PROOF OF CONCEPT: POZZOLAN BRICKS FOR SALINE WATER EVAPORATIVE COOLING IN CONTROLLED ENVIRONMENT AGRICULTURE

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ABSTRACT.

Control of indoor temperature and humidity is of critical concern for controlled environment agriculture systems in hot, arid regions. Evaporative cooling is a technology utilized for energy-efficient cooling and humidification of these systems. However, the evaporative cooling process consumes considerable amounts of water, as much as 80-90% of the water footprint for indoor food production in these regions. The use of saline water in place of fresh water in evaporative cooling systems offers a potential solution for greatly improving the sustainability of these systems. However, the use of saline water in industry-standard cellulose pad systems can cause premature clogging of the porous medium, leading to system failure and the need for porous media replacement. A new evaporative cooling technology consisting of crushed pozzolan volcanic rock formed into porous bricks was evaluated for use in controlled environment agriculture systems using saline water. Two brick designs were tested for proof of concept cooling of commercial-scale greenhouses. Temperature-based cooling efficiencies of the bricks were achieved that are comparable to cellulose pads. In addition, the pozzolan-based bricks showed impressive resistance to saline water and harsh environments, requiring no replacement over the duration of the experimental trials. The integration of the pozzolan evaporative cooling systems using sea or brackish water with a water-saving growing technology, such as recirculating aquaponics or hydroponics, shows promise for reducing the fresh water footprint of food raised indoors in hot, dry environments by as much as 80-90%.

29 **Keywords.**
30 *Evaporative cooling, pozzolan, controlled environment, salt, water conservation*

31 INTRODUCTION

32 To grow crops in controlled environment agriculture (i.e. Greenhouses) in hot regions of the world, a measure of cooling is
33 required to make the indoor environment suitable for crop production. The most widely-used method for greenhouse cooling
34 worldwide is evaporative cooling. Evaporative cooling is a technology that reduces the temperature of air while increasing the
35 relative humidity level (Dağtekin, Karaca, & Yıldız, 2009; Koca, Hughes, & Christianson, 1991; Malli, Seyf, Layeghi,
36 Sharifian, & Behraves, 2011; Sabeh, 2007). Humidity is added to the incoming air by forcing air through a wetted porous
37 media that has high surface area per unit volume. As air comes into contact with the wet surface, water moves from a liquid
38 state into its gaseous state. Heat energy from the incoming air is transferred to the water during the state change from liquid to
39 gas to overcome the latent heat of vaporization. When this happens, the air exits the system with a lower temperature and a
40 higher humidity. Evaporative coolers are known by a number of common names, including swamp cooler, desert cooler, pad
41 and fan, adiabatic cooler and others.

42 Evaporative cooling has a number of differences when compared with traditional vapor compression air conditioning (Table
43 1). Of significance for evaporative cooling are the lower energy use, the higher water use, and how the cooling potential varies
44 in non-humid vs. humid climates. Effective cooling in terms of a large temperature drop can only be realized if the air to be
45 cooled by the evaporative process has a low incoming relative humidity.

46 **Table 1. Comparison of cooling strategies. In this table, “air conditioning” is mechanical vapor compression.**

Evaporative Cooling	Air Conditioning
+Energy efficient	-Higher energy usage
~Effective in non-humid climates	+Effective in any climate
+Fresh outdoor air	~Air recirculation
~Adds moisture to the air	~Removes moisture
-High water use	+No water use
+Economical to operate	-Higher cost to operate

47
48 Cellulose pads are the current industry standard in evaporative cooling technology. These plasticized cardboard pads offer
49 a very high surface area per unit volume and are easy to wet because of their natural wicking properties. In addition, they are
50 relatively light and their cost is low (~\$50-\$75 USD per square meter). New pads offer excellent humidification and cooling
51 of dry, hot air, with an estimated cooling efficiency of 70-90%, depending on air speed and pad properties. (Koca et al., 1991;
52 Malli et al., 2011) However, a disadvantage of cellulose pads is that they may clog and lose cooling efficiency over time if

53 they are not maintained properly (Figure 1). Airborne dust and particulates mix with salts in the water to form crusts and
 54 cements that block airflow through the CP. Depending on the environment and the maintenance provided, a typical cellulose
 55 pads lasts from 3 months to 10 years, a conclusion based on anecdotal evidence from users at sites in the Middle East and North
 56 America. Other types of evaporative cooling media exist on the market, including porous plastic sheets, plastic balls, woven
 57 ropes, palm fronds, and other materials. (Ahmed, Abaas, Ahmed, & Ismail, 2011; Gunhan, Demir, & Yagcioglu, 2007; He &
 58 Hoyano, 2010; Johnson, Yavuzturk, & Pruis, 2003; C.-M. Liao & Chiu, 2002; C. M. Liao, Singh, & Wang, 1998) However,
 59 none of these materials has as large of a market share in controlled environment agriculture as cellulose pads.

60
 61 **Figure 1.** A new and a 4-year old cellulose pad installed at a greenhouse on the KAUST campus in Thuwal, KSA. The 4-year old pad is blocked with
 62 hard crusts of dust and salts, and requires replacement.

63 Evaporative cooling is estimated to contribute as much as 55-90% of the total water footprint of crops grown in greenhouses.
 64 (Lefers et al., 2016; Sabeh, 2007) In fact, when the water use from evaporative cooling is included in the total water footprint
 65 of the crop produced, the actual water input per unit of output is approximately equal to that of the same crop grown outdoors.
 66 (Sabeh, 2007) A possible solution is to replace the fresh water used in evaporative cooling with either sea or brackish water.
 67 (Davies & Paton, 2004; Dawoud, Zurigat, Klitzing, Aldoss, & Theodoridis, 2006; Ghaffour, Reddy, & Abu-Arabi, 2011;
 68 Goosen et al., 2003; Mahmoudi, Spahis, Abdul-Wahab, Sablani, & Goosen, 2010; Mahmoudi et al., 2009; Sablani, Goosen,
 69 Paton, Shayya, & Al-Hinai, 2003; Tahri, Douani, Abdul-Wahab, Amoura, & Bettahar, 2013; Zamen, Amidpour, & Firoozjaei,
 70 2013) Brackish groundwater and sea water resources are wide spread, therefore, the use of these resources is applicable around
 71 the globe. (Weert, Reckman, Gun, & Kempen, 2009) However, the use of a high salinity water source carries with it the risk
 72 of salt precipitation during the evaporative cooling process if the salinity is not monitored and managed closely. As water
 73 evaporates, the salt concentration in the solution increases, ultimately precipitating to form solid crystals if the concentration
 74 of any salt reaches its crystallization point. In addition, the mixing of airborne dust, particularly silica, with salts such as

75 calcium carbonate in sea or brackish water, can speed the formation of solids such as vaterite and calcite. (Lakshtanov & Stipp,
76 2010) (Kellermeier et al., 2013)

77 The clogging of evaporative cooling media is a concern for two reasons. First, the size of the porous media voids will be
78 reduced, increasing the velocity of the air that must pass through the voids in order to maintain the same overall volume airflow
79 rate. This increased velocity leads to increased pressure losses, corresponding to higher fan energy usage. The increased
80 velocity also leads to a shorter air/wetted media contact time, reducing the efficiency of the evaporative cooling and increasing
81 the expected output temperature. Second, the clogged medium will in time require replacement, placing an additional financial,
82 management and time burden upon the owner.

83 Due to the increased risk of evaporative cooling media clogging, along with the additional management burden of closely
84 monitoring the concentration of salts in the evaporative cooling solution, many growers have chosen to not use saline water.
85 For example, in areas of Saudi Arabia where brackish water is readily available, many growers have instead chosen to install
86 small-scale desalination plants to desalinate the brackish water and use the resulting fresh water in the evaporative cooling
87 process. This situation is not limited to Saudi Arabia alone, many areas around the globe face similar challenges. The
88 desalination of the brackish water before use in the evaporative cooler increases the energy consumption, as electrical energy
89 is commonly used in connection with reverse osmosis systems for desalination of these brackish water sources.

90 **MATERIALS AND METHODS**

91 To address concerns related to the clogging of cellulose pads evaporative cooling media, and to further enable the use of
92 brackish and/or seawater for agriculture, a novel system was developed and tested for evaporative cooling, as shown in Figure
93 2. (Al-Madhoun, 2016) Of special importance in the development of the new evaporative cooling media was long life, resistance
94 to harsh environments, local availability, cost, ease of construction, and ease of management. To meet these needs, porous
95 void media bricks were fashioned from a local pozzolan volcanic rock. Pozzolan rock is widely used in the Portland cement
96 industry, and is known for its exceptional resilience to harsh environments and long life (al-Swaidani, Aliyan, & Adarnaly,
97 2016; Khan & Alhozaimey, 2010). The pozzolan rock was sourced from scoria from the local Harrat Rahat (Saudi Arabia),
98 crushed and formed into permeable bricks with intentional voids for air and liquid passage. The scoria from the Harrat Rahat
99 has been recommended for use in pozzolanic concrete as lightweight aggregate, thermal insulating material, filter material, and
100 for other architectural applications. (Moufti, Sabtan, El-Mahdy, & Shehata, 2000) Although the technology was applied locally
101 using pozzolan from Harrat Rahat, the technology can be applied globally as well, as natural deposits of these materials are

102 available around the world. (Snellings, Mertens, & Elsen, 2012) Based upon the expected benefits of the pozzolan material,
103 permeable bricks of pozzolan were designed for evaporative cooling applications and a patent was applied for. The technology
104 was patent-pending at the time of writing of this manuscript. (Al-Madhoun, 2016)

105
106 **Figure 2.** Proposed evaporative cooling system for use with brackish water sources.

107 Two types of pozzolan bricks were manufactured and supplied for proof of concept testing in evaporative coolers. Both
108 types of bricks were manufactured using crushed pozzolan. From the crushed material, fine particles were removed to provide
109 additional porosity while large particles were removed to ensure a smoother finish. Pozzolan cement was used as the binder
110 for the bricks. Type 1 (T1) bricks (Figure 3) were manufactured using a hand press with standard 2 cm diameter cylindrical
111 holes and outer brick dimensions of 200 mm x 100 mm x 100 mm. Type 2 (T2) bricks (Figure 4) were manufactured using an
112 egg laying type mechanical press with conical holes for air passage (3 cm inlet, 2 cm outlet) and have outer brick dimensions
113 of 400 mm x 200 mm x 200 mm. T2 bricks were designed to have more surface area for air/liquid contact in the conical air
114 passage holes, with the expectation that this increase in surface area would lead to more liquid evaporation and therefore a
115 higher cooling efficiency. T2 bricks have 25% more surface area for air/liquid contact per unit volume than T1 bricks.

Figure 3. Type 1 pozzolan bricks for brackish water evaporative cooling. Holes for air passage are cylindrical. The brick structure is permeable to allow liquid passage through the body of the brick. Units are in mm.

Figure 4. Type 2 pozzolan bricks for brackish water evaporative cooling. Holes for air passage are conical, allowing for a 25% increase in surface area for air/liquid contact and evaporation as compared to the cylindrical holes in Type 1 bricks. Like Type 1 bricks, the brick structure is permeable to allow liquid passage through the body of the brick. Units are in mm.

To prove the concept of using the pozzolan bricks for evaporative cooling with salt water, two sets of experiments were conducted (Table 2). The first evaporative cooling system was set up using T1 bricks (Figure 5). This system was constructed on the King Abdullah University of Science and Technology (KAUST) campus in Thuwal, Saudi Arabia and was supplied with saline sea water from a near-shore well, with salinity levels around ~43 parts per thousand (ppt). The scale of the system mirrored that found in field-scale Saudi Arabian agriculture systems, with an evaporative cooler length of 12 m and a height of 2 m. The system included four rows of T1 bricks, each 100 mm wide with a 100 mm gap between each row of bricks (700 mm total thickness). The fans and water pump in the KAUST system ran continuously at a constant speed.

Table 2. Pozzolan brick evaporative cooling experiments

Pozzolan Brick Type	Experiment location	Evaporative Cooler Face	
		Area	Notes
Type 1	KAUST, Thuwal, Saudi Arabia	24 m ²	Seawater source liquid, hot and humid climate, 40 cm porous media thickness
Type 2	Gharbiya Farms, near Riyadh, Saudi Arabia	11.6 m ²	Brackish water source liquid, hot and dry climate, 40 cm porous media thickness

Figure 5. Type 1 pozzolan brick evaporative cooling system installed on the KAUST campus in Thuwal, Saudi Arabia.

T2 pozzolan bricks were used to construct an evaporative cooling system at the Gharbiya farms in the non-humid, central plateau near Riyadh, Saudi Arabia. The Gharbiya system was installed on an existing commercial greenhouse and operated using brackish water with a salinity of ~3 ppt. The T2 pozzolan system consisted of two sets of brick rows, each 200 mm thick with 60 mm of space in between rows, for a total system thickness of 460 mm. The T2 pozzolan system was operated side by side in parallel with a traditional cellulose pads evaporative cooling system in a next door greenhouse (Figure 6 -7). Both the pozzolan and cellulose pads cooling systems at Gharbiya farms were connected to greenhouse climate control systems that turned on and off based on internal greenhouse conditions. When the climate control system sensed that greenhouse temperatures were over an operator-determined set point, the water pumps of the cooling system and the fans at the outlet of the greenhouse were turned on. When the greenhouse temperature then dropped to another user-set temperature, the control system turned the pumps and fans off until the greenhouse temperature again increased above the set point. Therefore, the cooling systems did not operate continuously, but on an as-needed basis.

Figure 6. From top left to bottom right: a) outdoor view of evaporative cooling systems installed on experimental greenhouses at Gharbiya farms, near to Riyadh, Saudi Arabia. Greenhouse #1 cellulose pad (right) and Greenhouse #2 Type 2 pozzolan bricks (left). The cellulose pad system is located inside an intended dust filter (the visible green mesh enclosure.) b) close up view showing the condition of the in-use cellulose pad at the time of experimental testing and c) indoor view of the cellulose pad cooling system. Pictures taken Feb 24, 2015.

Figure 7. Experimental Gharbiya full scale system utilizing type 2 pozzolan bricks, installed at Greenhouse #3. Picture taken Feb 24, 2015.

Parameters of interest for monitoring included the change in temperature and humidity, the air speed, and the pressure drop through the evaporative cooler. A Testo model 435-4 data logger equipped with an internal differential pressure sensor (± 0.02 hPa from 0 to +2 hPa, $\pm 1\%$ of measured value up to +25 hPa) and connected temperature and relative humidity probes (model # 0636 9736, ± 0.3 °C, $\pm 2\%$ RH) and hot wire air velocity probe (model #0635 1535, ± 0.03 m/s + 4% of measured value) were employed for data collection. The water flow rate over the bricks was adjusted such that the rate was increased until all bricks were consistently wet. Air flow in the system was driven by single speed greenhouse exhaust fans, which pulled air through the evaporative cooler in the same manner as is common in pad and fan greenhouses. The system air flow was calculated using the methods outlined in (Wheeler & Both, 2002). A Vantage Pro2 weather station manufactured by Davis Instruments was utilized to capture outdoor and indoor climate data.

The cooling performance of the bricks was evaluated by the temperature based evaporative cooling efficiency (η), as shown in Equation 1.

$$\text{Temperature based evaporative cooling efficiency } (\eta) = \left(\frac{T_{db} - T_{exit}}{T_{db} - T_{wb}} \right) \times 100\%$$

Where

T_{exit} = dry-bulb temperature of air exiting the evaporative cooling bricks

T_{db} = dry-bulb temperature of air entering the evaporative cooling bricks

T_{wb} = wet-bulb temperature of air entering the evaporative cooling bricks

All temperatures input into the cooling efficiency equation were supplied by data collected via the Vantage Pro2 weather station and the Testo Model 434-4 data logger with associated probes.

RESULTS AND DISCUSSION

EVAPORATIVE COOLING PERFORMANCE OF TYPE 1 BRICKS

Results of evaporative cooling using seawater and T1 bricks are shown in Table 3. Evaporative cooling efficiency of the bricks was evaluated on the basis of temperature (η_T) (Koca et al., 1991; Malli et al., 2011). Because the bricks have a much lower percentage of void space than CPs, it is important to consider results against both face and void air velocity. Face velocity describes the velocity of air before entry into and after exit from the circular brick voids, *i.e.* the airflow divided by the total brick area in a 2D direction. Void velocity is the expected velocity within the designed brick voids, which is higher than the face velocity. Void velocity is the airflow divided by the total surficial void area in a 2D direction and is more appropriate for comparison with face velocities measured by other authors when using CPs.

Table 3. Comparison of KAUST system using seawater and type 1 pozzolan bricks with cellulose pad evaporative cooling system using fresh water.

	Type 1 Pozzolan Bricks Seawater Evaporative Cooling System at KAUST	Cellulose Pads Freshwater Evaporative Cooling ^[a]
Number of porous media rows	4	1
Total porous media thickness	40 cm	10 cm
Space between rows	10 cm	Not Applicable
Total system thickness	70 cm	10 cm
Face air velocity	0.5 m s ⁻¹	3.9 m s ⁻¹
Pressure drop	17 Pa	87 Pa
Void air velocity	3.9 m s ⁻¹	NA
Temperature based cooling efficiency	52%	70%
Pressure drop/media thickness	0.43 Pa cm ⁻¹	8.7 Pa cm ⁻¹
Cooling efficiency/media thickness	1.3% cm ⁻¹	7.0% cm ⁻¹

^[a] Literature results (Koca et al., 1991).

As can be seen from Table 3, the experimental T1 pozzolan system as constructed at KAUST was not as efficient in terms of temperature-based cooling efficiency (52%) when compared with a 10 cm cellulose pads system (70%) when the void velocity of the bricks is equal to the face velocity of the cellulose pads (3.9 m s⁻¹). However, if the number of porous media brick rows had been increased from 4 to 6 while holding the cooling efficiency per unit of media thickness constant at 1.3% cm⁻¹, it is possible that the T1 pozzolan system may have achieved a cooling performance similar to a single row 10 cm cellulose pad system (1.3% cm⁻¹ x 6 rows x 10 cm row⁻¹ = estimated cooling efficiency of 78%). However, it is yet unknown if the

cooling efficiency per unit of media thickness remains constant as the number of brick rows is increased or decreased, as the only configuration tested during the scope of this work was a four row configuration of T1 pozzolan bricks. Therefore, future work will be required to evaluate potential changes in cooling efficiency per unit of media thickness as both the media thickness and the number of rows of bricks increases or decreases.

EVAPORATIVE COOLING PERFORMANCE OF TYPE 2 BRICKS

Results of evaporative cooling using brackish water and T2 bricks, along with an existing onsite cellulose pads system, are shown in Table 4. The cooling systems were operating with brackish water having a TDS concentration of 2.7-3.3 ppt.

Table 4. Experimental results comparing cooling system performance at Gharbiya farms.

	Type 2 Pozzolan Bricks Brackish Water Evaporative Cooling System at Gharbiya	Cellulose Pads Brackish Water Evaporative Cooling System at Gharbiya	Cellulose Pads Freshwater Evaporative Cooling ^[a]
Number of porous media rows	2	1	1
Total porous media thickness	40 cm	10 cm	10 cm
Space between rows	6 cm	NA	NA
Total evaporative cooling system thickness	46 cm	10 cm	10 cm
Face air velocity	1 m s ⁻¹	2.8 m s ⁻¹	2.8 m s ⁻¹
Pressure drop	53 Pa	46 Pa	52 Pa
Average void air velocity	5.4 m s ⁻¹	NA	NA
Temperature based cooling efficiency	73%	71%	71%
Pressure drop/media thickness	1.3 Pa cm ⁻¹	4.6 Pa cm ⁻¹	5.2 Pa cm ⁻¹
Cooling efficiency/media thickness	1.8% cm ⁻¹	7.1% cm ⁻¹	7.1% cm ⁻¹
Porous media face area	11.6 m ²	4.2 m ²	NA

^[a] Literature results (Koca et al., 1991).

Results from side by side system operation demonstrated that the two row T2 pozzolan brick system compared well to the cellulose pads system in terms of cooling efficiency (73% vs. 71%) and pressure drop (53 Pa vs. 46 Pa).

In this experimental setup, the pozzolan system was sized with a face area ~2.7x larger than the cellulose pads system and installed on a greenhouse of identical size and construction. If the pozzolan system had been sized even larger, it is expected that the cooling efficiency would have slightly increased and the pressure drop would have decreased such that an equal pressure drop to the evaporative cooling system could have been achieved with a greater cooling efficiency. This expectation is based upon the fact that the velocity of the air through the bricks would have decreased, leading to a longer air/liquid contact time. From literature results with CPs, a lower air velocity through an evaporative cooling system gives a higher cooling efficiency with a corresponding lower pressure drop. (Malli et al., 2011)

209 **DURABILITY OF POZZOLAN BRICKS USING SALT WATER FOR EVAPORATIVE COOLING**

210 While the Gharbiya system was only operated for a short period of time, the KAUST system was operated semi-continuously
211 from May 2013 through May 2017 (approximately 4 years). During this time, salt was intentionally precipitated from the
212 seawater onto the bricks at various times during the course of system operation (i.e., water was allowed to evaporate such that
213 salt levels exceeded their respective crystallization points). The precipitated salts were then removed via pressure washing
214 and/or manual scrubbing with a brush (Figure 8). No changes in system efficiency or structural degradation of the pozzolan
215 bricks were noted as a result of salt accumulation and subsequent removal/cleaning. During the same period, a cellulose pads
216 system utilizing fresh water at a greenhouse only ~3km away clogged with dust and salts and required replacement (Figure 1).

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Figure 8. Sea salt accumulation and removal/cleaning from pozzolan bricks in KAUST full scale system.

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COMPARISON OF EVALUATED SYSTEMS

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The performance of the experimental systems varied based upon the design of the system, the type of bricks installed, and the number of rows of bricks. Table 5 compares the design details and performance of the systems.

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Table 5. Comparison of pozzolan brick experimental system performance.

	KAUST System	Gharbiya System
Pozzolan brick type	1	2
Porous media face area	24 m ²	11.6 m ²
Number of porous media rows	4	2
Total porous media thickness	40 cm	40 cm
Space between rows	10 cm	6 cm
Total system thickness	70 cm	46 cm
Face air velocity	0.5 m s ⁻¹	1 m s ⁻¹
Total pressure drop	17 Pa	53 Pa
Average void air velocity	3.9 m s ⁻¹	5.4 m s ⁻¹
Temperature based cooling efficiency	52%	73%
Pressure drop/media thickness	0.43 Pa cm ⁻¹	1.3 Pa cm ⁻¹
Cooling efficiency/media thickness	1.3% cm ⁻¹	1.8% cm ⁻¹
Surface area of air voids/media volume	0.25 cm ² cm ⁻³	0.31 cm ² cm ⁻³

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In terms of cooling efficiency, the Gharbiya system with T2 bricks performed better, both in terms of overall efficiency (73% vs. 52%) and in terms of efficiency per unit of media thickness (1.8% per cm vs. 1.3% per cm). This increase in cooling efficiency was expected, as the T2 bricks have 25% more surface area for air/liquid contact in the air passage holes when compared with the T1 bricks (conical = 0.25 cm² of hole surface area per cm³ of media volume vs. cylindrical = 0.31 cm² of hole surface area per cm³ of media volume). It should also be noted that this increase in cooling efficiency happened in spite of the fact that the average air velocity through the T2 bricks was faster (5.4 vs. 3.9 m s⁻¹). In the literature, it has been shown that a faster air velocity through CPs results in a lower cooling efficiency. (Malli et al., 2011) The fact that the T2 bricks performed better is likely due to the increased surface area in the air passage holes. The lower salinity of the brackish water used at Gharbiya (~3 ppt) as compared with seawater used at KAUST (~43 ppt) may have also contributed to the higher cooling efficiency, however, further experiments would be required to confirm how much effect the salinity of the water affected the cooling efficiency in comparison to the difference in brick design.

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The KAUST system with T1 bricks had a much lower pressure drop (17 Pa) when compared with the Gharbiya system with T2 bricks (53 Pa). However, the KAUST system was sized with double the porous media face area, leading to a lower exit air velocity from the brick voids (3.9 m s⁻¹ vs. 8.1 m s⁻¹) and therefore a lower pressure drop. The exit air velocity of 8.1 m s⁻¹ from the conical-shaped holes in the T2 brick design is higher than the average velocity of 5.4 m s⁻¹ as shown in Table 5 because the diameter of the holes at the exit (2 cm) is smaller than the diameter of the holes at the entry (3 cm), as is shown in Figure 4. Based upon results with CPs recorded in literature, the expected pressure drop through an evaporative system increases by

approximately 1.5x for every 1x increase in velocity through the system. (Malli et al., 2011) Using this relationship, the expected pressure drop at the KAUST system would have increased to 53 Pa if the exit air velocity had been increased to match that at the Gharbiya system (8.1 m s^{-1}). Incidentally, this value matches exactly with the pressure drop measured at Gharbiya (53 Pa). When the cooling efficiency is considered and compared taking into account the pressure drop (cooling efficiency / pressure drop), the larger KAUST system provided higher efficiency per unit of pressure drop (3.1% per Pa vs. 1.4% per Pa). This metric is driven by the air velocity through the bricks, where a higher air velocity leads to a decline in cooling efficiency and a larger pressure drop. To achieve a lower air velocity through the bricks while maintaining the same total airflow through the cooling system, the size of the system can be increased (more face area). A larger system means more capital expense up front for installation, but is expected to result in a better overall cooling performance and lower long-term operating expense due to lower fan energy requirements to overcome pressure drop through the system while achieving the desired total airflow.

When the pozzolan systems are compared with cellulose pads adiabatic cooling systems, there are a several differences. Pozzolan brick systems have a lower cooling efficiency per unit volume than new CPs. Therefore, more volume of installed bricks is required to achieve a desired cooling efficiency when compared with CP. Construction of a pozzolan evaporative cooling system will require more surface area than a cellulose pads system to achieve the same cooling efficiency with the same fan flow rate. Care should be taken during design to size the pozzolan evaporative cooling systems appropriately. The face area of an evaporative cooling system using T2 bricks is recommended to be ~2.5-3x larger than a cellulose pads system designed for the same airflow rate. Offsetting this, pozzolan brick systems have a lower pressure drop per unit of thickness when the void air velocity is taken into account. The necessary increase in porous media face area is also offset by the fact that the bricks are rigid, and as such can be incorporated into the structure of the building (i.e., they can be self-load bearing and are a long term solution). CPs, in contrast, must be supported by the building structure and replaced frequently. Unlike like cellulose pads systems, pozzolan brick systems are not damaged structurally if/when salt crystals precipitate in the system. Therefore, pozzolan brick systems can be considered more favorable for use with brackish or seawater than cellulose pads systems when/if salt precipitates on the evaporative cooling media. In addition, aggressive cleaning methods may be utilized when cleaning pozzolan brick systems.

Suggested future research beyond the proof of concept testing includes:

- **Cooling efficiency** varies with air velocity through the porous media. The studied installations only allow evaluation of cooling efficiency at one air velocity per site. Cooling efficiency of the bricks might be evaluated at other air velocities such that cooling efficiency vs. air speed curves can be generated for the pozzolan bricks similar to those curves found in other work, such as (Koca et al., 1991) (Malli et al., 2011).
- **Pressure drop** through the cooling system is directly related to energy requirements from the fan system and also structural design requirements for the greenhouse. No pressure drop vs. air speed curves have been generated for the

pozzolan bricks. Again, these curves could be developed similar to what is available for cellulose pads systems.

- **A hybrid pozzolan brick/cellulose pads cooling system** is suggested for evaluation. Pozzolan bricks are considered more favorable for use with brackish and/or seawater than CPs as it relates to maintenance and life expectancy. However, it is important to note that CPs have been used effectively for evaporative cooling with seawater, most recently by the Sahara Forest Project in Qatar and also by Seawater Greenhouse projects in Oman, Australia, and the Canary Islands. In conversations with staff from the Sahara Forest Project, it was noted that dust screens were useful to protect cellulose pads from clogging (V. Corless, Sahara Forest Project, personal communication, May 20, 2014). Therefore, it is suggested to build and test a hybrid pozzolan brick/cellulose pads cooling system utilizing seawater and/or brackish water, where the pozzolan bricks are used as the first contact evaporative cooling wall/dust screen and CPs are used as a second contact evaporative cooling wall where the salinity of the water is managed to prevent precipitation of salt crystals.
- **Structurally**, pozzolan bricks are very different from CPs. The bricks are rigid and have the potential to be used without support and/or in the structure of buildings and hedge fences. This may be one of the greatest advantages of the bricks, as it opens up doors for use in alternative applications where CPs would not be fit for purpose. However, the fundamental research into the structural capacity of the bricks is lacking. Loading capacity, responses to stress and strain, and long-term losses in structural integrity due to wear and tear from environmental conditions (including water and salt) have not been adequately evaluated.

CONCLUSIONS

To address concerns related to the clogging when using saline water, and to further enable the use of brackish and/or seawater for evaporative cooling in controlled environment agriculture such that significant fresh water savings can be achieved, two pozzolan evaporative cooler brick designs were developed for proof of concept testing. T1 pozzolan bricks had air passage holes that were cylindrical in shape, while T2 pozzolan bricks had air passage holes that were conical in shape, resulting in an increase in surface area for air/liquid contact of 25%. The pozzolan-based evaporative cooling medium was evaluated for cooling efficiency, pressure drop, and resistance to harsh environments. As it relates to these considerations, T1 and T2 pozzolan bricks were applied in proof of concept testing for EC, achieving the following:

- Pozzolan bricks had a lower cooling efficiency per unit volume when compared with CP.
- Pozzolan bricks had a lower pressure drop per unit volume when compared with CP.
- T2 pozzolan provided a higher cooling efficiency when compared with T1 pozzolan bricks.
- Pozzolan bricks were not noticeably damaged by salt precipitation. The bricks were manually cleaned and continued to operate without losses in effectiveness. Therefore, the bricks are considered suitable for continuous use with brackish and seawater.
- The pozzolan evaporative cooling system at KAUST operated using seawater for 4+ years using seawater. Cellulose pads utilizing fresh water at a site only ~3km away required replacement during this same period due to clogging via dust and salts.

The completed work effectively proved the concept of using pozzolan bricks for evaporative cooling with saline water. While the technology was empirically evaluated using sea and brackish water in Saudi Arabia, it has practical applications around the globe, as both saline water and pozzolan materials are available around the world. When applied in hot, dry climates, the technology has the potential to replace the use of fresh water in the evaporative cooler and reduce the water footprint of crops grown in controlled environment agriculture by 80-90%.

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