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Research Article
Effective Parameters on the Performance of Solar Desiccant Cooling Systems

M.M.S. Dezfouli

Institute of Product Design and Manufacturing (IPROM), Universiti Kuala Lumpur, 56100 Kuala Lumpur, Federal Territory of Kuala Lumpur, Malaysia

Abstract
The main issue of desiccant cooling system is less COP in compared with conventional cooling system. This issue is due to effect of component effectiveness and operation condition of desiccant cooling system. This study presents the effects of significant parameters (effectiveness of components and operation parameters, namely, regeneration temperature, airflow rate, rotational speed, solar system and outdoor condition) on the performance of evaporative and hybrid desiccant cooling systems in different climates. It was achieved that performance can be increased by reducing regeneration temperature and air flow rate, increasing the number of solar collectors and increasing the outdoor temperature and humidity. The optimal desiccant wheel rotation speed should be within the range of 5-10 r h^{-1}.

Key words: Solar cooling, effective parameters, performance, operation condition

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Corresponding Author: M.M.S. Dezfouli, Institute of Product Design and Manufacturing (IPROM), Universiti Kuala Lumpur, 56100 Kuala Lumpur, Federal Territory of Kuala Lumpur, Malaysia

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In recent years, solar-assisted desiccant cooling systems were considered as attractive, cost-effective and alternative Air Condition (AC) systems used to separately perform dehumidification and sensible cooling[1]. A desiccant cooling system is among the technologies used to reduce electricity consumption of conventional AC systems. Dehumidification and cooling can be performed separately in desiccant cooling systems. However, desiccant cooling systems yield less Coefficient of Performance (COP) than AC systems[2]. Furthermore, this difference in COP is the main problem of desiccant cooling systems. In recent years, considerable efforts have been carried out in regions with different climates to improve performance of desiccant cooling systems. The COP of a desiccant cooling system, as an indicator of system performance, is an important subject of interest among many researchers. The performance of a rotary DW depends on various parameters, such as regeneration temperature, rotation speed, wheel thinness, climate conditions, airflow rate and desiccant material[3]. To predict the performance of a DW in different cooling system configurations and operating conditions, many researchers have worked to find a numerical algorithm and develop a simulation model of a DW[4-12]. Designing a high-performance desiccant cooling system is a crucial issue that separates designers from engineers. To address this issue, the effectiveness parameters on the performance of a desiccant cooling system should be first identified. Then, the influence of each parameter on the performance of the system can be evaluated. Consequently, the parameters with a positive effect on system performance should be improved to achieve a high-performance desiccant cooling system. Desiccant cooling systems have various effectiveness parameters that can be categorized into component effectiveness and operating condition[13].

Effect of components effectiveness: Component effectiveness has a significant role in the overall performance of a desiccant cooling system. According to different configurations of a desiccant cooling system, several components can be used for the dehumidification, pre-cooling, cooling and thermal sources. However, a desiccant cooling system has key components, particularly a DW that is fixed in all configurations. Therefore, the effectiveness of a DW directly affects system performance. The efficiency of a heat recovery wheel, as a common heat exchanger used in many types of desiccant cooling system, has a direct relationship with the overall performance of a system.

Sphaier and Nobrega[14] have analyzed the impact of component effectiveness on the ventilation and recirculation desiccant cooling system performance. Their results show that, although all components can influence the overall system performance, the effectiveness of the heat recovery wheel and desiccant wheel have a greater influence. In the ventilation mode, by reducing the effectiveness of heat recovery wheel from 100-80%, the COP system[14] can have reducing in range of 30-50%. Uckan *et al.*[15] proposed a new configuration of desiccant cooling system by using several heat exchangers and an evaporative coolers as cooling device. Their results show that the effectiveness for the heat exchangers and evaporative coolers are highly dependent on the outdoor conditions[15].

Effect of operation condition of desiccant cooling system on the COP: Operation condition plays important role in COP and energy saving potential of solar desiccant cooling system. Several parameters such as regeneration temperature, air flow rate, solar radiation, rotation speed of desiccant wheel and ambient temperature/humidity have been considered as operation condition of solar desiccant cooling system. Effect of mentioned parameters on the performance of solar cooling system is evaluated in following subsections.

Regeneration temperature: Regeneration temperature has a significant effect on the performance of the evaporative and hybrid desiccant cooling system[16]. Many researchers evaluated effect of this parameter on the performance of system. Panaras *et al.*[17] investigated the impact of regeneration temperature on the performance of ventilation and recirculation. They found that by increasing the regeneration temperature and airflow rate, the COP of the system reduces. While in the same conditions, the COP of the ventilation mode was higher than that in the recirculation mode[17]. Chung and Lee[18] evaluated the effect of various kinds of design parameters on the performance of a desiccant cooling system under two different system configurations. the most prevailing parameter which has contribution ratio of 31.9 and 23.9% for each system configuration was regeneration temperature[18]. In order to reduce the regeneration temperature and increase performance of the system especially in hot and humid climate, the two stages desiccant cooling system have been recommended[19]. Due to isothermal dehumidification by means of two desiccant wheels, the requirement regeneration temperature in each step is less than regeneration temperature in one-stage desiccant cooling system. In order to improve performance of desiccant cooling system, Meckler[20] proposed a two-stage solid desiccant system integrated with an HVAC system[20]. La *et al.*[21] proposed a novel rotary desiccant cooling cycle with isothermal dehumidification and regenerative evaporative cooling. They found that the isothermal dehumidification was relatively lower temperature requirement for the heat source because the regeneration temperature[21] is reduced from 80°C to approximately 60°C. Ge *et al.*[22] evaluated the performance of a two-stage rotary desiccant cooling (TSRDC) system. It was found that the required regeneration temperature of the TSRDC system is low and the COP of the system is higher compared to the conventional system[22]. La *et al.*[23] performed a theoretical analysis of a solar-driven TSRDC system assisted by vapor compression AC. They concluded that the solar-driven two-stage desiccant cooling system is reliable and energy efficient[23]. Li *et al.*[24] investigated the TSRDC/heating system driven by evacuated glass tube solar air collectors. They found that average thermal COP in the cooling cycle was 0.97, when the cooling capacity was in the range from 16.3-25.6 kW under hot and humid ambient conditions[24]. In another study, Li *et al.*[25] carried out experimental investigation on a one-rotor two-stage desiccant cooling/heating system driven by solar air collectors. The average thermal COP in the cooling cycle is 0.95 in hot and humid climate conditions[25].

Angrisani *et al.*[26] investigated effect of regeneration temperature on the performance of desiccant wheel in a hybrid desiccant cooling (HDSC) system as experimentally. They analysed the desiccant wheel performance curves as function of regeneration temperature. It was achieved that, the selected regeneration temperature strongly affect the possibility for the desiccant wheel to completely balance the latent load[26]. Angrisani *et al.*[27] evaluated a small-scale polygeneration system based on a natural gas-fried micro-combined heat and power (MCHP) and a desiccant HVAC system as experimentally. Regeneration heat source was thermal power recovered from engine cooling and exhaust gas of a MCHP. Their experimental results confirm that the performances of desiccant wheel are strongly influenced by outdoor air properties and regeneration temperature. They found that the by application of polygeneration system instead of conventional HVAC system, at least 21.2% energy saving and 38.6% gas-emission reduction can be achieved[27].

Air flow rate: In a desiccant cooling system, there are two-air flow rate of process and regeneration. Even though changes in both process and regeneration airflow rates can affect the performance of a desiccant cooling system; the regeneration airflow rate is more sensitive. Panaras *et al.*[17] evaluated the effects of airflow rate on the performance of ventilation and recirculation. They found that for the same regeneration temperature, increasing both airflow rates will be accompanied by an increase in thermal energy consumption, which reduces the COP of the system[17]. Ge *et al.*[28] demonstrated that to improve COP without significantly affecting dehumidification capacity, the mass flow rate of regeneration air can be reduced to approximately one-third that of process air[28]. For a hybrid desiccant HVAC system, Angrisani *et al.*[29] studied the effects of process and regeneration airflow rates on DW performance. They calculated the performance parameter as a function of outdoor condition, regeneration temperature and airflow rates. Their results show that the effect of process and generation airflow rates is less than the effect of regeneration temperature on desiccant performance. Moreover, the higher influence on DW performance is attributed to regeneration temperature and process air humidity ratio rather than to process air temperature[29].

Effect of solar radiation on the performance: Kabeel[30] evaluated the effect of airflow rate and solar radiation intensity on the regeneration process of a solar-powered AC system by using a rotary honeycomb DW. They found that the aforementioned parameters are highly effective in the regeneration process[30]. Baniyounes *et al.*[31] simulated a model of a solar desiccant cooling system for an institutional building in Queensland by using TRNSYS. Their results show that by increasing the number of solar collectors (from 10-20 m^2), the SF and COP of the system increase from 22-69% and 0.7-1.2, respectively[31]. Fong *et al.*[32] used TRNSYS simulation to optimize a solar-assisted desiccant cooling system in Hong Kong by maximizing the SF of the system against the involvement of auxiliary heating. They found the ranges of COP and SF during the year to be 1.08-1.60 and 8-33%, respectively[32]. Hatami *et al.*[33] calculated the effects of operating parameters on reducing the required solar collector surface for various ambient conditions. The results showed that the required solar collector surface decreases by increasing outdoor dry bulb temperature and humidity ratio when outdoor air is used as the inlet in the regeneration airflow as shown in Fig. 1.

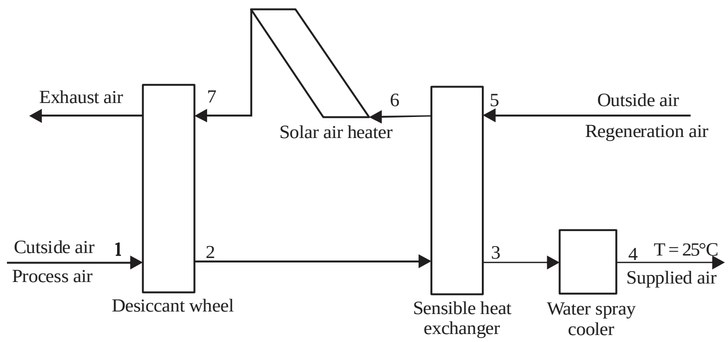

Fig. 1: Effect of operating condition on the requirement solar collector[33]

Although, a high outdoor wet bulb temperature in hot and humid regions causes a reduction in the required solar collector surface, an evaporative cooler cannot provide a suitable amount of supplied air to handle latent and sensible load in a room[33].

Rotation speed of desiccant wheel: One of the crucial parameters in the system performance of desiccant cooling devices is DW rotation speed. Ge *et al.*[34] evaluated the effect of rotation speed on the performance of a two-stage desiccant cooling system via computer simulation. They found that the optimal rotational speed ranges from 4-8 r h^{-1} for a regeneration temperature[34] ranging from 60-100°C.

The DW rotation speed is among the important parameters that influence DW and desiccant cooling performances. During high-speed rotation, DW performance is low because of insufficient time to release moisture from the desiccant material. In low-speed rotation, DW performance is also low because the desiccant material can reach saturation point. Therefore, to achieve high-performance dehumidification process, an optimal rotation speed should be determined based on the operating condition. The rotation velocity of a DW influences process air temperature and consequently, the capacity of a cooling device, particularly in a hot and humid climate. To determine the effect of rotation speed on DW performance, an experimental test on DW was conducted by Angrisani *et al.*[35]. They calculated the representative performance parameters, including dehumidification effectiveness and COP, to determine the effect of regeneration temperature on optimal rotation speed. The optimal rotation speed of DW is within the range of 5-10 r h^{-1} when regeneration temperature is 65°C; however, it generally depends on the operating conditions[35].

Effect of outdoor condition on the performance of desiccant cooling system: Panaras *et al.*[36] evaluated the performance of a desiccant cooling system as a function of regeneration temperature and airflow rate under two different weather conditions: moderate (32°C and 30% RH) and peak (36°C and 40% RH). Their results showed that with fixed-value operation, the COP of a system under moderate condition is less than that under peak condition. Therefore, to achieve the best performance for a desiccant system, the operation values based on the weather condition must be changed[36]. A comparison study between two kinds of desiccant material (silica gel and titanium dioxide) used in a desiccant cooling system in three types of climate (temperate, subtropical and tropical) was conducted by Enteria *et al.*[37]. They found that the specifications of a solar desiccant cooling system and its performance depend on the climate condition, whereas the required solar equipment and airflow rate increase from temperate climate to tropical climate[37]. La *et al.*[21] experimentally investigated on a hybrid two-stage solar desiccant system integrated with a Vapor Compression (VC) system under three different climates, namely, the temperate condition of Beijing, the subtropical condition of Shanghai and the hot and humid condition of Hong Kong. The results showed that by adopting a fixed operation for the cooling system under the three climates, different values of energy-saving potential and COP can be achieved compared with conventional VC systems. The energy-saving potential and COP of the system under temperate, subtropical and hot and humid conditions are 31, 34 and 22% as well as 0.95, 0.85 and 0.87, respectively[21]. Hong *et al.*[38] investigated hybrid desiccant cooling system with VC in different climates of China. They concluded that application of hybrid desiccant cooling system can save energy in hot, dry climates rather than in hot, humid climates[38]. Heidarinejad and Pasdarshahri[39]

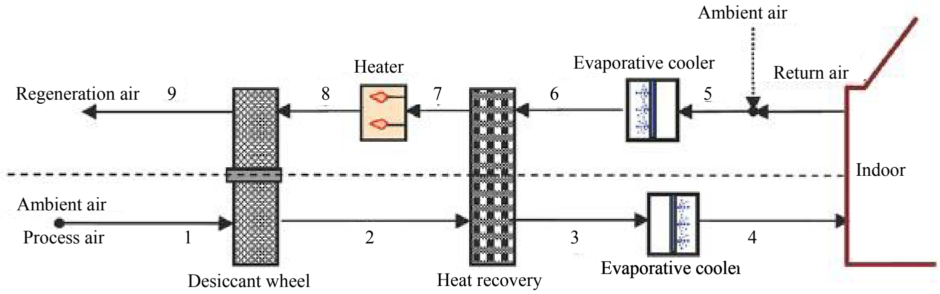

Fig. 2: Effect of outdoor condition on the performance of a desiccant evaporative cooling system[39]

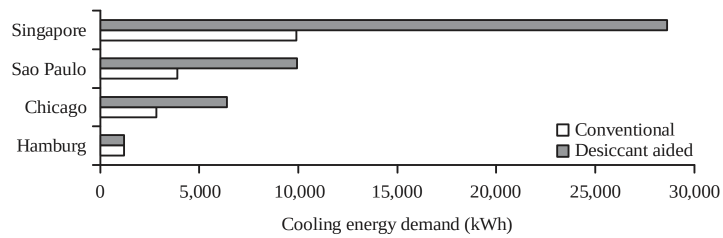

Fig. 3: Comparision energy cooling demand between conventional HVAC system and desiccant system in different climate conditions[40]

investigated the effect of outdoor condition on the performance of a desiccant evaporative cooling system in multi climate condition of Iran. The results show that by increasing the ambient temperature and humidity, the COP of system and the supply air temperature (temperature of point 4 in Fig. 2) will be increased[39].

Ge *et al.*[28] evaluated the effect of temperature and humidity on the performance of a two stage desiccant cooling system experimentally. They found that under constant operation condition, when the ambient temperature changed from 25-37, the COP increased from 0.7-1.2, respectively. This is due to a reduce requirement temperature from heat source by increase inlet temperature from outdoor in regeneration sector which cause to increase COP system. Also, they found that COP of the system increased from 0.6-1.0 when ambient humidity ratio increase from 10-30 g kg^{-1} under same condition. This is due to increase mass transfer rate and moisture removal capacity[28].

Figure 3 shows the total cooling energy demands of a conventional cooling system and a desiccant cooling system under four different climates, as presented by Wrobel *et al.*[40]. The results showed that by increasing the temperature and humidity ratio of ambient air from Homburg to Singapore, the cooling energy demands for both systems increase but the cooling energy demand for the desiccant cooling system is considerably lower than that for the conventional cooing system. Both systems require a comparable amount of energy in Hamburg (1185 kWh for hybrid vs 1242 kWh for conventional), whereas the desiccant cooling system in Singapore consumes approximately 1/3 of the energy required for the conventional cooling system (9952 kWh vs 28643 kWh)[40].

Lopez *et al.*[41] investigated a combined solar desiccant evaporative system with an Air Handling Unit (AHU) in a real building under two different climates (hot and dry and hot and humid) in Spain. They concluded that the hybrid desiccant system with AHU is appropriate for the hot and humid climate[41]. Figure 4 shows that, in a novel desiccant cooling system with two stages, namely, dehumidification and regenerative evaporative cooling, was designed and investigated under different climates by La *et al.*[42].

Their study demonstrated that ambient condition significantly affects the temperature of chilled water and consequently, supplied air. By decreasing ambient humidity ratio from highly humid to temperate outdoor conditions, the temperature of the supplied chilled water generally decreases[42] from 20-15°C.

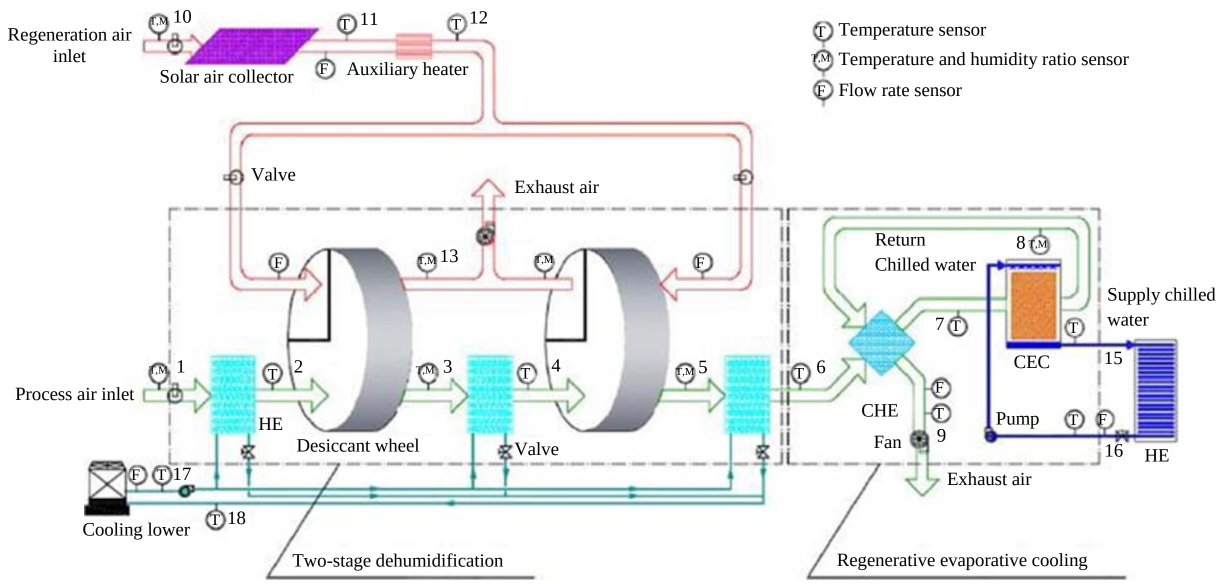

Fig. 4: Two stage evaporative desiccant cooling system under different climate conditions[42]

CONCLUSION

A considerable energy saving can generated by applying a desiccant cooling system instead of a conventional HVAC system. The amount of energy savings depends on the effectiveness parameters of system performance. This review paper focuses on the evaluation of important parameters that affect the performance of the system as well as on the effect of configuration type on the performance and energy-saving potential of a desiccant cooling system under different climates. The important parameters that significantly affect the performance of a desiccant system are configuration type; effectiveness of the components and operation parameters, such as regeneration temperature, airflow rate, rotation speed, solar system and outdoor conditions. The following guideline shows the effect of each parameter on the performance of a desiccant cooling system:

- The effectiveness of all the components can generally influence overall system performance; therefore, as the effectiveness of the components increases, system performance also increases. The effectiveness of a DW and that of a heat recovery wheel have greater influences on overall performance than the other components. The effectiveness of an evaporative cooler depends on the humidity ratio of inlet air and outdoor conditions
- Among the operation parameters, regeneration temperature has the greatest effect on system performance. By reducing regeneration temperature, the performance of the system can be increased considerably
- By reducing regeneration airflow rate without significantly affecting dehumidification capacity, the performance of the system increases
- Increasing the number of solar collectors enhances the SF and performance of a system; however, increasing outdoor temperature can reduce the required quantity of solar collectors and the initial cost for a desirable performance
- To achieve desirable performance, the optimal DW rotation speed should be within the range of 5-10 r h^{-1}. If the rotation speed falls below 5 r h^{-1} or above 10 r h^{-1}, then the performance of a system will be reduced
- By increasing outdoor temperature, system performance can be increased because regeneration temperature is reduced when a high outdoor temperature is used for the regeneration inlet
- By increasing outdoor humidity, system performance can be increased because of an increase in mass transfer rate and moisture removal capacity

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