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Applicability of solar desiccant cooling systems in Algerian Sahara: Experimental investigation of flat plate collectors

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Abstract: The increasing interest in the development of solar cooling technologies to their various economic and impressive environmental benefits, conducted us to study the feasibility of solar desiccant cooling systems in Algerian Sahara, particularly in the region of Biskra. Thus, we present in this paper, the results of an experimental investigation of solar flat plate collectors (FPCs) to test and estimate their heat regeneration capacity for solid desiccant cooling applications. The applicability of both Pennington and Dunkle cycles taking into account the effects of some parameters such as outdoor humidity and temperature and hot air temperature required to regenerate the desiccant wheel have been studied. From the psychrometric analysis, it was found that the Dunkle cycle is suitable in warm and semiarid climate. In addition, this study has allowed us to show that the temperature achieved by the flat plate solar air heaters in a large band of air flow rate can satisfy the energy needs for the dehumidification in desiccant cooling systems. Hot water produced by the solar water heaters and the stored one are in the operating temperature gap of the system (50-80 °C).

1. Introduction

Cooling is important in space conditioning of most buildings in warm climates. It is expensive, as is heating. Reduction in cooling loads through the use of solar energy will certainly be warranted. Solar air conditioning can be accomplished by three classes of systems: absorption cycles, desiccant cycles, and solar mechanical processes (Duffie 2013).

Many techniques were described for calculating the heat loss coefficient from the absorber of the solar flat-plate collector and the influences of emissivity of the absorber.

These techniques were presented for many applications such as drying, air conditioning and for producing drinking water from air using adsorbents driven by solar energy (Dieng and Wang 2001; Collie 1979; Majumdar 1998; Worek et al.).

It is important that the geography of this technology use begins to be well defined, and that a list of these system performances, mainly those of the best can be provided. For instance, that is relatively standard, first in various climatic and geographic sites and for Algeria. For example in very sunny sites (west) and relatively sunny at the end of autumn and at the beginning and mid winter (east), then in mountain sites (with once again, notable differences between east and west), high plateaus, and last, in Pre-Saharan and Saharan sites (Moummi et al. 2004).

Solar sorption heat pump and refrigeration devices are of significance to meet the needs for cooling requirements such as air-conditioning for example. They are also noiseless, non-corrosive and environmentally friendly. For these reasons the research activities in this sector are still increasing to solve the crucial points that make these systems not yet ready to compete with the well-known vapor compression system (Duffie 2013).

There are several kinds of sorption cooling systems which might be feasible for residential and industrial applications (Wang 2009):

1. Adsorption chiller using silica gel-water pair, powered by 60–85 °C hot water.
2. Absorption chiller using ammonia-water, could be generated by 80 °C hot water.
3. Absorption chiller using LiBr-water, with two-stage set-up which could be driven by 70-80 °C hot water (COP≈0.4), or one stage driven by 90 °C hot water (COP≈0.6).
4. Liquid desiccant (LiCl-water) cooling system driven with 50-80 °C hot water may have a cooling COP of about 0.6.
5. Solid desiccant cooling system (desiccant evaporative cooling, DEC) driven by hot air (50-80 °C) may reach a thermal COP of above 1.

A set of experimental results, related to the thermal performances of solar flat plate collectors (FPCs) and their applications, were carried out in our laboratories to enhance thermal performances of solar air heaters designed for drying and cooling applications

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Nomenclature

Ac	Collector surface area, m^2
C_p	Specific heat, kj/kg K
RH	Relative humidity, %
Ig	Global solar irradiance, W/m^2
Lc	Length of FPC, m
$\dot{m}$	Air mass flow rate, kg s^{-1}
Q_u	Useful energy gain, W/m^2
T	Temperature, °C
T_{fin}	Inlet temperature, °C
T_{fout}	Outlet temperature, °C
T_{amb}	Ambient Temperature, °C
U_L	Collector overall heat loss coefficient, W/m^2 K

Greek symbols

α_{abs}	Absorptance (dimensionless)
β	Collector tilt (degrees) (dimensionless)
τ_v	Transparent cover transmittance (dimensionless)
η	Thermal efficiency (dimensionless)

(Moummi et al. 2010; Aoues et al. 2011; Labed et al. 2009; Labed et al. 2012a; Labed et al. 2012b; Labed et al.2014). It is known that the setting up of a solar system, to satisfy a well-determined need in a given site, has to be done only after first having estimated the system productivity relative to the solar field actually available and then having an exact knowledge of the evolution of the climatic parameters (Moummi et al. 2010). This encouraged us to present here a research project aiming at the evaluation of the feasibility of solar-powered sorption cooling technology in Algerian Sahara climate.

This paper studies the feasibility of using a solar-powered solid desiccant system in Saharan climate with low generation temperatures (50-80 °C). We complete this study by an experimental performance evaluation of the flat plate collectors which may be used, as an important part, in the open-cycle dehumidification-humidification process.

2. Climate and energy considerations

The geographical position of Algeria (latitude < 36 N) means that the general climate which is spread out over a significant period of the year is hot and variable between wet and dry. This situation makes practically impossible to maintain the internal temperature of the buildings on a compatible level with human comfort. It is thus desirable to air-condition the building in the areas where the average daily temperature exceeds the threshold of comfort. This is the case of the four climatic zones of Algeria as shown on the figure 1 (Benhabiles 2008, Labed et al. 2014).

The daily temperature during the hot sequences exceeds 30 °C for the majority of the areas of the country (Benhabiles 2008). Biskra is located South-East of Algeria with a latitude of 34° 48’N, a longitude of 5°44’E and an altitude of 85m. The region of Biskra is situated in the zone D and characterized by a Saharan climate. The average daily temperature becomes unbearable in summer so that it exceeds the threshold of comfort (Table 1).

In Algerian Sahara, the most part of the electric power consumed in summer is used in the field of cooling of domestic, commercial and administrative buildings (Figure 2). Energy consumption patterns can be substantially reduced by energy conserving measures and/or by using solar cooling sorption systems, which have gained an increasing interest during latest years due to the rising demand for efficient energy use and higher comfort standards.

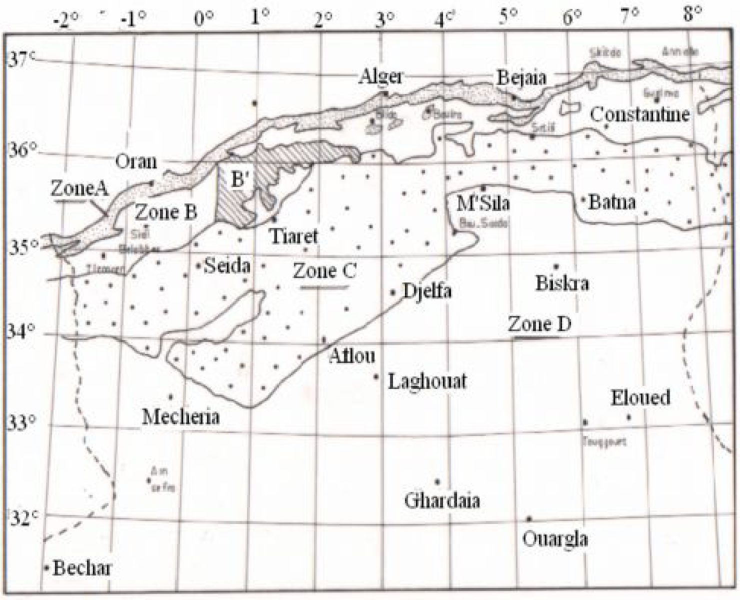

Fig.1. Climatic zones of Algeria (Benhabiles 2008).

Table 1. Summer basic conditions for different climatic zones in Algeria (Benhabiles 2008).

Climatic zones	**Basic conditions in summer**		
	Temperature (T_{amb})	**Diurnal difference**	**Relative humidity (H_R)**
Zone A			
< 500 m	34	9	44
500 – 1000 m	33.5	10	40
>1000 m	30.5	9	47
Zone B			
< 500 m	38	15	30
500 – 1000 m	37	15	28
>1000 m	35	14	28
Subfield B' : > 500 m	41	18	41
Zone C			
500 – 1000 m	39.5	20	18
>1000 m	36	18	22
Zone D			
< 500 m	**45**	**20**	**11**
500 – 1000 m	42	18	13
>1000 m	37.5	16	17

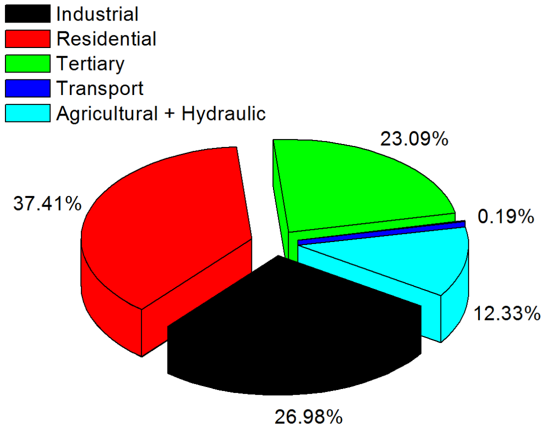

Fig.2. Electricity consumption by sector in Algeria 2005 (APRUE 2007).

Algeria is always looking for alternative energy sources; the government established the Commission for New Energy in 1982 to develop nuclear energy, solar energy, and other potential sources of power. Whereas solar power was proving to have considerable potential, particularly in desert locations, nuclear power may become a casualty of international concerns and allegations that it could be used for military purposes (APRUE 2007).

3. Applicability of SDC systems in Saharan climate

The components used in the construction of a solid desiccant cooling system include two slowly revolving wheels, heat exchangers, evaporative coolers and several other components between the two air streams from and to a conditioned space (Kim and Infante Ferreira 2008). Like all cooling systems, desiccant cooling air conditioning has some disadvantages due to the fact the apparatus is inconvenient in certain respects. the bulky volume of the machine, the intermittent and varying character of the operating conditions make the problems of cold compartment, the operating cost of solar water heater, energy storage and solar collector's acreage (Duffie 2013).

The working principle of a solid desiccant cooling system (Pennington cycle) is shown in Figure 3. In process air side, ambient air flows through the desiccant wheel in which the latent load is removed by the adsorption of desiccant material. Then a sensible heat exchanger is adopted in the system to remove the releasing adsorption heat and preheat regeneration air. Usually, an evaporative cooler is installed before process air is supplied to the conditioned room to adjust the temperature and humidity ratio of supply air (Wang et al. 2009). Simultaneously, in regeneration air side, return air from the conditioned space is cooled in an evaporative cooler and then flows through the heat exchanger to cool process air. Afterwards, regeneration air is heated up in the air heater to required temperature and used to regenerate the desiccant material (Wang et al. 2009).

We present in Figure 4 a graphical modeling of a solar solid desiccant cooling system (Pennington cycle). We have introduced the environmental conditions of a hot region as input data to simulate the climate of Biskra (T_{amb}=40° C, RH=30 %).

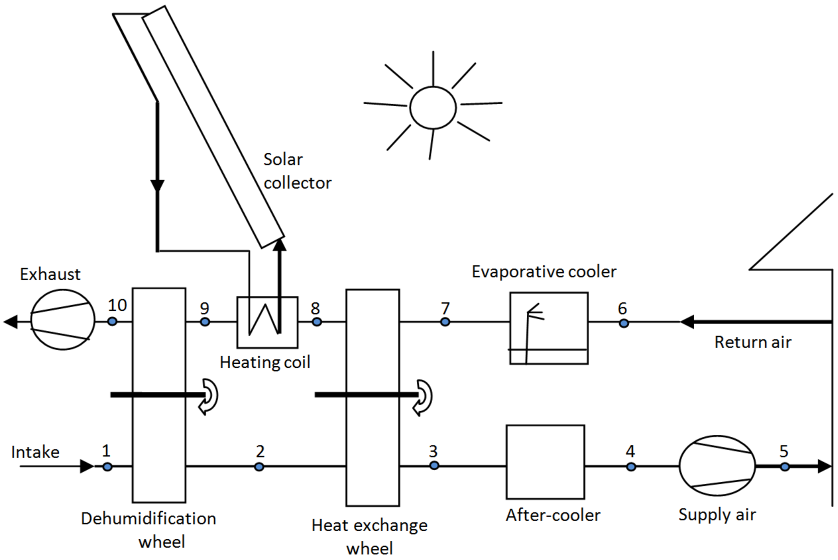

Fig.3. Schematic representation of Pennington cycle: A solid desiccant cooling system with solar collector (Pennington 1955, Kim and Infante Ferreira 2008).

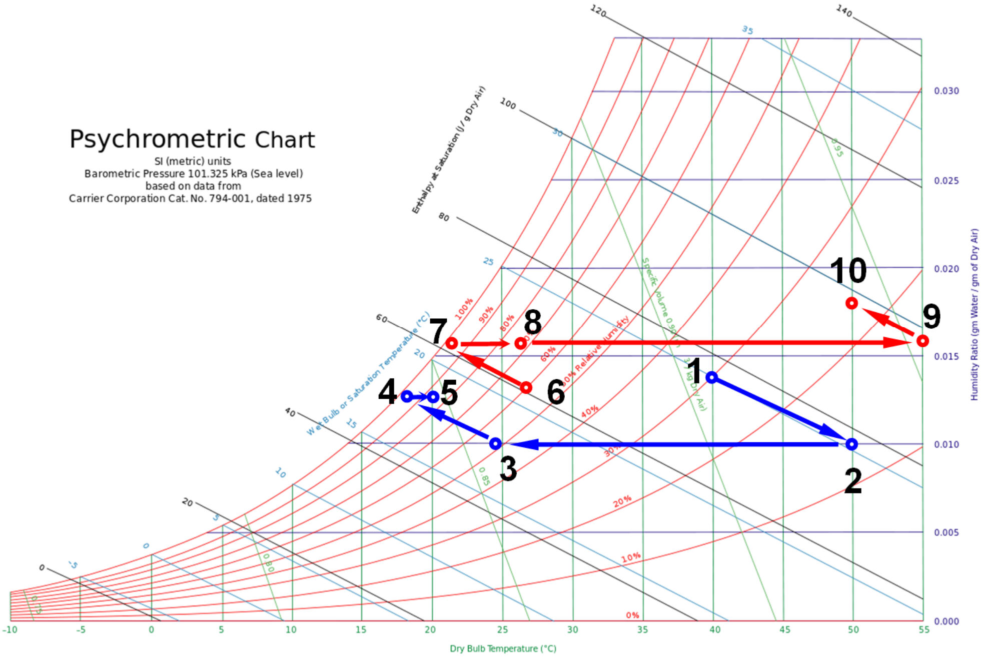

Fig.4. Processes on Psychrometric chart for Pennington cycle.

The initial conditions are chosen from meteorological data by calculating the summer average values of temperature and humidity (Table 2). The psychrometric chart for Pennington cycle shows that, air humidity in the building (point 5) is higher than the acceptable comfort conditions (ASHRAE 2013).

The Dunkle cycle, which has an additional sensible heat exchanger for improving the cycle performance, is presented in Figure 5. The working fluid of the system can be traced through the diagrams as follows: The return air from the space after having passed through an evaporative cooler (state 1) and heat exchanger (state 2) to give state 3, this air is dehumidified and heated to state 4 using a desiccant dehumidifier and is subsequently cooled by the second heat exchanger to state point 5, the cycle remainder is the same procedure as in Pennington cycle.

The psychrometric chart for Dunkle cycle is shown in Figure 6. The desiccant cooling system shows suitable blowing conditions in the building (point 7) when we introduce the same previous environmental conditions of a hot region as input data (T_{amb}=40° C, RH=30 %). This proves that, up to these climate values (ambient temperature and humidity), the Dynkel system is applicable in the Saharan regions (Table 3). But beyond these values the applicability of Dynkel system becomes uncertain. The major problem, which generally can be an obstacle in the Sahara and particularly in the region of Biskra, is the applicability of these systems in summer in very hot days (T_{amb} >> 40°C).

Table 2. Characteristic values of different points of Pennington cycle extracted from the Psychrometric chart

Point	Temperature [°C]	Relative humidity [%]	absolute humidity [$g_{water}/kg_{dry\ air}$]	Specific enthalpy [$kJ/kg_{dry\ air}$]
1	40	30	14	76
2	50	13	10	76
3	24.5	52	10	50
4	18	98	12.5	50
5	20	85	12.5	52
6	27	60	13.5	61
7	21.5	98	15.8	61
8	26.5	72	15.8	67
9	55	17	15.8	96
10	50	23	17.8	96

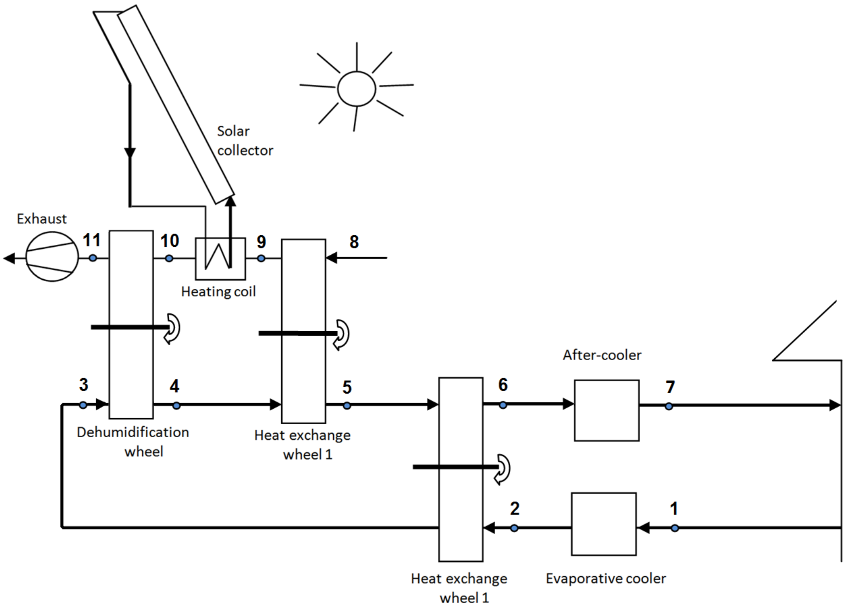

Fig. 5. A solid desiccant cooling system with solar collector (Dunkle 1965).

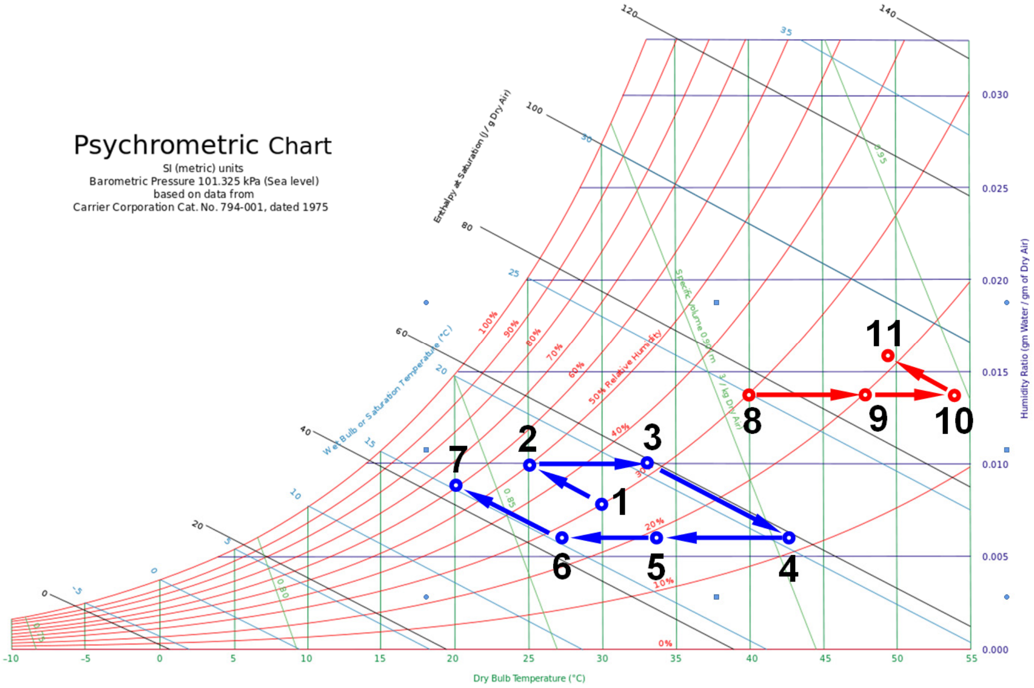

Fig. 6. Processes on Psychrometric chart for Dunkle cycle.

Table 3: Characteristic values of different points of Dunkle cycle extracted from the Psychrometric chart

Point	Temperature [°C]	Relative humidity [%]	absolute humidity [$g_{water}/kg_{dry\ air}$]	Specific enthalpy [$kJ/kg_{dry\ air}$]
1	30	30	8	50.5
2	25	50	10	50.5
3	33	32	10	58
4	43	12	6	58
5	34	18	6	49
6	27	28	6	43
7	20	60	8.9	43
8	40	30	14	76
9	48	20	14	84
10	54	15	14	90
11	49	21	16	90

4. FPCs and heat source needed

The most important feature of SDCs is its low regeneration temperature (50-80 °C). These temperature levels can be obtained easily through such collectors tested in the University of Biskra. In this section of the manuscript, we will concentrate our efforts on the study of the performances of FPCs as heat source for SDC systems.

4.1. Experimental setup, measuring and analysis

Tow FPCs were tested in the University of Biskra under similar environmental conditions in 2009. The collectors were placed on a stand facing south at an inclination angle equal to the local latitude.

In both FPCs, the air outlet and inlet cross-sections are equipped by divergent channel duct (Figure 7), the test facility permit to vary the mass flow rate of the air. In summary, the above experimental setup was instrumented for the measurement of the solar radiation, wind velocity, pressure drop, temperature of the atmosphere air, inlet and outlet air temperatures, surface temperature of absorber plate and the air mass flow rate.

All the FPC components have the same size: thickness of the single cover glass (5mm), height of the air gap between the cover and the absorber plat (25 mm), height of the air duct (25 mm), dimensions of the absorber (1.96 m × 0.9 m with the thickness of 0.4 mm) and thickness of the rear insulation (40 mm). Therefore, the materials used in the fabrication of all FPCs components are the same. The absorbers were made of galvanized steel with non selective black coating. The heated air flows between the inner surface of the absorber plate and the back plate with, or without, obstacles. The rear insulation is provided by a polystyrene sheet (30mm of thickness), which is sandwiched between two plywood sheets.

The useful energy gain had been established as below (Duffie et al. 2013):

$$Q_u = \dot{m} \cdot cp\left(T_{f,out} - T_{f,in}\right) \tag{1}$$

$$Q_u = \left(\tau_v \alpha_{abs}\right) A_c I_G - U_L A_c \left(T_{abs} - T_{amb}\right) \tag{2}$$

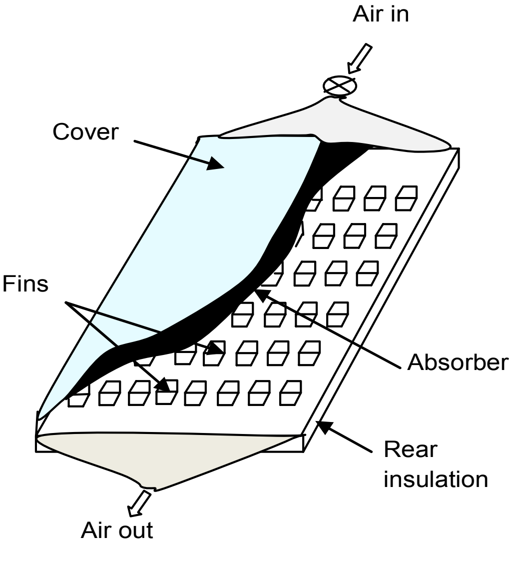

Fig.7. Experimental device (FPC).

The instantaneous collector efficiency relates the useful energy to the total radiation incident on the collector surface by Eq. (3):

$$\eta = \frac{Q_u}{A_c I_G} = \frac{\dot{m}cp\left(T_{f,out} - T_{f,in}\right)}{A_c I_G} \tag{3}$$

Concerning the experimental tests of the solar flat plat water heaters, we have used industrial solar water heating of the type (CESTH200) and we have modified its thermostat so that the water temperature at the outlet of the collector exceeds 80 °C. For the storage of heated water we have used a plastic tank of 0.3m^3 and 6 mm thickness, covered by a layer of local mud (20 mm).

4.2. Air heating

The basic method of measuring collector performance is to expose operating collector to solar radiation and to measure the fluid inlet and outlet temperature and the fluid flow rate addition, radiation on the collector, ambient temperature, and wind speed are also recorded. ASHRAE standard requires that, for the collector efficiency test, the solar insulation must be above 630 W/m^2 (Karim and Hawlader 2006). The variation of the efficiency (η) is studied as a function of variation in the air flow rate (Figure 8), and the improvements of thermal performances are important in relation to the FPC. It can be seen that the collector efficiency increases considerably with increasing air flow rate. Furthermore, the use of fin obstacles in the FPC channel duct increases the efficiencies of the collector; the efficiencies of the studied models are in decreasing order, respectively, as follows: i) with trapezoidal fins (model B) and ii) the FPC without obstacles (model N).

In Figure 9, we present the outlet temperatures of both FPCs compared to a referential temperature which is necessary for the functioning of solid desiccant cooling systems (50-80 °C). The average values of the outlet temperatures for both collector models recorded in different test days were presented. We can also observe that the temperatures achieved by the flat plate solar air heaters for different air flow rates can satisfy the energy needs for the dehumidification in the solid desiccant cooling systems (Figure 9).

Figure 10 presents the variation of the pressure drop and electrical power consumption as a function of variation of the air flow rate for both FPCs; with and without fins.

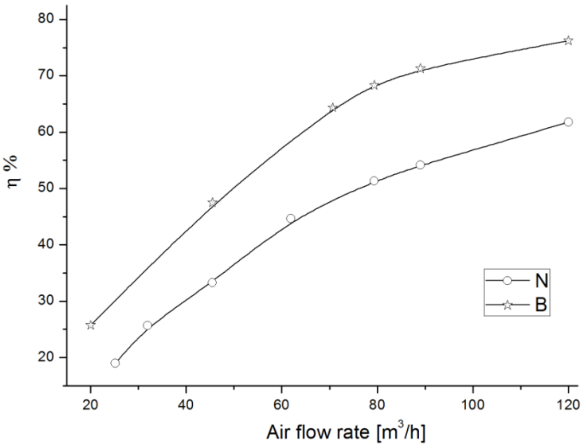

Fig.8. Variation of the FPC efficiencies, η, as a function of the air flow rate, $\dot{m}$, for different studied models (N, B-1 and B-2).

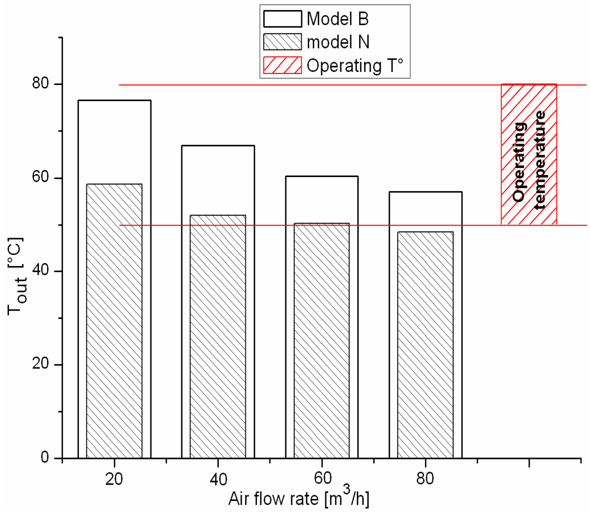

Fig.9. Average values of outlet temperatures for both collector models vs. the air flow rates (m^3/h) for both FPCs.

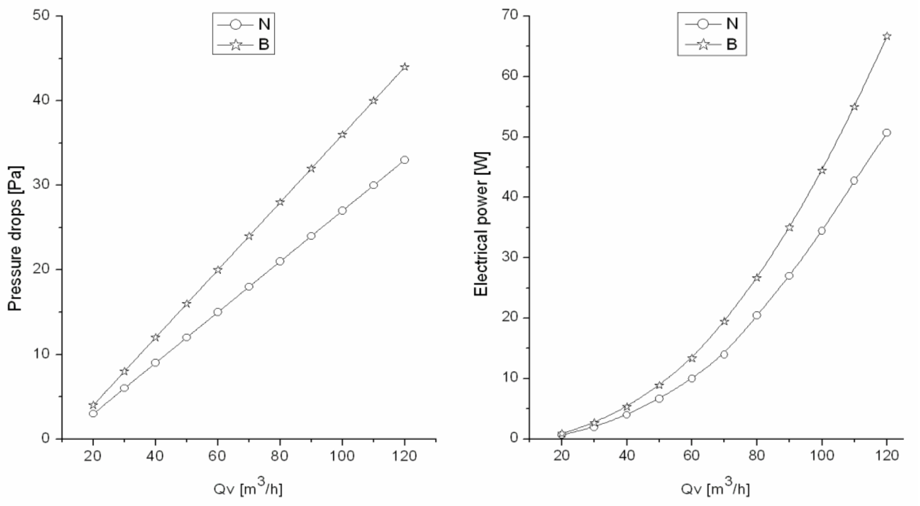

Fig. 10. Pressure drops (Pa) and electrical power consumption (W) vs. the air flow rate (m^3/h) for both FPCs.

The FPC with trapezoidal fins has a high degree of surface compactness, and substantial heat transfer enhancement is obtained. There is, of course, an associated increase in pressure drop due to increased friction and a form drag contribution from the finite thickness of the fins. They attaint the values 12.5, 19 and 37.5 Pa for air flow rates of 40, 60 and 80 m^3/h, respectively.

The FPC without fins presents the low pressure drops. They attaint the values 9, 15.5 and 22 Pa for air flow rates of 40, 60 and 80 m^3/h, respectively. These low values of the pressure drop results in lower fan electrical power consumption (Figure 10).

4.3. Water heating and storage

Most solar water heating installations are designed for use throughout the year. A solar collector used in a water heater will deliver more energy per unit area per year than a comparable installation will be used seasonally, such as winter space heating, summer air conditioning, or harvest time crop drying (Duffie 2013).

The system used in this part is industrial solar water heating (type CESTH200). Thus we have modified its thermostat to exceed 80 °C. The storage of hot water was assured by a plastic tank of 6 mm thickness and 0.3 m^3 volume, covered by a layer of local mud (2 cm). This mud is mixed with layers of Hay or Straw added to bind the mixture together. This mud was used in the past by Algerian people as building material for their thermal insulation characteristics. The hot water can be used in heating coil to heat air for many applications (Duffie 2013). For our case, we suggest the use of the hot water to heat the air which will be used as the wheel Dehumidifier.

Figure 11 presents the values of the produced hot water temperatures and the stored ones according to their produced quantities. The FPC water heater was tested in Biskra under similar environmental conditions (Jun 24-29, 2012). The stored water was also tested in the same period over 12 hours in the night. At the beginning of the storage process (18h00) the ambient temperatures was 40 ~ 42 °C, and it was 28~30 °C at the end of the storage tests (06h00). It is clear that the hot water temperatures achieved by the solar FPC and that of the stored water can satisfy the energy needs required to regenerate the desiccant wheel in the solid desiccant cooling systems (Figure 11).

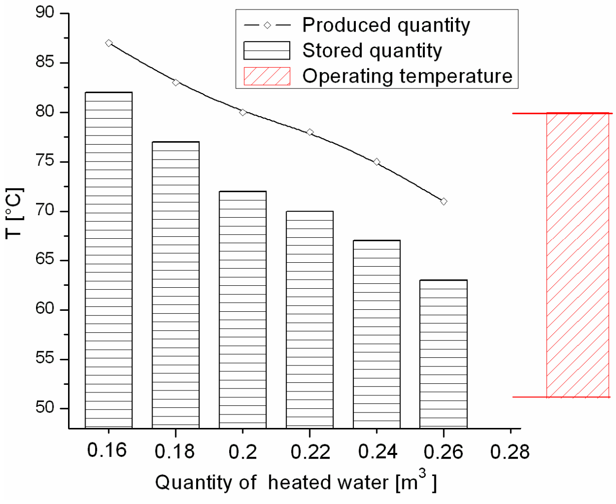

Fig. 11. Recorded values of the temperatures of the heated and stored water.

5. Conclusion

The use of solar energy in air conditioning systems in Algeria knows a remarkable development due to the high cost and the environmental problems caused by the intensive use of fossil fuels in conventional systems.

In this paper, we have studied the feasibility of a solar-powered solid desiccant system in Algerian Sahara, particularly in the region of Biskra, with low generation temperatures (50-80 °C). We have completed this study by an experimental performance evaluation of flat plate solar air heaters as an important component of the open-cycle dehumidification-humidification process.

For the tested climatic conditions (T_{amb}=40 °C, RH=30 %), we conclude that the air humidity in the building will be higher than the acceptable comfort conditions for the Pennington cycle. The solid desiccant cooling system can show a suitable blowing conditions in the building when we use the Dynkel model, for the same climatic conditions. The major problem, which generally can be an obstacle in the Sahara and particularly in the region of Biskra, is the applicability of the Dynkel model in summer in very hot days (T_{amb} >> 40°C), which will be the subject of our future research.

However, this study has also allowed us to show that, the temperature achieved by the solar FPCs in a large band of air flow rate can satisfy the energy needs for the dehumidification of desiccant wheel. Thus, the produced and the stored hot water are in the operating temperature gap of these systems (50-80 °C).

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