Effects of different air inlet temperatures and regeneration air inlet velocities on the performance of Hybrid Desiccant Air Conditioning System

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Abstract. A hybrid desiccant air conditioning unit is treated as an effective alternative to the conventional air conditioning system due to independent control of humidity, temperature, and eco-friendliness. The decrease in environmental impact and energy saving is more when the desiccant recovered by utilizing "free" thermal energy. This current work has experimented with a performance study of a hybrid desiccant air conditioning unit for typical humid and hot Indian (Aligarh) climatic conditions. Here, the effects of different air inlet temperatures at the process section, i.e. (28, 29.5, 31, 32.5, 34, 35.5 and 37℃) and regeneration section, i.e. (50-58.8℃) and different regeneration air inlet velocities (2.5 and 4.5 m/s) on the performance of hybrid desiccant air conditioning system are analyzed. Thus, optimization of performance parameters i.e. refrigerating effect, heat rejection rate, VCOP, ECOP, compressor work, dehumidification effectiveness, moisture removal capacity, DCOP, regeneration effectiveness and regeneration rate is identified for attaining maximum efficiency of hybrid desiccant air conditioning system under above operating states.

1. Introduction

People need to produce comfort conditions in the current world scenario, where the average temperature grows progressively. Vapour Compression Refrigeration System (VCRS) eliminates moisture from incoming air by cooling air beneath the dew point temperature through coolants, thus removing water vapour via condensation. In other words, moisture gets condensed and removed from the air below the dew point temperature. Thus, conventional vapour compression refrigeration systems concurrently cool and dehumidify incoming air. Whereas in Hybrid Desiccant Air Conditioning System comprises a rotor packed with desiccant substantial in which the incoming process air is dehumidified via desiccant substantial to compensate latent atmosphere loads. Here, the cooling coil has to handle the only sensible load in a desiccant-based air conditioning system. Thus, a desiccant-based air conditioning unit can be considered a possible alternative to a conventionally utilized refrigeration unit [1].

Some of the researchers worked in the field of hybrid desiccant air conditioning systems. Jia et al. (2006) [2] performed experiments on a desiccant-based air conditioning unit, incorporating a solid desiccant wheel and air conditioning system. It was noticed that when relative humidity and the
process air temperature was sustained at 55% and 30°C, respectively, a hybrid desiccant vapour compression refrigeration system economizes 37.5% electricity power as that of a conventional system. Fatouh et al. (2009) [3] experimentally examined performance data of solid desiccant vapour compression refrigeration system. This unit was comprised of the packed bed desiccant incorporated thru an R407C conventional air conditioning unit. It was noticed that with increment in mass flow rate of renewed air from 7.4 to 10.2 kg/min, provides decrement in renewal period via 87.5% and augmentation in desorption rate through 16% after 10 minutes of recovering. Furthermore, with an increment in renewal temperature from 45 to 55°C, reactivation time decreases by 25%. Described outcomes publicized that a desiccant based air conditioning unit lowers the compressor electric power and number of electric units around 10.2%. Mittal and Khan (2010) [4] estimated the performance and energy were preserving the capability of desiccant air conditioning unit in India, which was consist of a silica gel bed, a split type air conditioner of 1.0 ton, air ducts, a blower, and fitted in a room with a volume of 86.4 m³. During the test settings in the experimentation, suggested a 7 cm bed thickness with an extreme moisture removal capacity of 403 g/h. Optimal proportions of air ratios were: 10% of the outer air, 10% of return air and 80% of indoor air mixed with dry air leaving desiccant. The correspondent electricity saving was around 19%. Mandegari and Pahlavanzadeh (2010) [5] examined a desiccant wheel incorporating a vapour compression refrigeration system at different supplied-air humidities and temperatures. They had compared the performance of a desiccant air conditioning system to that of a conventional vapour compression refrigeration system on an experimental basis. They found that this technique of hybridization was much operative at high latent loads. Based on an economic study, they notified that this unit was high operative in nations where the cost of energy was high. Belguith et al. (2020) [6] examined a desiccant based air conditioning unit. Here, they discussed three arrangements of this refrigeration expertise for a test area of cooling capability of 1.8 kW underneath hot and dry weather conditions. It was noticed that arrangement which comprises of a desiccant wheel attached by a conventional vapour compression system, had the most satisfactory COP equivalents 2.48.

The prime aim of the current research paper is to determine various performance parameters of hybrid solid desiccant air conditioning system utilizing the waste heat from condenser for recovering at different air inlet temperatures at process section, i.e. (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different air inlet temperatures at regeneration section, i.e. (50-58.8°C) and different regeneration air inlet velocities (2.5 and 4.5 m/s). Thus identifying the optimum conditions of performance parameters for effective working of hybrid desiccant air conditioning system under above operating states.

2. Methodology and design of the experiment

Air first passes through the air pre-treatment section, which consists of electric heaters and a humidifier. Electric heaters can heat incoming treated air to desired hotness and, after that, humidified through a humidifier. After that, the hot and humid air is blown over the adsorption sector of the rotary desiccant wheel. When processed air streams over the desiccant exterior in the process zone, its vapour pressure is higher than desiccant outward; a more humid air condition generates a significant difference. Thus, the process part takes water vapour from moist air. The water vapour is adsorbed on the exterior of the desiccant and is condensed above it. Therefore, adsorption occurs. Then the air passes over the cooling coil of the vapour compression refrigeration unit and then sensible cooled down to ideal temperature. In the regeneration section, when regeneration air (waste heat from the condenser) streams over a desiccant surface, it kicks the desiccant exterior. It increases its vapour pressure, enhancing the difference between the desiccant
surface and the regeneration air. Thus, regeneration air evaporates moisture from a desiccant layer. Hence, regeneration takes place.

The experimental device (figure 2.1) consists of a pretreatment segment, a rotary desiccant wheel and a vapour compression refrigeration system. The air pretreatment segment consists of an electric heater and a humidifier. The experimental data has been collected for a desiccant based air conditioning unit in which the desiccant wheel is using waste heat from condenser for renewal at different air inlet temperatures at the process section, i.e. (28, 29.5, 31, 32.5, 34, 35.5 and 37℃) and different air inlet temperatures at regeneration section, i.e. (50-58.8℃) and different regeneration air inlet velocities (2.5 and 4.5 m/s). Here the air velocity at the process inlet is fixed, i.e. 1.5 m/s. The discharge pressure (P_{dis}) and suction pressure (P_{suc}) of refrigerant R-410a are measured with the help of Bourdon tube pressure gauges. The voltage (V) is measured through a voltmeter. The current (I) is measured with the help of an ammeter. A data logger measures the temperature of refrigerant R-410a at the different points of VCRs. The data logger also provides the different temperatures and relative humidity of air at entry and exit of process and regeneration segment of desiccant wheel. Specific humidity of air has been determined from relative humidity and dry bulb temperature through a Psychrometric calculator.

![Figure 2.1 Photograph of an experimental setup for Desiccant Air Conditioning System utilizing waste heat of condenser for the regeneration of Desiccant wheel](image)

### 2.1 Assessing device and Instruments

Dry bulb temperature and relative humidity and air are measured through Thermo-hygrometer. An anemometer measures air velocity. Table 1 shows the assessing device 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

Different performance parameters of hybrid solid desiccant air conditioning unit using the waste heat from condenser for regeneration are shown in equations (1-10) at different air inlet temperatures at the process section, i.e. (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different air inlet temperatures at regeneration section, i.e. (50-58.8°C) and different regeneration air inlet velocities (2.5 and 4.5 m/s):

1. Refrigerating Effect = \( (h_{ref1} - h_{ref4}) \) \( (1) \)
2. Heat Rejection Rate = \( (h_{ref2} - h_{ref3}) \) \( (2) \)
3. Compressor Work = \( (h_{ref2} - h_{ref1}) \) \( (3) \)
4. VCOP of hybrid system \[7\] = Refrigerating Effect/ Compressor Work = \( (h_{ref1} - h_{ref4})/ (h_{ref2} - h_{ref1}) \) \( (4) \)
5. ECOP of hybrid system \[8\] = Total Cooling Effect/ Total Electric Power Consumption \( (5) \)
6. Dehumidification Effectiveness (\( \eta_{deh} \)): symbolizes the ratio between actual and ideal dehumidification ability of desiccant wheel \[9\].
\[ \eta_{deh} = \frac{\omega_1 - \omega_2}{\omega_1} \] \( (6) \)
7. Moisture Removal Capacity (MRC): signifies mass flow rate of dampness detached by desiccant wheel \[9\].
\[ \text{MRC} = \rho_1 \times \dot{V}_p \times (\omega_1 - \omega_2) \] \( (7) \)
8. Dehumidification Coefficient of Performance (DCOP): signifies ratio among thermal power linked to air dehumidification and thermal energy provided for regeneration process \[9\].
\[ \text{DCOP} = \frac{\rho_1 \times \dot{V}_p \times \Delta h_{sv} \times (\omega_1 - \omega_2)}{\rho_1 \times \dot{V}_{reg} \times c_p \times (T_4 - T_1)} = \frac{\dot{V}_p \times \Delta h_{sv} \times (\omega_1 - \omega_2)}{V_{reg} \times (h_4 - h_1)} \] \( (8) \)
The latent heat of vaporization of water \( \Delta h_{sv} \) has been assessed using subsequent empirical cubic function \[9\].
\[ \Delta h_{sv} = -0.614342 \times 10^{-4} \times T_1^3 + 0.0158927 \times 10^{-2} \times T_1^2 - 0.236418 \times 10 \times T_1 + 0.250079 \times 10^4 \]
9. Regeneration Effectiveness (\( \eta_{reg} \)): implies latent load held by a desiccant wheel about thermal regeneration power needed for adsorption procedure of desiccant wheel \[10\].
\[ \eta_{reg} = \frac{\omega_3 - \omega_4}{\omega_4} \] \( (9) \)
10. Regeneration Rate (RR) signifies the mass flow rate of dampness detached by a wheel from the process side to the regeneration side \[10, 11\].
\[ \text{RR} = \rho_1 \times \dot{V}_R \times (\omega_3 - \omega_4) \] \( (10) \)
3. Results and Discussion

Figure 3.1 Refrigerating Effect variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet

Figure 3.2 Heat Rejection Rate variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet
Figure 3.3 Compressor Work variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet

Figure 3.4 VCOP variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet
Figure 3.5 ECOP variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet

Figure 3.6 Dehumidification Effectiveness variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet
Figure 3.7 Moisture Removal Capacity variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet

Figure 3.8 Dehumidification COP variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet
Figure 3.9 Regeneration Effectiveness variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet

Figure 3.10 Regeneration Rate (kg/hr) variation with air inlet temperature at 2.5 m/s and 4.5 m/s velocity of air at regeneration inlet and fix 1.5 m/s velocity of air at process inlet
Figure 3.11 Regeneration Effectiveness and Regeneration Rate (kg/hr) variation with regeneration air inlet temperature at 2.5 m/s velocity of air at regeneration entry and fix 1.5 m/s velocity of air at process inlet.

Figure 3.12 Regeneration Effectiveness and Regeneration Rate (kg/hr) variation with regeneration air inlet temperature at 4.5 m/s velocity of air at regeneration entry and fix 1.5 m/s velocity of air at process inlet.
Figures 3.1, 3.2, 3.4 and 3.5 show that the value of refrigerating effect, heat rejection rate, VCOP and ECOP decreases with rising air temperatures at process inlet at different regeneration air inlet velocities (2.5 and 4.5 m/s) and fix 1.5 m/s process air inlet velocity. But, figure 3.3 shows that compressor work enhances with an increment in different process air inlet temperatures. It is because as ambient temperature increases, the rate of heat transfer from the condenser decreases. With an increase 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. It is clear that at a fixed process, when regeneration air inlet velocity decreases from maximum (4.5 m/s) to minimum (2.5 m/s) value of refrigerating effect, heat rejection rate, VCOP and ECOP increases. It is because lower regeneration air inlet velocity maximizes contact time between desiccant surface and regenerated air. Thus at lower air velocity at regeneration inlet, higher desiccant material is restored in the regeneration sector. Hence, ultimately this desiccant material in the adsorption sector adsorbs more of water vapour. Thus more latent load is removed at lower regeneration air inlet velocity, which eventually increases refrigerating effect [9,10]. Figures 3.6, 3.7 and 3.8 show that the value of dehumidification effectiveness, moisture removal capacity and DCOP decreases with an increment in air temperatures at the process inlet. It is due to, as the adsorption process is exothermic, so preferred by lesser temperatures. Lower temperature provides a higher presence of moisture content in process air. There is a significant variance of vapour partial pressure between desiccant material surface and process air, which creates a more diffusion of water vapour drops from perspective to surface of desiccant material [9,11]. Figures 3.9 and 3.10 shows that the value of regeneration effectiveness and regeneration rate increases with an increment in air temperatures at process entry. As ambient temperature increases, it also affects regeneration temperature, which leads to the improved exclusion of water vapour from the rotary desiccant wheel during the regeneration period. Figures 3.11 and 3.12 show the variation of regeneration effectiveness and rate (kg/hr) with regeneration air inlet temperature at 2.5 m/s and 4.5 m/s air velocity at regeneration entry and fix 1.5 m/s velocity of air at process inlet, respectively. When regeneration air inlet velocity decreases from maximum (4.5 m/s) to minimum (2.5 m/s) velocity, the value of regeneration rate decreases. As with increment in air velocity at regeneration inlet, there is an increment in regeneration mass flow rate of air which also offers desiccant wheel in regeneration segment with large hot regenerated air, as it removes water vapour from the desiccant surface in regeneration sector and thus ultimately increases regeneration rate. Also, figures 3.11 and 3.12 show that the value of regeneration effectiveness and regeneration rate increases with an increment in air temperatures at the regeneration inlet.

4. Error Analysis
The error investigation completed in the current research paper depends on the strategy of root sum square detailed by Kline and McClintock [12], the performance parameters described in this work refrigerating effect, heat rejection rate, compressor work, VCOP, ECOP, dehumidification effectiveness, moisture removal capacity, dehumidification COP, regeneration effectiveness and regeneration rate are found by calculation from noted variables such as air velocity, temperature, relative humidity and all of these noted variables is described by a known value of uncertainty. Comparative uncertainty values obtained for the considered factors are, 11.7% for refrigerating effect, 1.7% for heat rejection rate, 10% for compressor work, 11.8% for VCOP, 11.7% for ECOP, 6% for dehumidification effectiveness, 6.8% for moisture removal capacity, 7% for dehumidification COP, 14.8% for regeneration effectiveness and 14.9% for regeneration rate.
5. Conclusions
The primary objective of the current research work was to highlight the possibility of a hybrid rotary desiccant air conditioning unit utilizing waste heat from condenser for recovering at different air inlet temperatures at the process section, i.e. (28, 29.5, 31, 32.5, 34, 35.5 and 37°C) and different air inlet temperatures at regeneration section, i.e. (50-58.8°C) and different air velocities at regeneration inlet (2.5 and 4.5 m/s) and fix (1.5 m/s) air velocity at process inlet. It was concluded that optimum conditions of performance parameters are identified for effective working of hybrid desiccant air conditioning system under above operating states which are as follows:

- Refrigerating effect, heat rejection rate, VCOP and ECOP decreases with an increment in different air temperatures at the process inlet. Compressor work enhances with an increment in different process air inlet temperatures.
- The regeneration temperature should increase the refrigerating effect, heat rejection rate, VCOP and ECOP, and regeneration temperature. To lower the compressor work, the regeneration temperature should be increased.
- When the air velocity at regeneration inlet slows down from maximum (4.5 m/s) to minimum (2.5 m/s), the value of refrigerating effect, heat rejection rate, VCOP and ECOP increases.
- Dehumidification effectiveness, moisture removal capacity and DCOP reduces with an increment in air temperatures at the process inlet.
- Whereas regeneration effectiveness and regeneration rate increase with an increase in air temperatures at process inlet.
- The regeneration temperature should be high to enhance dehumidification effectiveness, moisture removal capacity, DCOP, regeneration effectiveness and rate.
- When air velocity at the regeneration inlet decreases from maximum (4.5 m/s) to the minimum (2.5 m/s), regeneration effectiveness increases. Whereas, when regeneration air inlet velocity decreases from maximum (4.5 m/s) to minimum (2.5 m/s), the value of regeneration rate decreases.

Nomenclature

| Symbol     | Description                                      |
|------------|--------------------------------------------------|
| 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)           |
\(c_p\) air specific heat (kJ/kg K)

DW desiccant wheel

**Greek symbols:**

\(\Delta h_{vs}\) 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

\(\text{reg}\) regeneration

\(\text{dis}\) discharge

\(\text{suc}\) suction

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