Energy Conversion and Management 97 (2015) 323–339

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance investigation of solid desiccant evaporative cooling system configurations in different climatic zones

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ARTICLE INFO

Article history:
Received 26 November 2014
Accepted 7 March 2015
Available online 5 April 2015

Keywords:
Desiccant evaporative cooling
Ventilation cycle
Dunkle cycle
Climate zones
Dymola/Modelica

ABSTRACT

Performance of desiccant evaporative cooling (DEC) system configurations is strongly influenced by the climate conditions and varies widely in different climate zones. Finding the optimal configuration of DEC systems for a specific climatic zone is tedious and time consuming. This investigation conducts performance analysis of five DEC system configurations under climatic conditions of five cities from different zones: Vienna, Karachi, Sao Paulo, Shanghai, and Adelaide. On the basis of operating cycle, three standard and two modified system configurations (ventilation, recirculation, dunkle cycles; ventilated-recirculation and ventilated-dunkle cycles) are analyzed in these five climate zones. Using an advance equation-based object-oriented (EOO) modeling and simulation approach, optimal configurations of a DEC system are determined for each climate zone. Based on the hourly climate data of each zone for its respective design cooling day, performance of each system configuration is estimated using three performance parameters: cooling capacity, COP, and cooling energy delivered. The results revealed that the continental/micro-thermal climate of Vienna, temperate/mesothermal climate of Sao Paulo, and dry-summer subtropical climate of Adelaide favor the use of ventilated-dunkle cycle configuration with average COP of 0.405, 0.89 and 1.01 respectively. While ventilation cycle based DEC configuration suits arid and semiarid climate of Karachi and another category of temperate/mesothermal climate of Shanghai with average COP of 2.43 and 3.03 respectively.

1. Introduction

Demand for space cooling and ventilation has increased considerably during the last decade [1–3]. The improved standard of living, changes in life style and climatic conditions have led researchers to find energy efficient alternates of conventional HVAC systems. Cheap and energy efficient alternatives are available in market, however optimal configuration of these alternatives as standalone, hybrid and/or stand-by application is an area of extensive research. For instance, direct and indirect evaporative cooling has gained a lot of success in areas of hot and dry climate [4]. However, research concerning desiccant systems has been mainly concerned with modeling and simulation for performance evaluation of individual system components like desiccant wheels, enthalpy wheels, and evaporative coolers [5–11]. A theoretical model for the operation of a desiccant air conditioning system was developed on the basis of existing approaches for modeling of the main subsystems of such a system [12]. Various DEC systems can integrate these components to achieve desired comfort conditions. Different DEC systems configurations can be categorized based on operating cycles, for example ventilation, recirculation, and dunkle cycles [13]. Application of an open desiccant cooling process with ventilation and recirculation modes of the system operation was also reported [14]. However, system configuration performance in various climatic zones is relatively less explored in an efficient manner. Few recent studies use ideal models for the performance assessment of a typical DEC system configuration for various climatic conditions. In another study, an evaluation of various solid desiccant cycles for air conditioning in hot and humid climates of 16 cities of India was presented. It was found that the warm and humid climatic conditions result in the highest value of COP [15]. Likewise, a study concluded that that solid desiccant-based hybrid air-conditioning systems can give substantial energy savings as compared to conventional vapor compression

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http://dx.doi.org/10.1016/j.enconman.2015.03.025
0196-8904/

Nomenclature

CC	cooling capacity (kW)
COP	coefficient of performance (–)
Dh	change in specific enthalpy (kJ/kg)
Dx	change in specific humidity (kg of air /kg of water)
En	cooling energy delivered (kW h)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
t	time (h)
T	temperature (°C)
RH	relative humidity (%)

Subscripts

amb	ambient air
f	final
heater	heater heating source
in	inlet
pro	process air
o	initial
out	outlet
supply	supply air
ret	return air
reg	regeneration air

refrigeration based air-conditioning systems in Indian climates [16]. For climatic conditions in China, a study explored the performance of vapor compressor & desiccant (VC + D) cooling system and hybrid vapor compressor, desiccant and direct evaporative cooler (VC + D + EC) cooling system [17]. Results showed that more energy is saved in hot and dry climatic conditions compared to dry & humid conditions. Similarly a desiccant-evaporative cooling system is investigated to a ventilation and makeup mode operating cycle in Iranian climate. The results showed such systems are more effective than direct and direct–indirect evaporative cooling systems and provide a better thermal comfort even in hot and humid areas [18]. Additionally, an experimental exergo-economic assessment is performed in Turkey [19] and energy saving potential of a hybrid DEC system is determined for Beirut, Lebanon [20]. In another study, performance of two configurations of desiccant systems, conventional and recirculation were investigated through simulation based on outside conditions [21]. Analyses and comparison of a desiccant cooling system using regenerative evaporative cooling and a one-rotor two-stage desiccant cooling system configuration found that the system with regenerative evaporative cooling can handle air to much lower temperature while maintaining good thermal performance [22]. Similarly, various hybrid systems combining DEC with other energy sources are analyzed under various climate conditions [23,24].

Moreover, experimental investigations included a novel desiccant based air conditioning system configuration to improve the indoor air quality and reduce energy consumption [25]. In the system studied, the moisture of the fresh air was reduced passing through a solid desiccant wheel and then its temperature decreased through the "dry coil" of a vapor compression cycle. The study showed that a heat exchanger for pre-heating the regeneration air with exhaust air was feasible to install. Similarly, various other novel configurations of desiccant based evaporative air conditioning system are investigated [26,27].

System modeling and simulation can help in foreseeing the impact of system and sub-system on one another especially for an innovative system design [28]. With the advancements in technology, a number of alternative DEC system configurations are currently available [29]. Selecting an optimal system configuration for each climatic zone is a complicated task. Therefore a comprehensive study on the performance estimation of different DEC configurations under different climatic conditions is vital.

Nevertheless, application of DEC systems across the globe is a reality. Although performance of DEC systems under climatic conditions of specific countries were investigated (e.g. India, China, and Iran) no study was found to explore the performance of DEC systems under various climatic conditions around the world. Additionally, a specific system configuration is considered in various studies. It can be established from published studies that different configurations of DEC system have been investigated in specific climate zones; however no study covered their performances at a global scale. Therefore, the current study presents the performance comparison of five configurations of a DEC system under five different climatic conditions that cover a wide range of climates ranging from arid to continental. An Equation-based Object-Oriented (EOO) modeling and simulation approach [30,31] is applied through Dymola/Modelica tool. The five configurations are analyzed. Three basic configurations include ventilation, recirculation, and dunkle cycles, while the two modified configurations consist of ventilated-recirculation and ventilated-dunkle cycle system configurations. The amount of ventilation air inducted in ventilated recirculation and dunkle cycles is varied from 5% to 40% of outdoor air. Performance comparison of these system configurations is determined in terms of cooling capacity (CC), coefficient of performance (COP), and cooling energy delivered (En). Finally, an optimal DEC system configuration is suggested for each climatic zone based on the analyses of these assessment parameters.

2. Classification of desiccant evaporative cooling systems

Classification of DEC systems can be based on the operating cycles. A brief introduction in terms of DEC system schematics and psychrometric representation of different configurations based on the operating cycles is provided in Fig. 1 for the sake of completeness and future referencing in the model development stage.

2.1. Ventilation cycle system configuration

Ventilation cycle is a rotary desiccant cooling cycle. The process starts with the increase of temperature of ambient air with dehumidification (process 1–2). During the dehumidification, the process air loses moisture and increases temperature. Afterwards, the temperature of this air is reduced sensibly through the heat wheel (process 2–3) with subsequent addition of moisture using a direct humidifier (process 3–4). The regeneration side includes series of processes involving humidification (process 5–6), sensible heating (process 7–8) and desiccant wheel regeneration (process 8–9) as shown in Fig. 1(a) and (a1). In the lack of co-processing, ambient air can be used for regeneration as elaborated in Fig. 1(b) and (b1). The thermal performance of such cycle is lower in terms of specific cooling capacity and coefficient of performance