

Porous ceramics for building evaporative cooling

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Abstract: Porous ceramic evaporators are considered viable alternatives for cooling buildings. Performance of ceramic panels, placed in a duct within a climate chamber, was assessed under controlled dry bulb temperature, relative humidity, supply water pressure, and layout in the duct. Results showed higher porosity ceramic and higher water pressure delivered greatest cooling. Dry bulb temperature drops of 6-8 Kelvin were achieved parallel with a 30 % rise in relative humidity. Maximum cooling, 224 W/m² of ceramic surface, was recorded for a high porosity ceramic in a single row stack and water supplied at 1.0m head. Ceramic surface temperatures were around 2.5 K to 4.0 K above wet bulb, indicating potential improvement through better heat/mass transfer. Empirical formulae relate mean cooling performance to [es-e], ambient to saturated vapour pressure difference. Direct evaporative cooling, using porous ceramic evaporators, has demonstrated significant potential for building cooling.

Keywords: air conditioning, porous ceramic, evaporative cooling, free cooling

1. Introduction

Worldwide primary energy consumption is rising unabated. Partly due to greater use of air conditioning systems in buildings. Summer cooling demand on electricity, often outstrips supply in many parts of the world. As electricity is the predominant energy source for air conditioning systems, substantial energy savings and reduction in CO₂ emissions can be had by adopting passive cooling means. One such technology uses porous ceramic evaporators.

Cooling using porous material has been in use since ancient times. Porous water vessels are common in hot, dry countries. Achievement of evaporative cooling of the airstream has been effected by passing air through damp pads (Hicks et al.) [1], passing it through falling water (Gillet et al.) [2], or spraying into the airstream (Bowman et al.) [3]. The effectiveness of evaporative cooling in buildings has been borne out in researches; Nahar et al. [4] established that of a number of different mechanisms, evaporative cooling was found to perform the best for a conventional roof in the desert climate of Jodhpur, India. Wetted jute bags laid out on a reinforced concrete roof, brought an appreciable drop in indoor temperature. In a pharmaceutical complex in Ahmedabad, India, Ford et al. [5] demonstrated 36% savings in plant expenditure and 64% less energy consumption compared to conventional air conditioning by using an evaporative downdraught technique (PDEC) driven by microniser sprays.

Integrating porous ceramic cooling elements into

buildings to exploit evaporative cooling potential has been the subject of an EC research project. As such, characterising performance of prototype porous ceramic evaporative coolers has been undertaken.

2. Description of experimental setup

A porous ceramic evaporator is a closed, hollow, rectangular unit nominally: 315mm*165mm*35mm - wall 5mm thick. Holes on the side let in supply water and sensors, Figure 1. Test prototypes were fired at three temperatures of; 1110 °C, 1130degC and 1170 °C, giving average porosities of; 17.7 %, 13.0 %, 8.4 % respectively.

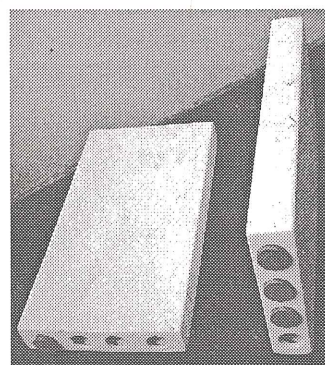


Fig. 1. Photo of prototype porous ceramic evaporators

A climate chamber with proper control of dry bulb temperature (DBT) and relative humidity (RH) was used for tests. Ceramic evaporators were placed in a 2430 mm high, vertical duct externally insulated by 70mm polyurethane. The duct cross-section measured 340 mm* 210mm internally, housing a single evaporator or two side-by-side (Fig. 2).

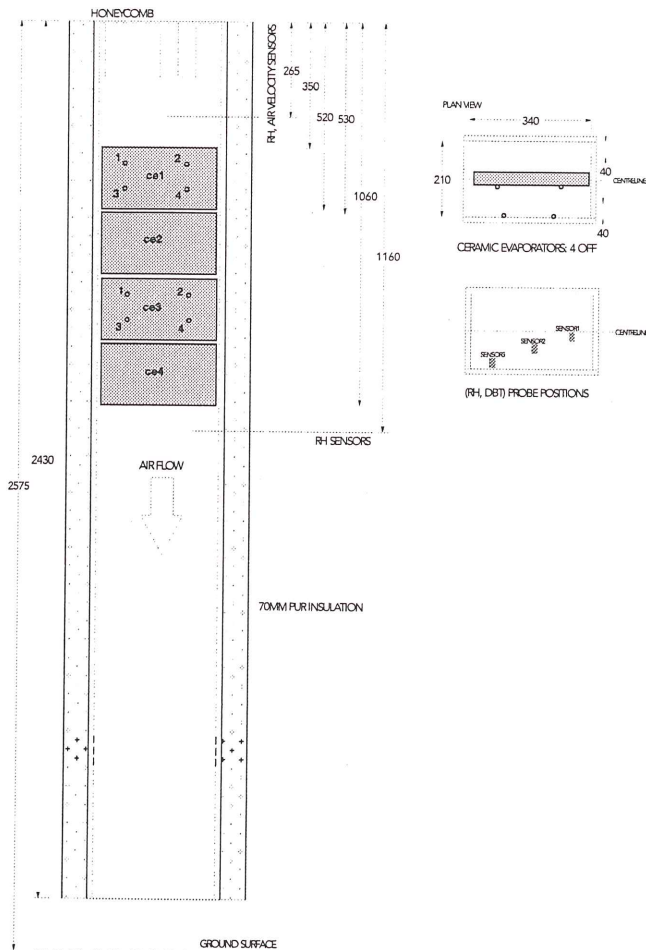


Fig. 2. Schematic of experimental duct general arrangement

Air enters through the duct top at controlled DBT and RH, and through honeycomb smoothing flow for velocity measurement. Air goes over the ceramic evaporators and exits the duct into the chamber. Water at 0.4m or 1.0m head was supplied to the ceramic evaporators from a tank. A drip tray collected seepage.

A climate cycle was set on the environmental chamber. Ambient RH was varied at two to three levels; nominally 25 %, 40 % and 55 %. At each RH level, ambient DBT was raised over the range 27 to 37 Celsius in equal increments. Air speed through the duct was held relatively constant. The water supply pressure to the ceramic evaporators was fixed. At each test level, the system was allowed to reach steady state before moving to the next level. Data was collected throughout the test covering; inlet and outlet DBT, RH, air velocity at inlet, and supply water temperature.

Air velocity was measured using two, TSI inc. 8455, hot wire transducers. Humidity and temperature using VAISALA HMP45A, combined RH and Pt100 temperature probes. Three probes were located 100mm downstream of the bottom evaporator, staggered at

middle, quarter distance, and wall zones of the duct cross-section. Type T thermocouples measured temperature of ceramic surface and the duct wall opposite at evaporators CE1 and CE3, first and third from top respectively. Barometric pressure was read from an Oregon Scientific mini weather station.

2.1 Experiment results

Typical DBT, RH, and velocity trends are shown on Figs. 3 to 5. In Fig. 3, a drop in air DBT occurs as it passes over the porous ceramic surfaces. The greatest drop is at the centre of the duct directly under the vertical evaporators. The other parts of the duct, namely at quarter distance and near the duct wall, experience a lower temperature drop. Mean ceramic surface temperature is far lower than outlet air. Further, the evaporator third in line from the top shows a lower surface temperature than the first. The plot of relative humidity, Fig. 4, shows moisture content of the air is also raised, and is distributed across the cross-section in a similar manner. In this instance, cooling of about 2 Kelvin is effected by a RH rise of about 10 %. Air velocity, Fig. 5, varies between (0.12 to 0.15)/ m/s over this test. The trends presented are typical of the experimental results seen throughout testing.

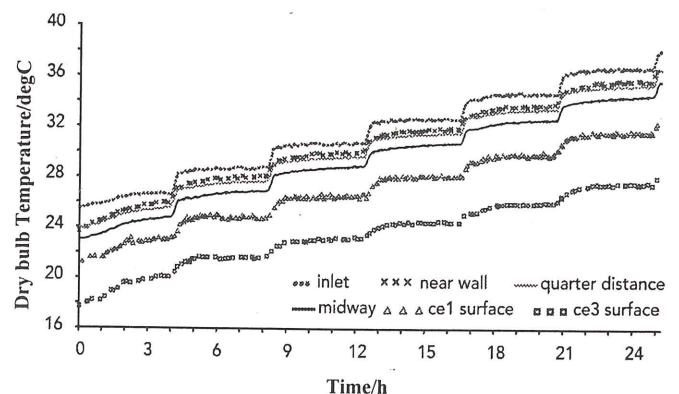


Fig. 3. Graph of typical duct air & ceramic surface dry bulb temperature (DBT) trends during a test

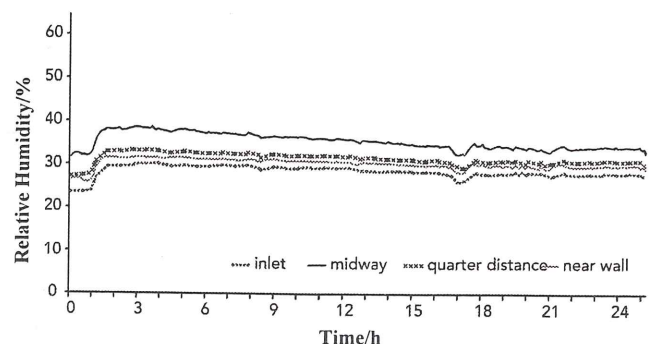


Fig. 4. Graph of typical duct air relative humidity (RH) trends during a test

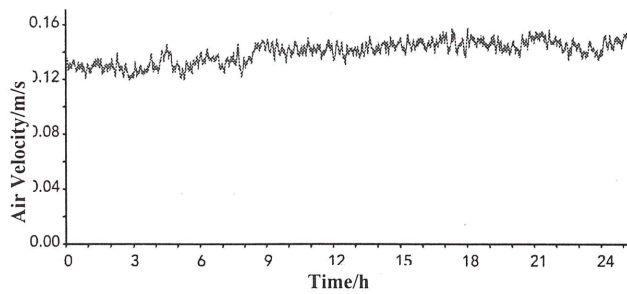


Fig. 5. Graph of typical mean air velocity trend during a test

2.2 Cooling performance

The cooling performance of the direct evaporative system is given by;

$$\text{Cooling}(Wm^{-2}) = \frac{\rho A_{duct} v c_p [T_{in} - T_{out}]}{A_{ce}} \quad (1)$$

where density, $\rho = \frac{P}{RT}$

Evaporative cooling performance is profoundly influenced by several factors; air temperature, humidity, air velocity, and to quite small extent barometric pressure. The parameter expressing the force driving evaporation of water from the wetted porous ceramic surface was found to be $[e_s - e]$. This is the ambient to saturated vapour pressure difference. Ambient vapour pressure, e , is a measure of the amount of water vapour present in the air, while saturated vapour pressure, e_s , is the maximum amount that could be held. Saturated vapour pressure is a function of temperature (Monteith et al.) [6]. The experimental results have shown the value of this parameter, as cooling is related to the combination of temperature, and humidity leading to a particular vapour pressure condition.

Statistical analysis of the parameters; relative humidity and dry bulb temperature at inlet, ambient vapour pressure, and cooling power was carried out. Mean and standard deviation, at steady state - last 1 or 2 hours, of each (RH, DBT) combination was calculated. Tables 1-4 summarise the results of the analysis, comprising inlet air temperature and relative humidity, mean air velocity, parameter $[e_s - e]$, and cooling power referenced to porous ceramic surface area.

2.3 Effect of porosity on cooling performance

The ceramic evaporators were placed within the experimental duct in twin row configuration. For each porosity, tests were repeated to quantify and compare

cooling. Figure 6 compares cooling performance of both medium and high porosity prototypes. Tables 1,2 present a summary of the data. Clearly, higher porosity yields consistently better cooling. Typical, dry bulb temperature drops of 6-8 Kelvin have been measured at a mean air velocity of 0.08-0.10m/s, accompanied by a 30% increase in relative humidity. Maximum cooling measured for the high porosity prototype was 145 W/m² compared to 126 W/m² for the medium porosity prototype. The low porosity ceramic evaporator gave no measurable cooling.

Table 1. Medium porosity prototype, twin row, high water head experiment conditions & results

No	DBT /°C	RH /%	velocity /(m/s)	$[e_s - e]$ /mB	Cooling /(W/m ²)
1	34.4	22.6	0.09	41.9	105
2	36.4	22.2	0.09	47.1	105
3	38.4	21.9	0.09	52.8	110
4	40.5	21.6	0.09	59.1	120
5	42.6	21.9	0.09	65.9	126
6	37.2	41.9	0.09	36.7	92
7	39.5	41.1	0.09	42.1	101
8	41.6	40.9	0.10	47.3	107
9	37.0	60.2	0.10	24.9	55
10	39.6	57.5	0.10	30.6	77
11	41.7	59.0	0.10	33.0	85
12	43.7	59.9	0.10	35.7	93

Table 2. High porosity prototype, twin row, high water head experiment conditions & results

No	DBT /°C	RH /%	velocity /(m/s)	$[e_s - e]$ /mB	Cooling /(W/m ²)
1	30.0	26.2	0.09	31.2	113
2	32.2	25.1	0.09	35.9	127
3	34.2	23.6	0.09	41.1	127
4	36.2	23.6	0.09	45.7	131
5	38.2	23.3	0.09	51.1	132
6	40.1	22.7	0.09	57.2	138
7	41.6	22.2	0.09	62.4	145
8	33.7	44.3	0.10	29.1	88
9	36.5	41.7	0.10	35.5	118
10	38.8	40.5	0.10	40.9	121
11	40.8	40.6	0.10	45.5	124
12	42.9	40.5	0.10	50.8	128
13	45.0	40.6	0.10	56.6	131

Table 3. High porosity prototype, single row, high water head experiment conditions & results

No	DBT /°C	RH /%	velocity /(m/s)	[e _s -e] /mB	Cooling /(W/m ²)
1	25.5	27.4	0.13	23.6	126
2	27.3	26.4	0.13	26.7	151
3	29.2	26.1	0.14	30.0	172
4	31.1	25.8	0.14	33.6	183
5	32.4	26.0	0.14	35.9	170
6	34.6	24.9	0.14	41.2	199
7	25.8	26.2	0.10	24.5	134
8	27.7	25.8	0.11	27.6	171
9	29.7	25.4	0.11	31.2	174
10	31.8	25.5	0.11	34.9	193
11	33.6	25.1	0.11	39.0	200
12	35.5	24.6	0.12	43.7	224

Table 4. High porosity prototype, single row, low water head experiment conditions & results

No	DBT /°C	RH /%	velocity /(m/s)	[e _s -e] /mB	Cooling /(W/m ²)
1	27.4	26.9	0.10	26.7	109
2	29.3	25.6	0.10	30.4	129
3	31.5	24.7	0.11	34.8	155
4	33.5	24.4	0.11	39.2	163
5	35.5	24.5	0.12	43.6	190
6	27.4	37.2	0.10	22.9	95
7	29.6	35.4	0.11	26.7	114
8	31.6	35.6	0.10	29.9	120
9	33.0	36.4	0.11	31.9	123
10	35.8	37.4	0.13	36.7	164
11	38.0	38.0	0.13	41.0	168
12	40.2	37.8	0.13	46.3	172
13	42.3	38.3	0.14	51.3	184

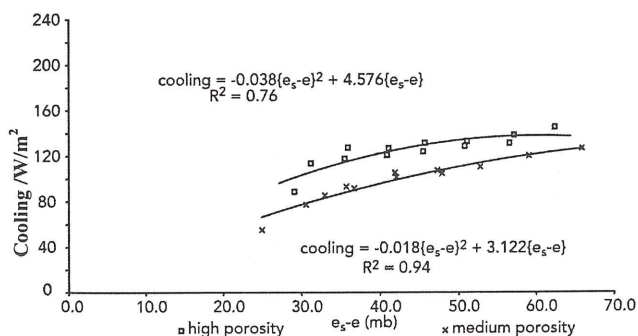


Fig. 6. Graph of effect of porosity on cooling performance: medium and high porosity ceramic evaporators

2.4 Effect configuration high porosity ceramic twin versus single row

A comparison of single with twin row configuration was carried out to reflect the particular applications of porous ceramic panels to a building envelope. The four high porosity ceramic evaporators were placed vertically inline within the experimental duct. The results, Fig. 7, show that ceramic evaporators in a single row provide higher cooling than in side-by-side configuration. A maximum cooling power of 224 W/m² is recorded compared to 126 W/m² for the same ambient dry bulb temperature of 36degC and nominally 25% relative humidity. The increased cooling may be assigned to; 1) less blockage of airflow through the duct. Air velocity is on average 44% higher; 2) the evaporators are stacked four high, and so dripping/seepage water flows over four ceramic evaporator surfaces compared to two; and 3) the four high stack has higher head of water, 0.35 m more at the bottom two ceramic evaporators.

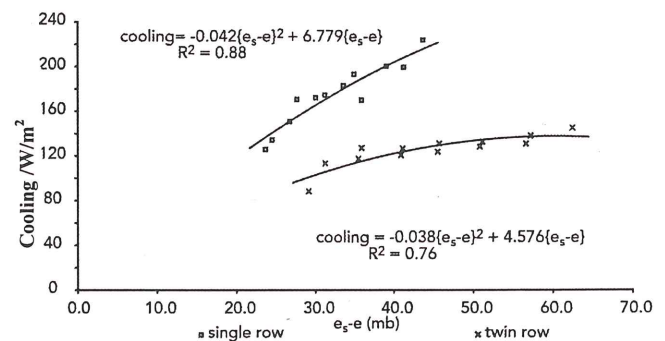


Fig. 7. Graph of effect of configuration on cooling performance: high porosity ceramic evaporators in single and twin layout within duct cross-section

2.5 Effect of water head

In the single row configuration and using high porosity evaporators, the supply water head was changed. Two levels, low and high were investigated. The low level corresponds to 0.4m head above top evaporator. The high level corresponds to 1.0m head above top evaporator. The supply head difference is 0.6m. Results show higher supply water pressure yields higher cooling, 190 W/m² for low head compared to the maximum of 224 W/m² for high head previously discussed.

2.6 Empirical models

Best fit of experimental data with respect to [e_s-e] yield empirical relations for the steady state mean cooling performance of porous ceramic evaporators for air velocity of 0.11-0.14m/s. These are shown on the graphs of Figs. 6-8.

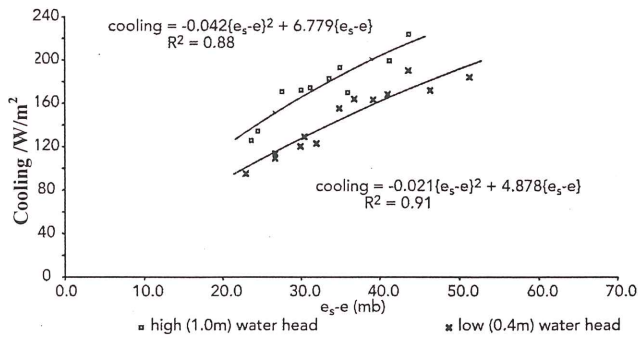


Fig. 8. Graph of effect of supply water pressure on cooling performance: high porosity ceramic evaporators

3. Conclusions

Porous ceramic evaporators have been tested under a variety of environmental conditions. Generally, the cooling effect of the ceramic evaporators is a function of; ceramic porosity, humidity, and temperature. Air velocity has not been explicitly investigated here, but it is influential in the heat/mass transfer occurring at the ceramic surfaces. A parameter expressing the force driving evaporation of water from the wetted ceramic surface was found to be $[e_s - e]$. This is the ambient to saturated vapour pressure difference. Empirical performance relationships of mean cooling power versus the parameter, $[e_s - e]$ for velocity range (0.09-0.11 m/s) have been derived.

While cooling is a function of porosity, configuration and supply water pressure also influence it. A high porosity evaporator provides higher cooling than a medium porosity prototype, while a low porosity evaporator provides no measurable cooling. The configuration that allows greater air mass flow over the ceramic surfaces, and more surface area for seepage flows to traverse, yields higher cooling. Hence a single versus twin row for the same duct cross-section gives better cooling. A higher water supply pressure also leads to increased cooling.

In a stacked configuration performance differences between top and downstream evaporators were to be expected. Top ceramic evaporators operate at lower head, and do not have benefit of droplet run-off from upstream. This is borne out by the difference in surface temperatures registered between top (CE1) and lower (CE3) ceramic evaporators. Ceramic surface tempera-

tures are quite low compared to airflow at outlet. These have been generally around 2.5 K to 4.0 K above wet bulb. In absolute terms, these are substantial compared to the outlet air temperatures recorded downstream of the ceramic evaporators. This shows the scope for improved cooling through better heat/mass transfer.

Dry bulb temperature drops of 6 K to 8 K have been achieved parallel with a 30 % rise in relative humidity. A maximum cooling of 224 W/m² has been measured during test of the high porosity ceramic evaporator placed in a stack four high with water supplied at 1.0m head. Porous ceramic in direct evaporative cooling has demonstrated significant potential for possible integration into buildings.

Acknowledgements

The authors are grateful to all the partners in the consortium; WSP Environmental Ltd., Axima Lab AG, Il Coccio Umidificatori S.r.l, and to the EU for funding this work, project: EVAPCOOL (contract number ENK6-CT2000-00346), under the Joule 5th Framework programme.

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