Energy and Buildings 68 (2014) 329–338

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Effective desiccant dehumidification system with two-stage evaporative cooling for hot and humid climates

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ARTICLE INFO

Article history:
Received 6 July 2013
Received in revised form 5 September 2013
Accepted 28 September 2013

Keywords:
Evaporative cooling
Desiccant dehumidification
Energy efficiency
Thermal comfort

ABSTRACT

This study examines the design and operation of a hybrid air conditioning system that uses 100% fresh air and integrates a solid desiccant dehumidification system with a two-stage evaporative cooling system to optimize the system operation with respect to energy and water consumption while maintaining occupant thermal comfort. The first stage consists of cooling a fraction of the dehumidified air stream using an evaporative cooling pad, mixing the cooled air with the remaining bypassed air fraction and then supplying it to the space in order to minimize water consumption and limit the indoor relative humidity to acceptable levels. The second stage consists of locally cooling the occupant's microclimate using a personalized evaporative cooler (PEC) that will allow for higher room bulk air temperatures. The system was implemented in an office space in Beirut and the optimization was carried using a derivative free genetic algorithm that handled three variables: the regeneration temperature; the air mass flow rate; and the fraction of air entering the evaporative cooler. The two-stage system achieved a 16.15% reduction in energy consumption and a 26.93% reduction in water consumption compared to a single-stage evaporative cooling system at the same thermal comfort level.

1. Introduction

The building sector is a major contributor to energy consumption worldwide and its contribution is expected to increase in the upcoming years. In fact, the building sector accounted for 41.1% of the total energy consumption in the United States in 2011 and this figure is expected to increase to 42.1% in 2035 [1]. Furthermore, the heating, ventilation and air conditioning (*HVAC*) system consumes the prime share of the energy consumption and can account in some cases for 70% of the total energy consumption of buildings [2]. While a variety of air conditioning systems is available in the market, the most common air conditioning system used is the direct expansion system that operates according to the conventional vapor-compression cycle. The relatively high energy consumption of such systems is due to energy drawn by the compressor that is the heart of the vapor-compression cycle. This is a stimulating factor to find more efficient alternatives to the conventional air conditioning systems. Such alternatives need to consume less energy, but most importantly provide the same level of thermal comfort for the occupants. Evaporative cooling presents itself as a potential alternative to the conventional air conditioning system in terms of lower initial cost, lower energy consumption during operation, and lower ozone depletion potential [3]. The operating system of an evaporative cooler is quite simple; it consists of a fan that draws air that passes through a wetted cooling pad. This causes water to evaporate due to its large enthalpy of vaporization, causing the dry bulb temperature of the air to drop and its humidity ratio to rise [3]. The evaporative cooler does not require any environment harming refrigerants, and draws a relatively small amount of power to operate the fan [3].

While researchers agreed that evaporative cooling is very energy efficient and environmentally friendly, its operation presents some drawbacks. The cooling potential of evaporative coolers is very dependent on the outdoor air properties and requires dry outdoor air to perform properly, and this rendered their use limited compared to units operating on the vapor compression cycle [3]. Furthermore, evaporative cooling systems can result in high values of the relative humidity inside the space especially in highly occupied spaces where internal moisture generation is high. El-Refaie and Kaseb [3] indicated that room relative humidity values as high as 80% may be obtained from evaporative coolers in residential applications where the room's sensible heat factor is as low as 0.7 and such high values do not lie in the acceptable range of thermal comfort constituting a favorable environment for the formation of mold and bacteria; therefore, the humidity ratio of the air cooled by the evaporative cooler needs to be low to avoid such high humidity levels in the space. Various dehumidification techniques are available, but solid desiccant technology integrated with a solar heating system is very appealing because it uses renewable energy in the dehumidification process, where the solar heating

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http://dx.doi.org/10.1016/j.enbuild.2013.09.040

Nomenclature

A	area (m^2)
c	specific heat (J/kg K)
d	distance between the occupant and the PEC (cm)
D_o	personalized evaporative cooler nozzle diameter (cm)
E	energy consumption (kWh)
EAF	exhaust air fan
EC	evaporative cooler
F_R	heat removal factor
FAF	fresh air fan
G	moisture generation rate (kg/s)
h_c	convective heat transfer coefficient (W/m^2 K)
h_r	radiative heat transfer coefficient (W/m^2 K)
H	enthalpy (kJ/kg)
HVAC	heating, ventilation and air conditioning
I	total solar radiation
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate (kg/s)
PEC	personalized evaporative cooler
PF	performance factor
q_{int}	internal heat load
Q_l	heat loss (W)
Q_u	useful heat gain (W)
T	temperature (°C)
TH	overall Thermal Comfort
U_L	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
V	volume (m^3)
W	humidity ratio (kg H_2O/kg dry air)
WC	water consumption (l)
WCR	water consumption rate (kg/s)
x	air fraction

Greek letters

α	surface absorptivity
δ	cost function weighing factor
ε	effectiveness
η	fan efficiency
ρ	density (kg/m^3)

Subscripts

a	air
af	antifreeze solution
aux	auxiliary heater
c	air properties reaching the occupant
db	dry bulb
in	inlet conditions
o	*PEC* nozzle exit conditions
out	exit conditions
reg	regeneration
t	storage tank
wb	wet bulb

system accounts for the high regeneration temperatures required to regenerating the desiccant material when high humidity levels are encountered. This system has been used and tested by Hammoud et al. [4] and proved to be very energy efficient. Finally, evaporative coolers consume water to operate, and this is a major problem in regions where water resources are limited. The problem remains of how to make use of such system in regions having hot and humid climates like Lebanon costal area and to limit the relative humidity level in the space to the acceptable comfort limits.

The proposed study will consider the use of a 100% fresh air cooling system integrated with a solid desiccant dehumidification system and a two-stage evaporative cooling system in an office space in Beirut. The first stage consists of dehumidifying the outdoor fresh air using a desiccant wheel regenerated using solar energy, cooling a fraction of the dehumidified air using an evaporative cooling pad then mixing it with the remaining bypassed air before being supplied to the office space. The second stage consists of using a personalized evaporative cooler *PEC* to locally cool the microclimate of the office occupants. The main idea behind a *PEC* is to limit the supply of cooled air to the occupant's vicinity while maintaining the space at higher temperature and lower relative humidity. Chakroun et al. [2] reported that using a *PEC* to supply air to the upper body segments of the human body, particularly the face, is enough to achieve the overall thermal comfort of the individual.

The two-stage evaporative cooling system presents two main advantages over the traditional single-stage evaporative cooling system. The first advantage is that lower room relative humidity levels can be achieved at lower regeneration temperatures compared to the single-stage system while the second advantage is that the *PEC* allows for higher bulk air temperatures in the space to be tolerated due to personalized cooling leading to a decrease in the supply air flow rate required and to higher supply temperatures. This will have an impact on the system's operating cost where a reduction in the two-stage evaporative cooling system cost is expected.

The objective of this study is to optimize the operation of a two-stage evaporative cooling system that uses a desiccant wheel for outdoor air dehumidification and solar energy for desiccant regeneration. The system does not use any mechanical cooling system and relies on existing sink temperatures to moderate the air temperature before being cooled using an evaporative cooling pad. The optimization is performed in terms of energy and water consumption, while maintaining a good thermal comfort level inside the office space. This is achieved by using a derivative free genetic algorithm that will find the optimal values of the regeneration temperature, the supply air flow rate, and the fraction of air cooled using the first stage of evaporative cooling.

2. System description

The two-stage evaporative cooling system is shown in Fig. 1. The hot and humid outdoor air is drawn using the fresh air fan *FAF-1* where it enters the adsorption compartment of the desiccant wheel. The air loses moisture to the desiccant material and exits the desiccant wheel at higher temperature and lower humidity ratio. Next to the fresh air enters a sensible wheel where it exchanges heat with the air exhausted from the room by means of the exhaust air fan *EAF-1*. The fresh air exits the sensible wheel at lower temperature and at the same humidity ratio, while the exhausted air leaves the sensible wheel at higher temperature. After that, the fresh air will be brought into a heat sink where it will be subjected to further cooling. The final step of fresh air treatment consists of taking a fraction of the air exiting the heat sink and cooling it using a direct evaporative cooler to further decrease its temperature below the sink temperature. The remaining air is bypassed across the evaporative cooling pad before being mixed again with the cooled fraction and supplied to the room. Once the treated fresh air comes inside the room, it picks up the load of the room and its temperature increases. The *PEC* handles the room air and supplies it to the individual's breathing zone at lower temperature. The air is exhausted from the room at the same flow rate of fresh air supply, and picks up heating energy at the sensible wheel, and at the regeneration coil in order to regenerate the desiccant. The hot water flowing inside the