Performance investigation of ground source heat exchanger with desiccant-based hybrid cooling system in humid climate

Ghassem Heidarinejad1,*, Umberto Berardi2 and Saeed Rayegan1
1 Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran
2 Faculty of Engineering and Architectural Science, Ryerson University, Toronto, Canada
*gheidari@modares.ac.ir

Abstract. A desiccant-based hybrid cooling is among the most cost-effective air conditioning systems. The main purpose of this paper is the assessment of the potential of ground-assisted direct evaporative cooler together with a desiccant evaporative cooling cycle integrated with a ground source renewable energy for the pre-cooler process. Simulation results obtained using the TRNSYS software are compared with experimental data. The simulation of the mentioned systems are conducted in Bari (south of Italy), Palermo (south of Italy) and Ramsar (north of Iran) for the humid-mild climate of July. Assuming the low regeneration temperature (Treg) for the desiccant wheel is one of the highlights of this paper. Utilizing ground source heat exchanger (GSHE) will result in increase of the system potential in providing thermal comfort. The average thermal comfort achieves in Bari, Palermo and Ramsar in 95.72%, 93.94% and 93.15% of the time from 6 AM to 6 PM in July with utilizing the combination of GSHE and desiccant cooling system. The COP of this cycle is highly dependent on the Treg, and varies in the range of 0.35-0.53, 0.34-0.6 and 0.34-0.52 for the maximum Treg of 50°C in Bari, Palermo and Ramsar, respectively.

Keywords: Desiccant cooling system, ground source heat exchanger, transient performance, comfort.

1. Introduction
Given the urgent demand for ending fossil fuel resources use, the applications of hybrid cooling systems coupled with renewable energy sources have found considerable importance for air conditioning applications. In this context, Kojok et al. [1] reviewed the hybrid cooling systems composes of different components. They summarized that solid desiccant wheel (DW), heat recovery wheel (HRW), direct evaporative cooler (DEC), ground source heat exchanger (GSHE), and solar collector have proposed in hybrid desiccant cooling systems. Many scholars studied the different configurations of desiccant cooling systems. Abbassi et al. [2] investigated several configurations of solar desiccant system using TRNSYS software. Their showed that the highest COP could be achieved through Dunckle configuration, which obtained 0.6. Bareshino et al. [3] assessed the dynamic simulation of a DW-based system combined with an electric chiller with a new adsorbent material. They used MILGO as a new adsorbent material and presented that it can reduce the moisture around six times higher than the current ones. Qadar Chaudhary et al. [4] investigated a solar desiccant cooling system integrated with an indirect evaporative cooler (Maisotsenko). Their results indicated that the mentioned system has a mean COP of 0.91 and a solar fraction of 70%. Heidari et al. [5] investigated the transient operation of the DW system combined with an ejector. They reported that this system is capable of reducing 84% of the electrical energy consumption compared to their reference system. Caliskan et al. [6] evaluated the exergy efficiency of the evaporative desiccant cooling system. Based on their results, DW has the most unsustainability in the system and has the exergy destruction ratio of 42.87%. Therefore, the suggested that DW should be improved. Heidarinejad and Khalajzadeh [7] proposed a DEC combined with a GSHE. Their results indicated that a GSHE could reduce the air temperature of 7-8°C in Tehran. They continued their work and simulated the GSHE coupled with an indirect evaporative cooler [8].
This study assesses the potential of the desiccant cooling cycle with low $T_{\text{reg}}$ and use of GSHE as the air pre-cooler. The novelty of this paper lays in the low $T_{\text{reg}}$ for DW and the application of GSHE as the pre-cooler as well as investigating their impacts on thermal comfort. Besides, based on the literature survey, study the combination of DW and GSHE are extremely limited. This paper aims to assess the usage potential of ground-assisted DEC as well as desiccant cycle integrated with a GSHE in the cities of Bari and Palermo (south of Italy) and Ramsar (north of Iran).

2. Hybrid system description

Figure 1 shows the desiccant cooling cycle in mix mode, which uses a GSHE as a pre-cooler. In this figure, $R_1$ and $R_2$ are the ratios of return air from the conditioned zone. So, a mixture of ambient air and return air for the conditioned zone (stream 1) enters the DW and its humidity ratio decreases. Its temperature also increases. Then, hot and dry air (stream 2) enters the HRW where its temperature decreases in a constant humidity ratio process. The temperature of the cooled process air (stream 3) will be decreased after passing through cooling coils of the GSHE. It then enters the first DEC (stream 4) where its temperature decreases while its humidity increases. In continue process air (at stream 5) enters the conditioned zone where its temperature and humidity ratio are increased. In the regeneration section, a mixture of ambient air and return air for the conditioned zone (stream 6) enters the second DEC where its temperature decreases while its humidity increases. Then regeneration air (stream 7) enters the HRW where its temperature raises. The regeneration air (stream 8) enters the heater so its temperature will be elevated up to the desirable $T_{\text{reg}}$. Eventually, regeneration air (stream 9) enters the DW and resulting in a decrease in its temperature and an increase in its humidity ratio. It then dumps to the ambient (stream 10). Since humidity can be controlled, desiccant systems assure better air quality. In fact, the absence of condensed water strongly reduces the presence of microorganisms such as bacteria, viruses, and fungi. So these systems are particularly recommended in applications in which severe hygienic conditions must be maintained (medical facilities and laboratories).

![Figure 1. Desiccant cooling cycle integrated with GSHE pre-cooler.](image)

To simulate the performance of DW, the model developed by Jurinak is used which is based on $F_1$-$F_2$ potentials [9]:

$$F_1 = \frac{-2865}{T^{1.490}} + 4.344\omega^{0.8624} \quad \text{and} \quad F_2 = \frac{T^{1.490}}{6.360} - 1.127\omega^{0.07969}$$

(1)

In the above equation, $T$ and $\omega$ are temperature and absolute humidity ratio, which are measured in K and $kg_{water}/kg_{dry \, air}$, respectively. It is noteworthy that the TRNSYS library was not included a relevant component to mode the DW. Therefore, we implemented a suitable FORTRAN code for this purpose.
The other used components exist in TRNSYS library. For modeling the HRW, first, the minimum air stream capacity of the HRW is calculated by:
\[ C_{min} = \text{MIN} \left( \left( \dot{m}C_p \right)_R, \left( \dot{m}C_p \right)_P \right) \] (2)
where, \( \dot{m}_P \) and \( \dot{m}_R \) are process and regeneration air flow rate, respectively. Considering sensible heat effectiveness for the HRW, maximum heat transfer can be calculated. To model DEC, saturation efficiency is considered, and its outlet temperature can be calculated by:
\[ T_{out} = T_{in} - \varepsilon_{EC} \times T_{wbd} \] (3)
where, \( T_{in}, T_{out} \), and \( \varepsilon_{EC} \) are inlet and outlet air dry bulb temperature and saturation efficiency of the DEC. \( T_{wbd} \) also depicts the wet bulb depression.

To model the conditioned zone, two major parameters of sensible heat ratio (SHR) and inlet-outlet temperature difference of the zone are considered. Also, the model developed by University of Lund is invoked for modeling the vertical GSHE. This model has been extensively used and validated in various studies, for example [10].

3. Results and discussion

3.1. Validation of results
To validate the results obtained from TRNSYS software, experimental results of Kodama et al. [11] are used. Parameters mentioned in Table 1 are used to validate the desiccant cooling cycle. Figure 2a) shows the desiccant cycle in ventilation mode tested by Kodama et al. Also, Fig.2b) represents the comparison of TRNSYS simulation results at state points 1-9 with experimental findings. As it can be seen, the results are in good agreement with the experimental measurements.

| Component                        | Parameter                   | Value        |
|----------------------------------|-----------------------------|--------------|
| Desiccant Wheel (DW)             | Effectiveness \( \varepsilon_{F1} \) and \( \varepsilon_{F2} \) | 0.14 and 0.75 |
| First direct evaporative cooler (DEC) | Saturation efficiency      | 0.903        |
| Second direct evaporative cooler (DEC) | Saturation efficiency    | 0.78         |
| Heat recovery wheel (HRW)        | Sensible effectiveness      | 0.85         |
| Zone                             | Sensible heat ratio(SHR)    | 0.853        |
|                                 | Temperature difference      | 11.5 °C      |
| Auxiliary heater                 | Efficiency                  | 1.0          |

Figure 2. a) cooling cycle in ventilation mode tested by Kodama et al.; b) comparison between current study and experimental results
3.2. Transient performance
Table 2 lists the parameters used for simulation of the cooling system. Here $T_{\text{reg}}$ represents the regeneration temperature of DW. The simulation is conducted for three mentioned cities with their weather in July.

Table 2. Data and parameters used for simulation of desiccant cooling cycle.

| Component           | Parameter, Value (unit and details)                          | Parameter, Value (unit and details)                          |
|---------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| DW                  | Performance parameters (F1 and F2), 0.14 and 0.75 (-)       | Maximum $T_{\text{reg}}$, 50.0 (°C)                          |
| HRW                 | Sensible effectiveness, 0.8 (-)                             | Process and regeneration air flow rate, 3000 (CFM)          |
| Both of DECs Zone   | Saturation efficiency, 0.85 (-)                             | Inlet and outlet $T_{\text{am}}$, 5 (°C)                    |
| Vertical GSHE       | Borehole depth, 75.0 (m)                                    | Fill thermal conductivity, 1.69 (W.m$^{-1}$.K$^{-1}$)       |
|                     | Number of boreholes, 0-4 (-) depends on application         | Pipe thermal conductivity, 0.42 (W.m$^{-1}$.K$^{-1}$)        |
|                     | Storage thermal conductivity, 1.8 (W.m$^{-1}$.K$^{-1}$)      | Thermal conductivity of layer, 1.8 (W.m$^{-1}$.K$^{-1}$)     |
|                     | Storage heat capacity, 2200 (kJ.m$^{-3}$.K$^{-1}$)           | Heat capacity of layer, 2200 (kJ.m$^{-3}$.K$^{-1}$)          |
| Cooling coil        | Inside tube diameter, 9.71 (mm)                             | Initial surface temperature, Annual mean temperature (°C)  |
|                     | Fluid flow rate, 0.8 (kg.s$^{-1}$)                          | Fluid density, 1000 (kg.m$^{-3}$)                           |
|                     | Fluid specific heat, 4.19 (kJ.kg$^{-1}$.K$^{-1}$)           | Fluid specific heat, 4.19 (kJ.kg$^{-1}$.K$^{-1}$)           |
|                     | Pipe thermal conductivity, 0.42 (W.m$^{-1}$.K$^{-1}$)        | Fluid density, 1000 (kg.m$^{-3}$)                           |

3.3. Usage potential of DEC using a vertical GSHE pre-cooling
Table 3 provides the thermal comfort establishment in Bari, Palermo and Ramsar in two time intervals from 6 AM to 6 PM and from 6 PM to 6 AM in July using DEC combined with a GSHE. Noted that, in this paper the percentage of provided thermal comfort are calculated based on the average results through the all simulation time-steps.

Table 3. Usage feasibility of DEC combined with GSHE.

| City    | System               | Number of ground boreholes | Thermal comfort (%) during July |
|---------|----------------------|----------------------------|--------------------------------|
|         |                      |                            | 6 PM to 6 AM | 6 AM to 6 PM |
| Bari    | DEC + GSHE           | 4                          | 82.10%        | 71.50%        |
| Palermo | DEC+ GSHE            | 4                          | 39.84%        | 19.69%        |
| Ramsar  | DEC + GSHE           | 4                          | 45.89%        | 30.01%        |

3.4. Assessment of the potential of desiccant cooling cycle
As seen in Table 3, desiccant cooling cycle is recommended to achieve thermal comfort in Palermo and Ramsar. Furthermore, in this part, in all cases the mixing ratio is considered constant and is equal to $R_1/R_2=1/3$ and the simulations are performed in July. Table 4 shows the results of evaluating the usage potential of desiccant cycle for three cities with the maximum $T_{\text{reg}}$ of 50 °C, which can be supplied by low-temperature sources.

Table 4. Usage feasibility of desiccant cooling cycle.

| City    | System               | Number of ground boreholes, Max $T_{\text{reg}}$, °C | Thermal comfort (%) during July |
|---------|----------------------|------------------------------------------------------|--------------------------------|
|         |                      |                                                      | 6 PM to 6 AM | 6 AM to 6 PM |
| Bari    | DW                   | 0, 50 °C                                              | 95.40%        | 90.26%        |
|         | DW + GSHE            | 4, 50 °C                                              | 98.36%        | 95.72%        |
|         | DW                   | 0, 50 °C                                              | 85.93%        | 77.81%        |
| Palermo | DW + GSHE            | 4, 50 °C                                              | 95.54%        | 93.94%        |
|         | DW                   | 0, 50 °C                                              | 82.51%        | 71.82%        |
| Ramsar  | DW + GSHE            | 4, 50 °C                                              | 96.84%        | 93.15%        |
According to Table 4, in Bari, use of desiccant cycle without assistance of ground source energy is capable to provide thermal comfort in more than 90.26% of the daytime hours. In Palermo and Ramsar, employing GSHE, significantly improves the thermal comfort.

Maximum $T_{\text{reg}}$ affects thermal comfort and the system COP. The COP variation of the cycle with 4 ground boreholes is compared for three maximum $T_{\text{reg}}$ of 60 °C, 50 °C and 40 °C in Bari, Palermo and Ramsar in Figure 3.

Figure 3. Variation of the COP of the hybrid cycle in July: a) in Bari; b) in Palermo; c) in Ramsar

Regarding Figure 3, COP of the system is highly dependent on the maximum $T_{\text{reg}}$. In this condition, COP of the system varies in the range of 0.5-1.1, 0.5-1.4 and 0.5-1.1 in Bari, Palermo and Ramsar, respectively for maximum $T_{\text{reg}}$ of 40 °C (except the times when the system is off). In addition, this trend can be seen for maximum $T_{\text{reg}}$ of 50 °C and 60 °C. It is noteworthy that the desiccant cycle is considered off in the hours when thermal comfort is achievable by DEC. At such situations, its COP is considered zero. Table 5 investigates the impact of maximum $T_{\text{reg}}$ on the achieved thermal comfort. As Table 5 shows, reduction of the maximum $T_{\text{reg}}$ decreases the provided thermal comfort. Figure 4 illustrates the impact of maximum $T_{\text{reg}}$ on the zone outlet air temperature of Palermo and Ramsar. Similarly, the system uses 4 ground boreholes.

Table 5. Effect of maximum $T_{\text{reg}}$ on thermal comfort.

| City     | System combination | Maximum $T_{\text{reg}}$ | Thermal comfort (%) during July |
|----------|--------------------|--------------------------|--------------------------------|
|          |                    | 40 °C, 50 °C and 60 °C   | 6 PM to 6 AM | 6 AM to 6 PM |
| Bari     | DW + GSHE          |                          | 94.66%       | 88.41%       |
|          |                    |                          | 98.36%       | 95.72%       |
|          |                    |                          | 99.59%       | 96.90%       |
| Palermo  | DW + GSHE          |                          | 82.03%       | 73.20%       |
|          |                    |                          | 95.54%       | 93.94%       |
|          |                    |                          | 98.62%       | 96.78%       |
| Ramsar   | DW + GSHE          |                          | 83.54%       | 75.04%       |
|          |                    |                          | 96.84%       | 93.15%       |
|          |                    |                          | 99.56%       | 100.00%      |

Figure 4. Variation of the zone outlet air temperature of Palermo and Ramsar in July: maximum $T_{\text{reg}}$ equal to 60 °C, 50 °C and 40 °C for case a), b) and c), respectively
Regarding Figure 4, zone outlet air temperature increases by decline of the $T_{\text{reg}}$. Figure 5 represents the impact of GSHE (with 4 boreholes) on the zone outlet air temperature with maximum $T_{\text{reg}}$ equal to 50 °C in Palermo and Ramsar.

![Figure 5](image)

Figure 5. Comparing zone outlet air temperature with and without utilizing GSHE in July: a) in Palermo; b) in Ramsar

4. Conclusions
This study evaluates the potential of ground-assisted DEC as well as combined with a desiccant cooling cycle for three cities of Bari, Palermo and Ramsar in July. Results indicate that ground-assisted DEC provides thermal comfort in more than 71.5% of daytime hours in Bari. Considering maximum $T_{\text{reg}}$ of 50 °C and exploiting GSHE, thermal comfort can be provided in Bari, Palermo and Ramsar in 95.72%, 93.94% and 93.15% of the time from 6 AM to 6 PM, respectively. Moreover, without using GSHE in the cycle, the achieved thermal comfort is decreases to the 90.26%, 77.81% and 71.82% for mentioned cities, respectively. Maximum $T_{\text{reg}}$ affects thermal comfort and the system COP. The COP varies in the range of 0.35-0.53, 0.34-0.6 and 0.34-0.52 for maximum $T_{\text{reg}}$ of 50 °C in mentioned cities, respectively

References
[1] Kojok F, Fardoun F, Younes R and Outbib R 2016 Hybrid cooling systems: A review and an optimized selection scheme Renew. Sustain. Energy Rev. 65 57–80
[2] Abbassi Y, Baniasadi E and Ahmadiakia H 2017 Comparative performance analysis of different solar desiccant dehumidification systems Energy Build. 150 37–51
[3] Bareschino P, Diglio G, Pepe F, Angrisani G, Roselli C and Sasso M 2017 Numerical study of a MIL101 metal organic framework based desiccant cooling system for air conditioning applications Appl. Therm. Eng. 124 641–51
[4] Chaudhary G Q, Ali M, Sheikh N A, Ihtsham S and Khushnood S 2018 Integration of solar assisted solid desiccant cooling system with efficient evaporative cooling technique for separate load handling Appl. Therm. Eng.
[5] Heidari A, Rostamzadeh H and Avami A 2019 A novel hybrid desiccant-based ejector cooling system for energy and carbon saving in hot and humid climates Int. J. Refrig. 101 196–210
[6] Caliskan H, Lee D Y and Hong H 2019 Enhanced thermodynamic assessments of the novel desiccant air cooling system for sustainable energy future J. Clean. Prod. 211 213–21
[7] Heidarinejad G, Khalajzadeh V and Delfani S 2010 Performance analysis of a ground-assisted direct evaporative cooling air conditioner Build. Environ. 45 2421–9
[8] Khalajzadeh V, Farmahini-Farahani M and Heidarinejad G 2012 A novel integrated system of ground heat exchanger and indirect evaporative cooler Energy Build. 49 604–10
[9] Jurinak J J 1982 Open cycle solid desiccant cooling: component models and system simulations (Wisconsin-Madison)
[10] Cacabelos A, Eguia P, Miguez J L, Granada E and Arce M E 2015 Calibrated simulation of a public library HVAC system with a ground-source heat pump and a radiant floor using TRNSYS and GenOpt Energy Build. 108 114–26
[11] Kodama A, Hirayama T, Goto M, Hirose T and Critoph R E 2001 The use of psychrometric charts for the optimisation of a thermal swing desiccant wheel Appl. Therm. Eng. 21 1657–74