Performance evaluation of hybrid desiccant air conditioning system regenerated by waste heat from air cooled condenser: Experimental Investigation

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Abstract. Heating ventilation and air conditioning units reject a large quantity of heat to the surroundings as waste. Thus proper reclamation of this unused heat could also enhance the COP of such arrangements and their lesser adverse effect on the environment. Therefore hybrid desiccant air conditioning unit using unused heat from condenser for regeneration can be more effective than the conventional air conditioning unit under hot and humid climatic conditions. In this paper, various performance parameters of hybrid desiccant air conditioning unit using unused heat from condenser is determined at different process air inlet temperatures (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different process air inlet velocities, i.e. (1.5, 2.5, 3.5 and 4.5 m/s) and at fix (2.5 m/s) air velocity at regeneration inlet. Refrigerating effect, heat rejection rate, VCOP, ECOP, dehumidification effectiveness, moisture removal capacity and DCOP decreases with increment in different air temperatures at process inlet. While compressor work, regeneration effectiveness and regeneration rate increases with increment in different air temperatures at process inlet. On the other hand, refrigerating effect, heat rejection rate, VCOP, ECOP, dehumidification effectiveness, regeneration effectiveness, and regeneration rate decrease with increased air velocities at process inlet. Whereas compressor work, moisture removal capacity and DCOP increases with an increase in air velocities at the process inlet. Thus, optimization of these performance parameters is determined to achieve the maximum efficiency of the hybrid desiccant air conditioning system under the above operating states.

1. Introduction
The accessible energy must be employed appropriately, as there is a high requirement for electrical energy creation and circulation. Around 45% of electric power in every household is used to function refrigeration, heating, ventilation and air conditioning schemes in our nation. All these systems reject a tremendous quantity of heat to the environment as waste. Therefore, proper reclamation of this unused heat could also expand the COP of such structures and their minor adverse effect on the surroundings. Incorporating a desiccant structure with a vapour compression refrigeration system can distinctly eliminate latent and sensible load under hot and humid climates. It also increases COP and decreases the energy consumption of a vapour compression refrigeration system. Incorporating a desiccant scheme with a vapour compression refrigeration system will also lower desiccant regeneration
temperature from (70–80)°C to (50–60)°C. Thus, the heat excluded by the condenser can contribute to renewal of desiccant in dehumidifier. Desiccant based air conditioning units have shown numerous benefits than that of conventional arrangements for dehumidification and cooling. Thus, their usage is also scattering for tertiary and domestic structures, mainly when renewal of desiccant can be acquired via utilizing accessible unused heat [1,2].

Few of the researchers worked in the area of hybrid desiccant air conditioning units. Ando et al. (2005) [3] proposed and experimentally investigated a four rotor desiccant cooling method equipped with two stage dehumidification. In this procedure, a restoration temperature of about 70°C could generate an adequate dehumidifying effectiveness at more air humidity. They attained heat from low grade energy like solar heat and unused heat as a replacement for electricity. Jalalzadeh-Azar et al. (2005) [4] constructed and examined cooling unit using a heat exchanger, reciprocating IC engine, desiccant dehumidifier and indirect/direct dehumidifier. Restoration of desiccant was executed via utilizing heat recovered from an IC engine. Lokapure and Joshi (2012) [5] aimed and constructed a heat exchanger in which COP of air conditioning unit was enhanced via 13% by recovering the waste heat. In this work, the principal stress was given on energy conservation by using the waste heat from the air conditioning system and thus improving COP. Angrisani et al. (2015) [6] investigated hybrid desiccant cooling unit with a desiccant wheel relating with small scale cogenerator. They scrutinized the performance by changing five operating conditions: rotational speed, restoration temperature, outside air temperature, volume airflow rates and specific humidity. They also examined different performance parameters based on primary, thermal and electric energy. They compared the hybrid desiccant cooling system with a micro cogenerator with additional electrical and thermal air conditioning systems. Jani et al. (2016) [7] discussed the principle of a solid desiccant cooling unit and its scientific uses and expansions. They highlighted numerous arrangements of desiccant cooling cycles, crossover/regular desiccant cooling cycles, various numerical models of a desiccant dehumidifier, execution assessment of the desiccant cooling framework and mechanical improvements. They also discussed the performance of solid desiccant cooling unit powered thru industrial waste/solar energy heat for regenerating the desiccant.

The main aim of research paper is to analyze various performance parameters of hybrid solid desiccant air conditioning system utilizing waste heat from condenser for restoration at different process air inlet temperatures (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and at different process air inlet velocities, i.e. (1.5, 2.5, 3.5 and 4.5 m/s) and fix (2.5 m/s) air velocity at regeneration entry. Thus identifying the optimum conditions of performance parameters for effective working of hybrid desiccant air conditioning system under above operating states.

2. Design of the experiment and Methodology

The experimental scheme contains a pretreatment segment, a solid desiccant wheel and a vapour compression refrigeration system (figure 2.1). The air pretreatment segment includes an electric heater and a humidifier. Experimental data has been collected for Hybrid VCRs in which the desiccant wheel is using waste heat from the condenser at different process air inlet temperatures (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different process air inlet velocities (1.5, 2.5, 3.5 and 4.5 m/s) and fix (2.5 m/s) restoration air inlet velocity. The suction pressure (P_{sa}) and discharge pressure (P_{da}) of refrigerant R-410a are measured with the help of Bourdon tube pressure gauges. The current (I) is measured with the help of an ammeter. The voltage (V) is noted with the use of a voltmeter. Data logger measures the temperature of refrigerant R-410a at the different points of VCRs. Data logger measures the experimental data at the entry and exit of process and regeneration sector of desiccant wheel, respectively. Humidity ratio of air has been calculated from relative humidity and dry bulb temperature with the help of a Psychrometric calculator.
The incoming air is heated through electric heater to the required temperature and then humidified through a humidifier. After that, hot and humid air is blown over process segment of the rotary desiccant wheel. When processed air streams over the desiccant exterior in the adsorption segment, its vapour pressure is higher than that of the desiccant outward due to the more humid air state, which generates a significant difference. Thus adsorption sector takes away water vapour from moist air. This water vapour is adsorbed on the exterior of the desiccant and is condensed above it. Hence, adsorption occurs. Then the air passes over the vapour compression refrigeration system's cooling coil and is sensibly reduced to an ideal temperature. In the regeneration sector, when restoration air streams over the desiccant exterior in the restoration segment, it heats the desiccant surface. It increases its vapour pressure which upturns the vapour pressure difference within regeneration air and desiccant surface. Therefore, restoration air evaporates the moisture from a desiccant layer. Thus, regeneration occurs.

Figure 2.1 Photograph of an experimental setup for Desiccant Air Conditioning System utilizing waste heat of condenser for renewal of Desiccant wheel

2.1 Assessing device and Instruments
A Thermo hygrometer measures the relative humidity and dry bulb temperature of the air. An anemometer measures air velocity. Table 1 shows Assessing devices and instruments.

| Equipment                          | Voltage          | Sampling Rate          | Range                      | Accuracy     |
|-----------------------------------|------------------|------------------------|----------------------------|--------------|
| Tweex 8 Channel Data Logger       | Single Phase 220V Standard supply | 5 seconds to 255 minutes | -10 to +85 °C
0 to 100 %RH | ±0.5°C
±2.5%                              |
| Digital Anemometer                | 3.0 V DC         | -                      | 0 to 30 m/s                | ±5%          |
2.2 Performance Factors

The different performance parameters of hybrid desiccant air conditioning unit utilizing the waste heat from condenser for renewal are shown in equations (1-10) at different process air inlet temperatures (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different process air inlet velocities, i.e. (1.5, 2.5, 3.5 and 4.5 m/s) and at fix (2.5 m/s) air velocity at regeneration entry:

1. Refrigerating Effect = \(h_{ref1} - h_{ref4}\)  
2. Heat Rejection Rate = \(h_{ref2} - h_{ref3}\)
3. Compressor Work = \(h_{ref2} - h_{ref1}\)
4. VCOP of hybrid system [8]=Refrigerating Effect/ Compressor Work = \(h_{ref1} - h_{ref4}\)/ \(h_{ref2} - h_{ref1}\)
5. ECOP of hybrid system [9] = Total Cooling Effect/ Total Electric Power Consumption
6. Dehumidification Effectiveness (\(\eta_{deh}\)): symbolizes the ratio between actual and ideal dehumidification ability of desiccant wheel [10].
   \[\eta_{deh} = \frac{\omega_{1} - \omega_{2}}{\omega_{1}}\]  
7. Moisture Removal Capacity (MRC): signifies mass flow rate of dampness detached by desiccant wheel [10].
   \[\text{MRC} = \rho_{1} \times \dot{V}_{p} \times (\omega_{1} - \omega_{2})\]
8. Dehumidification Coefficient of Performance (DCOP): signifies ratio among thermal power linked to air dehumidification and thermal energy provided for restoration process [10].
   \[\text{DCOP} = \frac{\rho_{1} \times \dot{V}_{p} \times \Delta h_{vs} \times (\omega_{1} - \omega_{2})}{\rho_{1} \times \dot{V}_{reg} \times C_{p} \times (T_{4} - T_{1})} = \frac{\dot{V}_{p} \times \Delta h_{vs} \times (\omega_{1} - \omega_{2})}{\dot{V}_{reg} \times (h_{4} - h_{1})}\]

The latent heat of vaporization of water \(\Delta h_{vs}\) has been assessed using subsequent empirical cubic function [10].
\[\Delta h_{vs} = -0.614342 \times 10^{-4} \times T_{1}^{3} + 0.0158927 \times 10^{-2} \times T_{1}^{2} - 0.236418 \times 10 \times T_{1} + 0.250079 \times 10^{4}\]
9. Regeneration Effectiveness (\(\eta_{reg}\)): implies latent load held by a desiccant wheel about thermal regeneration power needed for adsorption procedure of desiccant wheel [11].
   \[\eta_{reg} = \frac{\omega_{3} - \omega_{4}}{\omega_{4}}\]
10. Regeneration Rate (RR) signifies the mass flow rate of dampness detached by a wheel from the process side to the regeneration side [11, 12].
   \[\text{RR} = \rho_{1} \times \dot{V}_{R} \times (\omega_{3} - \omega_{4})\]
3. Graphs and Discussions

Figure 3.1 Variation of Refrigerating Effect with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet

Figure 3.2 Variation of Heat Rejection Rate with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet
Figure 3.3 Variation of Compressor Work with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet

Figure 3.4 Variation of VCOP with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet
Figure 3.5 Variation of ECOP with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet.

Figure 3.6 Variation of Dehumidification Effectiveness with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet.
Figure 3.7 Variation of Moisture Removal Capacity (kg/hr) with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet

Figure 3.8 Variation of Dehumidification COP with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet
Figure 3.9 Variation of Regeneration Effectiveness with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet.

Figure 3.10 Variation of Regeneration Rate (kg/hr) with Air Inlet Temperatures at different process air inlet velocity and 2.5 m/s air velocity at regeneration inlet.
Figures 3.1, 3.2, 3.4 and 3.5 show for all the different process air inlet velocities, the value of refrigerating effect, heat rejection rate, VCOP and ECOP decreases with increment in the distant air temperatures at the process a fix 2.5 m/s air velocity at regeneration inlet. But, figure 3.3 shows that compressor work upsurges with rise in various process air entry temperatures. It is so, as ambient temperature increases, rate of heat transfer from the condenser decreases. With the rise in ambient temperature, the air-cooled condenser is also affected and gets less cooled, increasing the load of the vapour compression refrigeration system. Thus due to this effect, less heat is absorbed by refrigerant from the air at the evaporator. Also, figures 3.1, 3.2, 3.4 and 3.5 shows that for all different process air entry temperatures, value of refrigerating effect, heat rejection rate, VCOP and ECOP declines with rise in various air velocities at process inlet and a fix 2.5 m/s air velocity at regeneration inlet. More incredible the air velocity at the process inlet minimizes the contact time between the surface of the cooling coil and incoming air. Thus, the refrigerant absorbs less heat from the incoming air due to lower contact time [9,12]. Figures 3.6, 3.7 and 3.8 show that the value of dehumidification effectiveness, moisture removal capacity and DCOP decreases with increased process air inlet temperatures. There is lower ambient relative humidity at higher ambient temperatures, which leads to drop in dehumidification effectiveness. At entry process, the air specific humidity also decreases due to lesser relative humidity, which causes air vapour pressure to fall adsorption potential [6,10]. Figures 3.9 and 3.10 show that the value of regeneration effectiveness and regeneration rate increases with air temperatures at process inlet. As ambient temperature rises, it also affects regeneration temperature, which also increases, which clues to enlarged removal of water vapour from the desiccant wheel during the renewal period. Thus the regeneration effectiveness and regeneration rate also increase with increment in the ambient temperature.

4. Error Analysis
The error investigation completed in the present work depends on root sum square strategy detailed by Kline and McClintock [13], the performance parameters described in this work i.e. refrigerating effect, heat rejection rate, compressor work, VCOP, ECOP, dehumidification effectiveness, moisture removal capacity, dehumidification COP, regeneration effectiveness and regeneration rate are found via calculation from noted variables such as velocity of air, relative humidity and temperature is described via a recognized value of uncertainty. The comparative uncertainty values obtained for the considered factors are, 9.5% for refrigerating effect, 1.8% for heat rejection rate, 8.3% for compressor work, 9.8% for VCOP, 9.5% for ECOP, 6.1% for dehumidification effectiveness, 6.9% for moisture removal capacity, 7.2% for dehumidification COP, 14.1% for regeneration effectiveness and 14.3% for regeneration rate.

5. Conclusions
The key objective of the current investigation was to explore the possibility of a hybrid solid desiccant air conditioning unit using the waste heat from condenser for regeneration at different process air inlet temperatures (28, 29.5, 31, 32.5, 34, 35.5 and 37℃) and at different process air inlet velocities, i.e. (1.5, 2.5, 3.5 and 4.5 m/s) and at fix (2.5 m/s) air velocity at regeneration entry. It was concluded that best conditions of performance parameters are identified for effective working of hybrid desiccant air conditioning system under above functioning situations, which are as follows:

- Refrigerating effect, heat rejection rate, VCOP, and ECOP decrease with increment in different air temperatures at process inlet and different air velocities at process inlet at a fixed 2.5 m/s renewal air entry velocity.
- Compressor work upsurges with rise in various air temperatures at process inlet, different air velocities at process inlet at a fixed 2.5 m/s restoration air entry velocity.
The regeneration temperature must be high to increase the refrigerating effect, heat rejection rate, VCOP and ECOP, and regeneration temperature. To lower the compressor work, the regeneration temperature should be increased.

The maximum value of refrigerating effect, heat rejection rate, VCOP and ECOP is 161.1 kJ/kg, 191.2 kJ/kg, 5.35 and 3.98 respectively at 28℃ process air entry temperature, 1.5 m/s processes and 2.5 m/s air velocity at regeneration inlet.

The minimum value of compressor work is 30.1 kJ/kg at 28℃ air temperature at process inlet, 1.5 m/s process and 2.5 m/s air velocity at regeneration inlet.

Refrigerating effect, heat rejection rate, VCOP, ECOP, dehumidification effectiveness, regeneration effectiveness and regeneration rate decreases with increment in various air velocities at process inlet and a fix 2.5 m/s air velocity at regeneration entry.

Compressor work, moisture removal capacity and DCOP increases with an increase in air velocities at the process inlet.

Dehumidification effectiveness, moisture removal capacity and DCOP decreases with increment in air temperatures at process inlet. In contrast, regeneration effectiveness and regeneration rate increase with rise in process air inlet temperatures.

Regeneration temperature should be high to enhance dehumidification effectiveness, moisture removal capacity, DCOP, regeneration effectiveness, and regeneration rate.

Nomenclature

- $c_p$: air specific heat (kJ/kg K)
- COP:Coefficient of performance
- VCOP: COP of vapour compression refrigeration system
- ECOP: electric coefficient of performance
- $h_{ref1}$: at the entry of compressor enthalpy of refrigerant in kJ/kg
- $h_{ref2}$: at the outlet of compressor enthalpy of refrigerant in kJ/kg
- $h_{ref3}$: at the outlet of condenser enthalpy of refrigerant in KJ/kg
- $h_{ref4}$: at the entry of evaporator enthalpy of refrigerant in kJ/kg
- MRC: Adsorption rate (kg/hr)
- $T_1$: at process entry temperature of the air
- $T_2$: at process exit temperature of the air
- $T_3$: at regeneration entry temperature of the air
- $T_4$: at regeneration exit temperature of the air
- $\omega_1$: at the process inlet humidity ratio of air
- $\omega_2$: at the process outlet humidity ratio of air
- $\omega_3$: at the regeneration inlet humidity ratio of air
- $\omega_4$: at the regeneration outlet humidity ratio of air
- $\dot{V}$: volumetric flow rate of air ($m^3$/hr)
- DW: desiccant wheel

Greek symbols:

- $\Delta h_{vg}$: latent heat of vaporization of the water (kJ/kg)
- $\rho$: density of air ($kg/m^3$)
- $\omega$: humidity ratio or specific humidity (kg/kg)
Subscripts:
P                        process  
reg                    regeneration  
dis                  discharge  
suc                      suction  

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