

A PILOT-SCALE STUDY FOR EVALUATING THE PERFORMANCE OF A FAN-PAD COOLING SYSTEM UNDER DIFFERENT CLIMATIC CONDITIONS OF SAUDI ARABIA

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ABSTRACT

In the present study, a special test setup was designed to evaluate the performance of a fan-pad evaporative cooling system under different climatic conditions in Saudi Arabia. Weather data for Riyadh representing arid climate, Jeddah representing humid climate and Abha representing moderate climate were analyzed. These data contained hourly readings for air temperature, relative humidity and solar radiation. An evaporative cooler consisting of a 10 cm thick cooling pad, suction fan and water pump was used. The cooling pad was installed in a 1080mm high, horizontal duct of square cross-section insulated by 50mm polyurethane. The duct cross-section measures 1000mm ×1000mm. A variable speed suction fan was fitted at one end and the pad was designed so that the inlet air passed through the wetted pads. Air temperature and relative humidity of the inlet air were changed to simulate dry, humid and moderate climatic conditions of Saudi Arabia. The inlet air was heated by two types of electrical heater. The heaters were fixed in a contraction-cone-profile that is mounted in the air duct. The inlet air temperature was controlled by a PID temperature controller. Electrical high pressure steam boiler was used to produce low pressure steam for heating and humidifying the inlet air stream. The boiler capacity is 57 kg/h steam at a pressure of 5.5 bar.

The weather data analyses showed that cooling of agricultural structures in Riyadh and Jeddah is very essential. The mean monthly temperature during summer in Riyadh area varies between 31.5°C and 36°C, and the relative humidity is between 14.4% and 20%. These conditions encourage the use of evaporative cooling.

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In Jeddah, the mean monthly temperatures during summer vary between 30°C and 33.5°C, and the relative humidity is between 57% and 82%. Cooling of agricultural structures in Abha is not necessary, except greenhouses that act as solar collectors. The mean monthly temperatures in Abha during summer vary between 22°C and 23.5°C, and the relative humidity was between 35% and 70%.

Averages of monthly solar radiation levels during summer vary between 570 and 619 W/m², for Riyadh, between 503 and 580 W/m², for Jeddah, and between 477 and 591 W/m², for Abha. Experimental results showed that averages of cooling efficiency were 82.4%, 72.2% and 75% under arid, humid and moderate conditions, respectively.

The highest air temperature drop through the pad was observed under arid dry conditions with a range of 12-32.5°C. Whereas air temperature drop was lowest under humid hot conditions with a range of 2.8-8.6°C. The drop under moderate conditions ranged from 6 to 15.3°C. The maximum cooling of 20612W was obtained for the arid climatic conditions compared to 11883W and 5992W for moderate and humid climatic conditions, respectively. Cooling water consumption rate increased by increasing both temperature of the inlet air and air speed through the pads. The consumption rates were 11.8 and 13.8 l/hr at inlet air temperatures of 40 and 45°C, respectively, when air speed was 0.5 m/s. The rate increased from 8.8 l/hr at air speed of 0.25 m/s to 19.8 l/hr at air speed of 1 m/s when the air temperature at the inlet was 40°C. The water consumption decreased as the relative humidity of the inlet air increased at the same temperature. The water consumption rate decreased from 13.8 l/hr to 5.8 l/hr by increasing relative humidity from 8% to 58%, respectively, at inlet air temperature of 35°C.

INTRODUCTION

Most regions in the Kingdom of Saudi Arabia have harsh environment for plant and animal production. In addition to water deficiency, the ambient temperature and relative humidity are not suitable for commercially produced plants and animals. Therefore, it is essential to cool agricultural structures by either evaporative cooling or refrigeration air conditioning that has high initial

cost and demand high input of power. Evaporative cooling systems are commonly used for cooling of agricultural structures in Saudi Arabia with comparatively low investment and less power input. Evaporative cooling has been reported for achieving a favorable environment for greenhouses crops (Montero *et al.* 1981; Kittas *et al.*, 2001); poultry and dairy houses for reducing heat stress on animals (Gates *et al.*, 1991; Bottcher *et al.*, 1991; Ryan *et al.*, 1992; Ali *et al.*, 1999; Arbel *et al.*, 1999; Zabeltitz, 2002; and Chen, 2003) and storage structure for fruits and vegetables (Helson and Wilmot, 1991 and Umbarker *et al.*, 1991). Kittas *et al.* (2001) observed that a fan-pad cooling system during summer in a commercial greenhouse producing cut roses and a half-shaded plastic roof reached 80% efficiency and succeeded in maintaining greenhouse temperatures that were cooler (up to 10°C lower) than outside. It has been reported by several researchers that evaporative cooling improved milk production and fertility for cows during summertime climates (El-Nouty *et al.*, 1990; Bucklin *et al.*, 1991 and Ali *et al.*, 1999). Also, use of evaporative cooling minimized the heat stress birds were exposed to during growth period (Deaton *et al.*, 1982; and Reece *et al.*, 1972).

Fans combined with wetted pads are the most widely used for greenhouses cooling (Montero *et al.* 1981; Jain and Tiwari, 2002). Evaporative cooling effectiveness depends upon several factors including width and density of pads and pad material used (Watt, 1953; Wiersma and Benham, 1974; Al-Helal and Al-Towejeri, 2001; Liao and Chiu, 2002). Increasing pads width increases resistance to air flow and air-water contact area, and minimize water evaporation rate as the air moves through the pads. Different pad materials are being used such as aspen pads, corrugated cellulose, plastic fibers and palm dates fibers. Generally, the pads width ranged between 5 to 10 cm for the aspen pads, and between 10 to 15 cm for the corrugated cellulose. Watt (1953) indicated that the optimum density for the vertical aspen pad is 32 kg/m³. Increasing pads density would increase resistance to air flow. Also, the face velocity of the air affects the contact between air and water, and high velocity of air carry-over of water droplets from the cooling pad to the interior. The recommended face velocities through the corrugated

cellulose pad with thickness of 10 and 15 cm are 1.25 and 1.75 m/s, respectively (ASAE, 2000).

Al-Helal and Al-Towejeri (2001) studied evaporative cooling efficiencies for palm dates fiber pad and cross-fluted cellulose pad were studied under arid conditions. Experiments were carried out during noon hours where averages of outside dry-bulb temperature and relative humidity were 44°C and 14.5%, respectively. The highest cooling efficiencies for cross-fluted cellulose pad and palm dates fiber pad (77% and 69%, respectively) was obtained with a thickness of 10 cm and a water addition rate of 11 l/min. The lowest cooling efficiency for cross-fluted cellulose pads (53%) was obtained when thickness and water addition rate were 5 cm and 3 l/s, respectively. The lowest cooling efficiency for palm dates fiber pad (47%) was obtained when thickness and water addition rate were 10 cm and 3 l/s, respectively.

Liao and Chiu (2002) developed a compact wind tunnel to investigate evaporative cooling pad-fan system performance in Taiwan region. Two alternative materials including one made of coarse fabric PVC sponge mesh 2.5 mm diameter in pinhole and one made of fine fabric PVC sponge mesh in 7.5 mm diameter pinhole were tested as pads. The effects of air velocity, water flow rate, static pressure drop across pad, and pad thickness on evaporative cooling efficiency were examined. Cooling efficiencies for coarse fabric PVC sponge ranged from 63.88 to 64.77%, 80.50 to 81.68%, and 81.75 to 86.32%, respectively, for 5, 10, and 15 cm thickness under normal operating air velocities of 1.0–1.5 m/s. Cooling efficiencies for fine fabric PVC sponge ranged from 47.22 to 57.23%, 62.93 to 72.25%, and 76.68 to 85.51% for 5, 10, and 15 cm thickness, respectively, under normal operating air velocities.

Limited data are available on the fan-pad evaporative cooling performance under climatic conditions of Saudi Arabia. One study evaluating the performance of three natural fibers to be used as wetted pads in evaporative cooling; date palm fibers (stem), jute and luffa was the study of Al-Sulaiman (2002). The average cooling efficiency was highest for jute at 62.1%, compared to 55.1% for luffa fibers, 49.9% for the reference commercial pad and 38.9% for date palm fiber. Alodan and Al-Faraj (2005) evaluated a new alternative cooling pads made from

galvanized metal sheets under arid conditions of Riyadh. The cooling efficiency ranged from 73% to 89% depending on the pads depth. Al-Helal et al., (2004) investigated the cooling efficiency for a fan-pad system for a photovoltaic powered greenhouse under extreme summer conditions of central regions of Saudi Arabia. The cooling efficiency averaged at 71%, with 8 to 17.3 °C reductions in ambient temperature.

The present study evaluated the performance of evaporative cooling in regions with arid, humid and moderate climates. Evaluation of the fan-pad system under different weather conditions requires an analysis of weather data such as air temperature, solar radiation and relative humidity. All are especially important factors for the evaporative cooling efficiency and dry-bulb temperature drop for the cooled air. The data was also used for defining weather characteristics during summer, deciding the need of air cooling before it enters any agricultural structures and determining the time of the day where the cooling load can reach its maximum level (peak). Because of the difficulties in field measurements, a pilot-scale study in the environmental control laboratory was performed to quantify system performance under controlled conditions.

MATERIALS AND METHODS

Procedure and instrumentation

This study was carried out in the environmental control laboratory, department of agricultural engineering at the college of food and agricultural sciences, King Saud University. An evaporative cooler consisting of a 10 cm thick Celdek cooling pad, suction fan and water pump was used. The cooling pad was installed in a 1m high, horizontal duct of square cross-section. The duct was made of Varifoam, thickness of 55mm (VF-55) composite a sandwich panel, coated with Polyester with standard bone white colore, and insulated by 50mm polyurethane foam insulation, U-value of 0.49 W/m²°C. The duct cross-section measures 1m ×1m. A variable speed suction fan (Type 8D92-3pp-21Q, Multifan, Venlo, Holland) was fitted at one end and the pad was designed so that the inlet air passed through a 10 cm thick, 90 cm by 90 cm cooling pad. The pad was of the cross-fluted cellulose type (Cel-dek, Munters®). Pads were installed vertically so that the pad was wetted by distributing

water over the pad top using a distribution pipe. The pipe was made of PVC, 25mm in diameter and had 4mm diameter holes drilled on 50 mm centers along the top of the distribution pipe. The water is forced upward, strikes a cover plate and trickles down to the pads. Water was supplied to the pad from a stainless steel sump (800mm × 450mm × 300mm) that serves as a reservoir. Water was continuously supplied to the sump from a galvanized metal water tank (1000mm × 500mm × 500mm) to replace evaporative and losses. It was added by having a water supply line to the sump that was controlled by a float (Figure 4). A pump (Pedrollo, Italy, 0.5 HP, 380V, 5-40 l/min) was used to move water from the sump to the top of the pads. The water was added to the pads at a constant rate. Figure 4 shows a diagram of the components of evaporative cooling pad system.

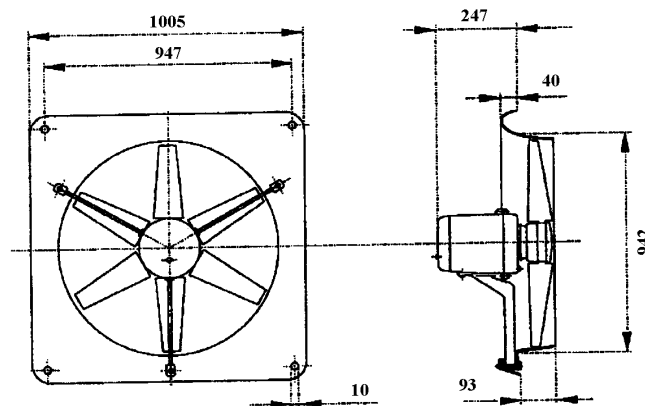


Fig. 1. Schematic illustration of the suction fan.

Air temperature and relative humidity of the inlet air were changed before passing through the cooling pads in order to simulate dry, humid and moderate climatic conditions. The inlet air was heated sensibly to increase its temperature and decrease its relative humidity by two electrical heaters. The first heater was composed of four duct heater units; each has a rated maximum capacity of 3 kW and a voltage of 220VAC. The second is consisted of three air fins tubular heater units, each with a rated maximum capacity of 3kW and a voltage of 220VAC. The heaters were fixed in a contraction-cone-profile that keeps a uniform air in the

duct, while decreasing the area to a 500×500 mm cross-section. The inlet air temperature was controlled by a PID temperature controller that displays both actual and desired air temperatures. The controller has input and output. The input was connected to a sensor for measuring temperature of the heated air, and the output was connected to a solid static relay that controls the operation of the heaters.

Electrical high pressure Electric steam boiler (ALKA Boiler, model ALKA 36E) was used to produce low pressure steam for heating and humidifying the inlet air stream. The boiler made of stainless steel, and makes steam by the heating of electric heater to generate steam within 7-8 minutes after switch-on. The boiler capacity is 57 kg/h steam at a pressure of 5.5 bar. The steam moved through a metal pipe having a diameter of 19 mm, and injected into the air stream inside the duct through a 9 pipes that had 3 mm-diameter holes drilled on 50 mm centers. All units (cooling pads, heaters and boilers) were installed in the duct.

Measurements

Measurements included air dry bulb temperature and relative humidity in front and in rear of the pad, and air speed in rear of the pad. Air temperature and relative humidity were measured with portable humidity and temperature sensors (DME 701, LSI, Italy). The air speed was measured using hot wire probe (DNE506, LSI, Italy). The signals were connected to computer (Dell, Optiplex Gx270, Pentium 4, 2.8 GHz, 8 GB, 512MB) by using data acquisition system type PCI-6229M and analyzed by LabView program from National Instrument. Data was collected each 10s by a data logger (LI-COR-1400) and averaged over a time of 1 min. The water consumption rate due to evaporation effect was measured by measuring water level decrease in the tank during the test period. The cooling efficiency (η) was evaluated based on the equation:

$$\eta = \frac{T_{in} - T_{out}}{T_{in} - T_w} \times 100$$

where T_{in} is the inlet dry-bulb temperature ($^{\circ}\text{C}$), T_{out} is the outlet dry-bulb temperature ($^{\circ}\text{C}$), and T_w is the thermodynamic wet-bulb temperature of the inlet air ($^{\circ}\text{C}$) which was found from the psychrometric chart using dry-bulb temperature and relative humidity readings.

The cooling power q (W) was given by:

$$q = m_a C_p (T_{in} - T_{out})$$

where m_a is the air mass flow rate (kg/s) and C_p is the specific heat of dry air (kJ/kg $^{\circ}\text{C}$).

The air mass flow rate (kg/s) was determined by:

$$m_a = V_a \rho$$

where V_a is the volumetric air flow rate (m^3/s) and ρ is the air density (kg/ m^3) which was defined by:

$$\rho = \frac{P}{R T}$$

where P is the ambient atmospheric pressure (Pa), R is the universal gas constant (J/kg K) and T is the air temperature (K).

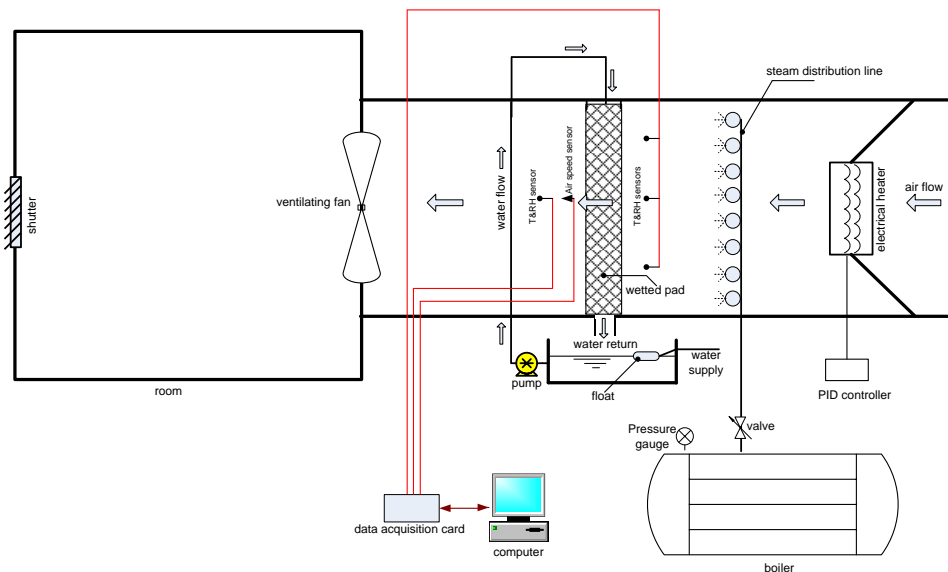


Fig. 2. Combined schematic of the evaporative cooling, heater, boiler and measurement system.



Fig. 3. Steam injection in the air duct

RESULTS AND DISCUSSIONS

Weather characteristics

Monthly averages of temperature, relative humidity and solar radiation for Uuaiana, Jeddah and Abha are shown in table 1. It is obvious from the table that Riyadh area is characterized by arid climatic conditions (high temperature and low relative humidity) throughout summer months, i.e., during May-September. The mean monthly temperatures during this period vary between 31.5°C and 36°C during May and August, respectively, while the mean monthly relative humidity vary between 14.1% and 20% during July and May, respectively. It is under these ambient that evaporative coolers are very effective. In Jeddah, however, the hot air associated with high relative humidity lowers effectiveness of evaporative cooling. The mean monthly air temperature ranges from 30 (May) to 33.5°C (August), while the mean monthly relative humidity's between 57 (July) and 82% (September). In Abha, climatic is more temperate during summer, and agricultural structures may not require the use of evaporative cooling, except greenhouse that are covered with transparent materials which allow shorter wavelength radiation (i.e. visible light) to pass through that is mostly transformed into thermal energy. This causes an accumulation of heat in the greenhouse that must be dissipated by either convective air through ventilators, or exhaust fans. The mean monthly temperatures during summer vary between 22°C and 23.5°C during May and July, respectively, while the mean monthly

relative humidity's vary between 35% and 70% during July and August, respectively. These conditions are more favorable for crop and animal production. The mean monthly solar radiation level during summer ranges from 570W/m^2 (September) to 619W/m^2 (June), from 503W/m^2 (September) and 580W/m^2 (June), and 477W/m^2 (July) and 591W/m^2 (September) in Riyadh, Jeddah and Abha, respectively.

Figure 4 shows solar radiation data, temperature and relative humidity for the hottest day of the year for the three cities. The figure shows that climate in the Riyadh area is characterized by desert climatic conditions; extreme heat during summer days and abrupt drop in temperature at night. Air temperature varies between 28.5°C and 44.7°C in Riyadh, between 31°C and 37°C in Jeddah and between 19°C and 32.6°C in Abha. The figure shows that heat in Riyadh becomes intense at 8:00 a.m. and lasts until midnight. Temperature and relative humidity during this period ranged from 35.6°C to 44.7°C , and from 8.3% and 14.4%, respectively, while solar radiation peaked at 1032 W/m^2 at midday. In Jeddah, however, heat becomes intense during the period 9:00-19:00 where temperature ranged from 35°C to 37°C , and relative humidity ranged from 70% to 87%, while the solar radiation peaked at 1003 W/m^2 at midday. In Abha, heat becomes intense during the period 11:30-16:00 where air temperature ranged from 30°C to 32.6°C , and relative humidity ranged from 13.1% to 35.6%, while the solar radiation peaked at 1222 W/m^2 at 13:30.

Evaporative cooling performance

Table 2 shows the averages of air temperature, relative humidity and humidity ratio for the air leaving the cooler, cooling efficiencies, temperature reductions and cooling powers under different operating conditions. The cooling efficiencies was between 77% and 87% ($\eta_{\text{avg.}}=82.4\%$) under operating arid conditions, between 65% and 84% ($\eta_{\text{avg.}}=72.2\%$) under humid conditions, and between 63% and 80.5% ($\eta_{\text{avg.}}=75\%$) under moderate conditions. Also, table 2 shows that the temperature reduction was the highest under arid conditions, ranged from 12°C to 23.5°C and averaged at 18.2°C . climatic conditions.

Table 1. Average (standard deviation) monthly air temperatures, relative humidity and solar radiations for Riyadh, Jeddah and Abha for the year 2001.

Month	Air temperature (°C)			Relative humidity (%)			Solar radiation (W/m ²)		
	Riyadh	Jeddah	Abha	Riyadh	Jeddah	Abha	Riyadh	Jeddah	Abha
1	12.4 (4.7)	22.7 (3.8)	12 (4.3)	60.5 (4.7)	66.1 (23.1)	73.7 (24.9)	448	450	509
2	15.2 (4.6)	23.1 (3.7)	14.8 (4.2)	44.8 (16.1)	67.2 (18.5)	72 (24.5)	475	447	531
3	21.2 (4.4)	26.8 (4)	16.7 (3.2)	51.5 (24.5)	68.1 (20.2)	74 (21)	483	524	516
4	26.6 (4.8)	20.3 (4.1)	19.6 (4.1)	27.9 (13.9)	66.3 (19.4)	61 (23.5)	575	582	606
5	31.4 (4.8)	30.4 (4.6)	22 (4.3)	20.2 (9.2)	60 (30.6)	52 (23)	602	567	570
6	33.4 (4.6)	31.7 (4.9)	23.5 (2.2)	14.4 (4.4)	60.8 (25.3)	35 (15.8)	619	589	530
7	35.4 (4.9)	33.3 (4.3)	23.5 (3.8)	16.6 (4.3)	56.6 (23.7)	55 (27.7)	598	581	477
8	36 (4.7)	33.4 (2.6)	22.6 (4.3)	19 (7.1)	76.5 (14.9)	69.7 (29.3)	579	510	523
9	32.7 (4.7)	31.9 (2.7)	22.4 (4.6)	19.2 (7.3)	82.4 (13.4)	37.2 (23.8)	570	503	591
10	27.3 (4.9)	30 (3.7)	19.3 (4.3)	19.6 (9.7)	82.4 (18.1)	52.9 (29)	451	494	564
11	19.6 (5.2)	27.4 (3.5)	15.4 (4.3)	38.1 (15.9)	75.6 (18.4)	67 (28)	455	445	529
12	15.6 (4.8)	25.6 (2.9)	14.8 (4.3)	66.9 (23.3)	78.8 (13.5)	77 (23)	417	372	495

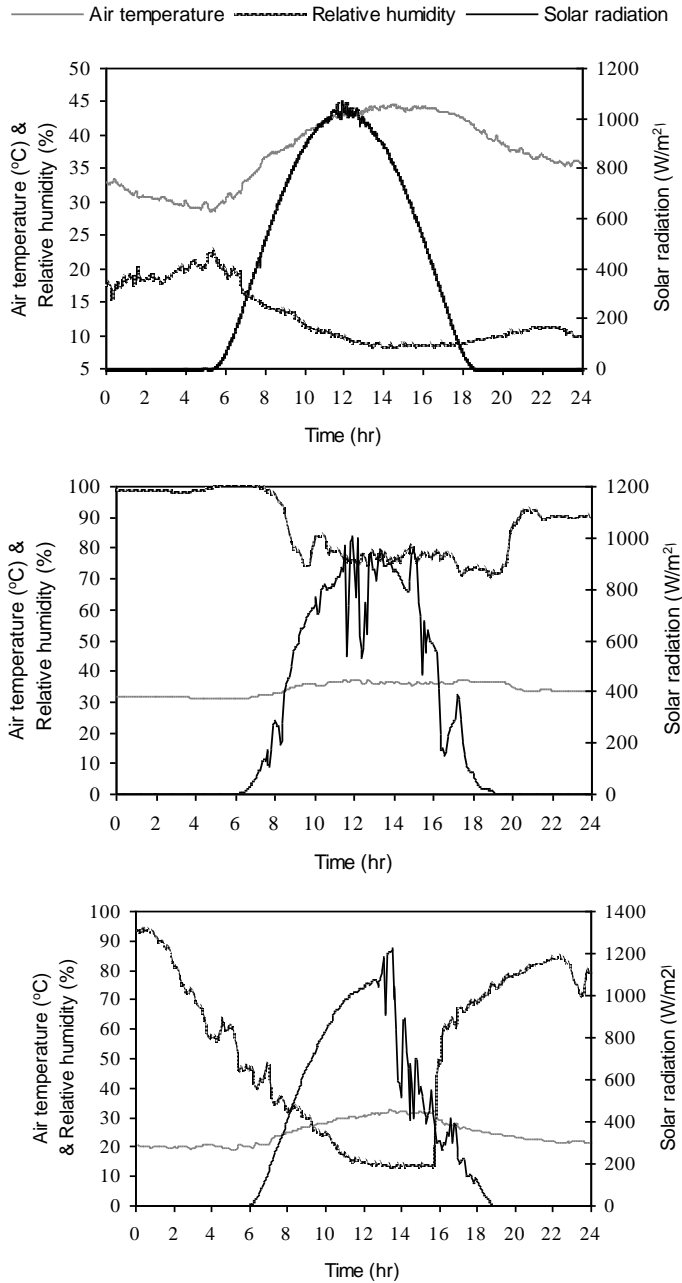


Figure 4. Hourly temperature (°C), relative humidity (%) and solar radiation (W/m²) for Riyadh on August 4, 2001 (top), Jeddah on August 17, 2001 (middle) and Abha on July 17, 2001 (bottom).

Table 2. Averages of temperature (T), relative humidity (RH) and humidity ratio (W) for the air entering (in) and leaving (out) the cooler, cooling efficiency (η), temperature drop (D) and the cooling power (q).

Climatic conditions	Air entering the cooler			Air leaving the cooler			η (%)	D (°C)	q (W)
	T _{in}	RH _{in}	W _{in}	T _{out}	RH _{out}	W _{out}			
Arid	30.5	16	0.00432	18	70	0.00900	77	12.5	14595
	35.4	11	0.00391	20.1	63.1	0.00925	80.5	15.3	17581
	40	9	0.00411	22	59.4	0.00980	82.2	18	20379
	40	12	0.00549	22.6	66.4	0.01139	84	17.4	19700
	45	12	0.00715	24.5	69	0.01331	87	20.5	22845
	45	7.6	0.00451	24	59	0.01100	84.3	21	23402
	50	8.5	0.00651	26.5	65.4	0.01422	82	23.5	25783
Average	40.8	10.9	0.00514	22.5	64.6	0.01114	82.4	18.2	20612
Humid	30	42	0.01114	23.2	70	0.01247	71.6	6.8	8033
	31	67	0.01906	27.6	86	0.02014	67	3.4	3887
	30	71	0.01907	27.2	88	0.02013	65	2.8	3308
	35	58	0.02070	30	85	0.02297	68	5	5063
	38.8	46.2	0.02028	31	83	0.02378	75	7.8	7125
	40	45	0.02109	31.4	83	0.02435	74.5	8.6	7620
	40	56	0.02646	32.2	88	0.02713	84	7.8	6911
Average	35	55	0.01969	28.9	83.3	0.02157	72.2	6	5992
Moderate	28	19	0.00444	17	71	0.00856	80	11	13923
	29	43	0.01076	23	70	0.01232	63	6	7332
	30.5	16	0.00432	18	70	0.00900	77	12	14525
	30	25	0.00659	19.7	74	0.01061	78	10.3	12168
	30	42	0.01114	23.2	70	0.01247	71.6	6.8	8033
	35.4	11	0.00391	20.1	63.1	0.00925	80.5	15.3	15317
Average	30.5	26	0.00686	20.2	69.7	0.01037	75	10.2	11883

For example, air at the inlet with temperature and relative humidity of 45°C and 7.6%, respectively, was cooled to 24°C, while the relative humidity increased to 59%. The lowest temperature reduction was achieved at operating humid conditions with a value range of 2.8-8.6°C ($D_{avg.}=6^\circ\text{C}$). For example, air temperature was reduced from 40°C to 31.4°, while the relative humidity increased from 45% to 83% as a result

of the evaporative cooling. Under operating moderate conditions, temperature reduction range was 6-15.3°C ($D_{avg}=10.2^{\circ}\text{C}$). The averages of air temperature at outlet were 20.2, 22.5 and 28.9°C under operating moderate, arid and humid conditions, respectively. On average, a maximum cooling power (cooling performance) of 20612W was obtained for the arid climatic conditions compared to 11883W and 5992W for moderate and humid climatic conditions, respectively.

Figure 5 shows water consumption during evaporative cooling (l/h) as a function of air speed at air temperatures of 35°C, 40°C and 45°C and relative humidity of 8% for the inlet air. The figure indicates that the highest amount of water consumption was 23.5 l/hr at air temperature of 45°C and air speed of 1m/s, while the lowest (7.3 l/h) was obtained at operating air temperature of 35°C and air speed of 0.25m/s. Cooling water consumption was found to be influenced by air temperature at the inlet. The average consumption of water at air temperature of 40°C and air speed of 0.5m/s was 11.8 l/hr, whereas, at air temperature of 45°C the consumption increased to 13.8 l/h. Figure also shows that cooling water consumption was increased by increasing air speed. For example, the consumption increased from 8.8 l/hr to 19.8 l/hr by increasing the air speed from 0.25m/s to 1m/s at air temperature of 40°C.

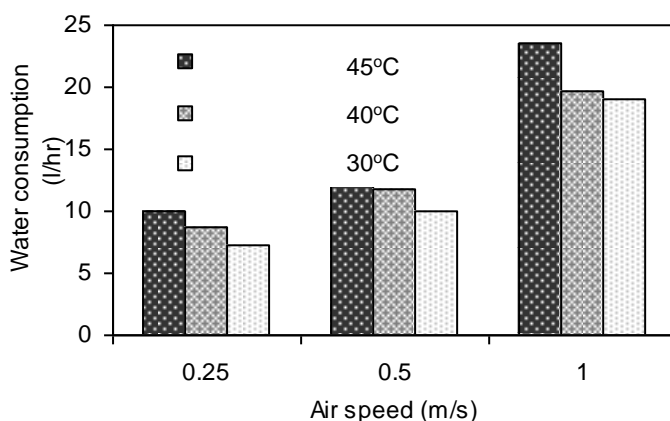


Figure 5. Water consumption rate during evaporative cooling (l/h) as a function of air speed at air temperatures of 35°C, 40°C and 45°C and relative humidity of 8% for the inlet air.

The effect of temperature and relative humidity for the air at inlet on water consumption for cooling at different values of air temperatures and relative humidity is shown on figure. The figure shows that, at the same air temperature, the rate of water consumption increased as the relative humidity for the inlet air decreased. At air temperature and relative humidity of 35°C and 8%, respectively, the water consumption rate was 13.8 l/h. When the relative humidity increased to 58% at the same air temperature, the rate of water consumption decreased by 58% (to 5.8 l/h).

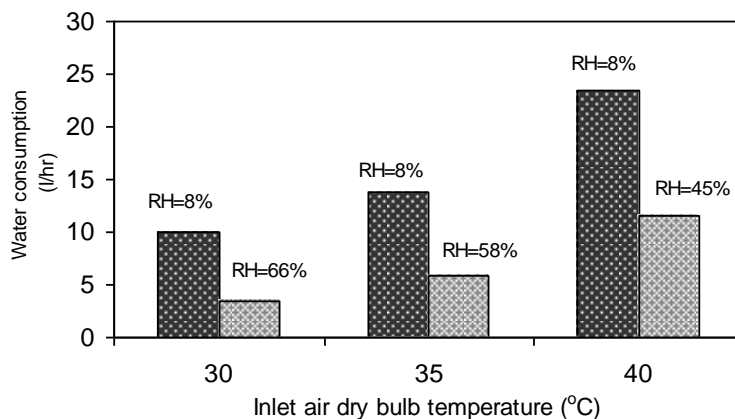


Figure 6. Water consumption rate during evaporative cooling (l/h) as a function of air temperatures and relative humidity for the inlet air.

CONCLUSIONS

The performance of a fan-pad evaporative cooling system has been investigated under a variety of climatic conditions. A test setup was designed particularly for small-scale evaporative cooling-process experiment. Weather data for Riyadh representing arid climate, Jeddah representing humid climate and Abha representing moderate climate were analyzed. The data was used for defining weather characteristics during summer, deciding the need for cooling of agricultural structures and determining the time of the day where the cooling load can reach its maximum level (peak). These data contained hourly readings for air temperature, relative humidity and solar radiation. Data showed that evaporative coolers are very effective under Riyadh conditions. In Jeddah,

however, the hot air associated with high relative humidity lowers effectiveness of evaporative cooling. In Abha, climatic is more temperate during summer; conditions are more favorable for crop and animal production. The cooling efficiencies averaged at 82.4% under operating arid conditions, at 72.2% under humid conditions and at 75% under moderate conditions. Reductions in air temperature were 18.2°C, 6°C and 10.2°C under arid humid and moderate conditions, respectively. The highest amount of water consumption was 23.5 l/hr at air temperature of 45°C and air speed of 1m/s, while the lowest (7.3 l/hr) was obtained at operating air temperature of 35°C and air speed of 0.25m/s. Cooling water consumption was found to be influenced by air temperature at the inlet. The average consumption of water at air temperature of 40°C and air speed of 0.5m/s was 11.8 l/hr, whereas, at air temperature of 45°C the consumption increased to 13.8 l/hr. Also, cooling water consumption was increased by increasing air speed. At the same air temperature, the rate of water consumption increased as the relative humidity for the inlet air decreased. At air temperature and relative humidity of 35°C and 8%, respectively, the water consumption rate was 13.8 l/hr. When the relative humidity increased to 58% at the same air temperature, the rate of water consumption decreased by 58% (to 5.8 l/hr).

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الملخص العربي

دراسة معملية لأداء المبرد التبخيري بالمرآوح والوسائد تحت ظروف مناخية مختلفة بالمملكة العربية السعودية

إبراهيم بن محمد الهلال

يهدف هذا البحث إلى دراسة أداء التبريد التبخيري تحت ظروف مناخية تحاكي مناخ المناطق الجافة والرطبة والمعتدلة بالمملكة. تم تحليل بيانات مناخية لثلاث مدن بالمملكة هي: الرياض وجدة وأبها، وتمت الاستفادة منها عند إجراء التجارب على نظام التبريد. تم تصميم مبرد تبخيري مكون من وسادة تبريد بسمك ١٠ سم من نوع (Celdek) ومروحة تهوية ومضخة للماء. استُخدمت وحدات لتغيير درجة الحرارة الجافة والرطوبة النسبية للهواء الداخل للمبرد. فقد تم تسخين الهواء تسخيناً محسوساً لرفع درجة حرارته وخفض رطوبته النسبية بمروره على سخانين. كما تم استخدام مرجل بخاري يعمل على إنتاج بخار سريع بمعدل ٥٧ كجم بخار/ساعة تحت ضغط ٥,٥ بار لترطيب وتسخين الهواء. رُكبت كل وحدة من الوحدات (التبريد والتسخين والترطيب) داخل قناة (١م × ١م). شملت القياسات درجة الحرارة الجافة والرطوبة النسبية للهواء قبل المبرد وبعده وسرعة الهواء بعد وسادة التبريد وقد سجلت البيانات كل ثانية وتم أخذ المتوسطات كل دقيقة. كما تم قياس معدل استهلاك المياه أثناء عملية التبريد التبخيري. أوضحت البيانات المناخية ضرورة تبريد الهواء في الرياض وجدة خلال موسم الصيف قبل أن يدخل أي منشأة زراعية. كما أن الرياض هي الأكثر ملائمة للتبريد التبخيري حيث تراوحت متوسطات درجات الحرارة خلال أشهر الصيف بين ٣١,٥°م و ٣٦°م، والرطوبة النسبية بين ١٤,٤٪ و ٢٠٪. أما الظروف المناخية الحارة الرطبة في مدينة جدة فهي الأقل ملائمة للمبرّدات التبخيرية، حيث تراوحت متوسطات درجات الحرارة بين ٣٠°م و ٣٣,٥°م، والرطوبة النسبية بين ٥٧٪ و ٨٢٪. أما في مدينة أبها، فتعد الظروف المناخية في فصل الصيف معتدلة وتكاد تكون الحاجة للتبريد معدومة. قد يستثنى من ذلك البيوت المحمية التي ترتفع فيها درجة الحرارة بسبب تجميع الإشعاع الشمسي. تراوحت متوسطات درجات الحرارة في أبها خلال أشهر الصيف بين ٢٢°م و ٢٣,٥°م، والرطوبة النسبية بين ٣٥٪ و ٧٠٪. وتراوحت المتوسطات الشهرية للإشعاع الشمسي خلال أشهر الصيف للرياض بين ٥٧٠ و ٦١٩ وات/م^٢، أما مدينة جدة فتراوحت تلك القيم بين ٥٠٣ و ٥٨٠ وات/م^٢، وفي مدينة أبها تراوحت بين ٤٧٧ و ٥٩١ وات/م^٢. بينت نتائج الدراسة أن متوسط كفاءة التبريد التبخيري بلغ ٨٢,٤٪ عند ظروف جافة، و ٧٢,٢٪ عند ظروف رطبة، و ٧٥٪ عند ظروف معتدلة. كما أن أعلى مقدار للخفض في درجة حرارة الهواء تم الحصول عليه عند الظروف الجافة، فقد تراوح ذلك المقدار بين ١٢-٢٣,٥°م. أما أقل مقدار للخفض في درجة حرارة الهواء تم الحصول عليه عند الظروف الرطبة، حيث تراوح بين ٢,٨-٨,٦°م.

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أما بالنسبة للمناطق المعتدلة فقد تراوح مقدار الخفض في درجة حرارة الهواء بين ٦-١٥,٣°م. كانت قدرة التبريد لكل من الظروف الجافة والمعتدلة والرطوبة ٢٠,٦١٢ و ١١,٨٨٣ و ٥,٩٩٢ وات، على الترتيب. كما بينت التجارب أن معدل استهلاك ماء التبريد يزيد بزيادة درجة حرارة الهواء الداخل للمبرد وبزيادة سرعة الهواء المار خلال وسادة التبريد. حيث بلغ معدل الاستهلاك أثناء التبريد ١١,٨ و ١٣,٨ لتر/ساعة عند درجات حرارة ٤٠°م و ٤٥°م، على الترتيب، عند سرعة ٥,٥ م/ث. كما ارتفع معدل الاستهلاك عند درجة حرارة ٤٠°م من ٨,٨ لتر/ساعة إلى ١٩,٨ لتر/ساعة عند زيادة سرعة الهواء من ٠,٢٥ م/ث إلى ١ م/ث. كما أن معدل استهلاك الماء ينخفض بزيادة الرطوبة النسبية للهواء الداخل للمبرد عند نفس درجة الحرارة. فقد بلغ معدل الاستهلاك ١٣,٨ لتر/ساعة عند درجات حرارة ٣٥°م ورطوبة نسبية ٨٪، في حين بلغ هذا المعدل ٥,٨ لتر/ساعة عند نفس درجة الحرارة ولكن عند رطوبة نسبية ٥٨٪.