Journal of Physics: Conference Series

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To cite this article: Amirreza Heidari *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012099

Combined desiccant-ejector cooling system assisted by Organic Rankine Cycle for zero-power cooling and dehumidification

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Abstract. This study presents a novel set-up for desiccant-based cooling and dehumidification systems. In this cycle, a solid desiccant and conventional combined cooling and power (CCP) systems, based on the ejector refrigeration cycle (ERC) and the organic Rankine cycle (ORC), are integrated to provide dehumidification and cooling, simultaneously. The ERC is integrated with the ORC for devising a self-powered design which has not been done until now. The proposed integrated system is useful for replacing the peak electricity demand with the heat demand, decreasing the pressure on the power grid in humid areas. Dynamic hourly simulation of the proposed system as well as a conventional system were performed to show the energy saving potential of the proposed system.

Key words: Solid desiccant dehumidification, Dedicated Outdoor Air System (DOAS), Ejector technology, Combined Cooling and Power (CCP)

1. Introduction

Air conditioning systems contribute to over 60% of the total energy consumption in buildings [1, 2] and the biggest share of building carbon emissions. The situation is worse in humid regions, as in these regions the cooling system should dehumidify air in addition to reducing its temperature. Vapor compression systems are usually used in humid climates for cooling air and dehumidification, resulting in extremely high electricity consumption during hot summer days. For example, the Bushehr province in Iran, with its hot and humid climate, has the highest per capita electricity consumption in the country, with 80% of this electricity consumption due to vapor compression cooling systems [3]. Therefore, energy efficient alternatives to these systems for hot and humid climates are necessary.

The earliest desiccant-based cooling system (DCS) was presented by Pennington [4]. Then many researchers have developed new configurations for desiccant-based cooling and dehumidification systems. La *et al.* [5] presented theoretical and experimental studies of a solar driven two-stage rotary desiccant cooling system coupled with a vapor compression air-conditioning system. Angrisani *et al.* [6] conducted an experimental study to investigate the performance of a DCS interacting with a small scale cogeneration system and compared their results with other air-conditioning systems. Heidari *et al.* [7] developed a hybrid desiccant-based cooling and dehumidifying system for co-production of cooling, fresh water, and hot water. This system uses return air from the building to condensate the moisture content of regeneration air to produce fresh water. In another study [8] they presented a novel configuration for a desiccant-based evaporative cooling system using waste heat recovery of the flare stack.

A literature review shows that the integration of these cycles has not been performed up to now. The great match between these systems served as the motivation for the present study to propose a novel self-powered desiccant-based cooling and dehumidifying system by integrating an ERC, an ORC, and a desiccant-based evaporative cooling system. The main objectives can be listed as follows:

- To propose a novel self-powered desiccant-based cooling and dehumidifying system;
- To investigate the ability of the proposed hybrid system to provide comfort conditions in a subtropical humid climate, using a dynamic hourly simulation;
- To compare the performance of the proposed self-powered cooling system with the conventional vapor compression cooling system.

2. Description of Systems

Conventional cooling and dehumidifying system

Figures 1 and 2 illustrate the schematic diagram of a conventional cooling and dehumidification system and the Psychrometric chart of processes, respectively. In this system, air dehumidification occurs through cooling the air down to its dew point temperature. First, air enters a cooling coil, where air temperature decreases down to the dew point resulting in condensation of air moisture content. The required cold water for the cooling coil is supplied by an air-cooled water chiller. Since the temperature of the resulted air is too low to be supplied directly to the building, air has to be directed into a heating coil where its temperature increases up to a suitable value. The hot water required for the heating coil is supplied by a natural gas boiler.

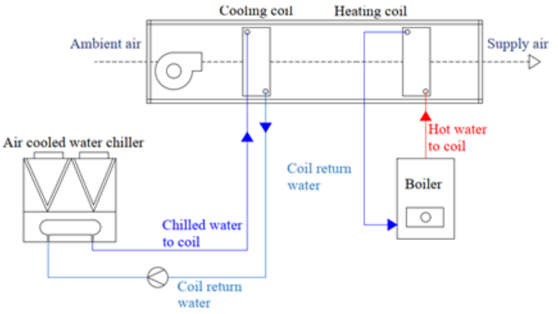

Figure 1: *Schematic diagram of the conventional desiccant-based cooling and dehumidification system*

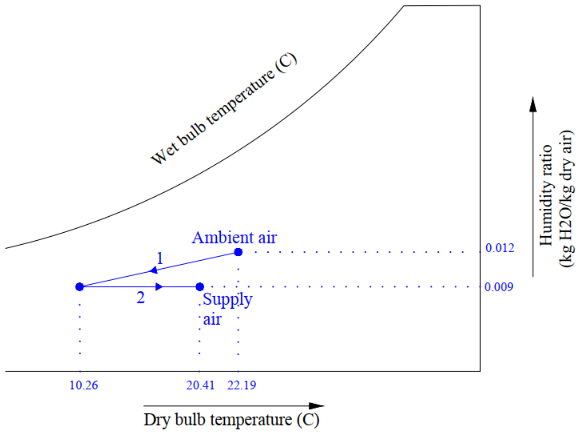

Figure 2: *Psychrometric diagram of the conventional desiccant-based cooling and dehumidification system (process 1: cooling coil, 2: heating coil)*

Self-powered desiccant-based cooling and dehumidifying system

Figures 3 and 4 depict the schematic diagram of the proposed self-powered desiccant-based cooling and dehumidifying system and the corresponding psycrometric chart of processes, respectively. In this system, the outdoor air is supplied into the air handling unit by a fan, and it passes through a silica-gel solid desiccant wheel. Air temperature increases as it passes through the desiccant wheel since moisture gets adsorbed by the desiccant material. Since relative humidity is reduced, an evaporative cooling system can be used at this stage to cool the air. Therefore, the dry air enters the evaporative cooling system and is cooled down due to the latent cooling while it adsorbs some moisture also. As the final stage, air enters the evaporator of the Ejector Refrigeration Cycle (ERC) where its further conditioned to reach the desired supply temperature by sensible cooling. Since the desiccant material adsorbes moisture, this adsorbed moisture needs to be regenerated to assure continuous operation of the system. For this purpose, the desiccant wheel is rotating continuously between two separated ducts, adsorbing moisture in the supply air duct, while discharging the adsorbed moisture during the regeneration. For desiccant wheel regeneration, the air from the building, which has less humidity than the ambient air, returns to the air handling unit. This air flows through the condenser of the Combined Cooling and Power (CCP) system, and it is pre-heated with waste heat of this cycle. Then, this preheated air enters the heating coil and reaches the required temperature needed to regenerate the desiccant material. Hot water required for the heating coil is produced by a natural gas boiler.

The CCP system is included in the proposed overall system to cover the power consumption of pumps and fans while providing sensible cooling. The proposed CCP system is based on the Organic Rankine Cycle (ORC) integrated with ERC for cogeneration of power and cooling. The CCP sub-system consists of a micro turbine, an ejector, a generator, an evaporator, a condenser, an expansion valve, and a pump, with R245fa as refrigerant. According to the layout of this system, the set-up initiates its operation after receiving its prime mover from the heat source via a generator. The saturated vapour is expanded through a turbine to generate electricity and then is fed into an ejector as primary flow of this component. The primary flow draws the secondary flow (flow at the outlet of evaporator) inside the ejector and ejects it after experiencing the reckoned phonomona inside of it (explained in the ejector modelling sub-section). The ejected flow is liquefied through a condenser through rejecting part of its heat load to the air stream at the outlet of coil, and then divided into two streams. One part of the flow is throttled through the expansion valve and then is evaporated into a saturated vapour state in order to chill the outlet air stream of the direct evaporative cooler, and then is fed into the ejector as secondary flow. The second part of the liquefied refrigerant is pressurized to the generator pressure via a pump, finishing the thermodynamic operation of the CCP system.

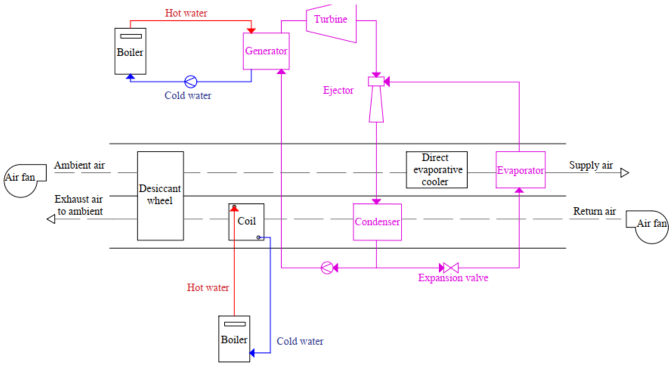

Figure 3: Schematic diagram of the proposed new self-powered desiccant-based ventilation and dehumidification system

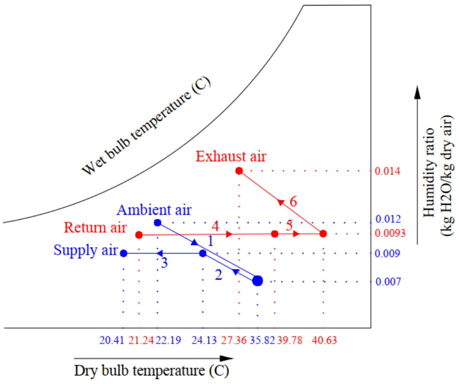

Figure 4: Psychrometric diagram of the proposed new self-powered desiccant-based ventilation and dehumidification system (process 1: adsorpyion in desiccant, 2: evaporative cooler, 3: evaporator coil, 4: Condenser, 5: heating coil, 6: regeneration in desiccant)

3. Methodology

In this study, the equations for the ejector cycle were developed in EES. A complete description of the equations of the ejector cycle is described in [9]. Then the ejector cycle (perpel cycle in Figure 3) is linked to the TRNSYS simulation environment. TRNSYS software is a componenet-based simulation environment, in which there are different components for modelling every element of the systems. Then different elements are connected together, and the hourly wheather data is imported to the simulation to perform hourly simulations. A complete description of the mathematical model of the TRNSYS components used in this study can be found in [7].

Simulations are done for Sydney, Australia, a city with humid subtropical weather, shifting from mild and cool in winter to warm and hot in the summer. This city is chosen because the proposed system is supposed to be used for moderate humid regions. For an easier comparison of energy use between two systems, the conventional system is adjusted to produce the same supply temperature and relative humidity as desiccant system in each hour. Both systems are supplying air to a 100 m^2 . To evaluate the performance of the two systems, the ISO 17772-1:2017 standard [32] for Category II (medium expectations) is used which proposes a relative humidity between 25% to 60% and a temperature between 24°C and 26°C for indoor air in summer.

4. Results

Figure 5 shows variations of indoor relative humidity, ambient relative humidity, and upper and lower limits of ISO 17772-1:2017 at different hours. As this figure illustrates, the indoor relative humidity is located in the comfort region. Similarly, Figure 6 shows the hourly variations of the indoor air temperature and ambient temperature as well as the higher limit of comfort temperature (based on ISO7730 standard) at different hours. The indoor temperature is always lower than the higher limit of ISO7730 standard temperature. This temperature is close to the ambient temperature in most of hours. This is because the Sydney weather has a good temperature during the summer, and the main purpose of this system is to reduce the humidity. The indoor air temperature is sometimes very low as it is assumed that the cooling system is always operating and no control system is considered. So it shows that the proposed system is able to provide low enough temperatures, so that, in real conditions, by implementing a proper control system to turn off the system, it would provide comfort conditions.

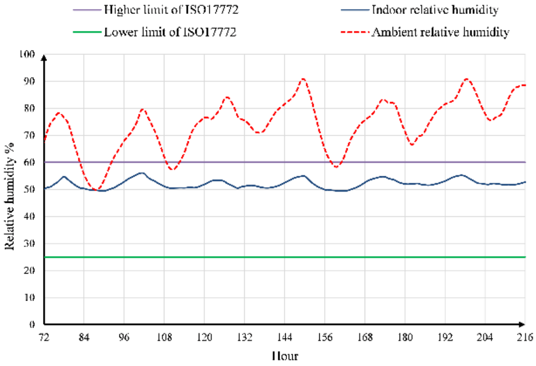

Figure 5: Hourly relative humidity of indoor and outdoor air through six summer days of Sydney.

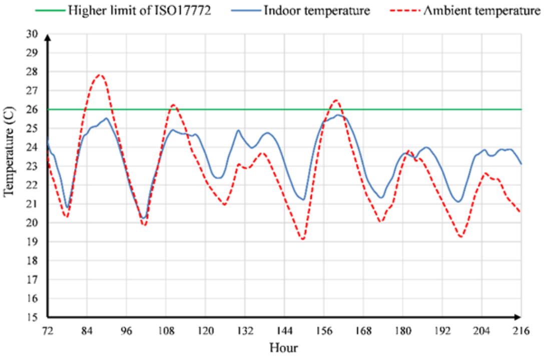

Figure 6: Hourly temperatures of indoor and outdoor air through six summer days of Sydney.

Figure 7 shows the hourly electricity consumption of the conventional system (CS) and self-powered desiccant-based cooling and dehumidifying system. The electricity consumption of the proposed system is constant during the time. This is because the electricity consumption of the proposed system only occurs in pumps and fans which are operating continuously. The electricity consumption of the proposed system is 2.7 kW and the power generation of the CCP cycle is 3.1 kW. Therefore, the total required power of this new system will be covered by the CCP cycle, and hence this system is completely self-powered. The conventional system, on the other hand, has a very high power consumption due to the use of a compression cycle. The proposed system will save a significant amount of 2,000 kWh electricity during 6 days. Figure 8 similarly shows the total natural gas consumption of the two systems. As can be seen, the total natural gas use of proposed system is higher than that of a conventional system, which is mainly due to the energy need for the sorption process.

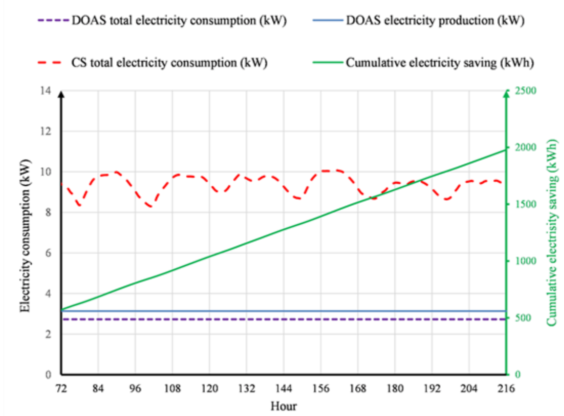

Figure 7: Hourly electricity consumption of the conventional and self-powered desiccant-based cooling and dehumidifying systems.

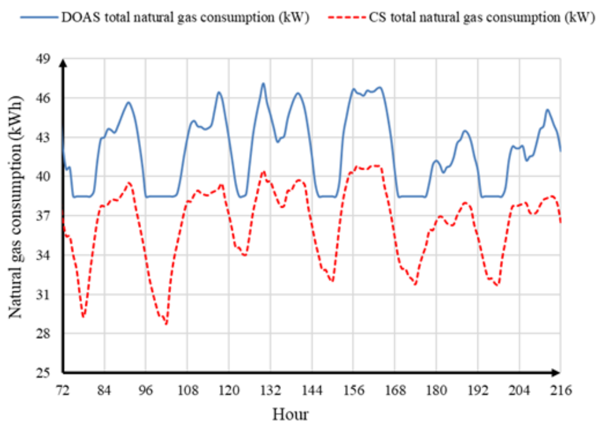

Figure 8: Hourly natural gas consumption of the conventional and self-powered desiccant-based cooling and dehumidifying systems

To compare the natural gas and power use simultaneously, the hourly total cooling rate and COP (equation 1) of both systems are shown in figure 9.

$$COP = \frac{Cooling\ rate\ (kW)}{Total\ electricity\ use(kW) + Total\ natural\ gas\ use(kW)} \qquad (1)$$

Due to the fact that the power consumption of the proposed system is significantly lower than that of the conventional system, the COP of this system is higher than that of the conventional system, while it consumes more NG. It is noteworthy to say that the proposed system considerable lowers the electricity consumption with regard to the conventional system, while it consumes more natural gas. Since electricity is a more valuable and more expensive energy carrier than natural gas, the proposed system will be an attractive alternative from energy viewpoint.

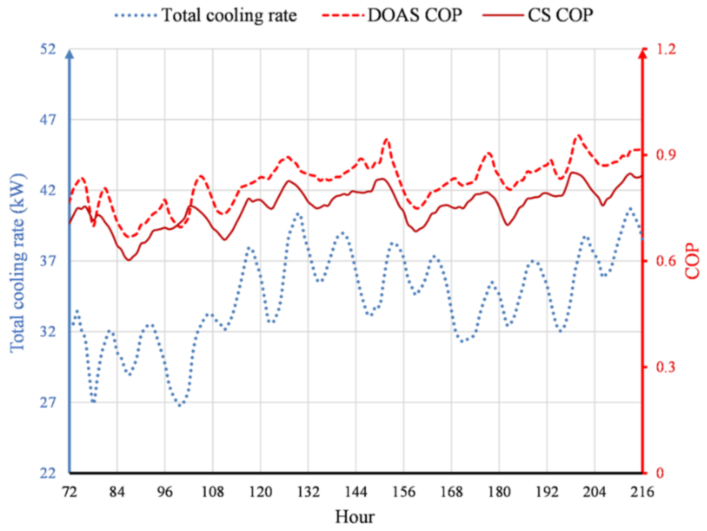

Figure 9 : Hourly coefficient of performance of the conventional and self-powered desiccant cooling and dehumidifying systems.

3. Concluding remarks

Performance enhancement of desiccant-based evaporative cooling systems is an interesting research topic among different scholars who aim to harvest available energy sources more efficiently. With this context, a novel self-powered desiccant-based cooling and dehumidifying system was proposed by integrating a DEC system, an ORC, and an ERC for a subtropical humid climate. A dynamic hourly simulation of the proposed system was carried out and results are compared with those of a conventional vapor compression cooling and dehumidifying system. The following results could be concluded from this study:

- ➢ The proposed system is able to provide comfort conditions in subtropical humid climates;
- ➢ The integrated ORC will cover all electricity consumption of the system. Therefore, the proposed system will operate with no electricity consumption, while the conventional vapor compression system will consume a significant amount of electricity for producing the same cooling capacity;
- ➢ As the proposed system operates with no electricity consumption, its COP is 9% higher than that of the conventional system, while it has a 14% higher natural gas consumption;

This study demonstrated the great potential of proposed novel system to utilize low grade heat for air conditioning in humid climate. Clearly, further research will be needed to enhance the performance of this system and to investigate its performance under other climates.

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