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Experimental performance analysis of a commercial desiccant wheel: correlation using experimental data

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Abstract: Desiccant wheel is the important component of any rotary desiccant assisted evaporative cooling system, as it has a great potential for energy saving and to minimise environmental impact. The performance analysis of an evaporative cooling system comprising of desiccant wheel is a tough work. In the present work an attempt has been made in order to investigate the importance of effectiveness method for prediction of performance of a desiccant wheel. A set of new and independent effectiveness parameters have been introduced to assess the performance of the desiccant wheel. Extensive experiments have been carried out to observe the variation of performance parameters as function of influencing operating parameters. Based on the experimental data correlations have been proposed for predicting the performance of desiccant wheel. The proposed correlations present a close agreement between experimental and predicted result.

Keywords: desiccant wheel, effectiveness method, effectiveness parameters, correlation

Introduction

Presently most of the HVAC researchers are looking towards new environment friendly technology for comfort air-conditioning in order to use renewable energy and to minimise environmental impact due to conventional system. An air handling unit equipped with evaporative coolers and desiccant wheel dehumidifier can fulfil the present requirement of comfort cooling as well as can utilise waste heat or solar energy as well. Evaporative coolers are used to handle sensible heat load whereas desiccant wheel handle the latent heat load. The dynamic energy analysis for the characterization of desiccant wheel is a tough work. To find out the behaviour of desiccant wheel by using effectiveness method using the operating parameters is a simple but effective method. A number of numerical and experimental methods have been used by different researcher in order to describe the performance of a desiccant wheel under different operating parameters.

Antonellis et al. [1] performed experimental test over a desiccant wheel under a wide range of operating conditions. A low regeneration temperature up to 80°C is used for regeneration of desiccant wheel. Based on the experimental results, correlations had been suggested for predicting the pressure drop and the outlet air conditions. They observed that the performance of desiccant wheel is strongly affected by different operating parameters such as speed of the wheel rotation, face velocity, humidity and temperature of process and regeneration air stream. Ruivo et al. [2] analysed a number of effectiveness parameters with the help of experimental data and concluded that, for a given sorption isotherm, change in enthalpy and adsorbed water content were the most appropriate independent effectiveness parameters for easy and accurate prediction of global behaviour of desiccant wheel. Ruivo et al. [3] tested the performance of a desiccant wheel with imbalance between the volume flow rate of regeneration and process air stream. All the experimental parameters were measured with one temperature and one humidity sensor. For the overall performance of desiccant wheel two pairs of effectiveness parameters were considered and validated. Jani et al. [4] developed a new model based on an artificial neural network for predicting the performance of a desiccant wheel. They also performed experiments to validate the model results. Close agreement between the experimental results and the results obtained by artificial neural network was reported by them. Lee et al. [5] compared the performance of a polymer desiccant wheel and other wheel made of different desiccant material by varying process and regeneration air velocity and wheel rotation speed. It has been reported that polymer desiccant wheel has somewhat higher dehumidification capacity. In some cases [6-8], in order to evaluate the performance of desiccant wheel, mathematical models have been developed and then validated with experimental data. These model results have been used for calculating some figures of merit associated to the wheel as a function of different variables. The performance of desiccant wheel is also analysed experimentally [9-12] while varying the flow rates of process and regeneration air. A solar thermal rotary desiccant wheel cooling system integrated with hot water production unit [13] has been analysed for evaluating its cooling performance, in terms of overall thermal coefficient of performance. In [14], a rotary desiccant wheel model has been validated by means of experimental data taken in a test facility and the data provided by manufacturer than a satisfactory comparison between obtained experimental results and manufacturer data is also performed.

A number of numerical and experimental works have been performed for addressing the global performance of desiccant wheel but still research is required, especially for finding out the most effective pair of effectiveness parameters with the corresponding correlations in order to design the energy efficient air handling system incorporating desiccant wheel. Therefore, the aim of the present research work is to determine the feasibility of new effectiveness parameters with respective correlation for the prediction of global performance of desiccant wheel and investigate the influence of variation in face velocities of process and regeneration air on these effectiveness parameters as a function of regeneration temperature.

Effectiveness Parameters

In a desiccant wheel, combined heat and mass transfer take place when process air or regeneration air pass through the wheel. Effectiveness parameters, if known for a set of operating parameters, can predict the conditions of the process air at exit from the wheel. Different researchers have used different effectiveness parameters, based on enthalpy, relative humidity, specific humidity and temperature. In total, 12 different efficiency and effectiveness parameters related to the desiccant wheel the performance can be defined. Any two of the effectiveness parameters are sufficient to predict the state of air at exit of a desiccant wheel, and hence, the performance of the wheel. The effectiveness of a heat exchanger relates the real and ideal behaviour of a heat exchanger where ideal behaviour work as a reference. Jurinak [15] proposed a pair of effectiveness parameters that has been widely used is based on the characteristic potential F1 and F2, which are basically psychrometric variables and depend on the value of temperature and water vapour content at any given state point. The characteristic potentials for active silica gel desiccant wheel were investigated by [15] and can be estimated by the following mathematical equations.

$$F1 = \frac{-2865}{T^{1.49}} + 4.344\, d^{0.8644} \qquad (1)$$

$$F2 = \frac{T^{1.49}}{6360} - 1.127\, d^{0.07969} \qquad (2)$$

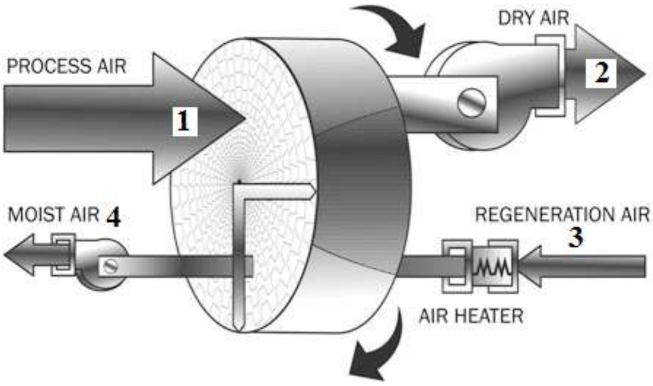


Fig. 1. Desiccant wheel

The temperature (T) and water vapour content (d) are expressed in Kelvin and kg/kg respectively. The effectiveness parameters based on the characteristic potential F1 and F2 are defined as follow;

$$\eta_{F1} = \frac{(F1)_1 - (F1)_2}{(F1)_1 - (F1)_3} \qquad (3)$$

$$\eta_{F2} = \frac{(F2)_1 - (F2)_2}{(F2)_1 - (F2)_3} \qquad (4)$$

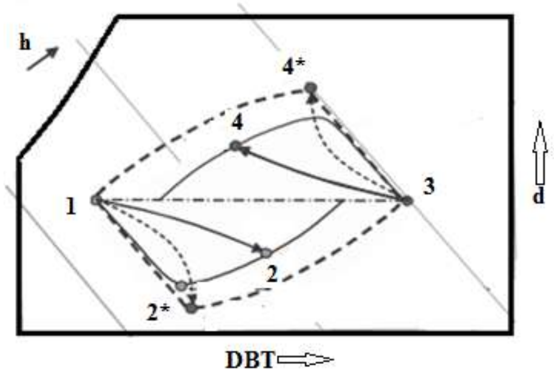


Fig. 2. Representation of ideal and real dehumidification behavior of desiccant wheel

Referring to Fig. 1, process air in and out is represented by 1 and 2 whereas 3 and 4 represent the regeneration air in and out respectively. The ideal and real behavior of desiccant wheel is represented in Fig. 2.For the process air, (1 - 2) represents the real dehumidification process where as the dotted line (1 - 2*) represents the ideal dehumidification process on psychrometric chart. In the same way for regeneration air, (3 - 4) represents the real desorption process whereas (3 – 4*) represents the ideal desorption process. The other popular effectiveness parameters as referred in literature are commonly related to specific enthalpy, relative humidity, and temperature. The effectiveness parameters suggested by Ruivo et al. [2] are based on relative humidity and enthalpy and are defined as follow;

$$\eta_{\phi}=\frac{\phi_1-\phi_2}{\phi_1-\phi_3} \tag{5}$$

$$\eta_{h}=\frac{\mathrm{h}_2-\mathrm{h}_1}{\mathrm{h}_3-\mathrm{h}_1} \tag{6}$$

Pahlavanzadeh [9] has used the effectiveness parameters based on temperature and water vapour content of moist air.

$$\eta_{T}=\frac{T_2-T_1}{T_3-T_1} \tag{7}$$

$$\eta_{d}=\frac{d_1-d_2}{d_1-d_{2,ideal}} \tag{8}$$

For ideal desiccant wheel the value of $d_{2,ideal}$ is taken as zero, which is an indication of complete dehumidification. A number of effectiveness parameters have been used by different researcher, it is important to define the most suitable effectiveness parameters in order to predict the performance of a commercially available desiccant wheel. In the present study some of the new non-dimensional parameters based upon relative humidity, specific humidity, temperature and specific enthalpy have been introduced in order to define the performance of desiccant wheel are as follow,

Non- dimensional relative humidity (RH) parameter:

$$RH^{*}=\frac{\left(RH_1-RH_2\right)}{\left(RH_1\right)}=\frac{\left(\phi_1-\phi_2\right)}{\left(\phi_1\right)} \tag{9}$$

Where ‘ ϕ ’ is the symbolic representation for relative humidity.

Non- dimensional specific humidity (SH) parameter:

$$SH^{*}=\frac{\left(SH_1-SH_2\right)}{\left(SH_1\right)}=\frac{\left(d_1-d_2\right)}{\left(d_1\right)} \tag{10}$$

Where ‘ d ’ is the symbolic representation for specific humidity.

Non- dimensional temperature (T) parameter:

$$T^{*}=\frac{\left(t_2-t_1\right)}{t_1}\quad (\mathrm{t}\, is\, in\, {}^{o}C) \tag{11}$$

Non-dimensional Enthalpy (H) parameter:

$$H^* = \frac{\left(h_2 - h_1\right)}{h_1} \qquad (12)$$

It may be mentioned that for predicting the performance of a desiccant wheel any two of thenon-dimensional performance parameters are needed, therefore if inlet conditions of process air and any two of above non- dimensional parameters are known then all the other property of process air outlet can be easily calculated.

Test facility

The schematic of the experimental setup for desiccant wheel test facility (Fig. 3) is located at Indian Institute of Technology (ISM) Dhanbad. In this paper the attention has been particularly focused on the performance of desiccant wheel which is the most important component of dehumidification system. The regeneration of the desiccant material is obtained by using air at temperatures 60–100 °C; the thermal energy for the regeneration is taken directly from an electric heater. In the test facility, silica-gel is used as a desiccant material because it can be efficiently regenerated at temperature as low as 60–100°C. The matrix of the rotor is made in honeycomb shape because it provides maximum surface contact area and moderate pressure drops with high structural durability. The desiccant wheel handles up to 600 m^3/h of process air and 200 m^3/h of regeneration air. The 75% of the total area of desiccant wheel is crossed by the process air, while 25% by the regeneration air. The diameter and thickness of the desiccant wheel are equal to 460 mm and 100 mm, respectively; nominal rotational speed equal to 27 RPH (revolutions per hour). Both air streams, the process air and the regeneration air are taken from ambient. The process air passes through the desiccant wheel and gets dehumidified whereas regeneration air is first heated by the heating coil interacting with the dehumidification system, and then it is used to regenerate the desiccant material of the wheel.

All the data are taken under steady state for a given set of operating conditions. The dry bulb temperature and relative humidity for the process and regeneration air streams are measured at inlet and outlet of process and regeneration air by using ‘K’ type thermocouples (accuracy: 0.5°C) and RH sensors (accuracy: ± 2.5% RH) respectively. The air flow rates of the process and regeneration air streams are measured by using hotwire anemometer (accuracy: ±03%). All the measured data which are obtained as a result of experiments are used for calculating the values of all the required non- dimensional parameters RH*, SH*, T* and H*.

Results and discussion

The performances of a desiccant wheel, in terms of humidity reduction and the outlet temperature of process air, depend on a number of operational and ambient parameters. The effects of the regeneration air temperature, as well as the velocity of process and regeneration air entering the desiccant wheel, are examined in this paper. For evaluating the performance of desiccant wheel some of the representative experimental results are presented in Fig. 4 and Fig. 5.

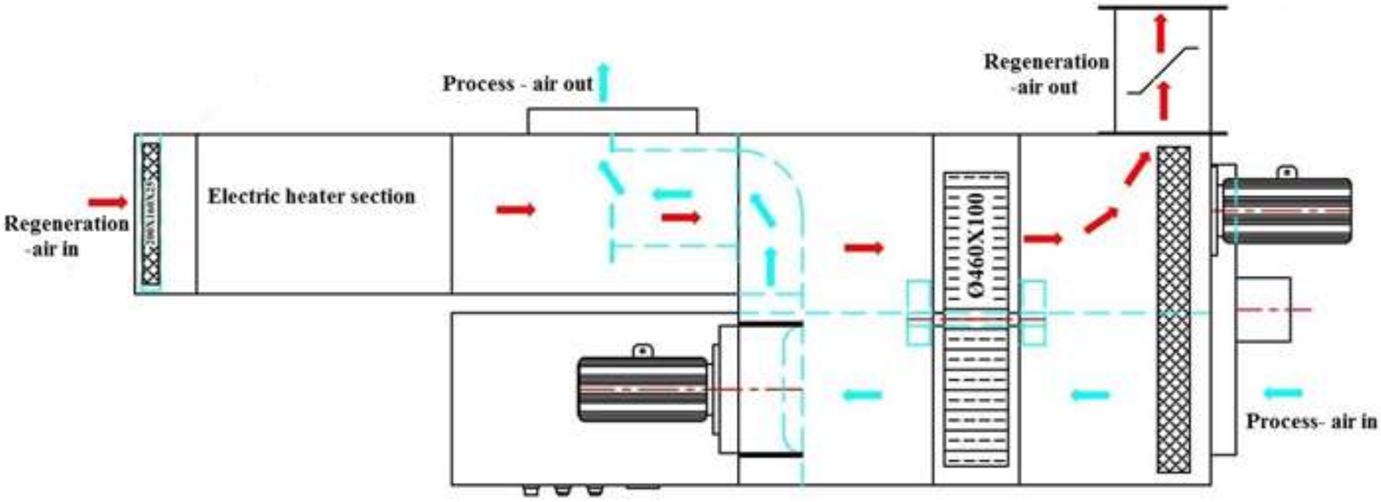


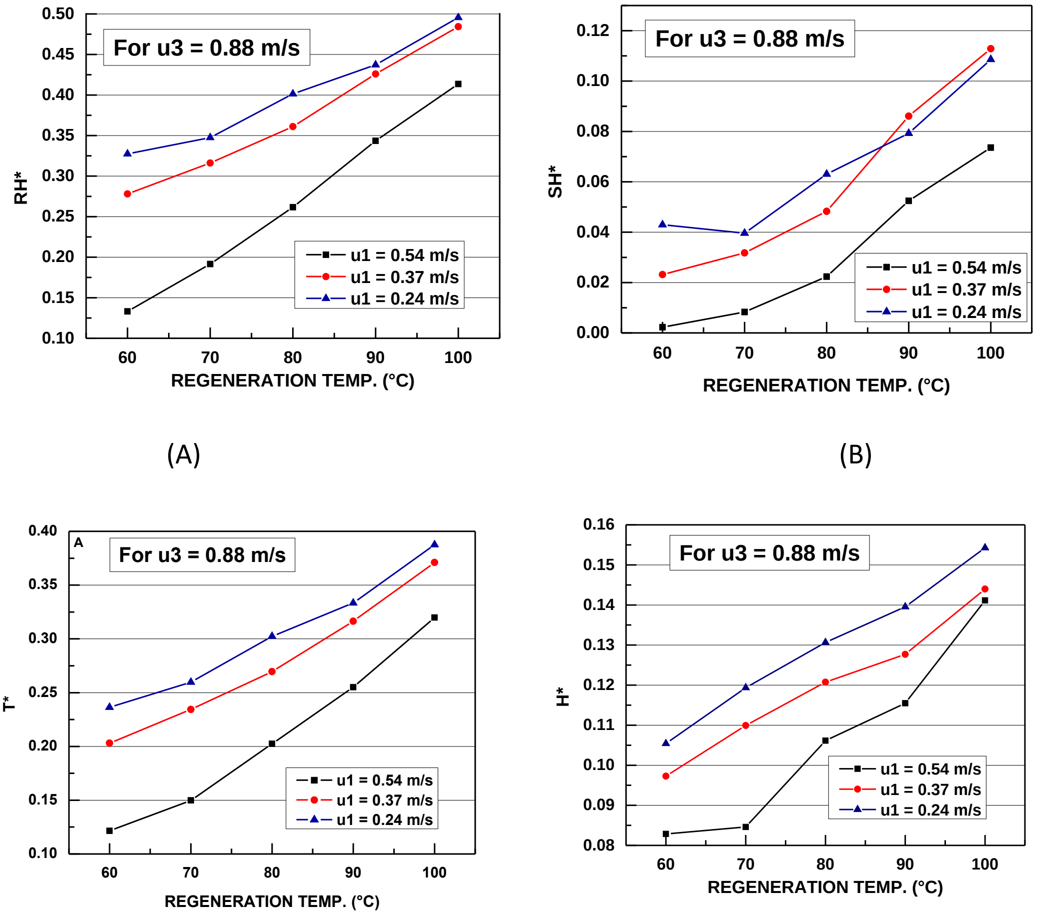
Fig. 3. Test facility layout.

Effects of Process air inlet velocity

To study the effect of process inlet air velocity, other influencing parameters, like regeneration inlet air velocity and rotational speed of desiccant wheel (27 RPH), have been maintained fixed. Fig. 4 exhibits the variation of four different performance parameters, RH*, SH*, T* and H*, of the desiccant wheel with varying regeneration temperature and for three different process air velocities with fixed regeneration air velocity of 0.88 m/s. When process air passes through the desiccant wheel, air is dehumidified, thus, relative humidity and specific humidity of process air are lower at exit than those at inlet of the wheel. Dehumidification of air is associated with increase in process air temperature and enthalpy. Thus, increase in the values any of the performance parameters, RH*, SH*,T* and H*, represent increase in dehumidification and better performance of the desiccant wheel.

The general observations from Fig. 4 are as follows:

For the same process air velocity, as the temperature of regeneration air increases, the dehumidification of process air in the desiccant wheel also increases. Thus there is increase in all the performance parameters: RH*, SH*, T* and H*. This is because, with increase in regeneration air temperature, the vapour pressure of the moisture present in the desiccant wheel increases due to which, the vapour pressure difference between the desiccant surface and regeneration air also increases leading to the higher removal of moisture from the desiccant wheel matrix. As desiccant wheel matrix is drier, higher amount of moisture from the process air can be adsorbed. Again, for a given regeneration air temperature, the dehumidification of process air decreases with increase in process air velocity, causing decrease in all the performance parameters. Increase in process air inlet velocity reduces the time of contact between the wheel and the process air causing less amount of moisture absorbed from the process air. However, the effect of higher process inlet air velocity on reduction in the performance can be compensated by increasing the regeneration air temperature. Therefore, larger amount of air per unit time can be dehumidified by increasing the process air inlet velocity and the desired performance of the wheel can be maintained by increasing the temperature of the regeneration air. It is seen from Fig. 4 that all the performance parameters increase steadily with increase in temperature of regeneration air for a given process air velocity. Figs.4A and 4B show maximum values obtained for RH* and SH* are 0.5 and 0.11, respectively, for the lowest process air velocity and the highest regeneration air temperature. The corresponding values of T* and H* are 0.38 and 0.155, respectively (Figs. 4C and 4D). It is also exhibited from the figures that at higher velocities of process air, the performance of the desiccant wheel may be very low and not acceptable. To obtain acceptable performance under such cases, the regeneration temperature is required to be increased.



(A)

(B)

(C)

(D)

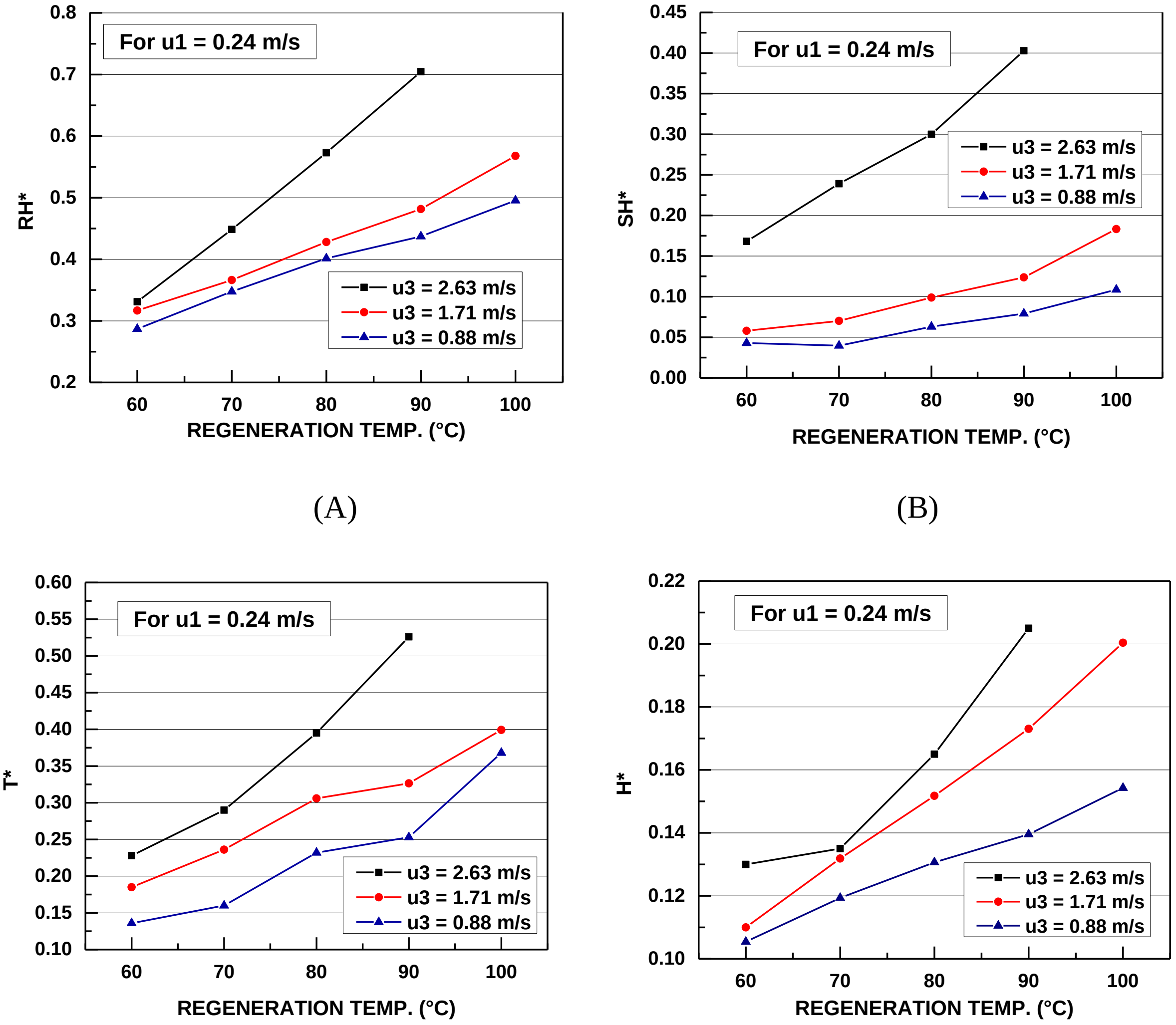
Fig. 4: Effect of regeneration temperature at various process air velocity (u1) and at a given regeneration air velocity (u3)

Effects of regeneration air inlet velocity:

Since the area of flow is fixed, increase in velocity of regeneration air also increase the mass flow rate of regeneration air, which, in turn, improves the desorption of moisture from the wheel in the regeneration section leading to better adsorption of the moisture in process area. Fig. 5 exhibits the variation of four different performance parameters, RH*, SH*, T* and H*, of the desiccant wheel with varying regeneration temperature and for three different regeneration air velocities with fixed process air velocity of 0.24 m/s.

The general observations from Fig. 5 are as follows:

For a particular regeneration air velocity, as the temperature increases, the dehumidification of process air in the desiccant wheel also increases with improvement of all the performance parameters. Again, for a given regeneration air temperature, the dehumidification performance of the wheel increases with increase in regeneration air velocity. Increase in regeneration air inlet velocity allows larger amount of regeneration air to flow through the regeneration section of the wheel causing desorption of greater amount of moisture from the wheel matrix.



(A)

(B)

(C)

(D)

Fig. 5: Effect of regeneration temperature at various regeneration air velocity (u3) and at a given process air velocity (u1)

It is also observed that by increasing the process air inlet velocity, it is possible to dehumidify larger amount of process air per unit time, and the associated drop in performance (as seen in Fig.4)can be compensated either by increasing the regeneration air temperature or by increasing the regeneration air velocity or by both of them. Form Fig.5 it is clear that both the regeneration air temperature and regeneration air velocity should be in accordance to the moisture load that is being removed from the desiccant wheel. If the moisture load of the desiccant wheel increases more energy must be supplied to the desiccant to insure complete regeneration of the desiccant wheel and keep the system in equilibrium. The effect of lower regeneration air temperature is similar to having lower regeneration air velocity, because the net heat available for regeneration is a function of regeneration air velocity and temperature difference between the air and desiccant wheel. We can also say that high regeneration air temperature and velocity will deliver more heat for regeneration and so the desiccant wheel can absorb more moisture in process area. However if the temperature of the regeneration air is constant and air velocity is increased beyond the required level, then the energy will simply be wasted because regeneration air leaves the desiccant wheel at higher temperature than necessary carrying heat off to the outside. So regeneration air velocity should be properly controlled. With increase in regeneration air velocity along with regeneration air temperature the value of all the non-dimensional performance parameters such as RH*, SH*, T*, and H* are increased (Fig. 5), because the dehumidification capacity of the desiccant wheel is increasing. It is also clear that for given moisture load of the wheel, high regeneration air velocity can reduce the regeneration temperature requirement for complete regeneration of the desiccant wheel.

Uncertainty analysis

This method allows the calculation of the uncertainty in results achieved by calculation from measured variables. Rather than sum the uncertainty values associated to the different measurements. According to this method, as the errors are statistically independent, they will somewhat counteract each other most of the time, and so, the square root of the sum of the squares of the specific uncertainties is a more demonstrative value of the whole random uncertainty. The root sum square method uses the following relation;

$$\omega_R = \left[\left(\frac{\partial R}{\partial x_1} \omega_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \omega_2 \right)^2 + \ldots\ldots\ldots + \left(\frac{\partial R}{\partial x_n} \omega_n \right)^2 \right]^{1/2} \qquad (13)$$

Where ω_R be the uncertainty in the result and $\omega_1, \omega_2, \ldots, \omega_n$ be the uncertainties in the independent variables and R is the result of experiment which is the function of independent variables $x_1, x_2, \ldots\ldots, x_n$. In the present work, all the performance parameters such as (RH^*, SH^*, T^*, H^*) are obtained by calculating temperature and relative humidity at the inlet and outlet of process and regeneration air stream and all these measured variables are characterized by a given value of uncertainty, which depends on the sensors accuracy. Fig.6, shows all the estimated uncertainty in $RH^*, SH^*, T^* \& H^*$ as a function of different regeneration temperature with the help of error bar. Here the velocity of regeneration air just before the wheel (u_3 =2.63 m/s) is taken as constant and two different velocity of process air (u_1=0.37 m/s and 0.31 m/s) has been used for showing the uncertainty variation.

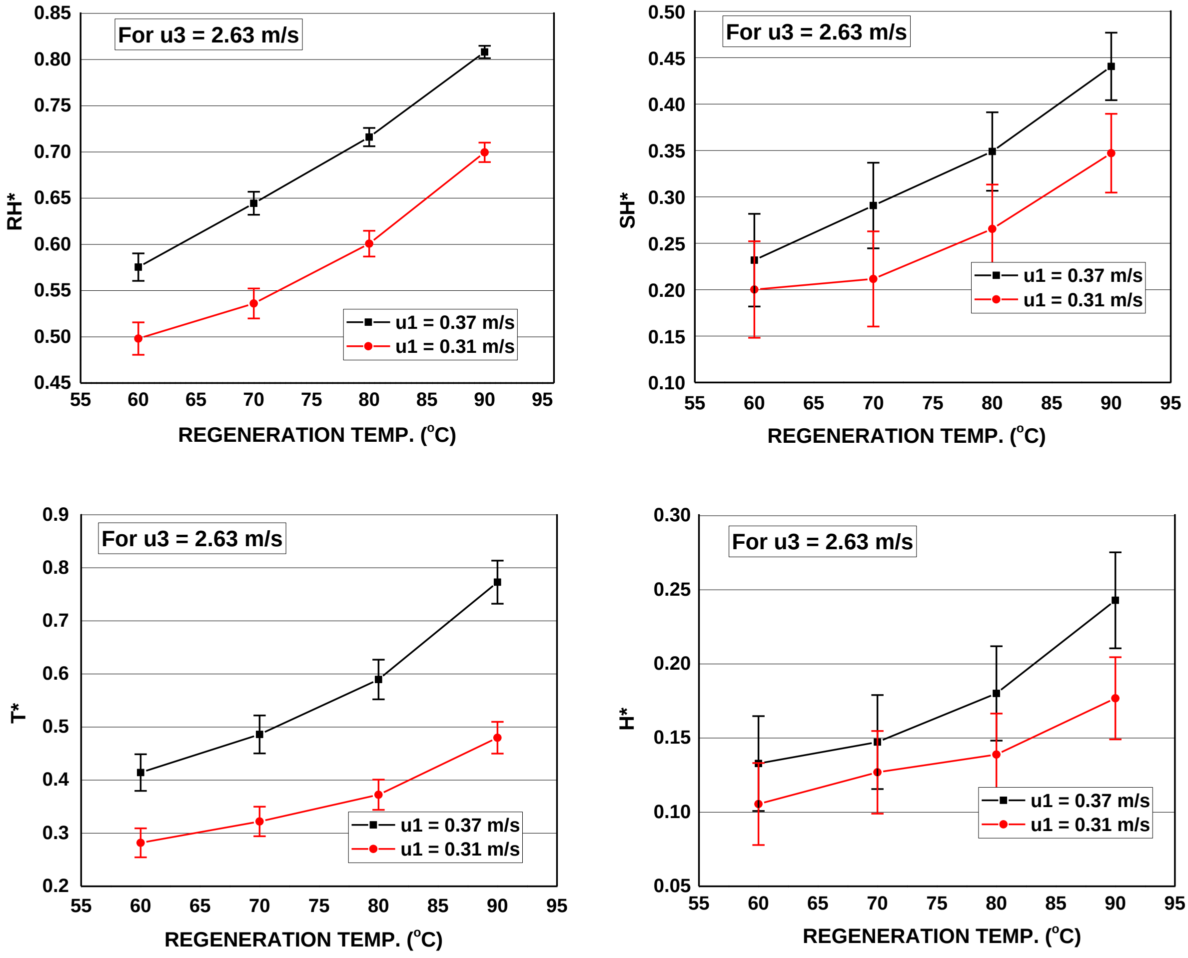


Fig. 6. Representation of uncertainty in RH^*, SH^*, T^*, H^* as a function of regeneration temperature

Effectiveness correlations

Extensive experiments have been performed by varying different operating conditions like process air inlet temperature (t_1) and relative humidity (ϕ_1), regeneration air inlet temperature (t_3) and relative humidity (ϕ_3), face velocities of process air (u_1) and regeneration air (u_3). The other parameters which influence the performance of desiccant wheel are RPH (revolutions per hour) of the wheel and the width of the wheel. But these parameters are not varied during this study, and hence, not been considered for correlations. To reduce the number of variables and to non-dimensionalize the variables, following non-dimensional parameters have been introduced.

Non-dimensional velocity, $X_1 = \frac{u_3}{u_1}$ (14)

Non-dimensional relative humidity, $X_2 = \frac{RH_3}{RH_1}$ (15)

Non-dimensional temperature, $X_3 = \frac{t_3}{t_1}$ (t is in °C) (16)

All the effectiveness parameters RH*, SH*, T*, and H*are strongly dependent on the inlet conditions of process and regeneration air as well as the face velocity of both air stream. Therefore, in order to predict the performance of desiccant wheel four independent correlations should be calculated. For the proposed correlations total three independent terms X_1, X_2 and X_3 are used. Finally the correlations proposed in this study for the prediction of RH*, SH*, T* and H* are as follow;

$$RH^* = 0.021\, X_1^{0.542} X_2^{0.793} X_3^{3.987} \quad (17)$$

$$SH^* = 0.001\, X_1^{1.165} X_2^{1.40} X_3^{6.456} \quad (18)$$

$$T^* = 0.003\, X_1^{0.638} X_2^{1.842} X_3^{7.685} \quad (19)$$

$$H^* = 0.023\, X_1^{0.191} X_2^{0.080} X_3^{1.525} \quad (20)$$

For the proposed correlations the value of square of the correlation between the response values and the predicted response values (R^2), Sum of Squares Due to Error (SSE), mean square error (MSE) and Root Mean Squared Error (RMSE) and maximum deviation between the measured and predicted results have been shown in Table 1.

Table: 1 Goodness of fit statistics for proposed correlations

Performance Parameter	Correlations	Goodness of fit statistics				Maximum deviation
		R^2	SSE	MSE	RMSE	
$RH*$	$RH^* = 0.021\, X_1^{0.542} X_2^{0.793} X_3^{3.987}$	0.886	0.291	0.003	0.050	± 10%
SH^*	$SH^* = 0.001\, X_1^{1.165} X_2^{1.40} X_3^{6.456}$	0.870	0.149	0.001	0.036	± 10%
T^*	$T^* = 0.003\, X_1^{0.638} X_2^{1.842} X_3^{7.685}$	0.917	0.157	0.001	0.037	± 8%
H^*	$H^* = 0.023\, X_1^{0.191} X_2^{0.080} X_3^{1.525}$	0.731	0.038	0.000	0.018	± 12%

$R^2$is the statistic which measures how successful the fit is in explaining the variation of the data. In the present study the fit explains 88.6%, 87%,91.7% and 73.1% of the total variation in the data about the average for RH*, SH*, T*, and H* respectively. SSE is the statistic which measures the total deviation of the response values from the fit to the response values. In all the non-dimensional effectiveness parameters the value of SSC for H* has minimum therefore it has smaller random error component, and that this fit will be more useful for prediction. The MSE value for all the non-dimensional parameters are closed to zero, which indicate all the correlation can be used for prediction. The RMSE indicate the standard error of the regression, and estimate of the standard deviation of the random component in the data. Fig.7 exhibits comparison of predicted and measured values of all the performance parameters. It can be seen that except for correlation for H^*, all the correlations exhibit good agreement between measured and predicted performance parameters. Thus, can be used for prediction of performance of the desiccant wheel.

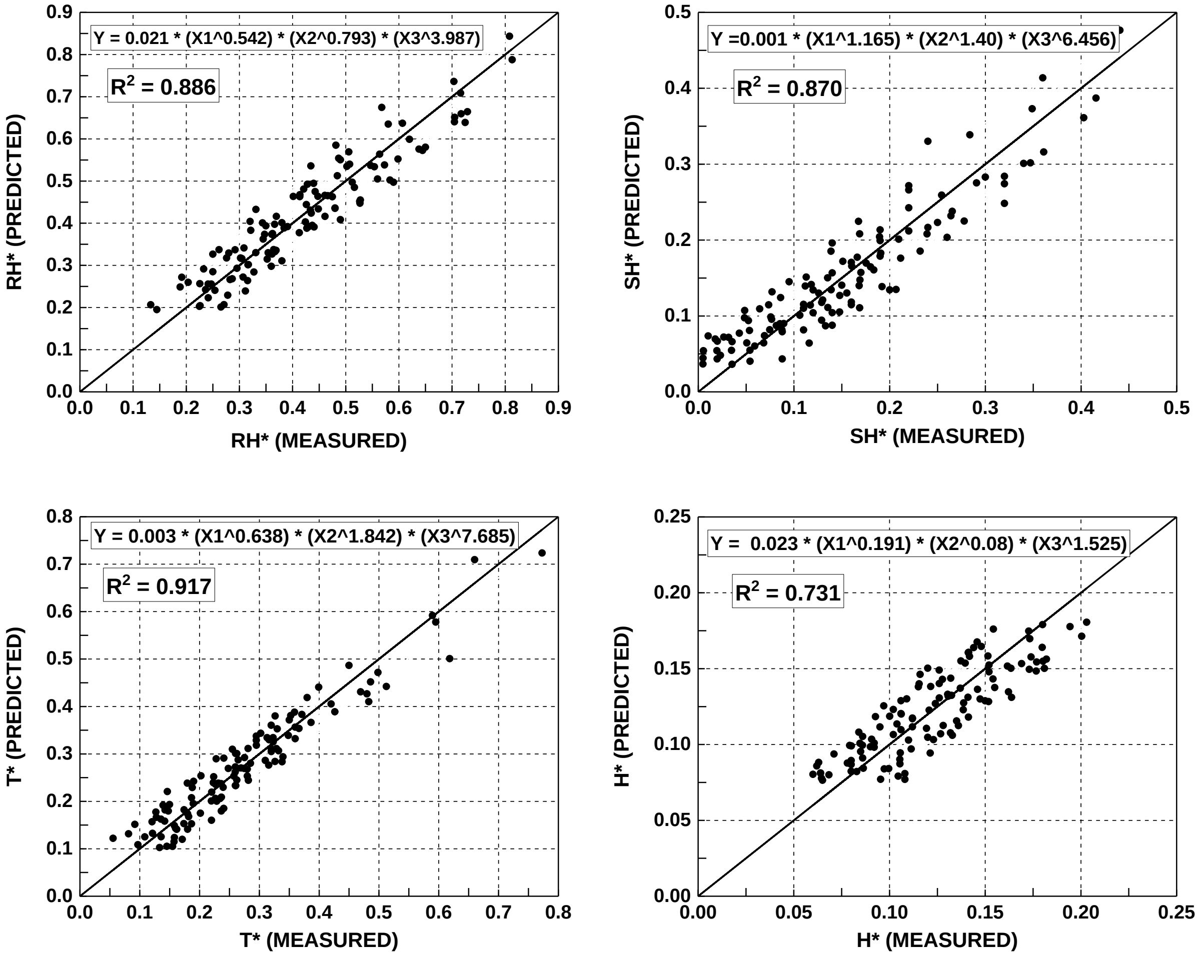


Fig. 7: Comparison between measured and predicted performance parameters

Conclusions

In the present study experiments have been performed under different operating conditions on a commercially available desiccant wheel and a set of new effectiveness parameters have been introduced to describe the performance of the wheel. The effectiveness parameters RH^*, SH^*, T^*, H^* are based on the difference of relative humidity, specific humidity, temperature and enthalpy, respectively of the process air at inlet and exit of the wheel. Following conclusions can be drawn from the experimental results:

- Increase in regeneration air velocity and/or regeneration air temperature increase the dehumidification performance of wheel while increase in process air velocity decreases the performance. However, the effect of higher process inlet air velocity on reduction in the performance can be compensated by increasing the regeneration air temperature. At higher velocities of process air, the performance of the desiccant wheel may be very low and not acceptable. To obtain acceptable performance under such cases, the regeneration temperature is required to be increased. By increasing the process air inlet velocity, it is possible to dehumidify larger amount of process air per unit time, and the associated drop in performance can be compensated either by increasing the regeneration air temperature or by increasing the regeneration air velocity or by both of them.

- Regeneration air temperature and regeneration air velocity should be in accordance to the moisture load of the desiccant wheel. If the moisture load of the desiccant wheel increases more energy must be supplied to the desiccant to insure complete regeneration of the desiccant wheel and keep the system in equilibrium. At the same time, the regeneration air velocity should be controlled to minimise wastage of energy. Higher regeneration air velocity is an effective method for reducing the requirement of high regeneration temperature for regeneration of the desiccant wheel. Thus, we can use low-temperature energy sources for heating the regeneration air.

Based on the experimental data, correlations have been proposed to predict the performance of desiccant wheel. It is shown that the proposed correlations predict fairly well the performance of the desiccant wheel and hence, the outlet condition of the process air. The maximum deviation between predicted and measured values for RH^*, SH^*, T^* are within ± 10%, whereas for H^* it is within ± 12%for all of the analysed cases. The developed correlation has a great practical significance and useful for the dynamic energy simulation of all the systems incorporating with desiccant wheel. The value of all the non-dimensional parameters RH*, SH*,T*, and H*are closed to zero which is one another indication that all the correlation can be used for prediction of performance of desiccant wheel.

Nomenclature

d	specific humidity(kg/kg)
F1, F2	characteristic potential
h	specific enthalpy(kJ/kg)
HVAC	heating ventilation and air-conditioning
H^*	non dimensional enthalpy parameter
P_v	vapour pressure
P_{vs}	saturated vapour pressure
RH^*	non dimensional relative humidity parameter

SH^*	non dimensional specific humidity parameter
T	temperature(K)
t	temperature(°C)
T^*	non dimensional temperature parameter
u1	process air face velocity (m/s)
u3	regeneration air face velocity(m/s)
w_{t^*}	uncertainty parameter in temperature
w_{φ^*}	uncertainty parameter in relative humidity
w_{d^*}	uncertainty parameter in specific humidity
w_{h^*}	uncertainty parameter in specific enthalpy
X	non dimensional parameter
Greek Symbol	
Φ	relative humidity
η	effectiveness parameter

Reference

[1].De Antonellis, Stefano, Manuel Intini, and Cesare Maria Joppolo. "Desiccant wheels effectiveness parameters: correlations based on experimental data." *Energy and Buildings* 103 (2015): 296-306.

[2].Ruivo, C. R., et al. "Effectiveness parameters for the prediction of the global performance of desiccant wheels–an assessment based on experimental data." *Renewable energy* 38.1 (2012): 181-187.

[3].Ruivo, Celestino R., and Giovanni Angrisani. "The effectiveness method to predict the behaviour of a desiccant wheel: an attempt of experimental validation." *Applied Thermal Engineering* 71.2 (2014): 643-651.

[4].Jani, D. B., Manish Mishra, and P. K. Sahoo. "Performance prediction of rotary solid desiccant dehumidifier in hybrid air-conditioning system using artificial neural network." *Applied Thermal Engineering* 98 (2016): 1091-1103.

[5].Kang, Hyungmook, and Dae-Young Lee. "Experimental investigation and introduction of a similarity parameter for characterizing the heat and mass transfer in polymer desiccant wheels." *Energy* 120 (2017): 705-717.

[6].Ge TS, Ziegler F, Wang RZ. A mathematical model for predicting the performance of a compound desiccant wheel (a model of compound desiccant wheel). Appl Therm Eng 2010;30:1005–15.

[7].Stabat P, Marchio D. Heat and mass transfer modeling in rotary desiccant dehumidifiers. Appl Energy 2009;86(5):762–71.

[8].Esfandiari FN, van Paassen D, Saidi MH. Modeling and simulation of desiccant wheel for air conditioning. Energy Build 2006;38:1230–9.

[9].Mandegari MA, Pahlavanzadeh H. Introduction of a new definition for effectiveness of desiccant wheels. Energy 2009;34:797–803.
[10].Subramanyam N, Maiya MP, Srinivasa Murthy S. Parametric studies on a desiccant assisted air-conditioner. Appl Therm Eng 2004;24:2679–88.
[11].Enteria N, Yoshino H, Satake A, Mochida A, Takaki R, Yoshie R, et al. Experimental heat and mass transfer of the separated and coupled rotating desiccant wheel and heat wheel. Exp Therm Fluid Sci 2010;34:603–15.
[12].Enteria N, Yoshino H, Mochida A, Takaki R, Satake A, Yoshie R, et al. Construction and initial operation of the combined solar thermal and electric desiccant cooling system. Sol Energy 2009;83:1300–11.
[13].Enteria N, Yoshino H, Satake A, Mochida A, Takaki R, Yoshie R, et al. Development and construction of the novel solar thermal desiccant cooling system incorporating hot water production. Appl Energy 2010;87:478–86.
[14].Panaras G, Mathioulakis E, Belessiotis V, Kyriakis N. Experimental validation of a simplified approach for a desiccant wheel model. Energy Build 2010;42:1719–25.
[15].J.J. Jurinak, Open cycle desiccant cooling - Component models and system simulations, PhD thesis, University of Wisconsin, Madison, 1982.
[16].Experimental methods for engineers, Eighth edition, J P Holman.