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Thermal Performance and Environmental Assessment of Evaporative Cooling Systems: Case of Mina Valley, Saudi Arabia

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***Abstract*—**This paper presents a detailed description of evaporative cooling systems used for space cooling in Mina Valley, Saudi Arabia. The thermal performance and environmental impact of the evaporative coolers were evaluated. It was found that the evaporative cooling systems used for space cooling in pilgrims' accommodations and in the train stations could reduce energy consumption by as much as 75% and cut carbon dioxide emission by 78% compared to traditional vapour compression systems.

***Keywords*—**Evaporative cooling, vapour compression, electricity consumption and CO_2 emission.

I. Introduction

THE desert climate that prevails over large parts of the Middle East region particularly in Saudi Arabia and other gulf states is hot and dry for most of the year. This, along with cheap energy, demographic increases and improvement of living standards, has led to sharp rises in energy consumption in the built environment, placing huge strains on the energy supplies particularly the electrical power sector. This high demand for electrical power is primarily driven by the growing use of air conditioning systems especially in summer when the average ambient temperatures is about 45°C [1]. The building sector in Saudi Arabia accounts for about three quarter of the total delivered electrical energy with residential buildings consuming over 50%, as shown in Fig. 1 [2].

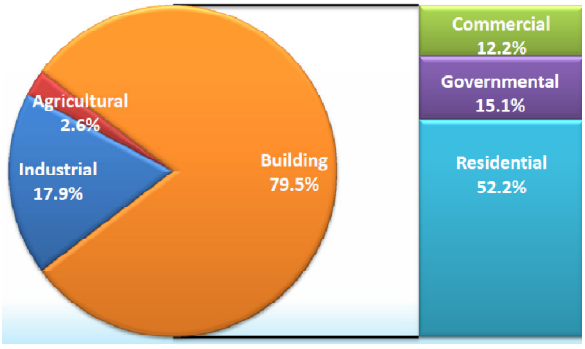


Fig. 1 Breakdown of power consumption in different sectors in Saudi Arabia 2009

A major part of the total delivered electrical energy is used to provide comfortable indoor climatic conditions for occupants. According to Proctor [3] about two thirds of power consumption in domestic buildings is for air conditioning. The majority of these systems run on conventional vapour compression cycles, which are energy intensive systems and suffer from low thermal performance in hot climate conditions. This has a negative environmental impact with total CO_2 emissions in Saudi Arabia of 466 Mt in 2009 and air conditioners contributing a total of 37.3 Mt [4].

This has led the authorities to look for alternative cooling technologies to improve energy efficiency and reduce electricity consumption. Therefore, the Saudi government opted for large scale installations of evaporative cooling systems in places like Mina Valley in Makkah where over 3million pilgrims converge on to the city every year. Fig. 2 shows an example of rooftop mounted evaporative cooling units for space cooling in purpose built pilgrims' accommodations. There are over 48,000 units installed in Mina Valley [5].

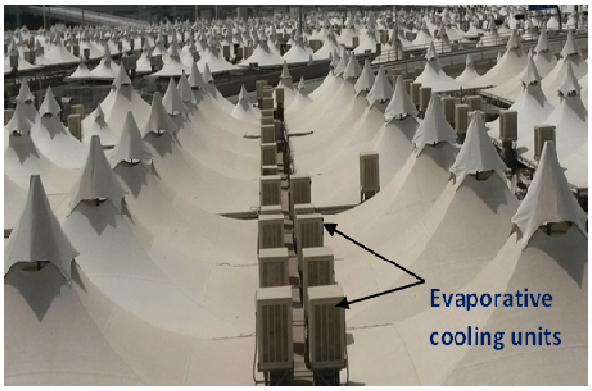


Fig. 2 Roof top mounted evaporative cooler for cooling in pilgrims' accommodations

A. Evaporative cooling technology

The process of space cooling by water evaporation has been practised by successive civilisations in the Middle East and other parts of the world. The principal of evaporative cooling is a simple process whereby evaporating liquid water to the surrounding air causes its temperature to decease. A schematic of a typical direct evaporative cooling process is shown on the psychometric chart of Fig. 3. These systems are often known as "swamp coolers" where a fan is used to draw in outside air through a wet pad media and circulates the cool air throughout the building.

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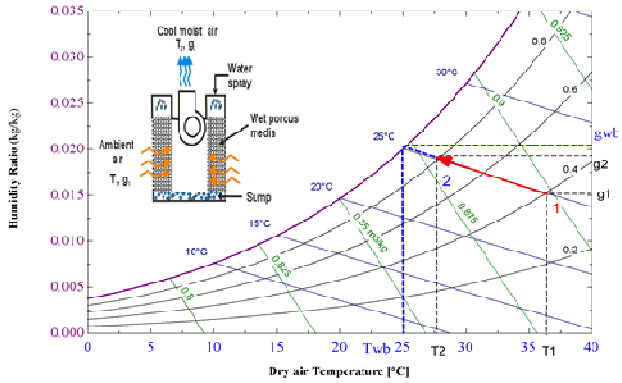


Fig. 3 Schematic of a direct evaporative cooling process

The energy required to evaporate water in a direct evaporative cooler is supplied by the sensible heat content of the air to be cooled, hence lowering its temperature, albeit at the expense of increasing its moisture content. The heat and mass transfer between the warm dry air and water surface is an adiabatic process and can be expressed as follows [6].

$$c_a(t_1-t_2)+c_v g_1(t_1-t_2)=(g_2-g_1)[(t_2-t_w)+h_{fg})] \quad (1)$$

where c_a, t_1 and t_2 are dry air specific heat, inlet and outlet temperature respectively; c_v g_1 , g_2 , t_w and h_{fg} are the water vapour specific heat, inlet moisture content, outlet moisture content, water temperature and water latent heat of evaporation respectively.

The rate of water consumption required for the evaporative cooling can be computed as:

$$\dot{m}_{wv}=\dot{m}_{da}(g_2-g_1) \quad (2)$$

where $\dot{m}_{da}$ is the dry air mass flow rate.

Modern evaporative coolers are simple proven technology with, high energy efficiency and low initial cost compared to current mechanical air conditioning systems [7]. Evaporative coolers also provide excellent ventilation as they use 100% fresh air from outside and could achieve up to 75% energy savings compared to conventional air conditioning systems [8].

The use of evaporative cooling technology, particularly direct evaporative cooling systems, is widely practiced in Saudi Arabia. However, there are few publications on the subject with the focus on measuring the operating parameters and cooling temperatures. Alamari et al. (2002) [9] evaluated the performance of evaporative coolers in sixteen permanent tents that accommodate pilgrims' in Mina Valley during the Hajj period. The author measured the indoor space conditions including dry-bulb temperature, wet-bulb temperature, and relative humidity of inlet and outlet supply air. The data collected was related to the number of occupants per tent with cases of crowded tents with occupants and semi-empty tents. However, apart from the measured air temperature and moisture content it is hard to draw any firm conclusion about the performance of the system.

Further research work was published by T. Habeebullah [10] in which the author investigated the possibility of using celdek paper and luffa sponge material to substitute for aspen wood to improve the efficiency of evaporative coolers. The results indicate that, the pressed luffa sponge of 175 mg/cm^3 density and 2 x 3 x 3cm dimensions was the most appropriate material to substitute for the wood flacks. The cooling effectiveness of direct evaporative coolers using this material approaches 96% for an air volume flow rate of 1.01 m^3/s.

Similarly, Masha et al. [5] presented an experimental study of an evaporative cooler using a 3 cm thick Aspen wood as wet media deployed in evaporative cooler in the Mina Valley. Results of this work are summarised in Table I.

TABLE I
AN EXPERIMENTAL STUDY OF AN EVAPORATIVE COOLER USING A 3CM THICK ASPEN WOOD AS WET MEDIA

Parameters	Average
Inlet Dry Bulb Air Temperature (^{O}c)	40.33
Outlet Dry Bulb Air Temperature (^{O}c)	27.01
Inlet Wet Bulb Air Temperature (^{O}c)	24.55
Outlet Wet Bulb Air Temperature (^{O}c)	24.2
Inlet Air Relative Humidity (%)	26.39
Outlet Air Relative Humidity (%)	73.88
Air Velocity (M/S)	3.6
Air Flow Rate (M^3/S)	0.84
Water Evaporation (Kg/H)	15.85
Cooling Effectiveness (%)	84.41
Cooling Capacity (Kw)	14.32
Air Velocity (M/S)	3.6

II. DESCRIPTION OF THE EVAPORATIVE COOLING TECHNOLOGY IN MINA VALLEY

Mina Valley is a residence to over 2 million pilgrims for a short period of 6 days per year during the annual pilgrimage to the holy places in Saudi Arabia. It is located about 7 km from Makkah city and is known as 'The Tent City'. The location is known for its hot and dry climate where typical temperatures vary between 19 and 43°C and relative humidity ranges from20 to 57% in July and January respectively.

A. Evaporative Coolers in Tents Accommodation

There are approximately 48,000 permanently erected tents with a total area of about 2.5km^2, as shown in Fig. 4 (a). Each tent is equipped with one or more evaporative air cooler units, air distribution ducts and a complete water supply network. Air distribution ducts made from galvanized steel deliver cool air to the occupied space at a rate of 1500 cfm for tent floor areas of 16m^2.

Two types of evaporative coolers have been installed depending on required air flow rate. There are about 37,411 evaporative coolers with a flow rate capacity of 6,000 cfm and a motor drive, of 1.5 hp and 6,312 units with 3,000 cfm capacity and ¾ hp motor. The average ambient inlet air condition in summer 2013 was 37^{o}C and 22% RH and the

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supply air delivered by evaporative coolers was 25°C and 63% RH. Fig. 4 (b) shows the evaporative cooling unit assembly.



(a)



(b)

Fig. 4 (a) Mina Valley pilgrims' tents (b) roof-top evaporative cooler unit

B. Evaporative Coolers in Aljamaraat Bridge

This is a 4-story walk through bridge used in the spiritual rituals. The large number of pilgrims converging on these walkthrough spaces requires the deployment of 114 evaporative cooling units rated at 60,000 cfm on each floor to provide comfortable climatic conditions. All the evaporative coolers are centrally controlled. The averages for inlet and supply air temperature and relative humidity delivered by evaporative coolers in July 2013 were 39°C and 24%; and 27°C and 62%, respectively.



(a)



(b)

Fig. 5 (a) Aljamarrat Bridge (b) Evaporative cooler unit

C. Evaporative Coolers at Mashair Railway Station

The railway station has the capacity for the transit of half a million pilgrims in only six hours. The waiting areas for pilgrims are equipped with evaporative coolers to provide comfortable conditions. There are 279 evaporative cooling units installed in nine train stations half of which are cooled by evaporative coolers rated at 26,000 cfm with 12 hp motors and the other half by those rated at 13,000 cfm with 6hp motors. Fig. 6 shows an example of the cooling units. Centrally controlled, the average inlet and supply air temperature and relative humidity delivered by those evaporative coolers during July 2013 was equivalent to that of the units installed on the Aljamaraat Bridge in the previous section.



Fig. 6 Evaporative cooling units in the train station

III. Thermal and Economic Evaluation of the Evaporative Cooling Systems

The performance of the evaporative cooling systems installed in different parts of Mina Valley is given in Table II in terms of the cooling capacity rates and volume flow rates.

TABLE II
COOLING CAPACITY OF INSTALLED EVAPORATIVE COOLERS

Cooled Site	Number of EC Units	Flow Rate (M^3/S)	Cooling Capacity (Kw)	Motor Rating (Kw)
Accommodation – EC1	37411	1.42	12	0.56
Accommodation – EC2	6312	2.83	24	1.12
Railway Station – EC3	139	6.14	53	4.47
Railway Station – EC4	139	12.27	107	8.95
AljamaraatBridge – EC5	456	28.32	246.8	37.28

The five evaporative cooler units (EC1 to EC5) recorded a cooling temperature difference of 12°C and an increase in relative humidity of about 39%.

In the following analysis, it is assumed that the tents are fully occupied for 6 days per annum and the railway stations are at maximum capacity for 5 days and the Aljamaraat Bridge is used for 3 days. For comparison, it is also assumed that a conventional vapour compression air conditioning system would have a COP of 3.5 [11].

A. Evaporative Cooling Energy and Cost Savings

The power consumption of evaporative coolers is limited to the power used by the fan and associated electric controls and water pump. The overall thermal performance of the evaporative cooler is determined by the COP (Q_c/P). Fig. 7 shows a comparative estimate of electricity consumption of an evaporative cooling unit and its vapour compression equivalent. For the Mina site, the deployment of evaporative cooling systems allows reduction of peak electricity demand from the grid by about 163 MW.

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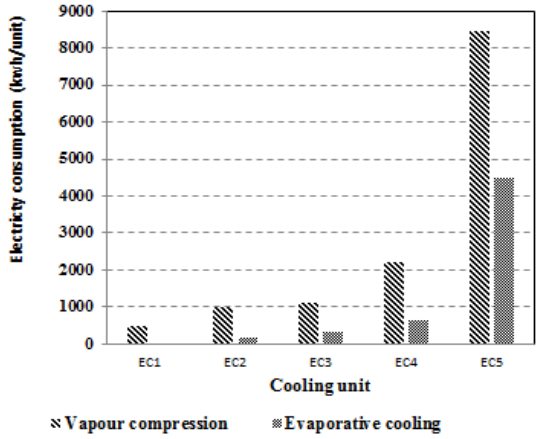


Fig. 7 Electricity consumption comparison between evaporative coolers and vapour compression

The total running cost of the evaporative cooling units over the period of the pilgrimage is estimated to be SAR 1.06 million, based on the current grid power tariffs of 0.175 SAR/kWh. If, however, a vapour compression system was deployed for air conditioning over the same period of time, the energy consumption cost will be as high as SAR 5 million. Hence, the installed evaporative cooling systems save on average over 70% in the running cost. Fig. 8 shows the savings realized by each scheme and the corresponding COP.

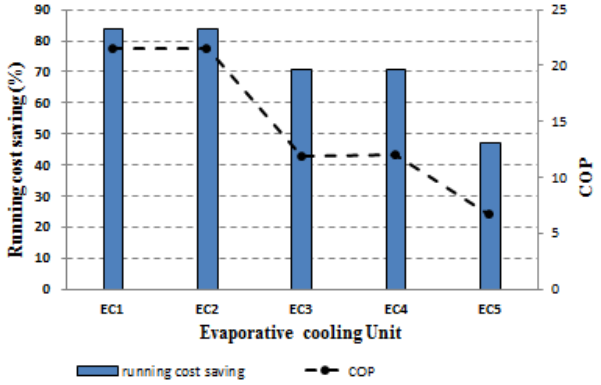


Fig. 8 Running Cost savings

B. Environmental Impact

The evaporative cooling has a positive impact on both providing constantly fresh air and reducing electricity demand and therefore carbon emissions. Based on the emission factor of the Saudi electricity generation mix of 0.75kgCO_2/kWh, the total amount of CO_2 reduction when comparing evaporative cooling and vapour compression systems to provide an equivalent cooling load is estimated to be 24600 tonne (i.e., a saving of 78%). Fig. 9 shows the emission savings from each evaporative cooler.

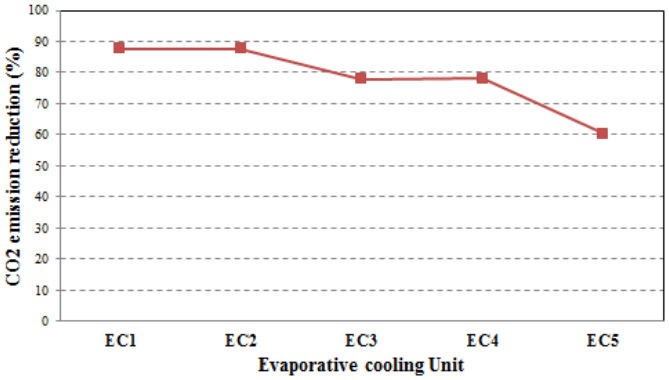


Fig. 9 The emission savings from each evaporative cooler

IV. Conclusion

It is shown in this simplified analysis that the evaporative cooling system is very suitable in a site like Mina Valley where the weather is hot and dry. The evaporative cooling system saves over 70% in energy consumption costs and reduces carbon dioxide emissions by 78% compared to using mechanical vapour compression systems. The evaporative cooling provides the required comfort level using 100% fresh air.

Acknowledgment

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