Experimental Investigation of Thermal Performance of Three Configurations Evaporative Cooling Systems (ECS) Using Synthetic Grass Wet Media Materials

Sultan Alfraidi*[1], Abdelhakim Mesloub[1], Mohammad Alshenaifi[1], Emad Noaime[1], Atef Ahriz[2], R. Boukhanouf[3]

[1] Department of Architectural Engineering, Ha'il University, Ha'il 2440, Saudi Arabia
[2] Department of Architecture, Echahid Cheikh Larbi Tebessi University, Constantine Road, Tebessa 12000, Algeria.
[3] University of Nottingham, Department of Architecture and Built Environment, Nottingham, UK.

*Corresponding Author: s.alfraidi@uoh.edu.sa

Abstract
Space cooling of buildings using evaporative cooling is a passive strategy that can provide thermal comfort for occupants and conserve energy. In this paper, an innovative evaporative cooling wet media material in the form of synthetic grass fibre mat was introduced to evaluate experimentally its effectiveness in Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IEC), and Dew point evaporative cooling (DPEC). A laboratory evaporative cooling module was constructed and tested using a fully instrumented test rig and was subject to environmentally controlled conditions of air temperature and relative humidity (RH) commensurate to those prevailing in hot and dry climates like the Middle East. The wet bulb effectiveness and cooling capacity of evaporative coolers equipped with the new wet media material were evaluated experimentally. The results show that these evaporative coolers performance correlate well with current technology. For instance, the ambient air temperature is reduced by as much as 12.9°C, 10.2°C, and 10.3°C for direct, indirect, and dew point modes, respectively. It was also shown that DEC achieved effectiveness 20% higher than indirect evaporative coolers. The work demonstrated that the new wet media can be a viable alternative to organic and non-organic counterparts.

Keywords: evaporative cooling; experiment; wet media; synthetic grass; hot climate

1. Introduction

The decoupling of buildings indoor climate from the surrounding environment to deliver essential thermal comfort for occupants consumes substantial amounts of energy and is one of the major contributors to climate change [1]. Today, increasing demand for buildings in many parts of the world has caused surges of electrical power demand particularly for space air conditioning. This is aggravated by heavy dependence on cheap and inefficient energy intensive mechanical air conditioning systems for thermal comfort. Therefore, the current focus is to develop thermal comfort solutions in buildings that can deliver net zero emission of greenhouse gases and other pollutants including high global warming potential refrigerants [2, 3]. Current mechanical air conditioning systems are expected to remain dominant while new and more sustainable solutions are being identified and developed [4]. The building sector worldwide contributes 40% of the total primary energy consumption and the equivalent of 33% of the carbon emitted into the environment [5]. Therefore, in many parts of the world there is renewed awareness to address the high energy demands, through for example integration of passive cooling techniques in sustainable architectural designs [6].

Indeed, for many centuries, in regions of the world with hot and dry climates, traditional cooling methods such as evaporative cooling were exclusively used to keep buildings cool in summer temperatures. For example, across countries in the Middle East evaporative cooling in building using porous water jars in wind catchers was widely practiced [7]. Moreover, evaporative cooling has the potential to maintain effectively favourable comfort levels in modern buildings and dispense full requirement of fresh air. Being low intensive energy process, evaporative cooling can reduce peak electricity demand, save as much as 75% on energy consumption and reduce carbon emission by 44% compared to vapour-compression air-conditioning [8, 9]. The drawback of evaporative cooling, however, resides in cooling performance being strongly dependant on the ambient conditions of temperature and humidity, limiting the application scope of the technology [10-13].

Previous research has addressed the design and performance challenges of evaporative cooling system both analytically and experimentally. For instance, Kumar and his team [14] investigated the performance of an evaporative cooling unit for varying ambient conditions. The authors found that the unit performs better under dynamic conditions than static conditions. Da Veiga, Güths, and Da Silva [15] presented and experimentally tested ~~a~~ model to forecast the effectiveness of evaporative cooling as a method to limit excessive heat gain in buildings' roofs. In most tests, the model was able to forecast with high precision the heat flux passing through the porous medium. Under specific conditions, the performance of the wet porous media can exceed that of its dry counterpart. Kowalski and Kwiecie [16] investigated evaporative cooling (EC) systems for an imaginary Polish industrial building using the TRNSYS 17 software in which it evaluated six systems in four Polish cities (Koszalin, Lublin, Suwalki and Wroclaw). By generalising the results, EC systems may be able to conserve energy in Poland's climate. Lapisa and colleagues [17] discussed the layout of commercial building envelopes for low-rise structures. It presented a Multi objective optimisation using the NSGA-II approach to determine the ideal design parameters for passive cooling solutions such as cool roofs and nighttime natural ventilation. Alshenaifi et al. [18] proposed a creative setup with three air outlet disposition of a passive downdraught evaporative cooling (PDEC) tower to be investigated numerically using CFD (Computational Fluid Dynamics) software; based on the findings, the input velocity and temperature had a substantial impact on the quality of the interior temperature. Furthermore, He, et al. [19] discussed a solar-powered reel dehumidifying system for evaporative cooling. Experimental tests showed that the system can decrease the indoor temperature and maintain the relative humidity. Dhamneya, Rajput and Singh [20] studied the performance of an evaporative cooling window air conditioner. The proposed solution performs better, saving 7.39% of energy in April and 5.18% in March. Boukhanouf et al. [21] proposed a heat pipe and porous ceramic tube regenerative evaporative cooler prototype. It described the cooler's construction and lab findings. Experimental results show that the cooler air supply temperature can be 14°C lower than ambient air.

Moosavi, Zandi, and Bidi [22] explored the cooling performance of a naturally ventilated house with a solar chimney and hybrid evaporative cooling. The hybrid evaporative cooling system and solar chimney lowered the atrium centre zone's air temperature by 0.7 °C. Leroux et al. [23] presented an evaporative cooling system with a porous evaporator wall. Using a mathematical model and an experimental setup, evaporator material properties and their effect on cooling system performance were determined. The calculated evaporator wall power ranges from 12 to 72 W/m^2. Zhang et al. [24] examined the influence of climatic factors on the evaporative cooling of porous building materials. According to their findings, the factors that had the greatest influence on the evaporative cooling process are the amount of solar radiation, the temperature of the air, the partial pressure of the water vapour, and the speed of the wind.

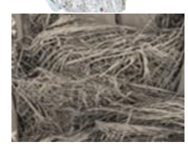
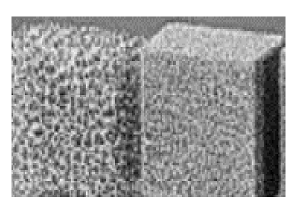
Many study have shown that Evaporative coolers offer higher overall energy efficiency than Vapour Mechanical Compression (MVC) system, particularly when deployed in favourable climatic conditions. The VMC systems are effective in temperature and humidity control and stable operation, but suffer from low Coefficient of Performance (COP) and sever adverse environmental impact, compared to evaporative coolers as shown in Table 1 [25-27].

Table Error! No text of specified style in document. comparison between some air-conditioning systems *[25-27]*

System type **Property**	**VMC cooling**	**Evaporative cooling**
COP	2 to 3	5 to 27
Power consumption	High	Medium/Low
Refrigerants	CFCs, HFCs	Water
Environmental Impact	High	Low

The concept of evaporative cooling involves a complex process of heat and mass transfer between a wet surface and an air stream flowing immediately over it. The air stream, often warm fresh air supply, loses its sensible heat in exchange for increased moisture content gained from water evaporating off the wet surface. The cool air can be supplied directly to buildings (DEC) to displace warm air or used to cool indirectly (IEC) through a heat exchanger air supply to buildings [7]. The main advantage of IEC is that it supplies air humidity can be controlled separately [10]. One of the key components of an evaporative cooling system is the wet media material, which is usually made of a porous structure of large surface area. The thermal properties of these materials are characterised by their affinity to absorb and hold liquid water; as well as enable fast evaporation [21, 28]. There are many types of materials used as wet media in evaporative coolers including metals foams, organic and synthetic fibres, and porous ceramics. Research works into these types of materials and their properties are summarised in Table 2.

Table 2: Types and properties of evaporative coolers wet media materials [8, 29, 30]

Material type	**characteristics**	**structure**
Organic fibres (Randomly packed wet pads)	• made from shredded organic matter fibres • have good water absorption properties • low thermal conductivity • high porosity (>50%)	 
Cellulose (rigid cardboard box/kraft paper)	• takes the form of rigid or corrugated paper • thermal properties can vary depending on the specific material and packing • Offers enhanced water evaporation	 
Standard randomly packed metal fibre wet pads	• high strength, low density, and thermal conductivity • made from copper, aluminium, and steel • The porosities range from 30–95% and depends on metal fibre length, fibre diameter, and the density	

Porous ceramic	• Have high thermal conductivity • Have large contact area and uniform water distribution • Durable and high water-retention capacity • Porosity depends on production temperatures (at baking temperature of 1250° C, a bulk porosity of 47% was reported)	

This paper introduces synthetic grass as wet media material in the form of flat mat sheets, commonly used in sport fields, landscaping, playgrounds, etc. These synthetic grass sheets are manufactured from plastics such as Polyethylene (PE) or Polypropylene (PP) and are structurally stable under wet conditions, high ambient temperatures, and UV exposure [31, 32].

The Synthetic grass fibres are implanted in a back support mat, which is also made of a combination of polypropylene and polyethylene. The back mat is coated with latex to hold the grass fibres in place and provide rigidity. The synthetic grass fibres are then cut to required height [33]. Figure 1 shows the form of grass mats, the backing material and the type of grass fibre shapes.

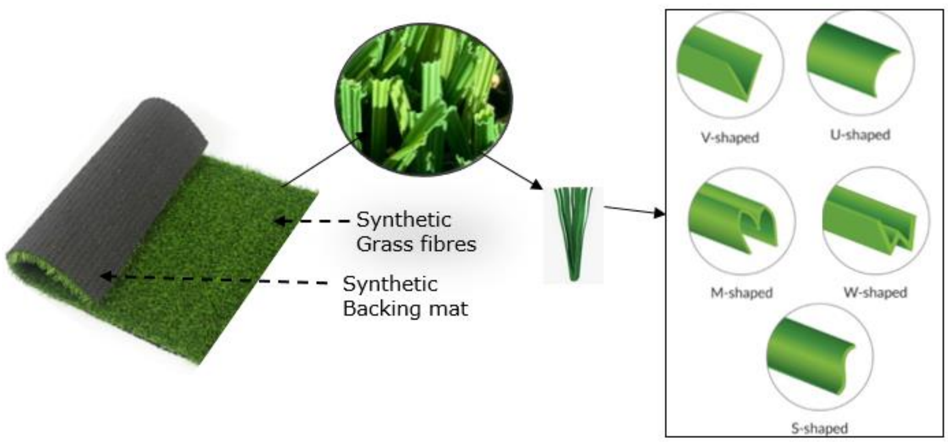


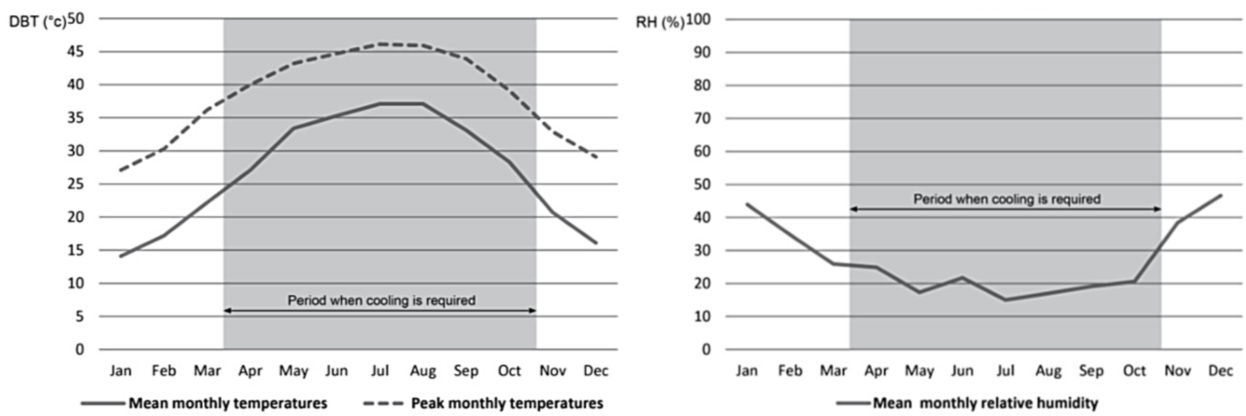
Figure 1: Sample synthetic grass sheet and fibre forms

1.1 Research gap and contribution

The adoption of synthetic grass mats in evaporative cooling systems can potentially contribute to increasing service-life span and minimising the requirement for maintenance. Synthetic grass fibres are made in various shapes to provide large wet surface area and air contact for enhanced evaporation process, are readily available and at low production cost. The synthetic grass mats can be installed in new or as replacement in evaporative cooling systems. Unlike organic wet media materials used in evaporative cooling systems, synthetic grass mat rolls do not require water or fertilizers to cultivate and are recyclable [31]. This work aims to evaluate experimentally this novel wet media material which is produced as a synthetic grass mat in three types of evaporative coolers: Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IEC), and Dew point evaporative cooling (DPEC). A comparative performance analysis, in terms of system effectiveness and cooling capacity, with similar published data of evaporative coolers was also conducted.

1.2 Target climatic condition for evaporative cooling

A further contribution of this research is to support the development and adoption of evaporative cooling systems as a sustainable solution to thermal comfort in buildings in hot and dry climate such as the arid and semi-arid regions of the world. These regions are characterised by extreme conditions of long and hot summers with temperatures often exceeding 40° C, and minimal precipitation. The average atmospheric temperatures has also been noticeably increasing due to climate change [34]. For example, many cities across the Middle East (Riyadh, Baghdad, Kuwait, etc.) routinely experience intense heat, with temperatures occasionally surpassing 50° C. Figure 2 illustrate prevailing average and maximum temperature and mean relative humidity in the city of Riyadh, KSA [35], where the deployment of air conditioning in buildings due to high temperature and low relative humidity (RH) lasts from April to October.



(a) (b)

Figure 2: Typical weather condition in city of Riyadh, KSA (a) Monthly Average and maximum air temperature (b) monthly mean RH

2. Methodology

The energy performance of a laboratory prototype evaporative cooler using synthetic grass fibres was evaluated under controlled climatic conditions. The experimental work made use of an environmental chamber, which enabled the precise control of the temperature and relative humidity (RH) of the air introduced into the prototype. The test conditions were set to span the wider outdoor temperature range prevailing in hot dry climates such as that of Middle East. To establish full performance of the synthetic grass media material, three configuration of evaporative cooling systems were considered namely Direct Evaporative Cooling (DEC), Indirect Evaporative Cooling (IEC), and Dew Point Evaporative Cooling (DPEC). Figure 3 gives an outline of the research methodology used to evaluate the performance of the experimental coolers.

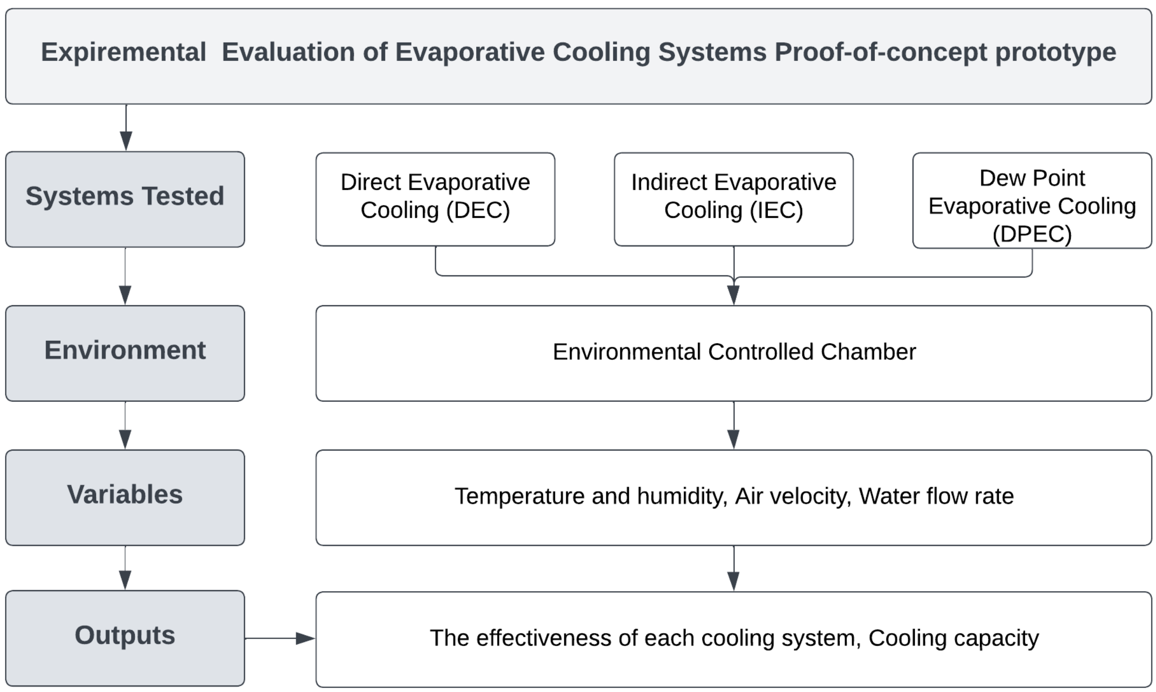
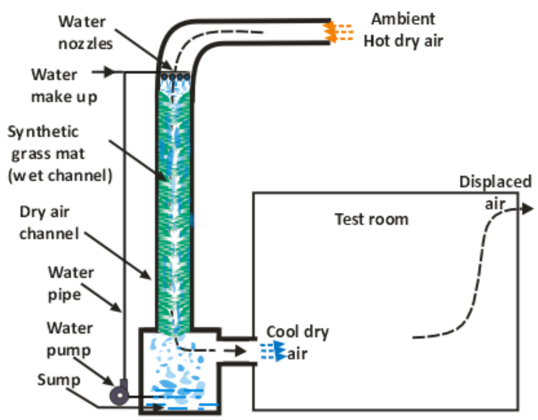


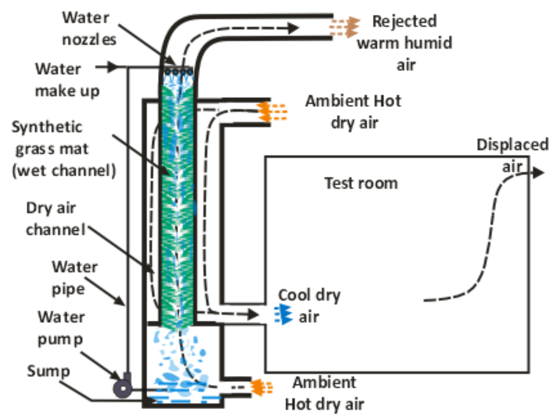
Figure 3: Schematic representation of the experimental method

2.1 Description of the Evaporative cooling system configurations

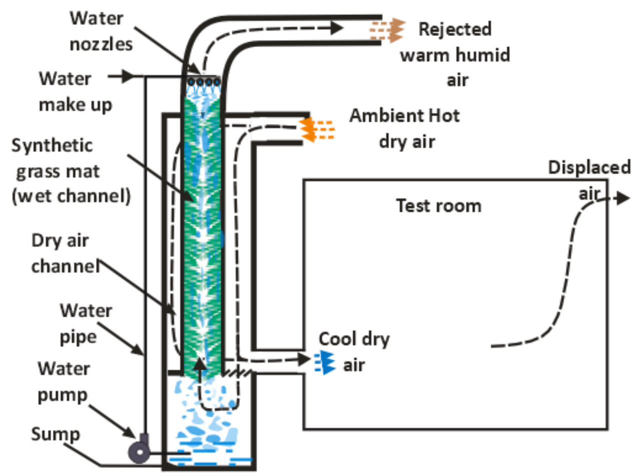
Each of the three configurations of evaporative cooling systems namely, Direct evaporative cooling (DEC), Indirect evaporative cooling (IEC) and dew point evaporative cooling (DPEC) requires a different mechanical arrangement and layout of the airflow channels. Figure 4 shows a schematic arrangement of the airflow channels of the three evaporative cooling systems.



(a) Direct Evaporative Cooling (DEC)



(b) Indirect Evaporative Cooling (IEC)



(c) Dew point evaporative cooling (DPEC)

Figure 4: Arrangement of tested evaporative cooling systems

2.1.1 Direct Evaporative Cooling (DEC)

In the DEC mode, the hot dry ambient air inlet is located at the top opening of the tower that houses the synthetic grass media. The ambient air flows through the free- passages in the wet media and fully brought into contact with sprayed water at the top of the wet channel. The cool and saturated air is then supplied to the test room, which is cooled through displacement ventilation. The supply air temperature of this system is limited to the wet bulb temperature. The excess water (i.e., not evaporated) is collected in a sump below the wet channel and recirculated by a water pump, as shown in Figure 4 (a).

2.1.2 Indirect Evaporative Cooling (DEC)

For the IEC mode, the airflow through the cooler is arranged into two separate channels, the wet and dry channel, which shares a heat transfer surface area. The ambient air is drawn into the wet and dry channels at two separate inlets. The ambient air admitted into the wet channel undergoes cooling through direct evaporation and is rejected to outside as warm and humid air. Concurrently, the ambient air drawn in through the dry channel inlet is cooled by transferring its sensible heat to the cool wet channel wall surface and is supplied into the test room for displacement ventilation. This arrangement has the advantage of supplying cooled air, without increasing its humidity. Like the DEC arrangement, excess water leaving the wet channel is collected in the sump and is recirculated by a water pump, as shown in Figure 4 (b).

2.1.3 Dew point evaporative cooling (DPEC)

The mechanical arrangement of airflow in the DPEC mode is similar to that of the IEC mode, as it employs separate dry and wet channels. However, in the DPEC mode, approximately 50% of the airflow from the outlet of the dry channel is redirected into the wet channel for the evaporation process as it comes into contact the wet synthetic grass media. The remaining cool and dry air from the dry channel is supplied to the test room for displacement ventilation. This allows the air supplied into the test room to be cooled to a temperature approaching the ambient air dew point temperature without increasing its moisture content. To control the amount of cool and dry air supply to the test room, a damper was placed at the inlet of the wet channel. Figure 4(c) shows the airflow arrangement of the DPEC mode.

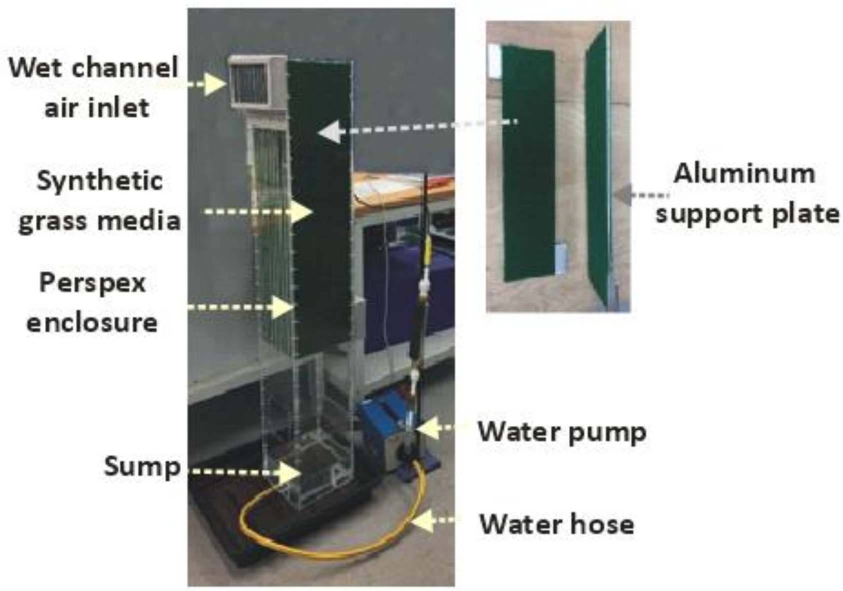
2.2 Laboratory rig set up

The core of the evaporative cooling system is the synthetic grass wet media module, as shown in Figure 5 (a). The module is made of multiple layers of grass mat backed by a thin aluminium plate for rigidity. The synthetic grass mats were then stacked vertically and separated by an air gap to allow airflow in between. Depending on the mode of operation of the evaporative cooling, the channels formed by the synthetic grass mats and the Aluminium back plate were arranged to allow for water and air direct contact (DEC) or wet and dry channels being separated to allow for indirect air cooling to take place, as explained previously. Table 3 summarises the main dimension of the core module.

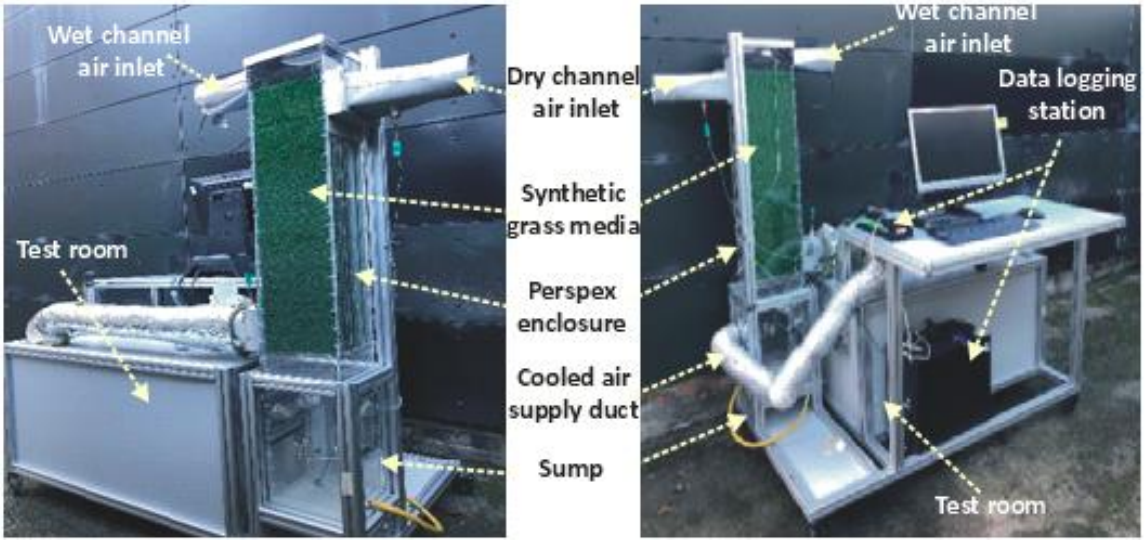
Table 3: Design parameters of the synthetic grass module

	Height (mm)	Width (mm)	Thickness (mm)	Number of layers (-)	Separation gap (mm)
Synthetic grass mat	800	800	3	9	-
Backing aluminum plate	200	200	1	5	-
Dry channel inlet/outlet	100	5	-	-	5
Wet channel inlet/outlet	100	5	-	-	3

The full test rig onto which the synthetic grass module is integrated was then placed on a wheeled bench to be freely moveable into the environmental chamber in the laboratory for testing under controlled temperature and relative humidity conditions. Figure 5 (b, c) shows the back and front view of the test rig with the dummy cooled test room connected to the cooler using a flexible duct.



(a)



(b) c)

Figure 5: Experimental set-up test rig a) synthetic grass fibres module (b) back view (c) front view

Furthermore, the test rig was equipped with thermocouples to measure airflow temperatures, anemometer to measure airflow velocities and hygrometer to measure air humidity at the inlets and outlets of the dry and wet channels. A data logging station was used to record measured parameters at fixed time intervals. A summary of the type of instrument and their specification used in the experiment is given in Table 4.

Table 4: Type of instrument and data logging

Instrument type	Description of use	Illustration
K-type thermocouples Range: --75 to +250° C Accuracy: +/- 2.2° C	located in the centre of the air flow passages to measure the temperature	
RS-232 humidity and temperature meters Temperature range: 0 to 60° C RH range: 0-95% Accuracy: ±3% RH and ±0.8 °C	Used to measure air temperature and humidity of the inlet and outlet of the dry and wet channel	
Testo 405- V1 hotwire anemometer Temperature Range: 0 to 50° C Accuracy: ±0.5° C and ±0.3 m/s + 5% Measured value	Testo 405- V1 is a portable hotwire anemometer used to measure the flow velocity at the inlet and exit of the dry and wet channel	

Data logger, data-taker model DT500, Series 2	Logs temperature readings from the thermocouples and humidity at fixed time interval and stored data is retrieved for analysis.	
Centrifugal liquid Pump- Model C16-C Charles Austen 220-240 V, 0.25 A, 50 Hz	Water circulating pump	
Ventilation inline-fan Vent-axia 220-240 V, 0.21 A, 50 Hz	Air circulating fan	

2.3 Performance indices

The measured operating parameters of the three evaporative coolers were used to calculate the cooling performance in terms of cooling effectiveness, potential cooling capacity and COP. These energy performance indices can be used to compare and identify the most effective cooling solutions for a given application. The cooling effectiveness of the system was evaluated using the wet bulb effectiveness which is the ratio of the difference between ambient air temperature and the supply air temperature to the difference between the ambient air temperature and its corresponding wet-bulb temperature. The wet bulb effectiveness is expressed by the following formula:

$$\varepsilon = \frac{T_{in} - T_s}{T_{in} - T_{wb}} \quad (1)$$

Where; ε is the wet bulb effectiveness of cooler; T_{in}: the Inlet ambient dry bulb temperature (°C), T_s: the supply temperature (°C) and T_{wb}: the inlet wet-bulb temperature (°C). Similarly, the Cooling capacity, Q_c, of the evaporative cooler is expressed as follows:

$$Q_c = \dot{m} c_p (T_{in} - T_s) \quad (2)$$

where, $\dot{m}$ is the mass flow rate (kg/s), c_p is the specific heat capacity of air (J/kg·°C) , T_{in} is the inlet dry bulb temperature (° C) and T_s is the supply dry bulb temperature(°C). The other important performance index is the coefficient of performance (COP) of the evaporative cooler. The COP is the ratio between the cooling capacity of a cooler and the power demand to operate the cooler, which in this case is represented by the power load of the water pump and air circulating fan. It can be written as:

$$COP = \frac{Q_c}{P_p + P_f} \quad (3)$$

where, Q_c (W) is the cooling capacity, P_w (W) and P_f (W) are the water pump and fan power demand. However, in this study, the power demand of the auxiliary equipment (the water pump and ventilation fan) were not optimised, and the COP calculation doesn't provide a precise representation of the energy performance of evaporative coolers.

However, in this work, the power demand of the auxiliary equipment (the water pump and ventilation fan) were not optimised and the COP calculation doesn't give an accurate picture of the evaporative coolers energy performance.

The final important parameters measured in this work is the water consumption rate of the evaporative coolers. The water consumption rate of an evaporative cooler depends on mainly on airflow rate in contact with the wet surface and the inlet and outlet moisture content of the air. This can be calculated by the following equation [25]:

$$\dot{V}_w = \frac{\dot{V}_a \, \rho_a}{\rho_w}\left(w_{a,out} - w_{a,in}\right) \tag{4}$$

where, $\dot{V}_w$ is the water evaporation (consumption) rate, m^3/s; $\dot{V}_a$: air flow rate in the wet channel, m^3/s; ρ_a is the air density, kg/m^3; ρ_w is water density, kg/m^3; $w_{a,out}$ is the moisture content of the outlet air, $kg/kg_{\text{dry air}}$;and $w_{a,in}$ is the moisture content of the inlet air, $kg/kg_{\text{dry air}}$.

2.4 Experimental testing conditions

It is well established that evaporative cooling technology is more effective in hot and dry climates. Hence, the focus of this work was to evaluate the suitability of the evaporator cooling system for the climatic conditions such as those prevailing in Middle East region. As such, the energy performance of the cooling system was tested over a range of controlled ambient air dry bulb temperatures (30° C, 35° C, and 40° C) and air relative humidities (25, 35, and 45 %). The small-scale testing of the system focuses on displacement ventilation where air in the test room is constantly renewed and airflow rates appropriate for this mode of cooling were selected. For example, the maximum airflow velocity for direct, indirect, and dew point evaporative cooling were 2.85, 1.65, and 1.85 m/s, respectively.

Similarly, the evaporative cooling effect consumes water through evaporation as it is brought in direct contact with air. The water is sprayed through nozzles on the grass fibres from the top of the wet channels and any excess water is accumulated in the sump and continuously recirculated. A water flow rate of 0.5 m^3/minute was selected as it provides maximum wettability of the synthetic grass fibres surface and minimum requirement for water recirculation.

3. Results and Discussion

3.1 Direct evaporative cooling (DEC) Configuration

In a direct evaporative cooling mode, the supply of air into occupied space is channelled through a wet channel and cooled to near its moisture saturation wet bulb temperature. This mode of operation may be necessary when the ambient air is very dry and the addition of moisture into the occupied space is required. The thermal performance of the laboratory synthetic grass fibres in direct cooling mode was evaluated at temperatures of 30, 35 and 40°C and at corresponding RH of 25, 35 and 45% with inlet air velocity of 2.85 m/s. The supply air is drawn in into the test room through the cooler wet channels.

3.1.1 Cooling performance

Under steady state operating condition of ambient inlet air temperature of 40° C and relative humidity of 30.9%, the air temperature of supplied air decreased to 27.1° C, a 12.9° C drop, as shown in Figure 6.

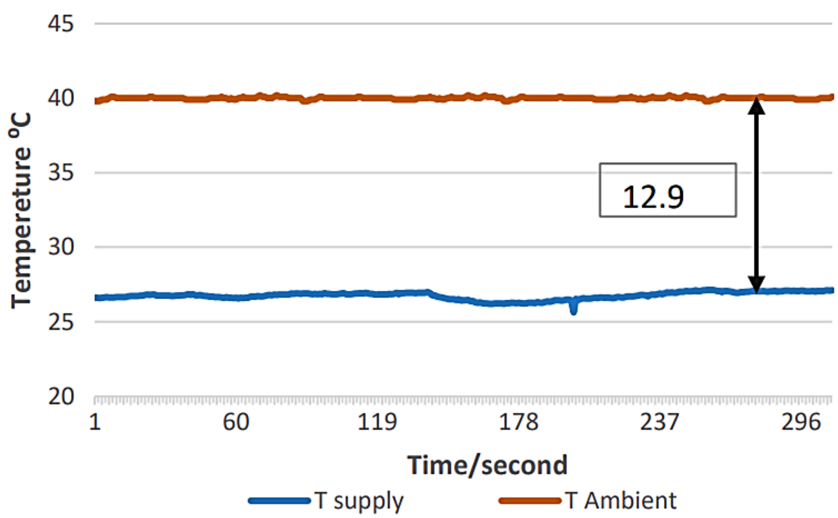


Figure 6: Steady state DEC inlet and supply air temperature (RH: 30.9%, airflow velocity: 2.85 m/s))

The overall steady state cooling performance of the direct evaporative cooler is summarised in Table 5. It is shown that the supply air temperature decreased to within 2° C of the wet bulb temperature (25.3° C) and its RH approaches full saturation (90.6%). In addition, the wet bulb effectiveness and cooling capacity of the DEC was estimated to be 87.7 % and 339.57 W, respectively.

Table 5: DEC mode operating parameters

Velocity Inlet Air	**Mass flow rate**	**RH Inlet Air**	**Temp Inlet Air**	**Temp Supply air DB**	**Temp Supply air WB**	**Temp Supply air DP**	**RH Supply air**	**Effectiveness**	**COP**	**Cooling capacity**
(m/s)	(kg/s)	(%)	(°C)	(°C)	(°C)	(°C)	(%)	(-)	(-)	(W)
2.85	0.027	30.9	40	27.1	25.3	19.61	90.6	0.877	3.20	339.57

3.1.2 Effect of inlet air temperature and RH on air supply temperature

The measured temperature of the DEC, shown in Figure 7, supports the general understanding that the effectiveness of direct evaporative cooling is favoured when ambient temperature is high, and RH is low. As discussed previously, at steady state operation of ambient inlet air at 40℃ and 25% RH, a temperature drop of 12.9°C was achieved; whereas at the same temperature and RH of 45%, the inlet air temperature reduction was only 10° C. The lowest value temperature drop (of 5.7° C) was recorded for inlet air of 30° C. Therefore, the temperature drop of the inlet air through the cooler improved as the ambient air temperature increased. This represents an advantage of evaporative coolers over mechanical vapour compression cooling systems.

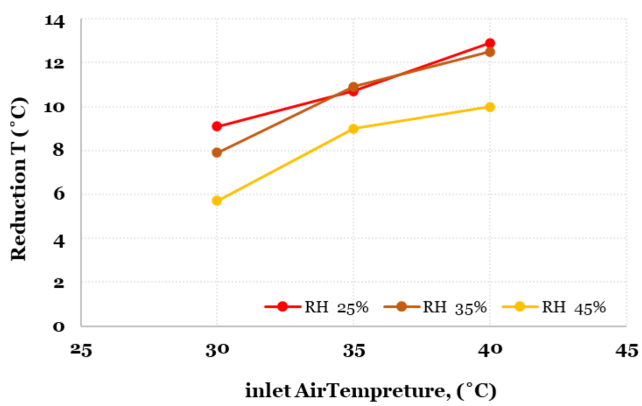


Figure 7: Supply air temperature drop (airflow velocity: 2.85 m/s)

3.1.3 Effect of inlet air temperature and RH on effectiveness

The effectiveness of the system was calculated using the wet bulb effectiveness formula given in Equation 1. The effect of ambient air temperature on the effectiveness of the DEC system was further evaluated at different temperatures and RH. As illustrated in Figure 8, the effectiveness of the DEC cooling system increased as the inlet ambient air temperature rose. The highest effectiveness peaked at 0.97, at inlet temperatures of 40° C and 45% RH, which is very close to the maximum limit of 100%. However, the effect of RH on the system effectiveness was less pronounced, as increasing ambient air RH had the opposite effect on the trend of cooling effectiveness.

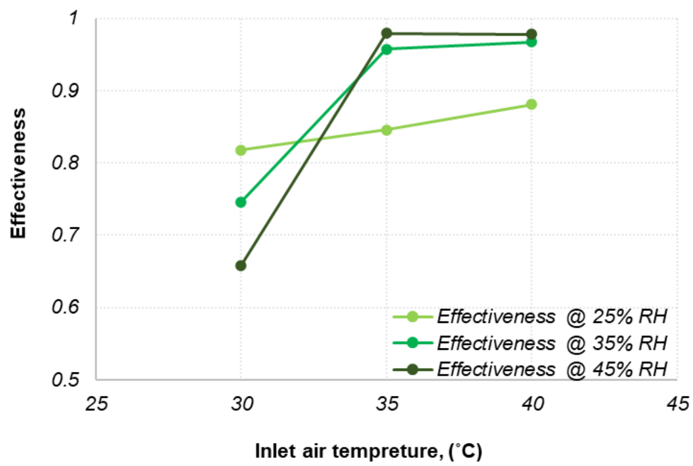


Figure 8: Effectiveness of DEC (airflow velocity: 2.85 m/s)

3.1.4 Effect of inlet temperature and RH on cooling capacity

In this work, the cooling capacity of the DEC system was presented relative to the synthetic grass fibres surface area. The effect of ambient air temperature and RH on cooling capacity is presented in Figure 9. This shows that the cooling capacity increases with increasing ambient air temperature. For example, for ambient air RH of 25%, the cooling capacity increased by about 27% (from 110.76 to 151.59 W/m^2) when the ambient air temperature increased from 30° C to 40° C. Equally, a similar improved cooling capacity trend can be observed for ambient air RH of 35 and 45%.

However, the cooling capacity of the cooler declined as the ambient air RH increased from 25 to 45%. This is a result of a drop in temperature difference between that of ambient air and cooled supply air. For example, at ambient air temperature of 40° C, the cooling capacity declined by about 20% as RH of the inlet air rose from 25 to 45%.

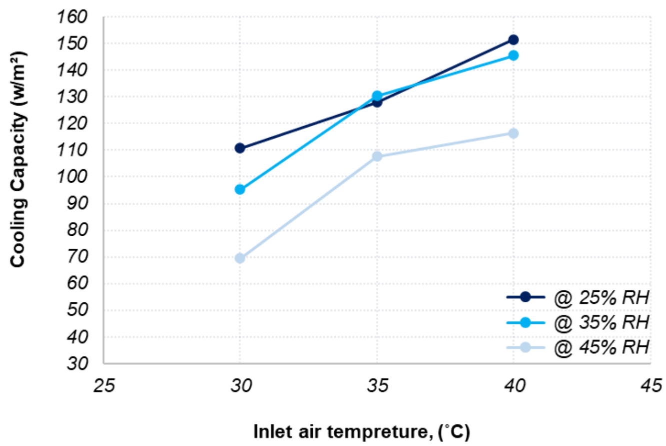


Figure 9: Cooling Capacity DEC (airflow velocity: 2.85 m/s)

3.2 Indirect evaporative cooling (IEC) Configuration

In this arrangement, the hot dry inlet air was forced through the dry channels into the occupied space. Equally, the ambient air was circulated through the wet channel to perform water evaporation and cool the air. The airflow in the dry channel is then cooling indirectly by transferring heat through the thin aluminium support plate separating the two channels. The optimisation of heat transfer process between the two airflows was not the subject of this work.

3.2.1 Cooling performance

Figure 10 show a selected steady state inlet and supply air temperature, which shows the IEC cooler maintains a temperature difference of 10.2° C.

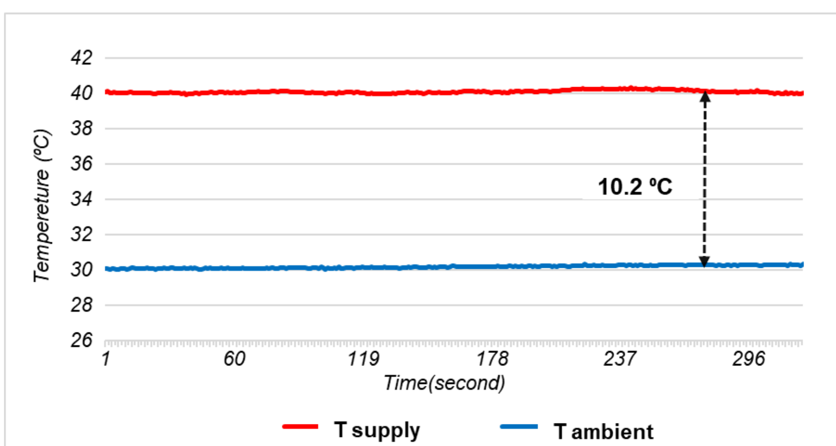


Figure 10: Steady state IEC inlet and supply air temperature (airflow RH: 29.1% and velocity: 1.65 m/s)

A summary of the measured steady state temperatures, calculated effectiveness and cooling capacity is also presented in Table 5.

Table 1: Measured steady state performance parameters in the IEC Configuration

Velocity Inlet Air	RH Dry channel	Temp Inlet Dry Channel	Temp Supply DB	Temp Inlet WB	Temp Inlet DP	Temp Inlet wet channel	Temp Outlet wet channel	RH Outlet wet channel	Calculated effectiveness	COP	Calculated cooling capacity
m/s	%	°C	°C	°C	°C	°C	°C	%	(-)	(-)	W
1.65	29.1	40.5	30.3	25.4	19.09	40.5	32.1	87.7	0.67	1.47	155.4

3.2.2 **Effect of ambient air temperature and RH on supply air temperature and cooling effectiveness**

The temperature drop through the IEC at ambient air temperature of 30, 35 and 40° C and corresponding RH of 25, 35 and 45% while the airflow rate was maintained at 1.65 m/s are presented in Figure 11. Likewise, this shows the highest temperature drops are yielded at higher ambient temperature and lower air RH. For instance, at ambient air temperature of 40° C and 25% RH, the airflow temperature decreased by 10.2° C.

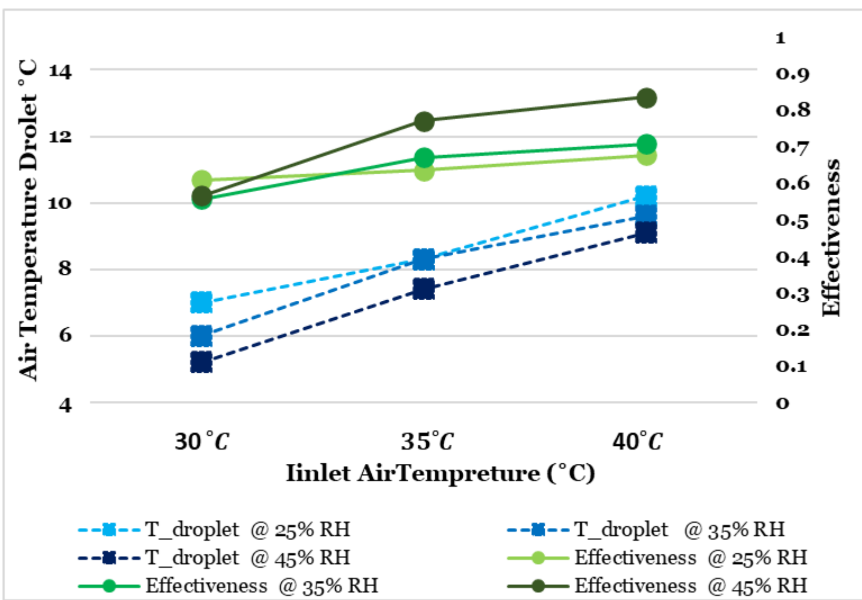


Figure 11: IEC cooler Effectiveness and air temperature drop (airflow velocity: 1.65 m/s)

In addition, Figure 11 shows the effect on the effectiveness of the IEC system follows a similar trend in that high effectiveness was achieved at high ambient inlet temperature and lower RH.

For instance, the effectiveness of the cooler increased from 0.56 to 0.85 for ambient inlet temperature increase from 30° C to 45° C at constant RH of 45% and airflow velocity of 1.65 m/s.

3.2.3 Effect of ambient inlet temperature and RH on cooling capacity

The influence of ambient air temperature and RH on the cooling capacity of the cooler is shown in Figure 12. This shows that the cooling capacity of the IEC increases with increasing ambient inlet-air temperature. Conversely, the cooling capacity decreases with increasing air RH. For instance, at inlet air RH of 25%, the cooling capacity increased from 49.4 to 69.39 W/m^2 as inlet air temperature increased from 30 to 40°C. In contrast, at ambient inlet temperature of 30° C, the cooling capacity decreased from 49.4 to 31.5 W/m^2.

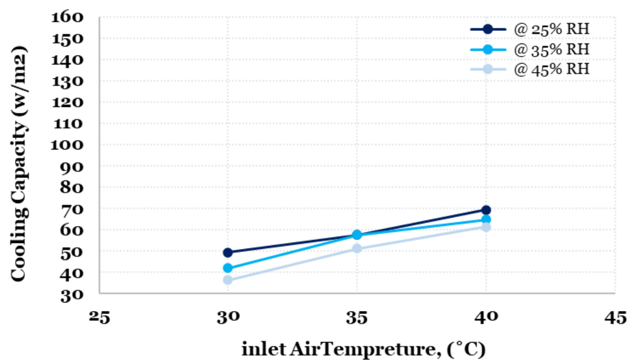


Figure 12: IEC cooler system Cooling capacity (airflow velocity: 1.65 m/s)

3.3 Dewpoint evaporative cooling operation mode

DPEC coolers have the advantage of supplying cooled air at temperature below wet bulb temperature of ambient inlet air by sacrificing a portion (up to 50%) of the dry channel cool outlet air for doing the evaporation work in the wet channel.

3.3.1 Cooling performance

Like in the previous cases, the steady state inlet and supply air temperature of the DPEC was recorded, as shown in Figure 13. The cooler maintains an operating temperature difference of 10.3° C when the inlet air temperature and RH are held at 41.8° C and 27.4%, respectively.

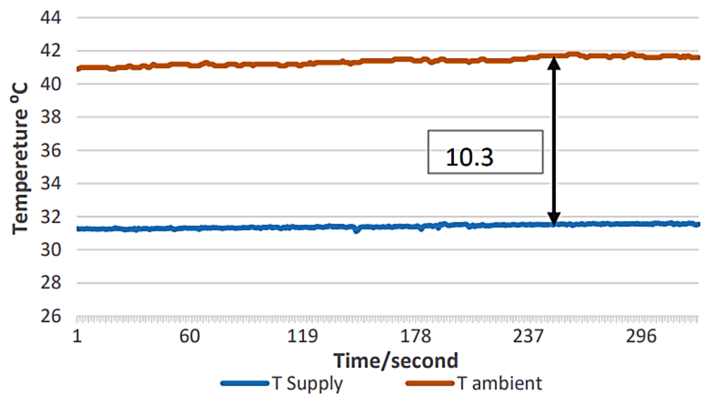


Figure 13: Steady state DPEC inlet and supply air temperature (RH: 27.4% and airflow velocity: 1.85 m/s)

Further details of measured operating parameters of the DPEC are summarised in Table 6. This shows that supply air temperature (31.5° C) is higher than the ambient air wet bulb temperature (25.5 °C), which indicates that the cooler did not achieve the sub wet bulb temperature condition. Equally, the wet bulb effectiveness and cooling capacity were 0.67 and 174.4 W respectively. A full optimisation of the design to operate in this mode would be required to improve its performance and achieve cooling air temperature below the corresponding wet bulb temperatures.

Table 2: Dewpoint evaporative cooling mode operating parameters

Velocity Inlet Air	**RH Dry channel**	**Temp Inlet Dry Channel**	**Temp Supply DB**	**Temp Inlet WB**	**Temp Inlet DP**	**Temp Inlet wet channel**	**Temp Outlet wet channel**	**RH Outlet wet channel**	**Calculated effectivene ss**	**COP**	**Calculated cooling capacity**
m/s	%	°C	°C	°C	°C	°C	°C	%	(-)		W
1.85	27.4	40.8	31.5	25.5	19.22	31.5	33.3	86.1	0.67	1.65	174.4

3.3.2 Effect of inlet air temperature and RH on supply air temperature

The effect of ambient air temperature and RH on the temperature of the air supply is shown in Figure 14. Similar trends to previous coolers arrangements were observed in this case too. For example, inlet ambient air temperature at 40° C and RH of 25, 35 and 45% achieved a drop in supply air temperature of 10.3, 9 and 7.6° C, respectively. Additionally, at ambient RH of 25% and temperature of 30, 35 and 40° C, the ambient air temperatures decreased by 10.3, 9.8 and 7.9° C, respectively.

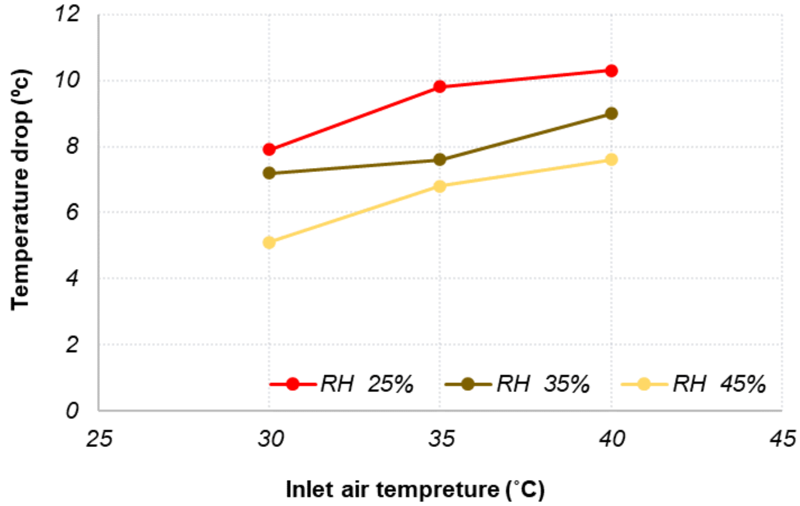


Figure 14: Supply air temperature reduction (air velocity: 1.85 m/s)

3.3.3 Effect of inlet air temperature and RH on effectiveness

The effect of inlet air temperature and RH on the effectiveness of the cooling tower in DPEC mode is shown in Figure 15. The wet bulb effectiveness increases as the ambient air temperature increases. The highest wet bulb effectiveness is 0.67 at an ambient air temperature of 40° C, while the lowest value is 0.53 at 30° C. the effect ambient air RH however does not show a clear correlation.

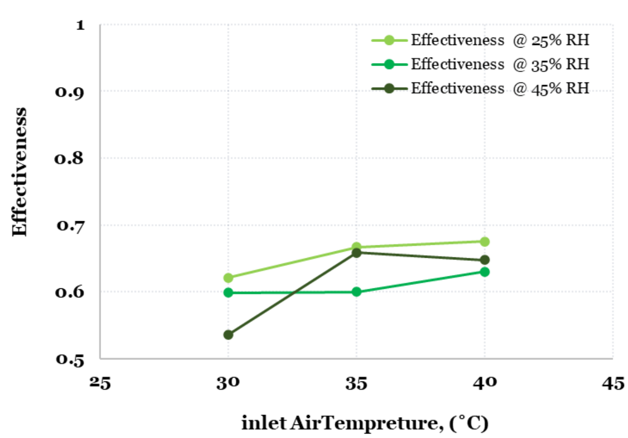


Figure 15: Effectiveness of DPEC (airflow velocity: 1.85 m/s)

3.3.4 Effect of ambient inlet air temperature and RH on cooling capacity

The measured cooling capacity of the DPEC arrangement is illustrated in Figure 16. This shows that the cooling capacity increases as ambient air temperature increases. The maximum cooling capacity was achieved at 40° C and RH 25%.

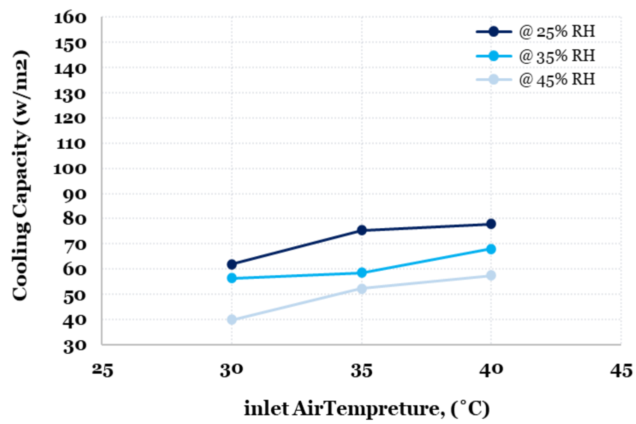


Figure 16: Cooling Capacity DPEC cooler system

Likewise, it can be observed that the cooling capacity of the cooler increased as the air RH decreased. For example, the cooling capacity declined from 77.8 to 56.4W as ambient air RH decreased from 45% to 25 %.

3.4 Comparative performance and Discussion

The experimental results compared the cooling capacity and supply air temperature reduction of three evaporative cooler designs using synthetic grass fibres as wet media, against published research by Musa [36], Ibrahim [37], Ford et al. [38] and Boukhanouf et al. [39]. These referenced works examined evaporative coolers with porous ceramic panels, as shown in Figure 17. The synthetic grass material used in this work produced higher cooling capacities and supply air temperature reduction in DEC cooling mode. However, in IEC and DPEC operating mode, the cooling capacity and air temperature performance is slightly lower than existing reported data.

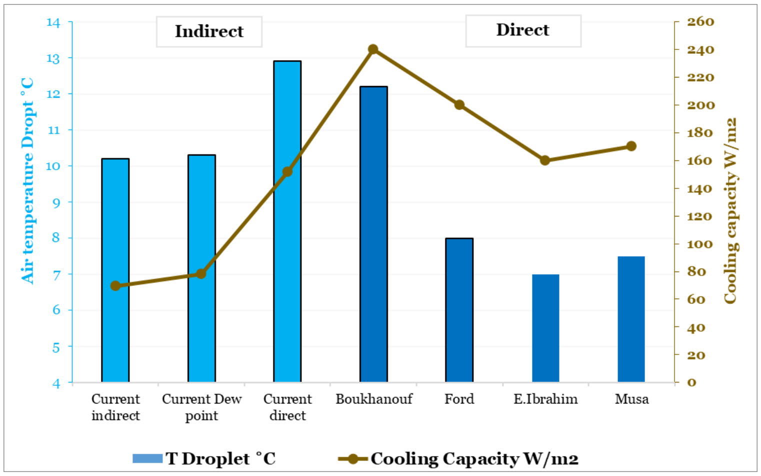


Figure 17: Comparison of experimental results of capacity and temperature drop (ambient air temperature: 40° C and RH: 25%

A further relevant comparison is evaluating water consumption of the synthetic grass wet media material and published work. Figure 18 shows that the proposed material has high water consumption rate and slightly lower effectiveness compared to previously reviewed works. The high-water consumption rate is mainly due to low water retention of synthetic grass fibres compared to low porosity ceramics or organic media. The synthetic grass fibres mats used in this work are designed for outdoor sport surface that allow fast drainage of rainwater.

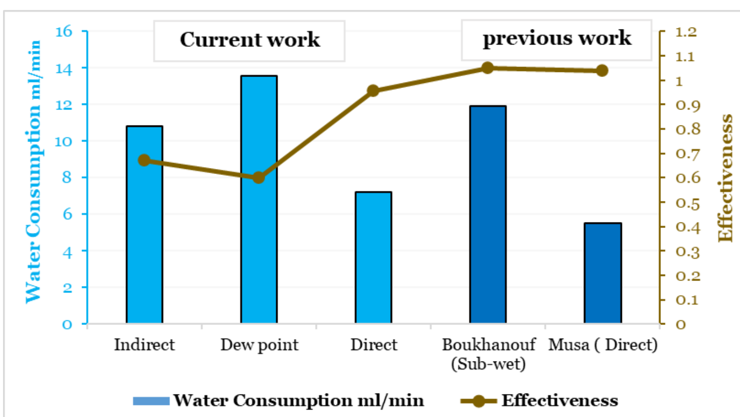


Figure 18: comparison results of water consumption and effectiveness (ambient air temperature: 35°C and RH: 35%)

3.5 Uncertainty analysis

The reliability of the presented experimental data was further analysed considering the instruments and sensors individual precision and combining them to estimate the overall uncertainty of the calculated key performance indices. This is critical for the consistency and reproducibility of measurements under identical conditions. The respective uncertainty of the calculated effectiveness and cooling capacity can be expressed as [40]:

$$\frac{e_{\varepsilon_{wb}}}{\varepsilon_{wb}} = \sqrt{\left(\frac{e_{T_{in}}}{T_{in}}\right)^2 + \left(\frac{e_{T_s}}{T_s}\right)^2 + \left(\frac{e_{T_{wb}}}{T_{wb}}\right)^2} \quad (5)$$

$$\frac{e_{Q_c}}{Q_c} = \sqrt{\left(\frac{e_{T_{in}}}{T_{in}}\right)^2 + \left(\frac{e_{T_s}}{T_s}\right)^2 + \left(\frac{e_v}{v}\right)^2} \quad (6)$$

where *e* is the thermocouple accuracy error, *T* is the measured temperature, e_v is the velocity reading accuracy error, and *v* is the measured velocity.

The results of the uncertainty calculation are given in Table 7. The results show that the relative uncertainty of effectiveness ranges from 3.04 to 3.23% indicating acceptable level of precision of the measured results of the three evaporative coolers. The relative uncertainty of calculating the cooling capacity was however slightly high ranging from 10.76 to 18.30%. This is greatly influenced by the accuracy (± 0.3 m/s) of the instrument used to measure the airflow velocity in the air ducts and the difficulty in obtaining a uniform airflow in narrow ducts.

Table 7 Relative uncertainty calculation for the evaporative cooling modes

	Inlet Air Velocity	**Inlet Air Temp**	**Supply air DB Temp**	**Supply air WB Temp**	**Effectiveness**	**Effectiveness relative uncertainty**	**Cooling capacity**	**Cooling capacity relative uncertainty**
	(m/s)	(°C)	(°C)	(°C)	(%)	(%)	(W)	(%)
DEC	2.85	40	27.1	25.3	0.87	3.23	339.57	10.76
IEC	1.65	40.5	30.3	25.5	0.67	3.10	155.4	18.30
DPEC	1.85	41.8	31.5	25.5	0.67	3.04	174.4	16.34

4. Research limitations

This work used experimentation to investigate the use of synthetic grass fibres as wet media in evaporative coolers. The experimental results show overall the performance of this type of media material is consistent and be used as a springboard for further research. One area is to consider theoretical analysis and heat transfer optimisation of the synthetic grass fibre structure, backing plate thickness and wet and dry channels separation gap. Equally, the uncertainty analysis revealed that the measured cooling capacity accuracy could be improved by using more accurate anemometer in measuring the airflow velocity. Finally, the energy consumption of auxiliary equipment such as fans and water circuiting pump could be considered, and the overall coefficient performance of the cooler be used as an additional performance index.

5. Conclusions

This research seeks to advance the design of evaporative cooling technology by investigating experimentally the performance of novel wet media material in the form of synthetic grass mats. A purpose laboratory test rig was built to test a synthetic grass fibre module in three modes of operation: DEC, IDE and DPEC. The effectiveness and cooling capacity the three arrangements were evaluated under controlled conditions of temperature, humidity, and airflow rate. The experimental results demonstrated consistency when compared to published work. This work yielded several key insights that can be summarized as follows:

- The synthetic grass fibres present a viable wet media material alternative for evaporative cooling systems that can enhance service life with maintenance.
- The three modes of operation of evaporative cooling achieved effectiveness ranging from 0.67 to 0.87. Similarly, the measured maximum temperature drop in the coolers ranges from 10.1° C to 12.9° C.
- The correlation between decreasing supply air temperature as ambient inlet air temperature increases demonstrates the principle of evaporative cooling as an appropriate technology for hot and dry climates.
- The evaporative cooling systems also achieved high cooling capacities ranging from 155.4 to 339.57 W. However, the system cooling capacity is reduced as air relative humidity increases, which suggest that local climatic conditions are a critical parameter for the performance of evaporative cooling systems.
- The experimental work showed that the Direct Evaporative Cooling (DEC) mode achieved higher performance. For instance, the temperature drop was nearly 20% greater that Indirect Evaporative Cooling (IEC) mode, albeit at the expense of increasing the air moisture content.

Acknowledgements

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