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A comparative study on energetic, exergetic and environmental performance assessments of novel M-Cycle based air coolers for buildings

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ABSTRACT

In this study, three various novel air coolers based on M-Cycle are evaluated using energy and exergy analyses based efficiency assessments along with environmental impact and sustainability parameters. The M-Cycle systems are considered to cool a building room air while their inlet air parameters are same, but outlet cooled air parameters are different. Systems I and III draw electricity directly taken from an electric grid in the building while System II, which is stand alone system, produces and draws electricity from its solar PV panels. In the energy analysis, wet bulb effectiveness, cooling capacity, Coefficient of Performance (energetic *COP*) and Primary Energy Ratio (*PER*) are found. In the exergy analysis, exergy input and output rates, exergy loss rate, exergy destruction rate, Exergetic Coefficient of Performance (COP_{ex}), Primary Exergy Ratio ($PE_{x}R$) and exergy efficiency are obtained for six different dead state temperatures changing between 10 °C and 35 °C. Also, sustainability assessments of the systems are obtained using sustainability index (*SI*) tool for these various dead state temperatures. Finally, environmental assessments of the systems are calculated from their greenhouse gas (GHG) emissions (gCO_2/kW h) due to their electricity consumptions. Maximum exergy efficiencies and sustainability assessments are found to be 35.13% and 1.5415 for System III and 34.94% and 1.5372 for System II, respectively. GHG emissions of the systems are calculated to be 2119.68 gCO_2/day, 153.6 gCO_2/day and 3840 gCO_2/day for Systems I, II and III respectively. So, System II becomes a good choose to prevent the global warming and to attain sustainable future.

1. Introduction

Air coolers are generally used in hot humid climates in order to create comfort air conditions for occupants living in the buildings. These commonly used systems require high energy consumption. Especially, conventional air coolers, which are not environmental and sustainable compared with novel systems, utilize large amount of electricity [1]. Also, one of the other large parts of the energy demand is generally related with building envelope and its environment. Reducing energy utilization of air coolers used for the buildings is a precaution for energy conservation and environmental protection in the world [2]. So, indirect evaporative coolers can supply necessary air conditions with their high efficiencies and low energy costs [3]. They can also lower air temperature and avoid adding moisture to the air. Furthermore, it can limit the supply air temperature above the wet bulb temperature of the outdoor air [4,5].

There is another, relatively new and novel indirect evaporative air cooling system based on patented "M-Cycle" to create comfort air conditions for the buildings with lowest energy consumption and highest efficiency. M-Cycle has got the wet and dry sides of a plate like indirect evaporative coolers, but with a much different airflow creating a new thermodynamic cycle (resulting in product temperatures which approach the dew point temperature of the air) [6]. This cycle uses the enthalpy difference of the air at dew point temperature and the air saturated at a higher temperature to reject the heat from the product, and also it allows the product fluid to be cooled into the dew point temperature of the incoming air ideally. The air is then pre-cooled before passing into the heat rejection stream where the water is evaporated [7].

Indoor air quality requirements have become more and more stringent with the continuous improvement of people living standard [8]. Also, energy percentages of air coolers in buildings may be over 50% of the total electric energy consumed. So, energy is used in sizeable quantities to provide comfort air conditioning in buildings [9]. The comfort air conditions consist of comfort air tem-

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Nomenclature

ex	specific exergy flow (kJ/kg or kJ/kg_w)
$\dot{E}x$	exergy rate (kW)
c_p	specific heat capacity (kJ/kg K)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s or kg_w/s)
P	pressure (atm or kPa)
$\dot{Q}$	cooling capacity rate (kW)
R	ideal gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy generation rate (kW/K)
T	temperature (°C or K)
v	specific volume rate (m^3/kg)
$\dot{W}$	energy (electricity) consumption (utilized energy) rate or consumed power (kW)
x	molar rate in the mixture (mol or kmol)

Greek letters

ε	effectiveness (–)
η	efficiency (%)
ϕ	relative humidity (–)
Ψ	exergy efficiency (%)
ω	humidity ratio or specific humidity (kg_w/kg_{da} or kg_w/kg)
$\bar{\omega}$	mole fraction ratio (–)

Subscripts

0	reference (dead state) condition
da	dry air
$dest$	destruction
db	dry bulb
dp	dew point
ex	exergy
f	fluid
g	gas
ha	humid air
in	input
$loss$	losses
out	output
pd	power distribution
sat	saturated
SI	supply inlet
SO	supply outlet
w	water
wb	wet bulb
v	water vapor

Abbreviations

COP	(energetic) coefficient of performance
COP_{ex}	(exergetic) coefficient of performance
EER	Energy Efficiency Ratio
EES	Engineering Equation Solver
GHG	greenhouse gas
HMX	heat and mass exchanger
NREL	National Renewable Energy Laboratory
PER	Primary Energy Ratio
PE_xR	Primary Exergy Ratio
SI	sustainability index

perature between 19.45 °C and 27.78 °C, minimum 0.012 humidity ratio and minimum 80% humidity level based on ASHRAE Standard 55-2004 (for Thermal Environmental Conditions for Human Occupancy) [10].

The open literature has been chronologically searched to obtain background studies of the M-Cycle, and a few studies related with only about description of the heat and mass exchanger (HMX) of the M-Cycle or energy/exergy analysis of the M-Cycle have been found. In this regard, Maisotsenko and Gillan [7] investigated the open perforated M-Cycle. It was found that at no time was water evaporated into the product air stream, and this cooling cycle was suitable for use with desiccant air drying systems as it did not add humidity to the product air. Gillan and Maisotsenko [11] presented the M-Cycle, which cooled the product fluid with the liquid evaporating into a gas from the atmosphere and returned it to the atmosphere, used for the gas turbine power generation. Compressor inlet air temperature was cooled below the wet bulb temperature by an atmospheric pressure HMX with the cycle. The M-Cycle created a compressed air saturator using heat from the turbine exhaust gases and cooled water for heat recovery in a compressor intercooler, while the saturator humidified and superheated the compressed air before entering a combustor to the amount desired. Shell and tube heat exchangers were used to be equipment. It was found that NO_x and equipment costs were lower than any other power cycle enhancement systems. Maisotsenko and Reyzin [12] investigated the M-Cycle based HMX for the electronics cooling. A large cooling capacity could be obtained from the M-Cycle cooler. It was found that air coolers based on the cycle had got higher Energy Efficiency Ratio (EER) than the best conventional air coolers. Gillan [6] explained how the M-Cycle is working. The M-Cycle allows the product fluid air to be cooled in temperature ideally to the dew point temperature of the incoming air. This was because of the pre-cooling of the air before passing it into the heat rejection stream where water was evaporated. The cycle was realized in a single device with a much higher heat flux and lower pressure drop than had been realizable in the past due to its efficient design. Zhao et al. [4] presented numerical investigation of a novel counter flow heat and mass exchanger used in the indirect evaporative dew point cooling systems. It was found that, wet bulb and dew point effectiveness and energy efficiency were largely dependent on the dimensions of the airflow passages, air velocity and working to intake air ratio. Zhao et al. [13] carried out the feasibility of a novel dew point evaporative cooling system within various regions of China. Lower relative humidity resulted in higher temperature differences between the dry bulb and dew point temperatures, and higher cooling capacity of the dew point system. Tap water could be used to support cooling of the dew point system. High ambient temperature caused some low-level cooling capacity as a major part of cooling energy. The system consumed more water in dry and hot climate regions than in mild and humid regions. Zhao et al. [14] studied about dynamic performance of the novel dew point evaporative air cooling system (M-Cycle) of the buildings based on weather conditions of the various UK regions. The required air volume flow rate varied with its application location. The dry and hot climates needed less air volume flow rate and less water compared with mild or humid climates. Riangvilaikul and Kumar [15] explained the results of an experimental study of a novel dew point evaporative cooling system for different air conditions. It was found that, wet bulb effectiveness is between 92% and 114%, while dew point effectiveness is between 58% and 84%, and these results were compared with some latest studies. Riangvilaikul and Kumar [16] presented the numerical and theoretical performances of a novel dew point evaporative cooling system operating under the various inlet air conditions. A dew point evaporative cooling system model was developed to simulate the heat and mass transfer processes. The model was used