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Solar unit for air conditioning and desalination: theoretical and experimental investigation of the desiccant wheel

Zied Guidara*, Alexander Morgenstern, Peter Schossig, Habib Ben Bacha

Laboratory of Electro-Mechanic Systems (LASEM), National School of Engineers of Sfax (ENIS), University of Sfax (US), B.P. 1173, Road Soukra km 3.5, 3038 Sfax, TUNISIA

Abstract: In this research, a presentation of a new solar unit for air conditioning and desalination is presented firstly. Secondly, a dynamic modelling study of the desiccant wheel is developed. After that, a simulation study and an experimental investigation of the behaviour of desiccant wheel are developed. Concerning the modelling study, mathematical equations are based mainly on thermal and mass balances. Concerning the simulation study, a finite differences method is applied to the partial differential equations. The experimental investigation is done in the chamber of commerce in Freiburg-Germany. Indeed, the variations of calculated and measured temperatures and specific humidity of dehumidified and rejected air are presented. Finally, this study shows that good agreement is found when comparing the model predictions with experimental data under the considered range of operating conditions.

Key words: Air conditioning; desalination; design; desiccant wheel; modelling; simulation; experimental investigation.

1. Introduction

Providing conditioned air and fresh water is a necessity in daily life. However conventional units which are used to satisfy this need, have a negative impact on the environment and consume an important quantity of electricity. So solving these problems should be realized without breaking the international commitments relative to the environmental protection. Indeed, these commitments mainly intend to reduce CO_2 emissions, avoid the use of harmful gases to the ozone layer and to the greenhouse effect used especially in the conventional air conditioners.

In this context, desiccant units of air conditioning present a promising solution for air conditioning, in terms of environmental protection and energy saves. In addition, desiccant dehumidification is advantageous in handling latent heat, easy to be regenerated using low-grade energy, such as solar energy [1].

Furthermore, with conventional units of air conditioning, the dehumidification of the air is done through a cooling operation under dew point temperature [2]. Thus, the air is too cold to be used as direct supply air to the conditioned space and has to be heated up again. This operation can be characterized as an energy consuming procedure [3] and in some cases it cannot ensure the achievement of temperature and humidity levels required by the user [4]. For temperate climates, standards configurations are typically employed. However, as far as the climates in the Mediterranean countries are concerned, other configurations of desiccant processes have to be implemented [5, 6]. In fact, a block of cooling in these configurations is generally installed, before or after dehumidifying the air. The cooling, on the other hand, is obtained through the use of cooling coils that are fed by cold water which is produced by machines with sorption technique or conventional refrigerated machines.

*** Corresponding author:** Zied Guidara
E-mail: ziedguidara@yahoo.fr.

G. Panaras et al [7] showed that the desiccant wheel is a basic element of desiccant air-conditioning systems, responsible for the dehumidification of the air.

In this research work, a new design of a solar air conditioning unit is presented: with desiccant wheel to dehumidify the air, solar collector to produce hot water for regeneration, humidifiers for humidification and a combination of heat exchangers-humidifiers to ensure the cooling of the air without the use of machines with sorption technique or conventional refrigerated machines. In addition, a desalination stage is used in this unit. Indeed, the functioning of this stage is based on the dehumidification- humidification process.

Furthermore, a modelling study which is based mainly on thermal and mass balances is developed. Thus, a simulation study and an experimental investigation of the functioning of the desiccant wheel are presented.

The content of this paper is organized as follows. Section 2 is dedicated to the design of the solar unit. In section 3, the functioning of the unit is described. Section 4, presents a modelling study of the desiccant wheel. In section 5, a simulation study and an experimental investigation of the functioning of the desiccant wheel are presented.

Finally, section 6 presents the main conclusion of this work.

2. Design of the solar air conditioning unit

The design of the solar air conditioning unit is presented in Fig. 1. Compared with standard unit, two stages are added. Indeed, the first one is responsible of the pre-cooling of the ambient air and the second one is dedicated to the desalination of the salty underground cold water. The pre-cooling stage is mainly composed by a humidifier HUM3 and a heat exchanger HEX3. The desalination stage is mainly composed by a humidifier HUM4 and a heat exchanger HEX4.

3. Description of the functioning of the unit

The principle of functioning can be described as follows:

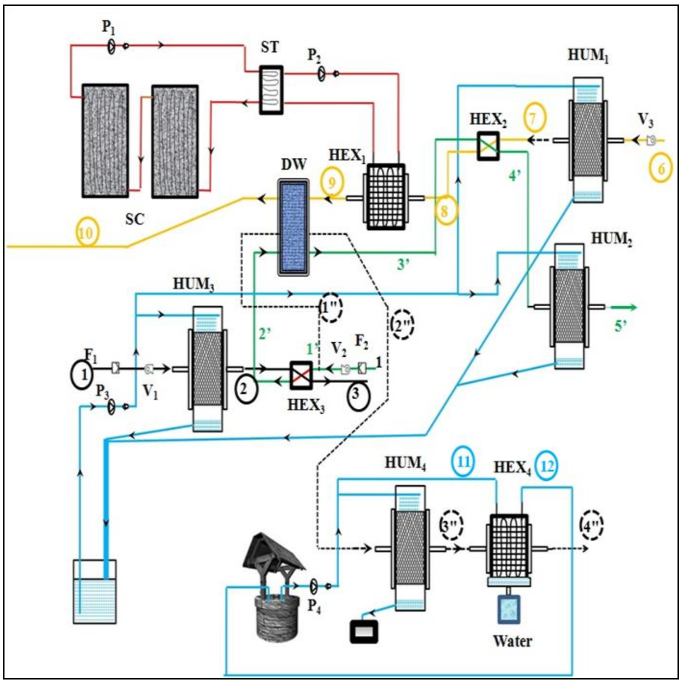

Fig. 1 Design of the solar unit

Two main cycles of functioning are distinguished concerning this unit.

The principle of functioning can be described as follows:

*Air conditioning cycle:

The ambient air is cooled close to the saturation line in a humidifier HUM3 (from 1 to 2). Then, this cold air (from 2 to 3) ensures in an air/air heat exchanger HEX3 a pre-cooling of the ambient air to treat (from 1, 1’ to 2’). Therefore, the first pre-cooling of the ambient air is finished. In fact, this stage is very important because it reduces the gradient of temperature which results from the dehumidification of the air which is an exothermic phenomenon. Then, the pre-cooled air is dehumidified and heated (from 2’ to 3’) by passing through a desiccant wheel DW. Later on, the dehumidified air is pre-cooled (from 3’ to 4’) in an air/air heat exchanger HEX2 by the air that returns from the space conditioned humidified and cooled (from 6 to 7) close to the saturation in the humidifier HUM1. Furthermore, the air is cooled (from 4’ to 5’) to the desired temperature and humidity in the humidifier HUM2 corresponding to the state of human comfort.

Concerning the regeneration, the air that returns from the conditioned space humidified and cooled (from 6 to 7) is pre-heated (from 7 to 8) by passing through an air/air heat exchanger HEX2.

Furthermore, the pre-heated air is heated (from 8 to 9) by passing through a water/air heat exchanger HEX1 where the hot water is produced by the solar energy from flat plate solar collectors and a storage tank. Then, this hot air passes through the hygroscopic wheel to ensure its regeneration (from 9 to 10).

*Desalination cycle:

The ambient air is dehumidified and heated (from 1, 1" to 2") by passing through a desiccant wheel DW. Then, the dehumidified air is humidified and cooled (from 2" to 3") close to the saturation in the humidifier HUM4 by the use of salty underground water. Later on, this cooled and humidified air passes through a water/air heat exchanger HEX4 to be dehumidified by cooling under its dew point temperature (from 3" to 4"). As a consequence a quantity of pure water is obtained by condensation at the exit of the heat exchanger water/air HEX4.

4. Modelling study

The modelling of the desiccant wheel is based on mass and thermal balances for the air flow and the desiccant. The desiccant wheel is divided in two parts, the first one is for the dehumidification and the second is for the regeneration (see Fig.2). The desiccant is the silica gel.

To develop the mathematical model, these assumptions are followed:

- hysteresis in the sorption isotherm for desiccant coating is neglected and the heat of sorption (adsorption/desorption) is assumed constant,

- the canals are adiabatic, impermeable, with the same material and identical,

- the air flow is uni-directional,

-the thermodynamic properties of dry air, vapour and desiccant are uniforms and constants,

-the heat and mass coefficients between the air stream and the desiccant wall are constant along the channel.

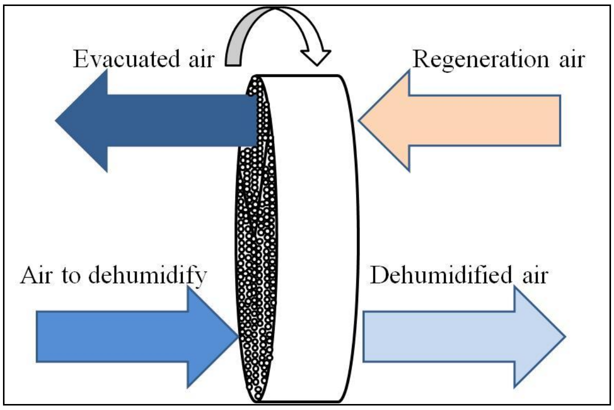

Fig. 2 The studied desiccant wheel

Thus, the mathematical model of the desiccant wheel is written as follows [8]:

$$A.\rho_a.C_{pa}.V.L.\frac{\partial T}{\partial x} + A.\rho_a.C_{pa}.L.\frac{\partial T}{\partial t} = h.A_{lat}.(T_p - T) \quad (1)$$

$$A.\rho_a.V.L.\frac{\partial \omega}{\partial x} + A.\rho_a.L.\frac{\partial \omega}{\partial t} = h_m.A_{lat}.(\omega_p - \omega) \quad (2)$$

$$A_d.Q_{ads}.\rho_d.L.\frac{\partial W}{\partial t} = h.A_{lat}.(T_p - T) + A_d.\rho_d.C_{pd}.L.\frac{\partial T_p}{\partial t} \quad (3)$$

$$A_d.\rho_d.L.\frac{\partial W}{\partial t} = h_m.A_{lat}.(\omega - \omega_p) \quad (4)$$

$$\omega_p = \frac{0.62188.\varphi_p}{\frac{p_{atm}}{p_{ws}} - \varphi_p} \quad (5)$$

$$p_{ws} = \exp(23.196 - \frac{3816.44}{T_p - 46.13}) \quad (6)$$

$$\varphi_p = 0.0078 - 0.05759.W + 24.16554.W^2 - 124.78.W^3 + 204.226.W^4 \quad (7)$$

5. Simulation study and experimental investigation

The numerical simulation is done by use of an explicit finite differential method. The experimental investigation is done in the chamber of commerce in Freiburg-Germany. The used desiccant wheel is DehuTech DT 15-1720. Transmitters' series FTW65 are used to measure relative humidity and temperature.

The working conditions, the thermodynamic properties and the geometrical size are listed in Table 1.

Table 1 The working conditions, the thermodynamic properties and the geometrical size

Parameter	Value	Unit
Density of the air ρ_a	1.016	(kg/m^3)
Specific heat of the air C_{pa}	1009	(J/kg.K)
Length of one canal L	0.3	(m)
Heat transfer coefficient h	50	($W/m^2.K$)
Mass transfer coefficient h_m	0.04955	($kg/m^2.s$)
Adsorption heat Q_{ads}	2300.10^3	(J/kg)
Volume flow of the dehumidified air	7500	m^3/h
Volume flow of the regenerated air	2500	m^3/h
Density of the desiccant ρ_d	1129	(kg/m^3)
Specific heat of the desiccant C_{pd}	921	(J/kg.K)
Space step Δx	0.01	(m)
Time step Δt	0.1	(s)
Radius of the hygroscopic wheel R	0.86	(m)

5.1 Variation of inlet parameters for the dehumidification and regeneration processes

The presented data are measured for a typical day in June from 9:00 to 15:53 h every minute. The variations of ambient air temperature and ambient humidity ratio are presented in Fig. 3. The results show that the minimum value of the ambient air temperature is equal to 25.7 °C at 9 am and the maximum value is equal to 34.4 °C at 2pm 25min.

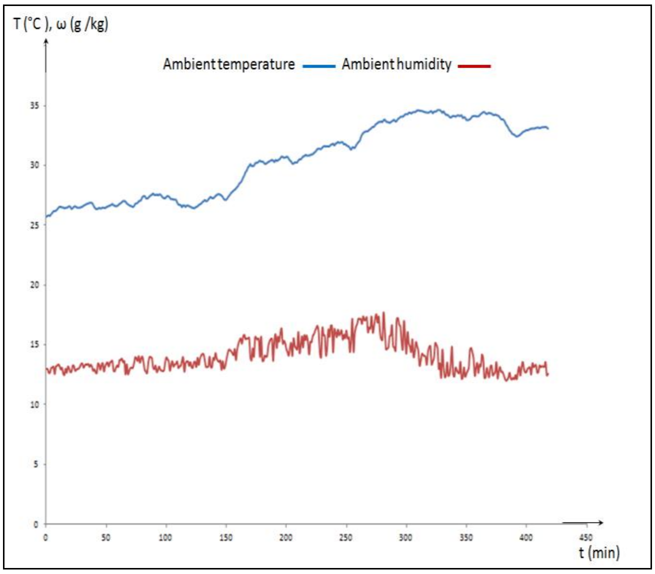

Fig. 3. Variations of ambient air temperature and ambient humidity ratio

The variation of solar radiation is presented in Fig. 4. The results show that the maximum value of the solar radiation exceeds 1000 W/m² 8 times and the minimum value is equal to 294 W/m² at 15:53 h.

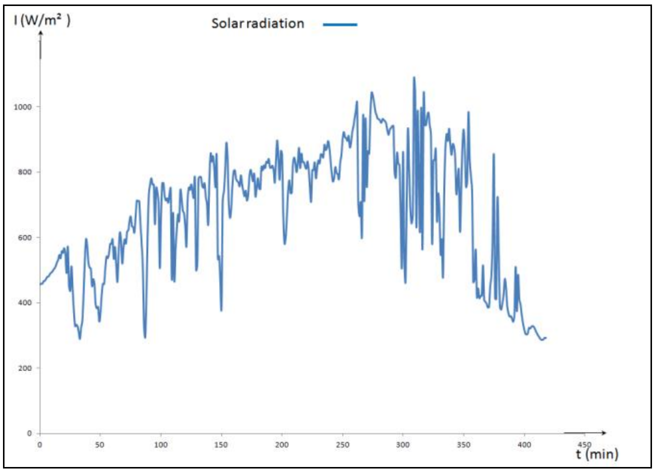

Fig. 4. Variation of solar radiation

The variation of regeneration temperature is presented in Fig. 5. The results show that the minimum value of the regeneration air temperature is equal to 37 °C at 9 am and the maximum value is equal to 70 °C at 1pm 48min.

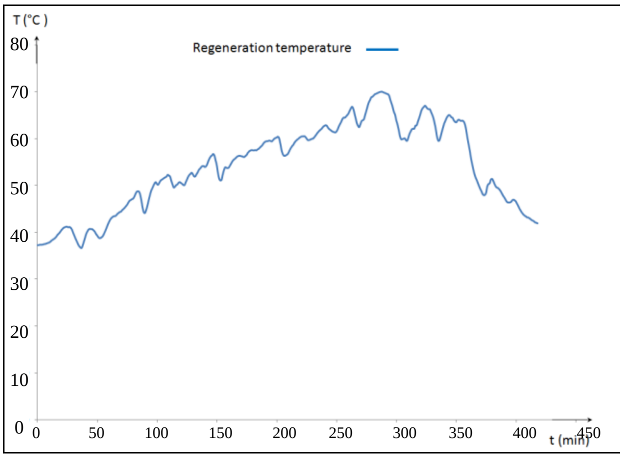

Fig. 5. Variation of regeneration temperature

Note that 18 points are considered to develop the simulation study as it is mentioned in Table 2. These values correspond to the measured values. Indeed, these 18 points are the inlet parameters for the desiccant wheel for the dehumidification and regeneration processes.

Table 2 Values of the used 18 points for the simulation of the desiccant wheel

Parameter	Ambient temperature (°C)	Ambient humidity (g/kg)	Regeneration temperature (°C)	Time (min)
Point 1	25.7	12.96	37.3	0
Point 2	26.5	12.91	41.2	25
Point 3	26.5	13.41	39.4	50
Point 4	26.8	13.87	45.9	75
Point 5	27.3	13.94	50.3	100
Point 6	26.5	13.13	51.2	125
Point 7	27.1	13.7	54.3	150
Point 8	30.2	15.54	56.5	175
Point 9	30.6	14.63	60.2	200
Point 10	31.2	16.42	60	225
Point 11	31.6	16.18	61.5	250
Point 12	33.4	17.55	65.9	275
Point 13	34.2	14.25	63.8	300
Point 14	34.4	15	66.7	325
Point 15	33.7	12.56	63.4	350
Point 16	34.1	13.53	48.4	375
Point 17	32.9	12.72	46.5	400
Point 18	33.15	13.16	42.7	413

5.2. Profiles of air temperature and air humidity ratio in the dehumidification process

Fig. 6 shows the variation of numerical and experimental dehumidified air temperature. The results show that the higher the temperature of the ambient air to dehumidify, the higher is the temperature gradient between the air to dehumidify and the dehumidified air. The numerical temperature gradient is between 0K and 14.4 K. Concerning the experimental gradient, it is between 2.9 K and 11.1 K.

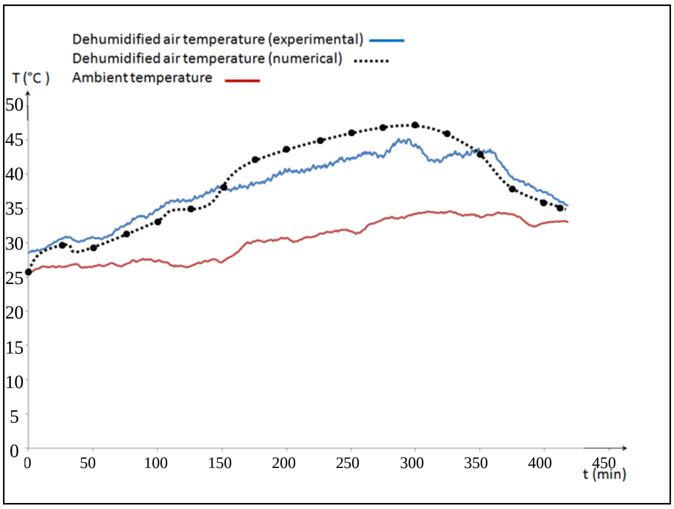

Fig. 6. Variation of numerical and experimental dehumidified air temperature

Fig. 7 shows the variation of numerical and experimental dehumidified air humidity ratio. The results show that the higher the humidity ratio of the ambient air to dehumidify, the higher is the specific humidity gradient between the air to dehumidify and the dehumidified air. The numerical humidity gradient is between 0 g/kg and 6.49 g/kg. Concerning the experimental gradient, it is between 1.84 g/kg and 5.83 g/kg.

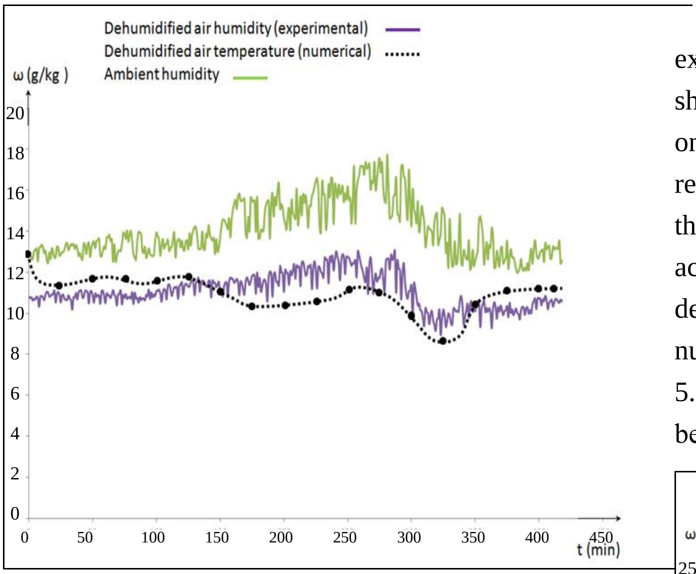

Fig. 7. Variation of numerical and experimental dehumidified air humidity

5.3. Profiles of air temperature and air humidity ratio in the regeneration process

Fig. 8 shows the variation of numerical and experimental rejected air temperature. The results show that the higher the regeneration temperature, the higher is the temperature gradient between the regeneration air and the rejected air. The numerical temperature gradient is between 0K and 22.6 K. Concerning the experimental gradient, it is between 7.14 K and 25.58 K.

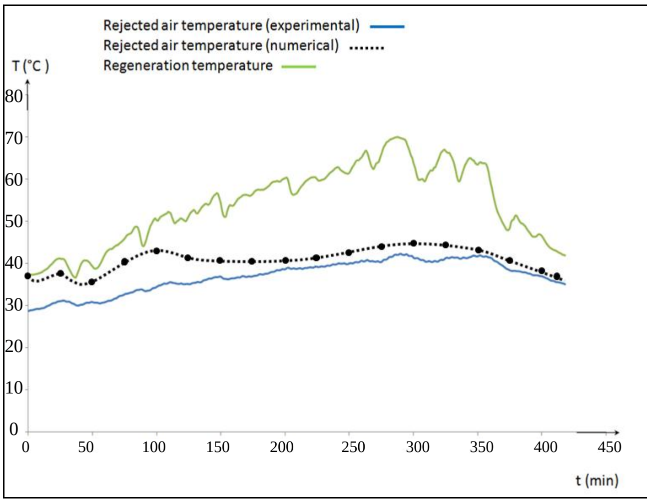

Fig. 8. Variation of numerical and experimental rejected air temperature

Fig. 9 shows the variation of numerical and experimental rejected air humidity ratio. The results show that the regeneration phenomenon is effective only between 125 min and 360 min. Consequently, in real time between 11am 5min and 3pm. This is due to the regeneration temperature which reaches an acceptable level to ensure the regeneration of the desiccant wheel in the same period of time. The numerical humidity gradient is between 0 g/kg and 5.75 g/kg. Concerning the experimental gradient, it is between “-0.61” g/kg and 3.76 g/kg.

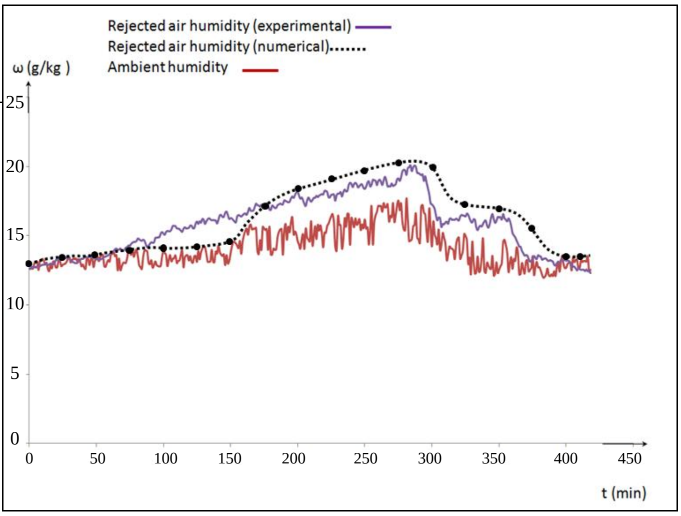

Fig. 9. Variation of numerical and experimental rejected air humidity

6. Conclusion

A design of a new solar unit for air conditioning and desalination is developed where the cooling operation is ensured mainly by the use of a humidifier and a heat exchanger. Furthermore a modelling study is detailed for the desiccant wheel.

As seen through the simulation study and the experimental investigation, the regeneration phenomenon can be done by use of relatively low temperature. Indeed this value does not exceed 70 °C.

This can be beneficial as it can facilitate the design of the regeneration stage.

Also, minimizing the value of the specific humidity and the value of the temperature of the air to dehumidify is very interesting. This can be beneficial as it facilitates the cooling of dehumidified air in desiccant solar air conditioning unit. Therefore a pre-cooling stage before the dehumidification stage is interesting.

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