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To cite this article: Selvaraji Muthu *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1123** 012055

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Performance Enhancement of Rotary Desiccant Wheel using Novel Homogenous Composite Desiccant Designs

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Abstract. Rotary solid desiccant wheels are used as sensible and latent heat recovery wheels in the Desiccant-HVAC systems. The two major types of these wheels include enthalpy (total energy recovery) wheels which remove sensible heat and latent heat from process air and transfer them to regeneration air, and dehumidification wheels which transfer a significant amount of moisture (latent heat) at the same time minimizes heat transfer. In this work a set of novel design of hybrid rotary desiccant wheel constructed using a composite homogeneous mixture of solid desiccants (multiple types of silica gel and molecular sieves) are proposed. The transport phenomena taking place in the proposed set of novel design of hybrid rotary desiccant wheel are simulated numerically using an in house finite volume method based CFD code. The performances of these wheels are compared with conventional type of wheels made of molecular sieves and silica gel, respectively. The results show that the performance of these hybrid wheels are enhanced by up to 40 % by using these novel composite wheel designs.

1. Introduction

Dehumidification of moist air in a HVAC (Heating Ventilating, filtering and Air conditioning) system using desiccant adsorbents is one of the promising technologies to meet the demands of in-door thermal comfort regulations and norms [1]. Desiccant technology has received great attention due to its certain unique features such as overcoming the un-wanted release of adsorption heat, low level of electrical power for the system and utilization of waste heat or low grade thermal energies [2].

Rotary desiccant wheel (RDW) consists of a substrate embedded with a matrix of air passages across its thickness. The surfaces bounding these matrix structures are coated with solid desiccant materials of various types. During dehumidification process, the moisture contained in the humid air that is passing through RDW is adsorbed by the desiccant material layers and simultaneously the released adsorption heat stored in the desiccant is transported along with the processed air. When the moisture trapped in the desiccant reach its saturation level, hot regeneration air is passed through the RDW in counter flow



direction so that the moisture adsorbed in the desiccant layer is removed, making it dry again, as shown in Figure 1 [3, 4]. The heat energy source required during regeneration of the wheel can be obtained from waste heat and or low grade heat resources such as other thermal equipment, solar energy, etc.

Significant theoretical researches on numerical simulation have been done to analyze the performance of these desiccant based HVAC (D-HVAC) units. A one-dimensional numerical model was built [1] to simulate the impacts of structural parameters on RDW performance under various operating conditions and obtained the heat and mass transfer correlation based on Nusselt and Sherwood numbers. The developed model is validated against the experimental data on the both air side and desiccant layer heat and mass transport properties of a RDW under various operating conditions [5, 6].

In this paper, the concepts of hybrid wheel with homogeneous mixture of different types of desiccant are presented. The purpose of this research is to develop a novel design of hybrid RDW using homogenous mixture of multiple desiccant types to predict the performance and compare the heat and mass transfer phenomena in H-RDW for the application in D-HVAC system. The aim is to predict the performance improvement potential of hybrid wheel [7-12] in comparison to conventional silica gel and molecular sieves wheels.

2. Problem Description

Figure 2 depicts the proposed novel honey comb structure of desiccant channel and the layer formation made up on homogeneous mixture of different type of desiccants. The hybrid wheel can be made using common substrate on which by coating or impregnating the non-homogeneous mixture of multiple desiccants through the depth of the wheel. The packing of desiccant in the hybrid wheel fulfills to the pore standards defined by IUPAC [13] and is reproduced in Figure 3. Accordingly, the desiccants (any type of silica gel, SG) having the adsorption capacity isotherm as per type-III (Mesopores) is used as descending concentration starting from the inlet side of the process air. The remaining layer thickness is coated with desiccants such as Zeolites, Molecular Sieves and MS (3 Å , 4 Å)) having the adsorption capacity isotherm as per type-I (Microspores).

A mathematical relation to calculate adsorption capacity of hybrid desiccant wheel with homogeneous mixture of desiccant types with fixed concentration ratios is given by [1]:

$$W = W_1\alpha + W_3\beta \quad (1)$$

Where W_1 is the adsorption capacity of desiccant having isotherm as per Type-I (Molecular sieves desiccant), W_3 is the adsorption capacity of desiccant having isotherm as per Type-III (Silica gel desiccant), α is the concentration factor of Type-I desiccant, β is the concentration factor of Type-III desiccant. A comparison of isotherms of desiccant wheels made of conventional Silica gel and Molecular sieves with that based on the homogeneous mixtures (50:50% concentration ratios) of conventional Silica gel and Molecular sieves is shown in Figure 4. Similarly, in Fig.5 isotherm of desiccant wheel based on the homogeneous mixtures (50:50% concentration ratios) of Composite Silica

gel and Molecular sieves is compared with the isotherms of wheels based on composite Silica gel and Molecular sieves. The prediction of performance of the proposed hybrid wheels are predicted using CFD simulation. In general, the desiccant wheel can be of any one particular type of desiccant and or a mixture of particles of different sizes of different type of desiccants [14]. The assumptions, nomenclatures and geometrical data adopted in the simulation are referred from Selvaraji et al. [3, 4], and [7-12].

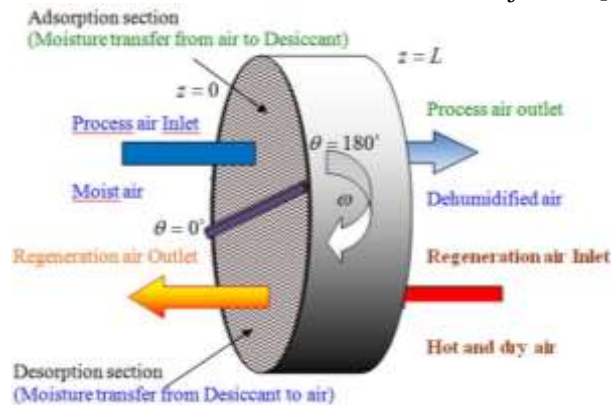


Figure 1. Schematic of rotary solid desiccant wheel (RDW)

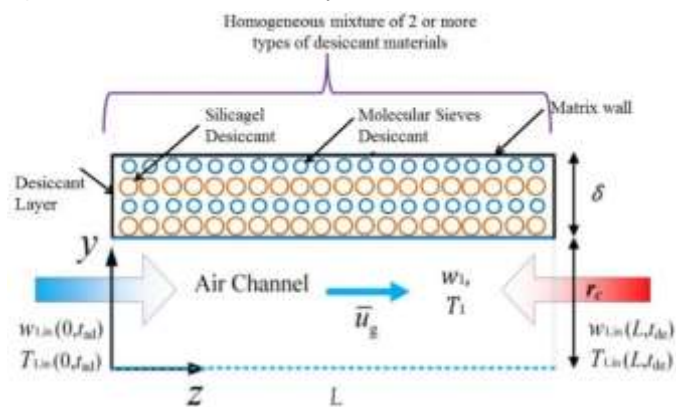


Figure 2. Novel honeycomb channel layer of hybrid solid desiccant wheel with silica gel and molecular sieves desiccant materials coated over matrix wall, $a=3.5$ mm, $b=1.75$ mm

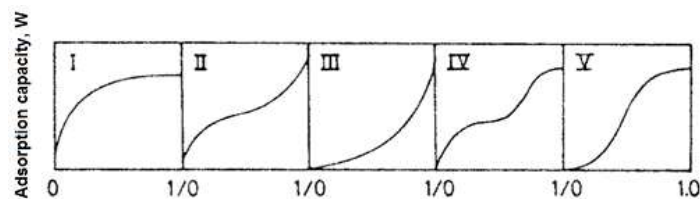


Figure 3. Classification of desiccant isotherm [8]

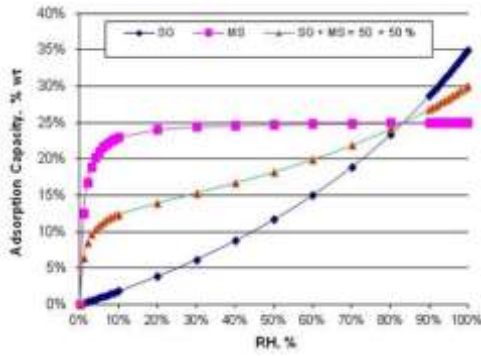


Figure 4. Isotherm of Homogeneous mixture of
SG : MS

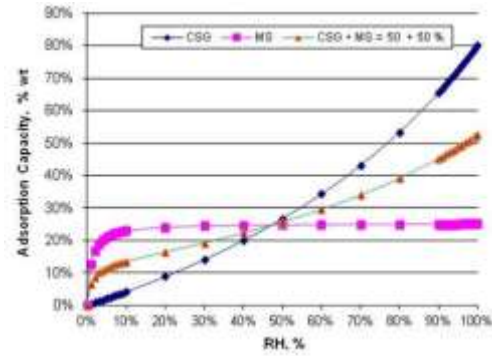


Figure 5. Isotherm of Homogeneous mixture of
CSG : MS

3. Governing Equations

The governing equations are derived based on the conservation of moisture and conservation of energy for air and desiccant medium. The moisture content conservation in the process side and regeneration side air stream is given by

$$d_e \left(\frac{\partial(\rho_a Y_a)}{\partial t} + \omega \frac{\partial(\rho_a Y_a)}{\partial \theta} + u \frac{\partial(\rho_a Y_a)}{\partial z} \right) = K_y (Y_d - Y_a) \quad (2)$$

Moisture content conservation in the desiccant layer of rotary solid desiccant wheel is given by

$$\delta \rho_d \left(\frac{\partial W}{\partial t} + \omega \frac{\partial W}{\partial \theta} - \frac{\partial}{\partial z} \left(D_e \frac{\partial W}{\partial z} \right) \right) = K_y (Y_d - Y_a) \quad (3)$$

Sensible energy conservation in the process and regeneration air is given by the below equation

$$d_e c_{pa} \left(\frac{\partial(\rho_a T_a)}{\partial t} + \omega \frac{\partial(\rho_a T_a)}{\partial \theta} + u \frac{\partial(\rho_a T_a)}{\partial z} - d_e \frac{\partial}{\partial z} \left(K_a \frac{\partial T_a}{\partial z} \right) \right) = h(T_d - T_a) + c_{pv} K_y (Y_d - Y_a) (T_d - T_a) \quad (4)$$

Sensible energy and adsorption energy conservation in the desiccant layer is given by

$$c_{pd} \rho_d \delta \left(\frac{\partial(T_d)}{\partial t} + \omega \frac{\partial(T_d)}{\partial \theta} \right) - \delta \frac{\partial}{\partial z} \left(K_d \frac{\partial T_d}{\partial z} \right) = h(T_a - T_d) + c_{pv} K_y (Y_a - Y_d) (T_a - T_d) + K_y (Y_a - Y_d) \quad (5)$$

4. Results and Discussion

With variable operating parameters, the performances of the rotary solid desiccant wheels are presented for H-RDW in comparisons to conventional RDW in detail. In this work, the primary parameters are used to investigate the system performance are the moisture removal capacity (D) of process air side, relative moisture removal efficiency (η) with respect to inlet moisture content and desiccant dehumidification coefficient of performance (DCOP) and are given by the equations (6), (7) and (8), respectively.

$$D = Y_a|_{z=0} - Y_a|_{z=L} \quad (6)$$

$$\eta = \frac{Y_a|_{z=0} - Y_a|_{z=L}}{Y_a|_{z=0}} \quad (7)$$

$$DCOP = \frac{m_{phg}(Y_{a|z=0} - Y_{a|z=L})}{m_r(h_{r,in} - h_{r,amb})} \quad (8)$$

4.1 Effect of process and regeneration air inlet temperatures on D

The performance of proposed hybrid RDW system is predicted for different inlet temperature of process air, T_p from 20°C to 40°C. Fig. 6 shows the performance trend of D for conventional SG wheel and H-RDW. It can be found that MRC reduces as temperature increases, but the H-RDW is significantly having higher performance, which is about 27% higher than conventional SG wheel at 40°C.

Fig.7 shows the performance trend of D for the different inlet temperature of regeneration air T_r from 60°C to 120°C. It can be clearly seen that D increases for increase in temperature of regeneration air, as the thermal driving energy for wheel has increased and that has given a performance improvement of about 32% at 120°C for the hybrid RDW compared to conventional RDWs.

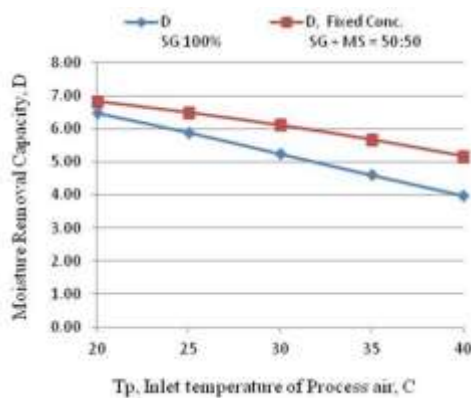


Figure 6.Performance (D) impact due to inlet temperature increase in process air

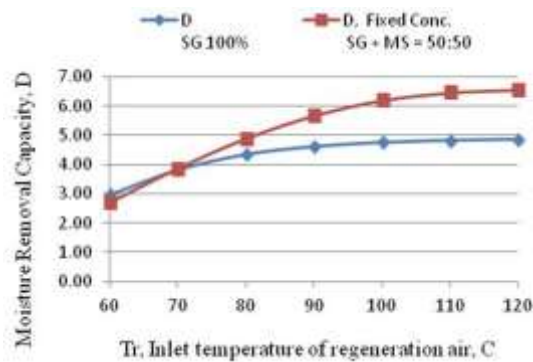


Figure 7.Performance (D) gain due to inlet temperature increase in regeneration air

4.2 Effect of moisture content of process and regeneration air-stream on D

The effect of inlet moisture content of process air on system performance is shown in Fig. 8. It is evident that, a significant increase in D is achieved using hybrid wheel for the entire range of operation. This is due to the fact that the latent heat load in the process air section has increased. This in turn enhances the moisture removal capacity by about 12% at 10 g/kg inlet moisture and about 30% increase at 30 g/kg. Fig. 9 shows the trend of Moisture Removal Capacity D (MRC) of H-RDW. It can be found that MRC reduces as temperature increases, but the H-RDW is significantly having higher performance, which is about 24% higher than conventional SG wheel at 10 g/kg inlet moisture of regeneration air-stream.

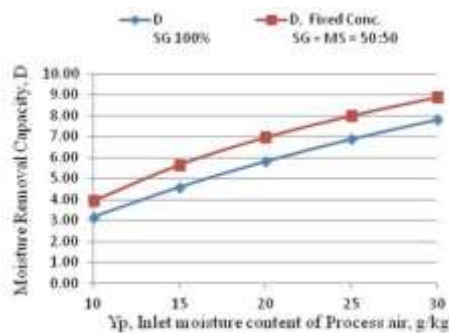


Figure 8.Performance (D) gain due to inlet moisture content increase in process air-stream

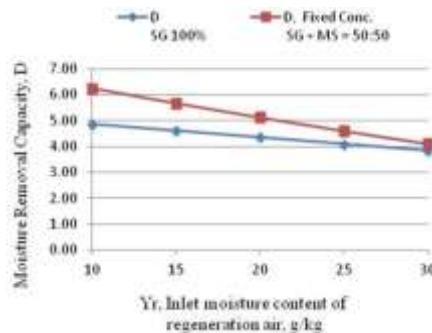


Figure 9.Performance (D) impact due to inlet moisture content to increase in regeneration air-stream

4.3 Effect of temperature of process and regeneration air-streams on RMRE & DCOP

The performance of this novel H-RDW system has been predicted for RMRE and DCOP for different inlet temperatures of process air T_p from 20°C to 40°C. Fig. 10 shows the performance trend of RMRE of conventional SG wheel and H-RDW. It can be found that RMRE reduces as temperature increases, but the H-RDW is having higher performance at 40°C. In Fig. 11, it can be observed that RMRE nearly keeps constant and DCOP decreases with respect to increase in regeneration temperature T_r from 60°C to 120°C. This is due to the fact that although T_r changes, moisture content of both process air and regeneration air kept constant and the driving potential for moisture transfer almost keeps constant, therefore RMRE keeps constant. But at the same time, regeneration air with lower T_r can cool the RDW section of process air-stream better, which leads to that more sensible load of process air can be removed and DCOP increases at about 60°C - 70°C.

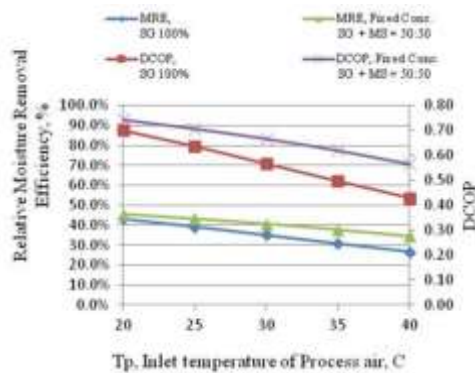


Figure 10. Performance impact (RMRE & DCOP) due to inlet temperature increase in process air-stream

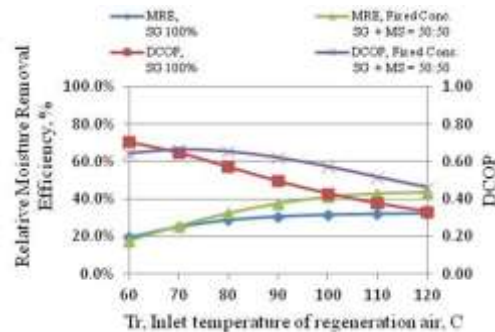


Figure 11. Performance impact (RMRE & DCOP) due to inlet temperature increase in regeneration air-stream

4.4 Effect of moisture content of process air and regeneration air-stream on RMRE & DCOP

The influence of inlet moisture content of process air-stream on system performance in terms of RMRE and DCOP are shown in Fig. 12. There is a significant increase in DCOP achieved in hybrid wheel over entire range of operation due to the fact that the latent heat load in the process air section has increased, however since the regeneration temperature of the air is fixed, then the wheel performance in terms of RMRE is slightly decreased. Fig. 13 shows the performance trend of RMRE and DCOP of H-RDW. It can be found that MRC reduces as inlet moisture of regeneration air increases, but the H-RDW is significantly having higher performance, which is about 20% higher than conventional SG wheel at 10 g/kg inlet moisture of regeneration air.

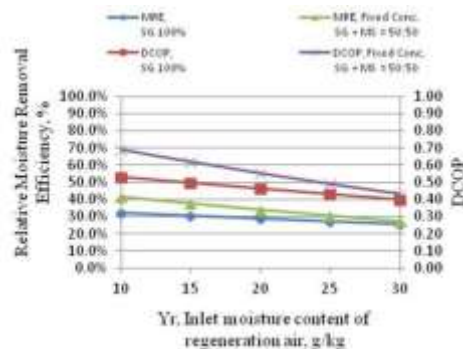
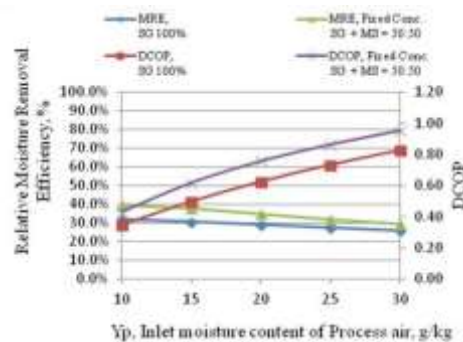


Figure 12. Performance (RMRE & DCOP) due to inlet moisture increase in process air-stream

Figure 13. Performance impact (RMRE & DCOP) due to inlet moisture increase in regeneration air-stream

4.5 Effect of temperature of regeneration air-stream on DPT & DCOP with angle of regeneration section of 180°

The potential performance improvement of the H-RDW is predicted for the 4 cases of mixture concentrations (SG : MS \rightarrow 20:80%, 40:60%, 60:40%, 80:20% and together with conventional MS and SG wheels , named as 0:100 % , 100:0%, respectively and regeneration section angle fixed as 180°. In Fig.14, it can be clearly seen that the dew point temperature (DPT) achieved at the outlet air-flow of different wheel configurations and it decreases while the regeneration air-stream temperature increases. It also be seen that the optimum low value of DPT is achieved from the H-RDW of having concentration of 20:80% SG: MS). In Fig.15, it can be clearly observed that the DCOP decreases for increase in regeneration air temperature. The optimum DCOP value is achieved from H-RDW for the concentration of 40:60% SG: MS.

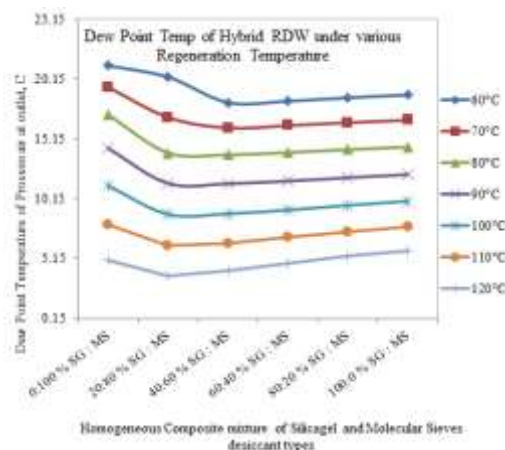


Figure 14. Dew Point Temp of Hybrid RDW under various Regeneration Temperature (regen angle 180°)

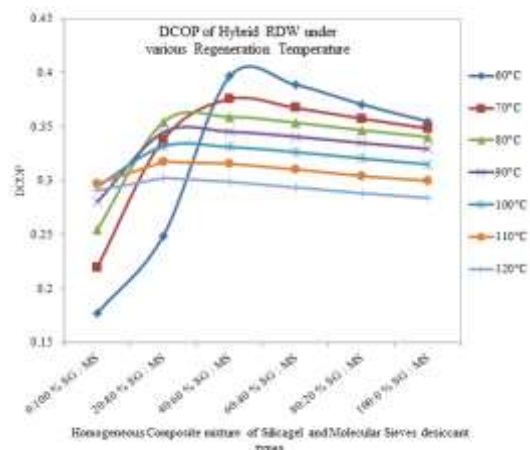
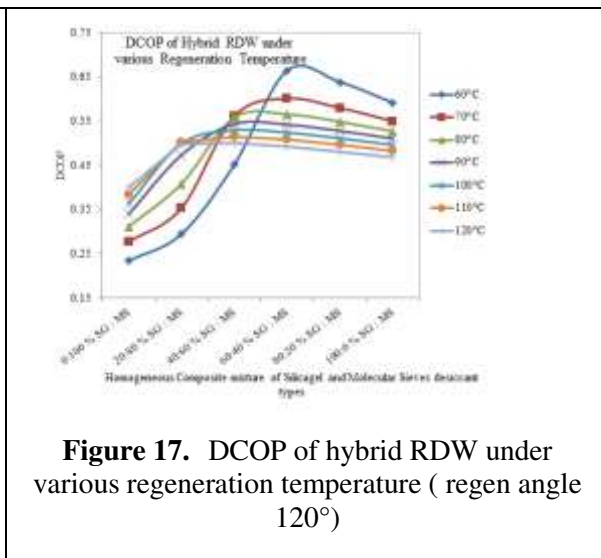
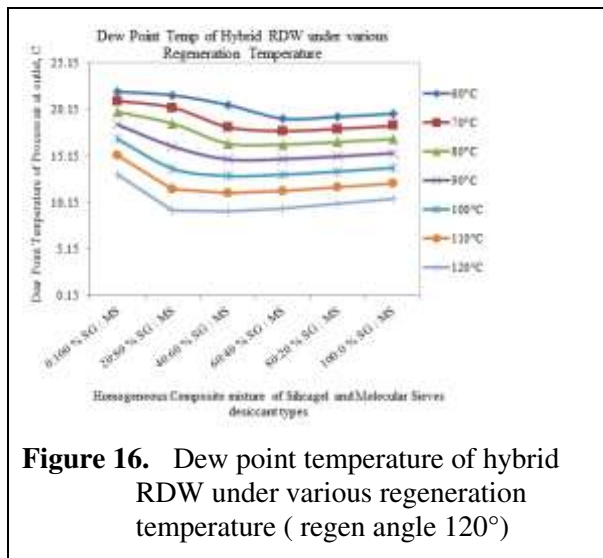


Figure 15. DCOP of Hybrid RDW under various Regeneration Temperature (regen angle 180°)

4.6 Effect of temperature of regeneration air-stream on DPT & DCOP with angle of regeneration section of 120°

Fig.16 shows the dew point temperature (DPT) achieved for the H-RDW configurations with regeneration section angle fixed of 120° and it decreases while the regeneration air-stream temperature increases. It also be observed that the optimum low value of DPT is achieved from the H-RDW of having concentration of 20:80% SG: MS, as low as 9.14°C, however, the same H-RDW has given as low as 3.7°C DPT with the regeneration angle of 180°. In Fig.17, it can be clearly noted that the DCOP

decreases for increase in regeneration air temperature. The optimum DCOP value is achieved from H-RDW for the concentration of 60:40% SG: MS and as high as 0.66, which is 65% higher DCOP compared the value of 0.4 for regeneration angle of 180°.



5. CONCLUSION

The hybrid wheel design using homogeneous composite mixture of desiccant is explained in detail in comparison to conventional desiccant wheels. The performance improvement by using H-RDWs for a range of operating parameters is presented using different concentration ratio of mixtures. Since the hybrid rotary solid desiccant wheels are made of both SG and MS desiccant concentrations of homogeneous mixtures, the optimum performance can be achieved at wide operating conditions by bring the positive aspects of both SG and MS solid desiccants. The moisture removal capacity of the process air-stream and relative moisture removal efficiency with respect to moisture content of inlet of process air of hybrid desiccant wheels are enhanced by 17% to 24% compared to conventional desiccant wheels. The MS wheel is inferior to SG wheel at 90° and 60°C regeneration temperature in terms of MRC and RMRE; whereas the hybrid rotary solid desiccant wheels are showing the potential of superior performance than SG wheels at different regeneration section angles. The benefit of hybrid wheel design is clearly able to be seen in the “pressure dew point” achieved while comparing the conventional wheels for a wide range of regeneration air temperatures and the optimum lowest values are given by 20:80% SG : MS hybrid wheel. Optimum DCOP is achieved for hybrid wheel design of 40:60% SG : MS and 60:40% CG:MS with the regeneration section angle of 180° and 120° respectively, while comparing the conventional wheels for different regeneration air temperatures. With this hybrid rotary solid wheel design, the moisture removal capacity of process air-stream and relative moisture removal efficiency referring to process air inlet and overall DCOP can be enhanced.

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