not reach the decision makers early enough in the design (e.g. builders, building owners, designers, developers, etc.).

Conclusion

The proposed passive evaporative cooling system using porous ceramic media addresses the requirement of cooling in the residential sector of hot-dry regions as well as its building integration. These principles have been part of the vernacular architecture of many countries across the world but have been progressively abandoned for energy intensive solutions. Previous research explored the application of porous ceramic evaporators to the cooling of non-domestic buildings; however, the development of a fully defined system for residential application was an unexplored area requiring further investigation.

The described research concluded that porous ceramic evaporators can be integrated into existing apartments as part of a minor intervention if cooling loads are small, and if the system is part of a raft of passive design measures aimed at improving the building performance. More effectively, the system could be integrated into the whole building as part of a major refurbishment. This would maximise the benefits of reduced cooling loads, improve performance of the building envelope and more effectively integrate the PCS into the building's ventilation and control strategy. The inclusion of a passive cooling system, as standard specification for the refurbishment of degraded housing blocks in many south European cities, could drastically improve the thermal comfort conditions of the occupants and reduce the use of room air conditioning.

If applied on a large scale, this could result in annual energy savings of 31kWh/m^2 and reduction of 9Kg/m^{2}yr of CO_2 (and other greenhouse gas) emissions into the atmosphere. The outline specification and cost analysis defined various costing scenarios for different contexts and types of applications within the residential sector. The life cycle cost analysis demonstrated that, despite the greater initial capital cost, the PCS is competitive to mechanical cooling and, over twenty-five years, its cost is half that of a conventional 'mini-split' unit.

In recent years a market assessment of the applicability of a number of passive downdraught evaporative cooling systems in Europe, China and India has been undertaken and a process of dissemination has been initiated, where the different players of the building sector are targeted to promote these innovative technologies through symposia and workshops. 'Promotion and Dissemination of Passive and Hybrid Downdraught Cooling' (PHDC) is the subject of a recently concluded EC project (www.phdc.eu) coordinated by the University of Nottingham, which focused on the organisation of symposia and workshops in Europe, China and India in order to promote the potential of PHDC technologies through the dissemination of post-occupancy evaluation studies of buildings employing PHDC, and the publication of a design sourcebook.[30]

Notes

1. B. Ford, 'Passive Downdraught Evaporative Cooling: Principles and Practice', arq 5.3, 2001, pp. 271–80.
2. P. Thomas and others, Cost Benefit Evaluation, VT 1.5. *Solar Passive Heating and Cooling*, Davis Langdon Consultancy, EC, ALTENER Cluster 9 – Part I (4.1030/C/00-009/2000) (2003).
3. J. Molina and others, (2003). Personal communication on energy consumption and environmental data in buildings.
4. INE (Instituto Nacional de Estadistica), *Avance de resultados de los Censos de Población y Viviendas 2001,* 2003.
5. U. Eicker, *Solar Technologies for Buildings* (Chichester: Wiley), 2003.
6. European Commission DGXVII, 'Buildings Overview – Market Overview and Trends', 2004. Available from: <http://europa.eu.int/comm/energy_transport/atlas/htmlu/bomarover.html> [Accessed August 2004].
7. World Resources Institute, 'Energy and Resources – Spain' [online], Earthtrends Country Profiles, 2003. Available online from: <http://earthtrends.wri.org/pdf_library/country_profiles/ene_cou_724.pdf> [Accessed September 2004]
8. Molina and others.
9. BSRIA, *West European Room and Packaged Air-conditioning Market* (Bracknell: BSRIA Ltd, 2003).
10. McQuay Air Conditioning, *Refrigerants Bulletin*, 'Going ... Going ... Green: 10 Things You Should Know About HVAC Refrigerants and Phaseout Schedule', 2004. Available from: <http://www.mcquay.com/eprise/main/mcquaybiz/Lit_Systems/Flyers/GoingGoingGreen.pdf> [Accessed 12 January 2009].
11. F. Pearson, 'New, Natural and Alternative Refrigerants', in: *Building Sustainability, Value and Profit* [online]. CIBSE-ASHRAE Conference, London, 24–27 September 2003. Available from: <http://www.cibse.org/index.cfm?action=showpage&TopSecID=4&PageID=366> [Accessed 14 June 2004].
12. M. Santamouris, *Advances in Passive Cooling* (London: Earthscan, 2007), ISBN 9781844072637.
13. S. Alvarez and J. M. Salmeron-Lissen, 'Passivhaus Spain' in *The Passivhaus Standard in European Warm Climates – Design Guidelines for Comfortable Low Energy Homes: Technical Guidelines Part 2 – National Proposals in Detail*, edited by B. Ford, R. Schiano-Phan and D. Zhongcheng, Passive-on IEE Project, September 2007. Available online from: <http://www.passive-on.org/CD> [Accessed Jan 2010].
14. A. Cain, F. Ashfar and J. Norton, 'Indigenous Building and the Third World', *Architectural Design*, 45 (4), 1975a, pp. 207–24.
15. Y. Tabbaa, 'The Salsabil and Shadirwan in Medieval Islamic Courtyards', *Environmental Design: Journal of the Islamic Environmental Design Research Centre*, 1, 1986, pp. 34–37.
16. H. Fathy, *Natural Energy and Vernacular Architecture* (Chicago: University of Chicago Press, 1986).
17. A. Cain and others, 'Traditional Cooling Systems in the Third World', *The Ecologist*, 6 (2), pp. 60–65, 1976.
18. M. Bahadori, 'An Improved Design of Wind Towers for Natural Ventilation and Passive Cooling', *Solar Energy*, 35 (2), 1985, pp. 119–29.
19. A. Konya, *Design Primer for Hot Climates* (London: Architectural Press, 1980).
20. A. Cain, F. Ashfar and J. Norton, *Oman: the Problems and Potentials of the Indigenous Built Environment in a Developing Country*, Thesis (Diploma), (London: Architectural Association, 1975b).
21. J. Steele, *An Architecture for People – the Complete Works of Hassan Fathy* (New York: Whitney, 1997).
22. 'The Architecture and Engineering of Downdraught Cooling: A Design Sourcebook', ed. by B. Ford, R. Schiano-Phan and E. Francis, PHDC Press, June 2010. Available from: <http://www.phdc.eu>. ISBN 978-0-9565790-0-3.
23. B. Ford and R. Schiano-Phan, *Passive Downdraught Evaporative Cooling using Porous Ceramic in Non-Domestic buildings – Development of Key Components (Evapcool).* Final Report, EC Project ENK6-CT2000-00346, 2003. Available from: <http://phdc.eu> [Accessed January 2010]
24. W. Curtis, 'Zaragoza: Reflections on Water', in *Architecture Today* 191, September 2008, pp. 16–25.
25. B. Ford and R. Shiano-Phan, 'The Application of Downdraught Evaporative Cooling Systems in Non-Domestic Buildings. A Case Study: the Green Office, Tehran', IFCO Conference, Tehran, Iran. 15–18 February 2004.
26. R. Schiano-Phan, 'The Development of Passive Downdraught Evaporative Cooling Systems using Porous Ceramic Evaporators and their Application in Residential Buildings', Ph.D. Thesis, British Library, London, November 2004.
27. Alvarez and Salmeron-Lissen.
28. P. Sprecher, 'Analysis of a Case Study Building in Tehran using Dynamic Thermal Modelling and CFD Deliverable n. 10', in: *Passive Evaporative Cooling using Porous Ceramic – Development of Key Components* (EVAPCOOL), EC Project no. ENK6-CT-2000-00346, 2003.
29. H. Klan, 'Freie Konvektion in offenen Fluidschichten', Chapter Fd 1. *VDI-Wärmeatlas*, 8. Auflage, 1997.
30. 'The Architecture and Engineering of Downdraught Cooling: A Design Sourcebook'.

Illustration credits

arq gratefully acknowledges:
Author, 1, 2b, 11a–b, 12, 13, 14, 15 , 16, 17, 18b, 18e
Mehdi Bahadori, 4
Alan Cain, 3a–b
Brian Ford with Rosa Schiano-Phan, 6, 7a–b, 8a–b
Allan Konya, 5
Mosquera Adell, 18c–d
Omid Saberi, 10
Oficina del Plan de Sevilla, 18a
James Steele, 2a
Zaragoza Expo 2008, 9a–b

Acknowledgements

I would like to acknowledge the support and assistance of: Professor Brian Ford for the contribution to the work described and the supervision of my Ph.D. research; WSP Environmental Ltd. for sponsoring the Ph.D. research described in this article; Dr Simos Yannas for the valuable supervision during my Ph.D. studies at the Architectural Association in London; and the partners of the PHDC dissemination project, which is partially funded by the European Commission.

Biography

Dr Rosa Schiano-Phan is an architect and environmental design consultant. Formerly a senior sustainability consultant at WSP Environmental and a Research Fellow at the Department of the Built Environment, University of Nottingham, she currently works as a Lecturer in Sustainable Environmental Design at the Architectural Association, School of Architecture in London.

Author's Address

Dr Rosa Schiano-Phan
Architectural Association
School of Architecture
36, Bedford Square
London WC1B 3ES
schiano-phan_ro@aaschool.ac.uk


INTERNATIONAL JOURNAL OF
Cultural
Property
VOLUME 16 2009 NUMBER 1
CAMBRIDGE