GLOBAL EFFICIENCY OF DIRECT FLOW VACUUM COLLECTORS IN AUTONOMOUS SOLAR DESICCANT COOLING: SIMULATION AND EXPERIMENTAL RESULTS

Paul Bourdoukan[1], Etienne Wurtz[2], Maurice Spérandio[1] and Patrice Joubert[1]

[1]LEPTAB: Laboratoire d'Etude des Phénomènes de Transfert Appliqué au Bâtiment, University of La Rochelle, Avenue Marillac, 17042 La Rochelle France
[2]LOCIE: Université de Savoie
Campus scientifique, 73376 Le Bourget du Lac

ABSTRACT

Using solar thermal energy is an interesting option for heat driven air conditioning e.g. desiccant cooling, but it is very important to know with which efficiency this renewable energy is used. In this paper a solar installation of direct flow vacuum tube collectors dedicated for desiccant cooling is investigated. First a model of the mentioned collectors is presented and implemented into the simulation environment SPARK then it is validated experimentally. After, simulations of autonomous operations are run and the global efficiency is calculated. Finally the effect of increasing the regeneration temperature on the efficiency is studied.

KEYWORDS

Solar desiccant cooling, vacuum collectors simulation, experimentation, efficiency, SPARK

INTRODUCTION

Conventional air conditioning using CFC refrigerants and having high electrical consumption has an important environmental impact. Desiccant cooling with rotating dehumidifier using water as a refrigerant and solar energy represents an alternative technique for vapor compressing systems (Jurinak et al. 1984). During the last 20 years this technique was subject of an increasing interest. Some researches focus on the modeling process of the desiccant wheel (Jurinak 1982) and (Stabat 2003), others on the optimization of the cycle by introducing new configurations and components (Kang and Maclaine-cross 1989). Studies were achieved by evaluating the COP which was compared to the reversal COP (Lavan et al. 1982) and (Pons and Kodama 2000). Other works were dedicated to the control of the system and its different operating mode (Maalouf et al. 2005), in fact desiccant cooling can operates under different mode depending on outside conditions and the availability of solar energy. (Maalouf 2006) studied the potential of desiccant cooling and the limitations of this technique due to outside temperature and humidity. All of the cited studies assumed that solar energy is available when needed considering that the regeneration temperature is low and can be provided by solar energy. Or it is true that solar energy can provide the regeneration energy but it is very important to evaluate the global efficiency of the solar installation. (Henning et al. 2001) studied the potential of flat plate collectors in autonomous operation as well as the solar fraction for solar assisted desiccant cooling. Few studies were dedicated to the global efficiency for solar desiccant cooling using direct flow vacuum collectors. This paper investigates the efficiency of such installations and the effect of increasing the regeneration temperature.

DESICCANT COOLING OPERATIONS

Principle

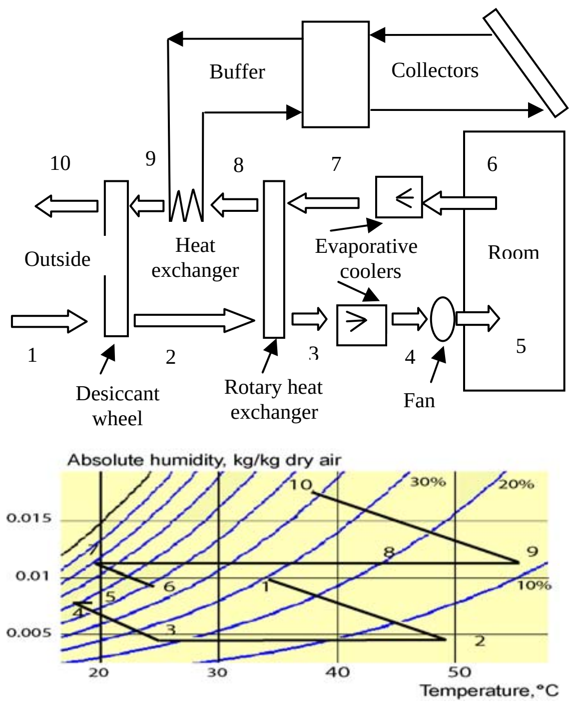

Figure1 Desiccant cooling and evolution in the psychometric chart

Figure (1) shows the solar desiccant cooling installation. An air handling unit is coupled to a solar installation via a heat exchanger. Outside air (1) is first dehumidified in the desiccant wheel (2); it is then cooled in the rotary heat exchanger (3) by the return air before undergoing another cooling process this time by evaporative cooling (4); then it is introduced in the room (5). The return air (6) is cooled to saturation by evaporative cooling (7) it cools the fresh air in the rotary heat exchanger (8) before being heated by solar energy in the heat exchanger (9) and finally regenerates the desiccant wheel (10) by carrying out the humidity and then is rejected outside.

Operations

Desiccant cooling is a very suited process for non residential buildings e.g. seminar rooms (Henning et al. 2001), banks etc. where the space is occupied during the day, thus air conditioning load matches with the available solar energy.

The air handling unit can operate under different modes (Maalouf et al. 2005), simple ventilation (only fans), indirect evaporative cooling (return humidifier and the rotary heat exchanger) and desiccant mode (all the components are operating e.g. the regeneration heat exchanger). During summer mornings and till noon the temperature is usually below 30°C as shown in the figure (2). The indirect evaporative cooling mode is sufficient to keep the local temperature in the comfort range, thus no need of regeneration is present before noon. Solar energy is then stored in the buffer. Later on, when the desiccant mode is required the buffer can provide the minimum regeneration temperature for air (60°C).

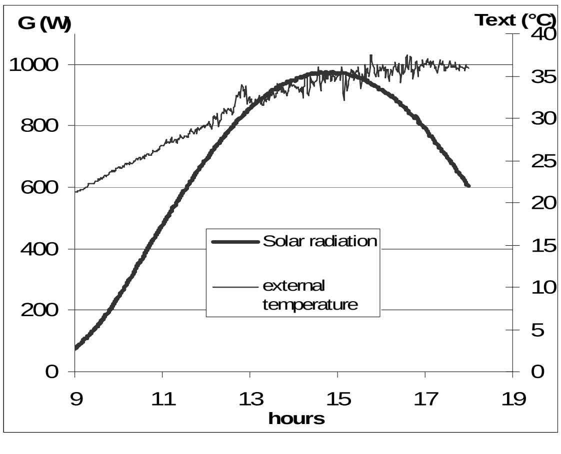

Figure 2 Metrological conditions for a typical summer day

In order to investigate the efficiency of vacuum collectors used in desiccant cooling a model of a solar installation with the mentioned collectors is presented in the following section and validated experimentally.

MODELING

Solar installation for desiccant cooling

The investigated solar installation is shown in the figure (3) below. Direct flow collectors feeding a storage tank via a counter-flow water to water heat exchanger. At the outlet of the tank a cross-flow water to air heat exchanger is used for regeneration.

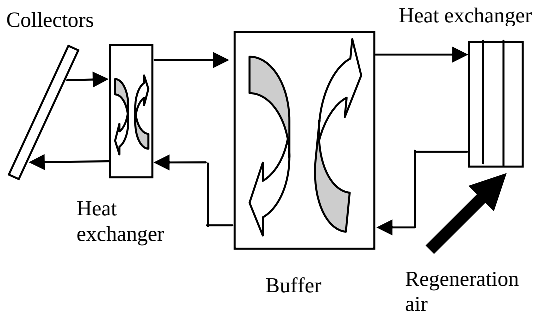

Figure 3 Solar installation for desiccant cooling

Direct flow vacuum tube

A direct flow vacuum tube is made of a glass cover, a collector plate absorber and a copper U tube. Heat transfers from the collector plate absorber to the solar circuit fluid via the copper heat transfer U tube itself fed by another tube. The design of the latter incorporates a patented dividing strip configuration, which separates the flow and the return of circuit fluid through the solar collector tubes. The collector plate and the heat transfer tube are vacuum-sealed inside a glass tube. This provides exceptional insulation.

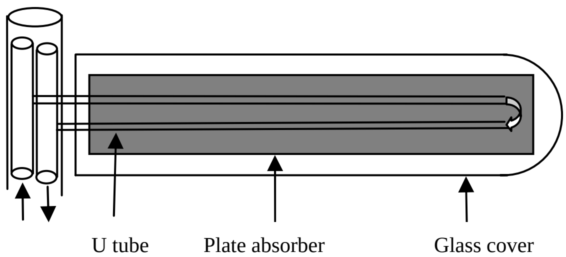

Figure 4 Direct flow vacuum tube collector

The model proposed is based on the mathematical model proposed by (Kamminga 1985) and (Schnieders 1997), and on the assumptions proposed by (Praene et al. 2005).

- The properties of the tube's material are independent of the temperature.
- The temperature gradient along the absorber and the glass cover is negligible.
- The glass cover is clean.

- The convection doesn't occur in the tube du to the vacuum.

The glass cover, the absorber and the fluid are considered separately. Each has its heat capacity *C* and its temperature *T*. It is considered that the fluid's temperature is function of the fluid direction and the conduction along this direction is neglected. The glass cover exchanges heat by convection with the ambient air and by radiation with the sky and the plate absorber, the latter exchanges by convection with fluid while receiving the solar radiation. With the solar radiation G, the fluid velocity u and the ambient temperature T_a each component's equation can be written:

$$\rho_g V_g C_g \frac{\partial T_g}{\partial t} = \varepsilon_g.\sigma.S_g(T_{sky}^4 - T_g^4) + \varepsilon_p \sigma.S_p\left(T_p^4 - T_g^4\right) + S_g h_g(T_a - T_g) \quad (1)$$

$$\rho_p V_p C_p \frac{\partial T_p}{\partial t} = \varepsilon_p.\sigma.S_p(T_g^4 - T_p^4) + G.\tau\alpha.S_p(T_p^4 - T_g^4) + S_{pf} h_f(T_f - T_p) \quad (2)$$

$$m_f.C_f\left(\frac{\partial T_f}{\partial t} + u\frac{\partial T_f}{\partial x}\right) = S_{pf} h_f(T_p - T_f) \quad (3)$$

Storage tank and heat exchangers

The storage tank is modeled by one node since no stratification can occurs because of two pumps operating in opposite directions as described in figure (3). The equation of the storage tank is then:

$$\rho_b V_b C_f \frac{\partial T_b}{\partial t} = m_{col} C_f(T_i - T_b) + m_{reg} C_f(T_{o,reg} - T_b) + h_b S_b(T_a - T_b) \quad (4)$$

The heat exchangers model is based on Ntu-effectiveness relations for heat exchangers (Kays and London 1984) and (Incropera and Dewitt 1996).

These equations are introduced into SPARK a general simulation environment that supports the definition of simulation models and the solution of these models via a robust and efficient differential/algebraic equation solver (Sowell and Haves 2001). In SPARK, the modeler describes the set of equations defining a model as an equation-based object. At the lowest level, an atomic object, in SPARK language, characterizes a single equation and its variables. Then macroscopic objects can be created as an assembly of various atomic or macroscopic objects. The entire model is built by connecting the different necessary objects. It is necessary to observe that the model is input/output free. The particular problem to be solved is then described by imposing the adequate input data (boundary and initial conditions) and by specifying the variables to be solved. So in this environment it is not necessary to order the equations or to express them as assignment statements (algorithms) in opposition to conventional modular environments.

In the following section the model is validated experimentally.

EXPERIMENTAL VALIDATION

Experimental setup

An experimental solar installation with vacuum tube collectors similar to that shown in figure (3) is used to validate the collector's model. Temperature at the outlet of collectors as well as the storage and ambient temperature are measured using Pt100 sensors. The global solar radiaton in the collectors plane is measured too using two pyranometers. The calculated outlet temperature of the collectors and the buffer temperature will be compared to the measured ones under the same conditions of solar radiation and ambient temperature.

Results

A summer day is selected to validate the model. Figure (5) shows the measured solar global radiation in the collectors' plane.

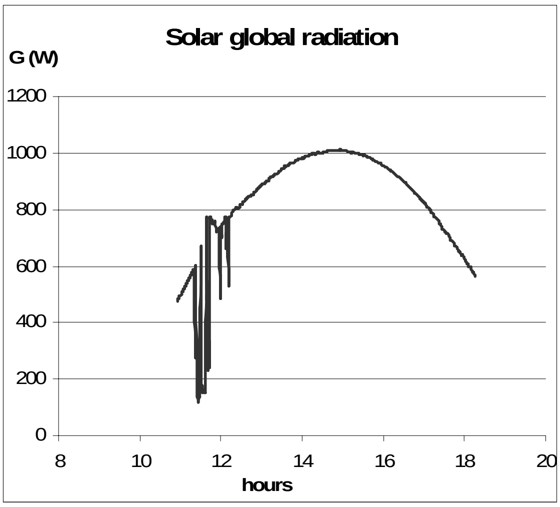

Figure 5 Measured global radiation W.m^{-2}

Figure (6) shows a comparison between the measured and calculated collectors' outlet temperature for the studied day. The temperature is very well predicted by the model even during perturbation. The difference between the measured and calculated temperature varies from 3°C to -1,5°C.

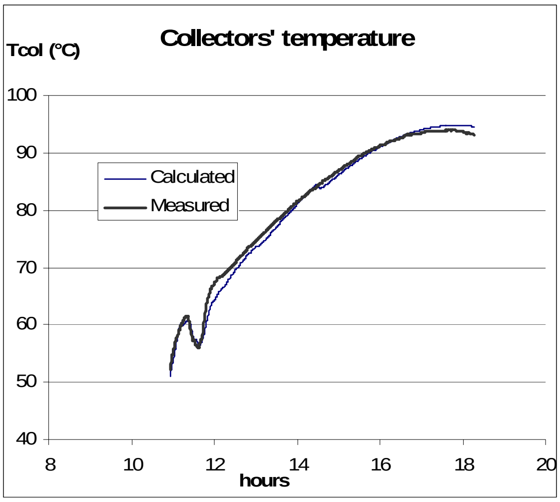

Figure 6 Comparison between measured and calculated collectors' temperature

Figure (7) compares the buffer's measured and predicted temperature for the same day. The maximum difference varies from -2°C to 1,5°C. It means that the tank's equation is, in this situation, acceptable and no stratification is to be considered.

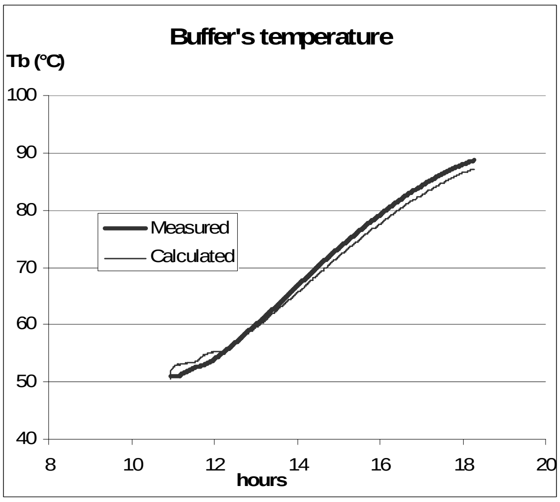

Figure 7 Comparison between measured and calculated buffer's temperature

From the upper figures it can be seen that the collectors' model is acceptable and can predict accurately the collectors and the buffer's temperature.

APPLICATION TO DESICCANT COOLING

In autonomous operations the regeneration energy is provided only by solar collectors. An important property to study is the global efficiency of the solar installation used for autonomous solar desiccant cooling.

Global efficiency

It is the ratio of the energy used for consumption (regeneration) to the solar energy received by the total collectors' area. Having the regeneration power used at the outlet of the storage tank and the total solar power received by the collectors, by integrating; the regeneration energy and the received solar energy can be determined.

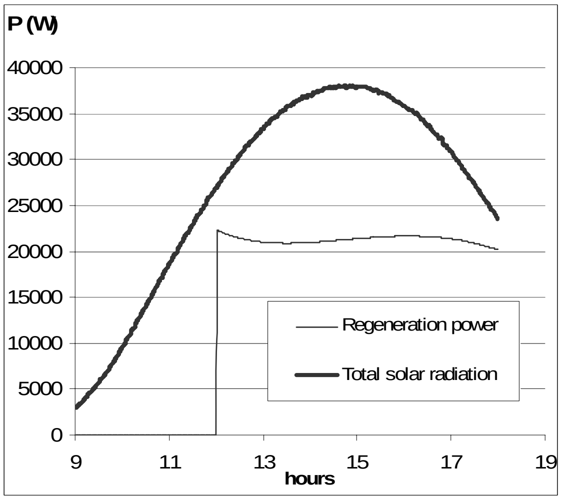

Figure 8 Total received solar power in comparison with the regeneration power

$$E_{regeneration} = \int_{regeneration} P_{regeneration}.dt \qquad (5)$$

$$P_{regeneration} = m_{reg} C_f (T_o - T_i) \qquad (6)$$

$$E_{received} = \int_{storage} G_{received}.dt \qquad (7)$$

$$\eta = \frac{E_{regeneration}}{E_{received}} \qquad (9)$$

The global efficiency is a very important property characterizing the importance of coupling a thermal process to a solar installation.

Simulations

In order to evaluate the global efficiency of the installation simulations are run for the measured meteorological conditions shown in figure (2). As described in the second paragraph, in the morning while the air handling unit is operating in indirect evaporative cooling solar energy is stored in the buffer and when desiccant mode is required the regeneration heat exchanger is fed by the buffer itself. Figure (9) shows the results.

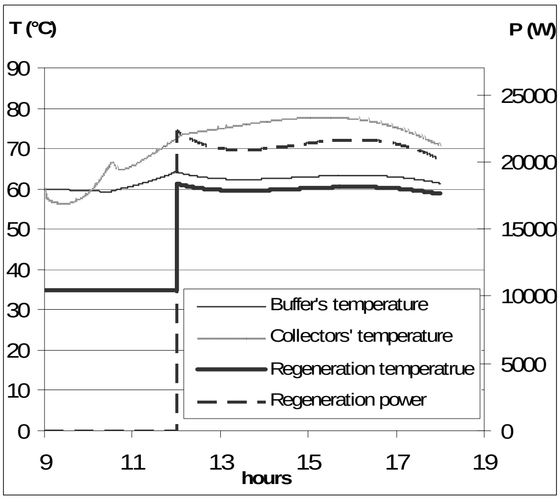

Figure 9 Results when regeneration starts at 12h

For this case the regeneration temperature is always acceptable (60°C), the buffer's temperature is almost constant too during regeneration period and the regeneration power varies from 23000 W to 20000 W. The calculated global efficiency using equations (5) to (9) is 0.55. This efficiency is relatively high for these types of installations. This efficiency is attained because vacuum collectors have a proper efficiency varying from 0.6 to 0.75. For flat plate collectors the global efficiency under such operating temperature is very less than 0.3.

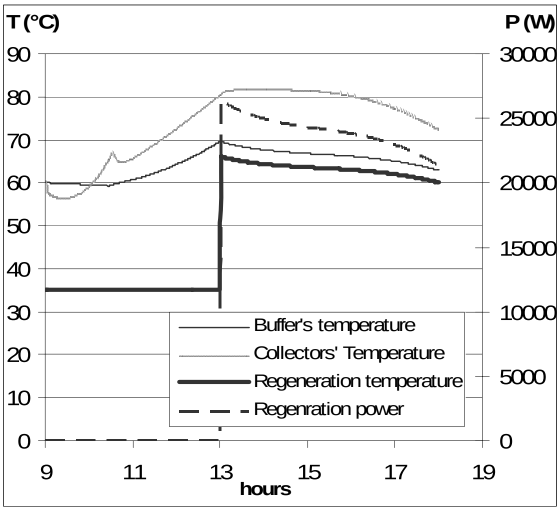

Figure 10 Results when regeneration starts at 13h

Desiccant wheel have a higher performance when increasing the regeneration temperature. In the case studied before the regeneration temperature is almost constant and limited to 60°C. In order to increase it with the same collectors' area the desiccant mode is delayed to 13h and after to 14h (it is possible because at these hours the space is usually unoccupied and indirect humidification is enough). Simulation results are shown in the figures (10) and (11) below.

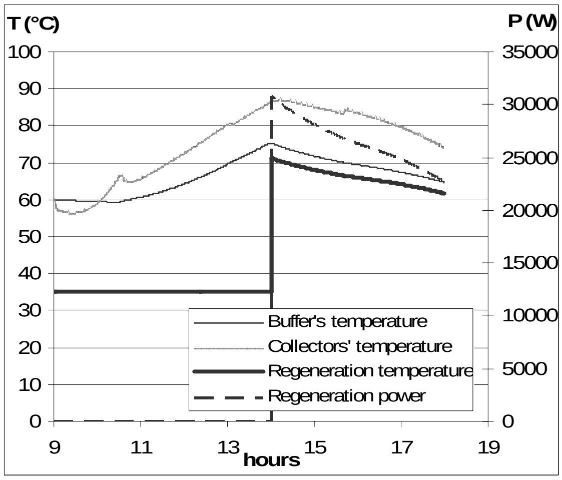

Figure 11 Results when regeneration starts at 14h

When the desiccant mode is delayed more energy can be stored thus the buffer's temperature increases as well as the regeneration temperature.

When desiccant mode begins at 13h the regeneration temperature varies from 67°C to 60°C at the end of the day while the regeneration power varies from 27000W to 21000W. In this case the global efficiency is 0.51.When the regeneration starts at 14h the regeneration temperature varies from 72°C to 62°C and regeneration power varies from 31000W to 23000W, the global efficiency is then 0.45.

This decrease in the global efficiency is du to the fact that in this case the collectors are operating on higher temperature. For the last case the collectors are operating at a temperature exceeding 80°C most of the time. Under these conditions the proper efficiency of the tube decreases which affects the global efficiency of the installation. It is obvious that the use direct flow vacuum collectors is very promising in solar desiccant cooling, its global efficiency attains 0.55 for 60°C of regeneration temperature. Increasing of 12°C the regeneration temperature for the same collectors' area decreases the global efficiency of 10%.

CONCLUSION

A model of direct flow vacuum tube collectors is implemented into the simulation environment SPARK then validated experimentally. The comparison between experimental and simulation results for the same operating conditions, shows that the model is accurate with a maximum error of 4.6%. The use of this type of collectors in solar desiccant cooling is then investigated. A solar installation for autonomous operation in desiccant cooling is simulated and its global efficiency is evaluated. Results show that vacuum tube collectors have a great potential in solar desiccant cooling operating with a global efficiency of 0.55 for a regeneration temperature of 60°C and 6 hours of desiccant mode.

Increasing the regeneration temperature of 12°C reduces the global efficiency to 0.45 in autonomous operations.

NOMECNCLATURE

Symbol

C	heat capacity ($J.kg^{-1}.K^{-1}$)
E	energy (J)
G	solar global radiation ($W. m^{-2}$)
h	heat transfer coefficient ($W.K^{-1}m^{-2}$)
m	mass flow rate ($kg.s^{-1}$)
P	power (W)
S	area (m^2)
T	temperature (K)
u	fluid velocity ($m.s^{-1}$)
V	volume (m^3)
x	coordinate in the fluid direction (m)
ε	emissivity
η	efficiency
$\tau\alpha$	transmission absorptance coefficient
σ	Stefan Boltzmann constant ($W.K^{-4}m^{-2}$)
ρ	density ($kg.m^{-3}$)

Subscripts

b	buffer
col	collector
f	fluid
g	glass
i	inlet
p	plate absorber
pf	plate-fluid
o	outlet
reg	regeneration

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