Experimental study of BIPV(Building Integrated Photovoltaics) modules running as solar passive air heaters for the regeneration of a desiccant wheel.

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Abstract— **Moisture control has become an important fact for the last years. It has influence on human health and comfort, as well as the quality of certain services and processes. Therefore, it plays an important role for many industries, storage systems, transport and the preservation of products. For this reason, air-conditioning systems are integrating a dehumidifier device called desiccant wheel. The desiccant wheel is in charge of reducing the moisture caused by the process air and requires a hot spot for regeneration. This hot spot can be supported by solar thermal energy. This study evaluates the thermal potential of the ventilation and cooling system in a PV modules' installation. It is done according to the exploitation of the thermal energy transferred to the refrigerant as support to the hot spot, contributing to the regeneration of the desiccant wheel. For this to happen, an experimental installation has been developed, which consists of two inclined PV modules, with an air-flow channel below them. This system enables PV cells to refrigerate, thus improving the electric performance as well as making use of the residual heat generated from this process. One of the two modules is disposed of a series of plates interspersed in its cooling channel, with the aim of modifying the air flow, rising its residence time below the module and making the increase in air temperature more significant. Natural and forced convection have been tested at several air speeds for different irradiance conditions and ambient temperatures. This study deals with the analysis of the thermal potential of these installations under different conditions and its possible applications to the regeneration of desiccant wheels.**

Keywords—PV cooling duct; air-conditioning system; desiccant wheel; refrigeration; dehumidification

I. Introduction

Refrigeration is a process which deals with preserving the quality, condition and welfare of certain elements within a system. Moisture is one of the most important factors to be taken into account in this process. Inadequate moisture values may reduce the life span of the elements of production, may alter the products or decrease the individuals' comfort. Moisture control also allows the enhancement of the performance of the refrigeration systems. Changing the thermal state of a moist air flow requires more energy than another one with lower moisture level. This happens because the presence of water molecules increases its heat capacity, i.e. the necessary quantity of energy to modify its temperature.

Desiccant materials have become very important in dehumidification processes. One of the elements with an increasing use is the desiccant wheel. This device requires a hot air flow for its regeneration. For this purpose, solar thermal energy can serve as a support, shaping the so-called applications of solar refrigeration via desiccants. The regeneration means a critical point, as it requires an air temperature from 80 to 90ºC for it to be carried out.

This study poses the use of PV modules refrigerated by air as a support system for the hot spot which is necessary for the regeneration of desiccant wheels. In this way, the electric performance of the PV modules is enhanced, although it is seriously affected by the temperature. Thus, this process aims at improving the global efficiency of the system.

There is some previous research on experiments related to this one. Brinkworth [1] made an estimate of the flow and the heat transfer that take place in the cooling duct of PV modules, which is a similar setting to the one proposed in the present study. Sandberg and Moshfegh [2] derived expressions for the mass flow rate rate, velocity and temperature rise in the air gap behind solar cells considering the effect of the geometry (aspect ratio of the channel) and location of these solar cells. The influence of temperature on the air velocity profile at the air gap behind the PV module is shown by Sandberg and Moshfegh [3] too. Ryan and Burek [4] investigated the effects of geometry on the thermal characteristics of buoyancy-driven flow in a vertical heated channel and they determined that the height has an additional positive effect on the thermal behaviour, independent of the channel depth-to-height aspect ratio. Previous studies of our research group, as Mazón [5] and Kaiser et al. [6] develop an experimental study dealing with the electric response of PV modules when refrigerated by means of placing an airflow below it. The system is tested at different speeds, aspect ratios and ambient conditions. It studies the performance of natural and forced convention, employing a high-pressure fan for the latter. The results obtained show how the increase in cooling air speed enhances the electric performance of the module. Furthermore, an increment in the air enthalpy is observed at low speeds as a consequence of its longer residence time below the module. The data obtained are applied to the evaluation of the thermal potential of the installation. However, the instrumentation and methods employed for the test are not suitable to achieve this purpose. In this sense, an experimental installation is designed and built up in order to assess the thermal potential of the ventilation and cooling system of PV modules.

II. DESCRIPTION OF THE EXPERIMENTAL PROCESS

The experimental process focuses on the design, construction and testing of an experimental installation that presents two different settings. In one of them there is an airflow below a PV module, passing through a duct with no obstacles. The other one consists of a series of plates which are interspersed transversally to the direction of the airflow in the duct. The installation is tested by natural and forced convection and different speeds, keeping the dimensions of the duct constant.

A. *Description of the experimental insallation*

The experimental installation consists of two inclined PV modules (270 W, ET Solar, ET P672270), placed in parallel on an insulating surface. A duct of rectangular section is left so that the air can flow below them, as it is shown in Fig. 1. Each module has their own independent ventilation duct. The duct in module B is disposed of six plates made of methacrylate which are interspersed in transversal direction from the airflow, which can be seen in Fig. 2. In this way, the air is obliged to describe a zigzagging path, thus increasing its residence time below the module, so that the air temperature between the input and the output increases.

In both settings, the section of the duct is 0.992 m wide and 0.16 m high. Its length coincides with the PV module's, being 1.956 m. The input and output sections of the duct are similar. For the forced convection test, a suction fan is installed in each setting. The suction operation allows to obtain a regular airflow, with a more levelled velocity profile and a better arranged disposition of the particles thanks to its adaptation to the available section. The connection between the ventilation duct of the module and the fan is made through metallic pipes, adjusting the rectangular section of the duct to the circular section of the fan.

In both settings, five air temperature sensors are installed both at the input and at the output. Nine Resistance Temperature Detectors (RTD) are attached to module A on its

Fig. 1. Overview of the installation.

Fig. 2. View of the inside of the ducts. Setting A (Left). Setting B (Right).

back side to measure the module temperature, and nine more are added to the insulating surface. For setting B, twelve RTD are placed on both the module and the insulating surface. In this way, we can obtain detailed information about the thermal conditions of the installation. The measure of the air speed in each setting is obtained by means of two hot-wire anemometers situated in the pipe which communicates the duct with the fan. The anemometers remain symmetrically installed in the circular section, where the flow coming from the duct is stabilized, which allows for a general measure of the racked flow. This means an enhancement in respect of its installation underneath the module, where the variations in the flow direction due to geometry and obstacles can lead to wrong measures. Relative pressure sensors of high precision are also installed at the input and output of the fan with the aim of quantifying the loss of load in each system and of knowing the operating point of each fan.

The solar radiation is measured by a pyranometer, while other environmental conditions, such as atmospheric pressure, moisture, wind speed and direction, are measured with a meteorological station placed on our laboratory roof just beside the experimental facility. The ambient temperature is measured with a sensor located at the air gap input at module B.

All data are registered and recorded by means of a data logger, together with an acquisition software elaborated by LabView®.

B. *Description of the tests*

In the procedure, natural and forced convection measuring is taken. For the latter, the fans have an analogical speed controller with several identified positions. It is tested at positions 1, 3 and 6. Measures are taken on a daily basis during the end of summer within a sunny period. The data acquisition system is in charge of collecting the measures from the sensors, obtaining pairs of values every fifteen minutes.

III. EXPERIMENTAL RESULTS

For the objectives proposed in this study to be met, it turns interesting to analyse certain thermal variables with different testing ambient conditions. The most representative variables are the thermal power obtained from the system and its thermal performance. Similarly, one of the effects sought in this project is the increase in air temperature when flowing through the duct, which is directly related to the thermal potential. Another factor to be considered is the thermal effect of the ventilation on the temperature of the PV modules due to its influence on the electric efficiency.

The thermal power is calculated regarding the difference in the air temperature between the input and the output of the duct, by means of the following operation:

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \qquad (1)$$

$\dot{Q}$ represents the thermal power, $\dot{m}$ the mass flow rate, C_p the specific heat at constant pressure, and ΔT the air temperature step between the entry and the exit. The mass flow rate is calculated according to the air density at ambient conditions, ρ; the air passage section, A and the average value of the measured velocities by the anemometers, v_m, as shown in (2).

$$\dot{m} = \rho \cdot v_m \cdot A \qquad (2)$$

The thermal performance is understood as the proportion of the energy obtained thermally from the system, regarding the incident energy in the system coming from the solar radiation. Its calculation is expressed by the following operation:

$$\eta_{therm} = \dot{Q}/(G_T \cdot S_{mod}) \qquad (3)$$

η_{therm} is the thermal performance, G_T the measured solar irradiance, and S_{mod} the area of the PV module.

A. *Mass flow rate levels*

Tests were taken at different fan positions. These positions correspond to the values of mass flow rate which are determined in both tested settings. These values are going to affect to a large extent the levels of thermal power that have been reached.

By natural convection, the flow is established due to the difference in temperature among the air masses. This, together with the influence of the outside wind, makes the mass flow rate which goes adopt low and wide-ranging values. However, when generated by forced convection by means of a suction fan, the values tend to keep constant and the wind speed barely influences.

By natural convection, the mass flow rate is lower than 0.16 kg/s in setting A, whereas in setting B it does not exceed 0.10 kg/s. The presence of the interspersed plates in setting B makes air speed inside reduce. Despite this, the high influence by the ambient conditions leads to rather mixed results.

By forced convection, the speed levels which have been reached are superior. When the fan is at position 1, the flow values reach around 0.3 kg/s in setting A, and 0.2-0.25 kg/s in setting B. As the position of the fan is intensified, the speed reached in the duct increases. In this way, at position 3 the mass flow rate presents 0.4 kg/s in both settings, whereas at position 3 the values are placed at 0.9-1 kg/s for setting A and 0.4 kg/s for setting B.

In setting B, the mass flow rate registered at position 3 and 6 is similar. This fact may be due to the inner geometry of the duct, where the load loss, generated by the presence of the interspersed plates, can lead to reaching this limit. This effect, at position 6, also makes the difference in mass flow rate registered in A and B distance itself largely. This can be observed in Fig. 3, which represents the average values of mass flow rate which have been reached at each fan position.

B. *Air temperature step*

The main objective of this study is to determine the thermal potential of the cooling system by air from PV modules. In this sense, the temperature step between the inlet and outlet of the duct becomes relevant, taking into account that it is intended to be applied in the regeneration of desiccant wheels, where temperatures of 80-90ºC are required.

By natural convection (Fig. 4), the highest temperature steps are observed both in setting A and B. It shows an increasing lineal evolution of this variable with the irradiance, reaching differences in temperature between the inlet and outlet up to 8ºC in A and 18ºC in B for irradiance values near 900 W/m^2.

Although some noticeable uncertainty is observed in the measures, especially in setting B, it can be largely seen that the air temperature step in B is superior to the one registered in A. This difference is more noticeable as the irradiance increases.

By forced convection, the same behaviour is kept. The temperature step reached in setting B is still higher than the one in setting A, and the difference between both of them is increased the higher the irradiance gets. Furthermore, the temperature step is reduced as the air speed in the duct increases, as shown in Fig. 5. It also generates a great difference among the levels obtained in both natural and forced convection. Fig. 5 also shows how the uncertainty in the temperature measures is emphasized in natural convection, due to the high influence of external agents such as the wind in the generation of the flow.

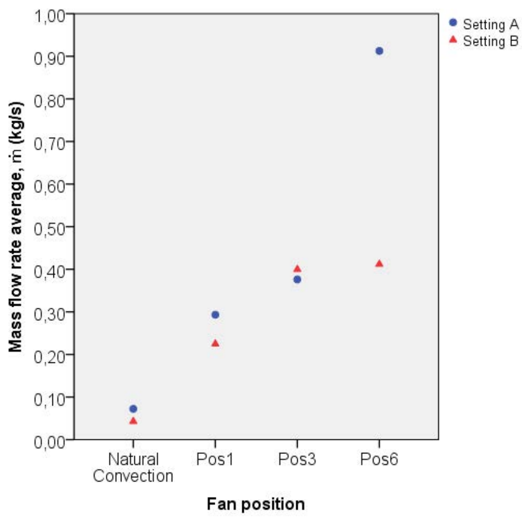

Fig. 3. Mass flow rate average for the different fan positions.

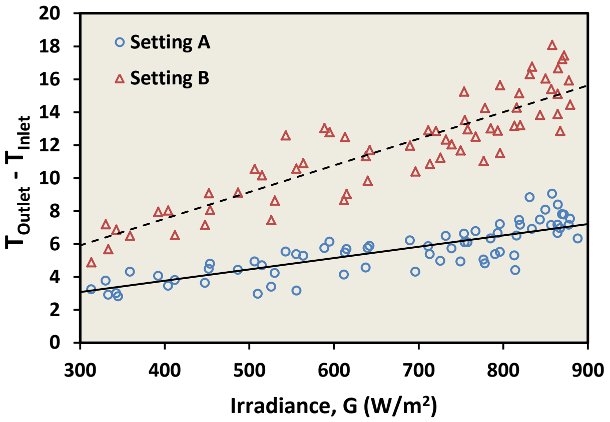

Fig. 4. Temperature step between the inlet and outlet of the duct by natural convection.

The reason why it reaches higher temperature steps by natural convection is because the air speed in the duct is lower than in the other cases, which implies a longer residence time of the air below the PV panel, favouring a more efficient heat transfer between the internal surface of the module and the air. Furthermore, by forced convection, the increase in air speed provokes a larger heat evacuation per unit of time and a lower contact time between the air and the PV module, which prevents them from reaching temperature steps as high as in natural convection.

On the other hand, setting B manages to increase the air enthalpy to a larger extant than setting A in all cases. The presence of the interspersed plates in B obliges the air to describe such a route that the time spent on moving from the inlet to the outlet of the duct is longer than in A, where it does not find any obstacle. Once more, the increase in residence time of the air below the PV panel contributes to enhancing the heat exchange. This happens both by natural and forced convection. This interior disposition of the duct in B also leads to a more efficient use of the surface which is available for the heat exchange between the reverse side of the PV panel and the air. That is, the air comes into contact effectively with practically all the surface of the inner side of the PV panel. However, in setting A, where the flow is free, despite the fact that the convection is generated by suction, the air is not adapted equally to the volume of the duct as its crossover section is not so restricted.

C. Thermal power

The analysis of the thermal potential is going to allow the determination of the energy potential of the system from the viewpoint of the use of PV panels as solar air collectors.

As it happens with the values of mass flow rate, the thermal power by natural convection also presents a high dispersion. This prevents us from describing a specific behaviour of this variable under such conditions. Despite that, it can be observed, overall, that setting B is capable of obtaining better results, as it manages to increase the air temperature to a greater extent.

By forced convection there is a lineal tendency between the thermal power and the irradiance (Fig. 6). The increase in the received solar energy leads to a higher temperature step, passing on higher power values.

The thermal power is obtained from the experimental data from other variables. For it to be calculated, the values of mass flow rate and temperature step collected during the experimental process are needed, as established in (1). The little uncertainty that the data from these variables present is largely multiplied when getting the result between both and with the specific heat at constant pressure. In this way, it is not possible to determine precisely the power levels that have been reached, although certain ranges can be found.

Generally, higher thermal power levels are obtained in setting B, because the temperature term becomes more important than the variations of mass flow rate. The most favourable cases in setting B register power values around 1500 W at irradiance levels of 850-900 W/m^2. This happens with the fan in position 3 and 6, where similar levels of mass flow rate have been registered. Setting A reaches its highest power (1000-1200 W) at position 6 of the fan, as there a higher level of mass flow rate is achieved. In this case, the power increases due to the increase in velocity, even though the air temperature step is reduced.

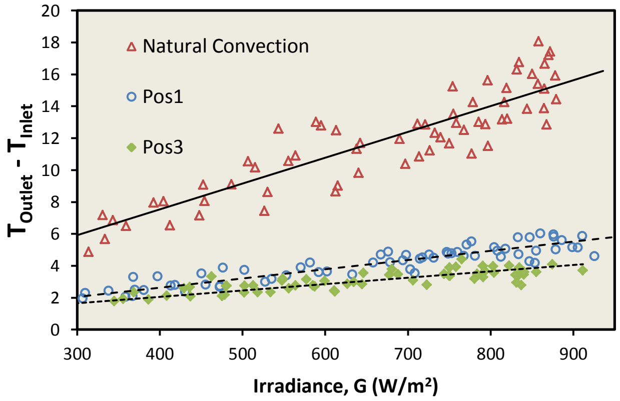

Fig. 5. Temperature step between the inlet and the outlet of the duct for different fan positions in setting B.

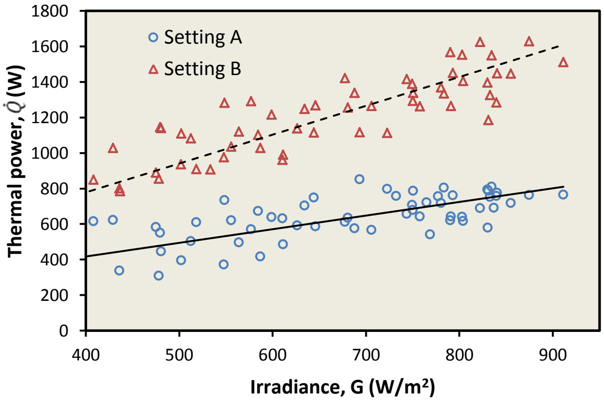

Fig. 6. Thermal power for fan at position 3.

An interesting aspect shown in this study is the result of comparing the values of thermal power obtained in both settings. Setting A does not reach higher thermal power than setting B in any situation. Setting A attains its maximum at position 6 of the fan, where a mass flow rate of 0.9-1 kg/s is registered. However, at the same position of the fan in setting B, it presents a lower mass flow rate (≈ 0.4 kg/s), although the power registered is superior to A. Therefore, it is clear that, although the mass flow rate is higher in A than in B, the capacity of B to generate a major temperature step implies a considerable advantage for the consecution of thermal power. This fact is more clearly observed in Fig. 7, which presents the power obtained in setting A at position 3 of the fan, together with the one gained in setting B at position 1 of the fan. At first sight, setting A should obtain higher power, since the air speed is higher. However, the temperature step presented in B at lower speeds holds a greater weight over the value of thermal power.

D. Thermal performance

In order to determine the proportion of the energy of the solar radiation that the system is able to use in the shape of thermal energy, the thermal performance is called upon.

It deals with a variable that is only useful to analyse drawing from certain values of irradiance, since for low values the thermal energy that enters the system becomes inferior to the extracted energy, because the latter depends on the air speed in the duct.

The thermal performance follows certain linearity according to the irradiance, presenting a light tendency to decrease as the latter increases. Again, setting B achieves better results, as well as yields.

Although it is not possible to obtain decisive conclusions regarding this variable, due to the uncertainty derived from the calculation of the thermal power, interesting behaviours are observed, to the extent of obtaining in setting B a performance over 80% by forced convection, and an overall performance of 50% in setting A. In order to interpret these results accurately, it has to be taken into account that, when calculating the thermal performance, the power of the system outlet is not only

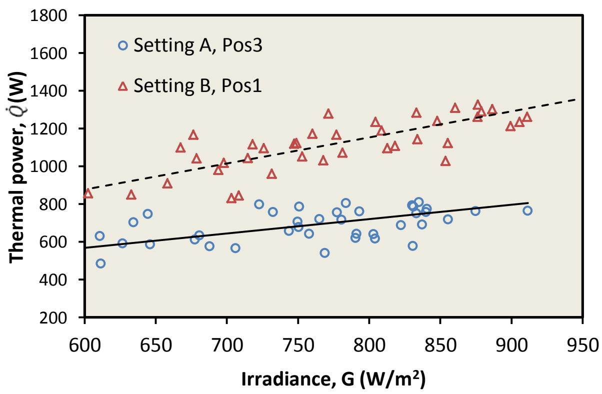

Fig. 7. Comparison the thermal power in Setting A for fan at position 3 versus Setting B for fan at position 1.

a product of the thermal effects, but of the kinetic energy of the air inside the duct.

E. PV module temperature

The main purpose of the ventilation and refrigeration of PV modules is to improve its electrical efficiency, which is severely affected at high temperatures. This research tries to give a different approach to the PV modules, but keeping and improving its original function.

Several researches, as [5], analyse the refrigeration by air of PV modules and how the reduce of its temperature affects the electrical efficiency. The present study incorporates the alternative proposed in setting B, which includes a series of plates interspersed in the duct, trying to improve the thermal and electrical behaviour.

The module temperature is reduced as the air velocity increases, as it was expected. 15ºC reductions are achieved between natural convection and the fan at position 6. This difference is obtained at high radiation levels, over 800 W/m^2 (Fig. 8). That behaviour is observed both A and B.

Although both settings manage to reduce the module temperature to the same extent, the temperature levels reached in B are lower. This is especially noticeable at irradiance values over 400 W/m^2, as shown in Fig. 8. That phenomenon is related to the results obtained regarding the air temperature step between the inlet and the outlet. Setting B produces higher air temperature steps due to a more effective heat exchange with the module surface. That implies higher heat dissipation and, therefore, a more outstanding reduction of the module temperature.

The electrical efficiency of the module can be determined assuming the traditional linear expression for the PV electrical efficiency given by Evans and Florschuetz [7]:

$$\eta_c = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \quad (4)$$

η_c is the electrical efficiency of the PV cell, η_{Tref} is the electrical efficiency at the reference temperature, β_{ref} is the reference temperature's coefficient, and T_c and T_{ref} are the cell and the reference temperatures, respectively. The quantities T_{ref} and β_{ref} are normally given by the PV manufacturer. However, in [6] is done an estimation of these values for the same model of PV module used in this work; the estimated values are $\eta_{Tref} = 0.15$, $\beta_{ref} = 0.006$ and $T_{ref} = 25$ºC.

The electrical efficiency is enhanced as the air velocity increases in the duct. That occurs in setting B clearly, where the efficiency is enhanced up to 1% between natural convection and the fan at position 6.

On the other hand, the comparison between both settings shows how in B, a major temperature reduction leads to an improvement of the efficiency regarding A. Setting B reaches its maximum mass flow rate level (≈ 0,4 kg/s) from the fan at position 3, where the lowest module temperature is registered too. In this case, as shown in Fig. 9, the enhancement in electrical efficiency between A and B could even result in 1%.

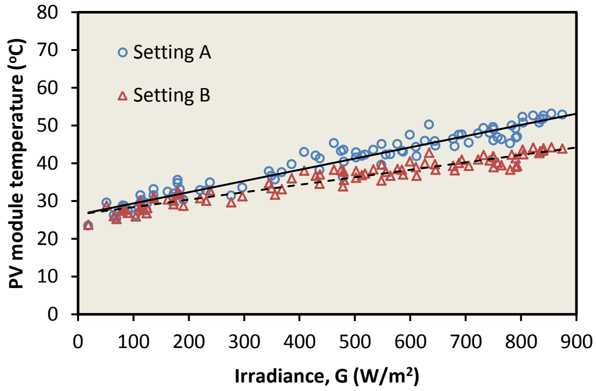

Fig. 8. PV module temperature for fan at position 3.

IV. CONCLUSIONS

The main purpose of this study is to check the adequacy of the use of PV modules for the regeneration of desiccant wheels. As it has been already mentioned, temperatures of 80-90ºC are necessary. The advantage of using PV modules in this regard, instead of other technologies which employ solar thermal energy, is that in this way it achieves a more compact and simple desiccant cooling system without barely maintenance needs.

In this way, a solar installation consisting of two photovoltaic panels with an air channel below them and an aspiration fan in each one is experimentally studied. One of these two systems is disposed of a series of plates which are interspersed in transversal direction from the airflow. Several sensors and a data acquisition system are installed to characterize the thermal behaviour of the photovoltaic modules. The installation is studied for different levels of refrigeration air velocity.

Regarding the air temperature step between the inlet and the outlet of the channel, it is noted that better results are obtained by natural convection, reaching an increment of about 7-8ºC in setting A and even 17ºC in setting B. By forced convection the air velocity increases and lower steps are achieved, although they are interesting too. According to the results, it is not possible to feed the regeneration process of a desiccant wheel directly with the experimental installation studied. However, the data collected show that the employment of several modules would be interesting. In this sense, it could be posed the installation of a refrigeration duct which includes a series of PV modules, so that the temperature step achieved in each one could be added until reaching the necessary value (80-90ºC in this case). Thus, the hot spot required to regenerate a desiccant wheel could be attained. The results obtained in this research could be also extrapolated to other applications, such as any process where a preheating step would be required.

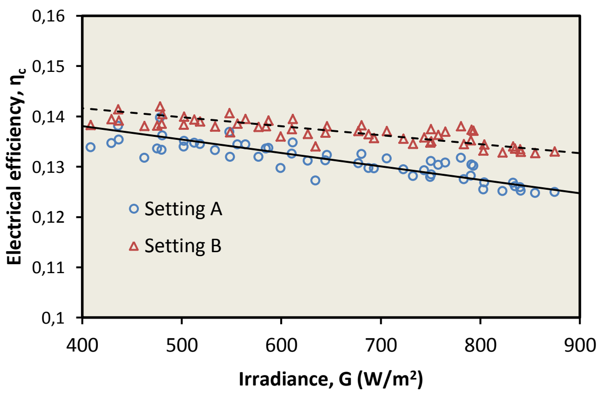

Fig. 9. Experimental efficiency of the PV module for fan at position 3, based on the traditional linear expression for the PV electrical efficiency [7], using the experimental coefficients of [6].

With respect to the thermal power, interesting data are obtained by natural convection due to high temperature steps. However, the randomness of the flow in these conditions does not allow carrying out an effective control on the generated power. That means a drawback in the application to the regeneration of desiccant wheels. By forced convection, the mass flow rate levels are more stable and, although lower temperature steps are obtained, the thermal power generated reaches useful values, to the extent of producing up to 1500 W in B for the fan position 3. It is also noted that setting B obtains higher power values than A, even working at lower mass flow rate levels. Thus, with less energy expenditure, better results can be obtained.

Setting B reduces the PV module temperature to a large extent, thus enhancing the electrical efficiency up to 1% with respect to setting A. The enhancement of the electrical efficiency, in combination with the waste heat exploitation, give rise to the optimization in the system's global energetic saving.

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