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Experimental Study on the Comparative Thermal Performance of a Solar Collector Using Coconut Coir over the Glass-Wool Thermal Insulation for Water Heating System

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Abstract: This study presents the comparative results of experimental investigations of the thermal performance of two solar water heaters. These technological devices operate under thermosiphon conditions. The first uses the coconut coir, a local vegetable fiber, cheap and available and the second, the glass wool, an imported and expensive material, as thermal insulations. Two complete collectors test facilities, operating in the same conditions, equipped with a data acquisition system, have been assembled and tested for comparing their thermal performances. These tests are performed under various minimum and maximum daily solar intensities, ranging from 220 to 1000 W m^{-2}, from cloudy to sunny days, with the daily outside temperature ranging between 25 to 40°C. The comparative results show an average efficiency of 64% for the two systems when the water mass flow rate reaches 0.010 kg sec^{-1}. The increase in temperature through the absorber of the first collector is higher than 40°C, when it is 50°C for the second one. The outlet hot water temperature of the first one reaches 80°C and more, when it is 90°C for the second one. The results show that the first system is quite suitable for application elsewhere and particularly in Africa, at an acquisition cost of 25% cheaper than the traditional one, where there is a plentiful supply of coconut coir.

Key words: Solar water heater, flat plate solar collector, natural circulation, mass flow, coconut coir, fiber glass

INTRODUCTION

In developed countries, energy consumption in the building sector represents a major part of the total energy budget. In the European Union, this is approximately equal to 40% of the total energy consumption. Most of this amount is spent for hot water production and space heating (Kalogirou, 2004). One way to reduce this amount of energy is to use an alternative energy, clean, renewable, which respects the environment. That is why attention has been focused on solar energy for heating, air-conditioning, drying, production of hot water, for the last decades. In addition to its advantages, solar energy is an inexhaustible and non-polluting source of energy.

Fortunately, Côte d'Ivoire, where this study is performed, like most Sub-Saharan African countries, has a high annual sunning rate. The solar water heater, consequently, seems to be a viable alternative to conventional fuels or electricity for the production of domestic hot water in these countries.

The solar water heating system most used for the domestic needs is the thermosiphon solar system with natural circulation. It is one of the most interesting technological device, the simplest and the most largely widespread of solar energy exploitation. Its remarkable effectiveness coupled with the simplicity in its design, autonomy of operation, the minimization of its maintenance make it an interesting alternative to the system using an auxiliary pump. It is made of a collector, a storage tank, connection pipes and a data acquisition chart. The collector is composed of a plate reflector, a series of riser and header tubes, a glass cover, an envelope and a heat insulation system. To avoid the use of a circulating pump, the collector must be positioned at a lower level than the storage tank in order to allow a convective thermal loop between the exchanger of the storage tank and the collector. Thus, when the sunbeams strike the collector surface, the density of the fluid in the collector becomes lower than that contained in the exchanger. The hot water of the collector goes up into the exchanger and the cold water of the exchanger goes down into the lower header tube.

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Solar water heater has been developed and investigated in details by many research groups (Karaghouli and Alnaser, 2001; Chang *et al*., 2002; Kudish *et al*., 2000). Its thermal performance has been studied for example by Nahar (2003) who presents panoply of techniques implemented in various works to reduce the thermal losses in the absorber in order to improve the collector effectiveness. In these studies, one minimizes for example the convective movements between the absorber and the glazing by using special transparent insulating materials. The same technique is used by Abdullah *et al.* (2003), with optical effectiveness materials very high to the solar radiation. The transparent insulating materials used by these authors are honeycombs structures of various configurations. Located between the absorber and the glazing, they have to remove or to minimize the air convective movements between the absorber and the glazing. The same thermal performance is studied by Esen and Esen (2005) to find out how the thermal performance of a two-phase thermosiphon solar collector was affected by using different refrigerants.

The summary of these previous works reveal the importance attached to the study. In spite of the fact that Africa, generally and Côte d'Ivoire, in particular, are very suitable for utilizing solar energy to heat water, the system is not yet widely applied, because of its relatively high acquisition cost.

The objective of the study is to conceive and develop new types of solar water heaters as powerful as traditional ones, easy to implement and to exploit, which do not require a specialized manpower, which use a local vegetable fiber, cheap and available, instead of an imported and expensive one, as heat insulators. The work consists in comparing through an experimental study the thermal performances of two collectors. One uses the coconut coir and the second, the glass wool, as heat insulators. The two collectors operate in the same conditions. The coconut coir collector is 25% cheaper than the glass wool one (Appendix 1). The results are also compared to those of previous works using other heat insulators. The study is articulated around basic phenomena intervening in the process of the solar heating system: (1) measurements of physical parameters which govern natural circulation by thermosiphon, like the total radiation and diffuse receipt by the collector, temperatures in various points of the system (connecting pipes, inlet and outlet of the absorber, etc.), (2) determination of the comparative thermal effectiveness.

MATERIALS AND METHODS

Theoretical analysis: The performance of a flat plate collector depends on its design parameters: Type of absorber, type of glass cover, thickness and type of insulation. Beside these, the performance also depends on the meteorological and operating conditions (Nahar, 2003). This study, based on the same analysis as that of Abdullah *et al.* (2003), is presented in order to bring a comprehension of the operation of the various components of the system. The useful energy (Q_u) recovered by the plate collectors is expressed by the heat balance of these collectors under steady-state conditions. It is given by Hottel and Whillier Equations (1991):

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{1}$$

$$Q_u = A_c I_T(\tau\alpha) - A_c U_G(T_{abs} - T_a) \tag{2}$$

Where, $\dot{m}$ is the water mass flow rate (kg sec^{-1}), C_p is the specific heat (J kg^{-1} K^{-1}), T_o and T_i are outlet and inlet water temperatures (K), A_c is the collector area (m^2), I_T is the incident radiation (W m^{-2}), τ is the transmission coefficient, α is the absorption coefficient, U_G is the global heat loss coefficient (W m^{-2} K^{-1}), T_{abs} and T_a are absorber and ambient temperatures. A measure of the collector performance is the collector effectiveness. It is defined as:

$$\eta = \frac{Q_u}{A_c I_T} = \frac{\dot{m}C_p(T_o - T_i)}{A_c I_T} \tag{3}$$

According to Karaghouli and Alnaser (2001) the collector instantaneous efficiency is influenced by several factors such as: The materials used, the design of the absorber, the properties of the glass, weather and operating conditions. So, it could be expressed in the form of the following euation:

$$\eta = \frac{Q_u}{I_T A_c} = F(\tau\alpha) - F'U_G\left(\frac{T_{abs} - T_a}{I_T}\right) \tag{4}$$

Where, F' ($\tau\alpha$) and F' U_G are two major parameters that constitute the simplest practical collector model. F' ($\tau\alpha$) is an indication of how energy is absorbed by the absorber and F' U_G (W m^{-2} K^{-1}) is an indication of how energy is lost. F' is the collector efficiency factor.

The evaluation of the thermal losses is complex. For their calculation, empirical equations were developed by Hottel and Woertz (1942). So, the total energy lost (Q_L) through the collector is expressed as:

$$Q_L = A_c U_G (T_{abs} - T_a) \quad (5)$$

In which U_G is the global heat loss coefficient of the system. It is the sum of respective heat loss coefficients, through the top (U_t), the bottom (U_b) and the edges (U_e) of the collector to the surrounding by conduction, convection and infrared radiation (Koyuncu, 2006).

$$U_G = U_t + U_b + U_e \quad (6)$$

In which;

$$\frac{1}{U_t} = \frac{1}{U_1} + \frac{e_g}{k_g} + \frac{1}{U_2} \quad (7)$$

In stationary state, one considers that there is no accumulation in the glass and one neglects e_g/k_g.

U_1 is the heat exchange coefficient between the collector absorbing surface and the glass. It is expressed as:

$$U_1 = U_{1r} + U_{1c} \quad (8)$$

In which U_{1r} and U_{1c} are, respectively the radiative heat exchange coefficient and the convective and conductive heat exchange coefficients. U_2 is the heat exchange coefficient between the glazing and the surroundings. It is expressed as:

$$U_2 = U_{2r} + U_{2c} \quad (9)$$

To quantify these heat exchange coefficients, let us note the following points:

- The radiative heat exchange between two parallel plates A and B of emissivity ε_A and ε_B is written

$$Q_{1r} = \frac{\sigma(T_A^4 - T_B^4)}{1/\varepsilon_A + 1/\varepsilon_B - 1} = U_r (T_A - T_B) \quad (10)$$

Where, σ is Stefan-Boltzmann constant.

$$U_r = \frac{\sigma(T_A^4 + T_B^4)(T_A + T_B)}{1/\varepsilon_A + 1/\varepsilon_B - 1} \quad (11)$$

The radiative heat exchange between a plate B and the sky is expressed by:

$$Q_{2r} = \varepsilon_B \sigma (T_B^4 - T_{sky}^4) \quad (12)$$

- The convective heat exchange between A and B is written as:

$$Q_c = U_c (T_A - T_B) \quad (13)$$

One has thus the possibility to express the energy loss between the collector-glass and the glass-surrounding medium by:

$$Q_{L,col-g} = U_{1c}(T_{abs} - T_g) + U_{1r}(T_{abs} - T_g) = U_1(T_{abs} - T_g) \quad (14)$$

$$Q_{L,g-a} = U_{2c}(T_g - T_a) + U_{2r}(T_g - T_a) = U_2(T_g - T_a) \quad (15)$$

U_{1c}, U_{1r}, U_{2c}, U_{1c} are expressed below:

$$U_{1c} = 1.1\ (T_g - T_\alpha)^{0.25} \text{ (Petitjean, 1980)} \quad (16)$$

$$U_{1r} = \frac{\sigma\varepsilon_a (T_{abs}^4 - T_g^4)}{T_{abs} - T_g} = \sigma\varepsilon_a (T_{abs}^2 + T_g^2)(T_{abs} + T_g) \quad (17)$$

(Petitjean, 1980)

With

$$\varepsilon_a = \frac{1}{1/\varepsilon_g + 1/\varepsilon_{abs} - 1}$$

$$U_{2r} = \frac{\sigma\varepsilon_g (T_g^4 - T_{sky}^4)}{T_g - T_a} \text{ (Petitjean,1980)} \quad (18)$$

By considering that $T_\alpha = T_{sky}$ (Petitjean, 1980) the relation (18) becomes:

$$U_{2r} = \sigma\varepsilon_g (T_g^2 + T_a^2)(T_g + T_a) \quad (19)$$

As the average wind velocity (V) in Yamoussoukro is lower than 4 m sec^{-1} (Bassigny and Gougou, 1996), U_{2c} is expressed as:

$$U_{2c} = 2.2\ (T_g - T_\alpha)^{0.25} + 4V \quad (20)$$

The expression of the conductive heat transfer coefficient through the bottom of the collector is:

$$U_b = \frac{k_{ins}}{e_{ins}} \frac{(T_{abs} - T_b)}{T_{abs} - T_a} \text{ (Petitjean, 1980)} \quad (21)$$

In which k_{ins} is the thermal conductivity of the insulation and e_{ins} its thickness.

The expression of the conductive heat transfer coefficient through the edges of the collector is:

$$U_e = 1.42\left(\frac{T_w - T_f}{L}\right)^{1/4} \text{ (Koyuncu, 2006)} \tag{22}$$

The preceding relations make possible to lead to the general expression of U_G (Petitjean, 1980) as:

$$U_G = \left[\left\{U_{1c} + \frac{\sigma(T_{abs} + T_g)(T_{abs} + T_g)}{1/\varepsilon_{abs} + 1/\varepsilon_g - 1}\right]^{-1} + \left\{\begin{matrix} 2.2(T_g - T_a)^{0.25} + 1.42\left[\frac{T_w - T_f}{L}\right]^{0.25} \\ +\varepsilon_g\sigma(T_g^2 + T_a^2)(T_g + T_a)\end{matrix}\right\}^{-1}\right]^{-1} \tag{23}$$

The total heat losses (Q_L) thus determined associated to the optical and thermal properties of the collector, allow also the determination of the effectiveness.

Experimental study and procedure: The general experimental device contains two collectors, a solar integrator, a pyranometer and a data acquisition chart. The two collectors are identical in the design and the realization (Appendix 1 the materials used and the manufacturing costs). They are 2 m^2 surface each one. A diagrammatic representation of one of them is presented on Fig. 1 and their principal physical characteristics are presented in Table 1.

The works were performed in Yamoussoukro, the political capital city of Côte d'Ivoire, a West African country, located between 5 and 11° Northern latitude. Yamoussoukro is located at 6.54° Northern latitude (Bassigny and Gougou, 1996). The annual solar energy received in this area lies between 1650 and 1950 kW h m^{-2} (Benallou and Bougard, 1990).

To determine the optimal position of the collectors, preliminaries measurements of temperatures and sunning were realized while varying the inclination angle of the collectors. The results make possible the determination of the optimal tilt angle which is 10±2° (Nanga *et al*., 1998).

Table 1: Principal physical characteristics of the system

I-Collector		II-Storage tank and piping	
Surface	$A_c = 2$ m^2	Tube 4-1 length	$L_{41} = 2.57$ m
Internal diameter of tubes	d = 0.01 m	Tube 2-3 length	$L_{23} = 1.18$ m
Tube thickness	e_t =0.001 m	Exchanger length	$L_e = 6$ m
Absorber tube number	N = 12	Tube internal diameter	d = 0.01 m
Tilt Angle	I = 10°	Storage tank position	horizontal
Collector length	L_c = 2.2 m	Storage tank height	0.39 m
Collector width	l_c = 1 m	Copper thermal conductivity	380 W m^{-2} K^{-1}
Absorber length	L_{abs} = 1.95 m		
Optical efficiency, $(\tau\alpha) = 0.83$ (Cardonnel, 1983)			

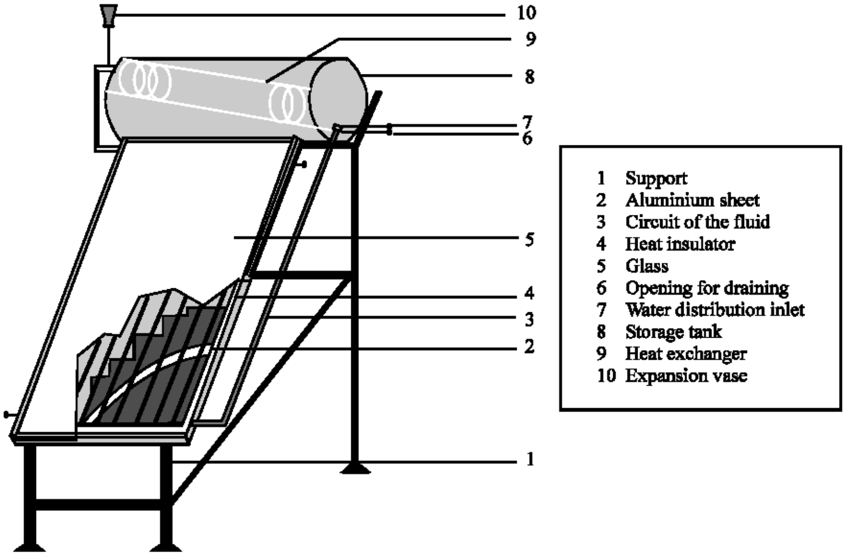

Fig. 1: Front view of one of the solar water heater, the storage tank and the connection pipes

So, the two collectors are oriented to the South at a tilt angle of 10° compared to the horizontal. These collectors are composed each of a transparent glazed cover and an absorber which transforms the solar radiation in heat. A 3 cm thickness blade air separates the glass from the absorber (Cardonnel, 1983). These absorbers are thermally insulated at the back and on the lateral sides, one by the glass wool and the other by the coconut coir. Each thermal insulation is 5 cm thickness. The coconut coir has a lifespan of more than ten years when it is under shelters (Ekoun, 20071).

- The total incident solar radiation (I_T) is measured using a pyranometer Kipp and Zonen CM10. It is connected to a numerical integrator, allowing the reading of instantaneous powers and the energy received, by digital display, over one given period. In order to convert directly the radiation received into heat, the pyranometer is tilted in the same position as the collectors. The relative uncertainty of this device given by the manufacturer is ±2%.
- In order to avoid perturbing water flow of each collector, one uses probes of low dimensions made up of diode 1N4148 with silicon of 1.6 mm diameter, of ± 0.5°C precision. The probes are plunged in the liquid, at the inlet and the outlet of the collectors and the storage tanks. They are also welded on the absorber tubes, at the back of the collectors, on the reflectors and the glasses and are exposed to ambient air. They allow the following of the temperatures evolution. All the probes used for measurements are calibrated before using. The average relative uncertainty of the temperatures measured by the probes is ±4%.
- The experimental procedure focuses mainly on the following of the evolution of the heat fluxes and temperatures of these systems. The different measurements recorded are realized every ten minutes. The temperatures are recorded at 16 points of each system: the extremities temperatures of the absorbers, the collector's inlet and outlet primary fluid temperatures, the exchanger's inlet and outlet primary fluid temperatures, the secondary fluid temperatures (hot water to use) at the inlet and outlet of the storages tanks (not presented here), the internal and external glass cover temperatures and ambient temperature. The devices are under monitoring over long sunny and cloudy days. A measurement power station made of a data acquisition chart, a computer and the KIPP and ZONEN integrator collect the data. These are then treated using a data processing program.
- The experimental mass flow rate is obtained by calculation from the establishment of heat and mass transfer balance between the inlet and outlet collector hot water according to the relation:

$$I_T(\tau\alpha)\eta A_c = \dot{m}_{ex} C_p (T_{f2} - T_{f1}) \tag{24}$$

With the efficiency (η) expressed as:

$$\eta = F'(\tau\alpha) - FU_G\left(\frac{T_{abs} - T_a}{I_T}\right) \tag{25}$$

Substituting η by its expression in Eq. 24, one obtains:

$$\dot{m}_{ex} = \frac{I_T(\tau\alpha)A_c}{C_p(T_{f2} - T_{f1})}\left[F(\tau\alpha) - FU_G\left(\frac{T_{abs} - T_a}{I_T}\right)\right] \tag{26}$$

With:

$$T_{abs} = \frac{T_{i,abs} + T_{o,abs}}{2} \tag{27}$$

Where, $T_{i,\,abs}$ and $T_{o,\,abs}$ are respectively the inlet and outlet temperatures of the absorber.

The reading of the temperatures T_{f1}, T_{f2}, T_{abs} and T_a, on the one hand, the incident heat flux, on the other hand, allows the determination of the instantaneous experimental fluid mass flow rate ($\dot{m}_{ex}(t)$) with an overall accuracy of ±6.5%.

The experiments were performed without hot water withdrawal, at different meteorological conditions, from August to October 2004, then from January to September 2005.

RESULTS AND DISCUSSION

The thermal performance study of a solar collector presents two forms. The first form is established starting from the temperature levels recorded. Indeed, from maximum and minimum heat fluxes recorded, what can be the average temperature levels which can be recorded from the absorbers, the collector's outlet primary water temperatures? In the second form, one defines its effectiveness according to the temperature reduced parameter

$$\frac{T_{abs} - T_a}{I_T}.$$

All these results and data, essential to situate the level of the quality of the collector, are presented for favourable weather conditions (sunny time) and unfavourable weather conditions (cloudy time), since the device is designed and installed to provide permanently hot water without any form of weather restrictions.

Heat fluxes and temperatures: Figure 2a and b present the evolution with the time of the heat flux, the ambient temperature, the average temperature of the two absorbers, for the coconut Coir Collector (CC) and that of the Glass Wool (GW), for a very sunny time (Fig. 2a) and for a very cloudy time (Fig. 2b). Figure 3a and b present also the evolution with the time of the heat flux, the ambient temperature and the outlet hot water temperature of the two collectors, respectively in the case of a very sunny time and in the case of a very cloudy time. The maximum and minimal values of heat fluxes and temperatures recorded in all these cases, the times to which these values are recorded are recapitulated in Table 2. Analysing the data of this table, one can make these observations:

- From Fig. 2, one can notice that the outlet hot water temperature of the collector is higher than that of the absorber because it is an average temperature

  $$T_{abs} = \frac{T_{i,abs} + T_{o,abs}}{2} \quad .$$

  Thus, for an incident heat flux of 1000 W m^{-2} one records the maximum average absorber temperature level of 69°C for the coconut coir collector when that of the glass wool is 75°C for a very sunny time. For heat fluxes of 220 W m^{-2} which concerns very cloudy times, one records the maximum average absorber temperature level of 37 and 48°C, respectively for the two types of collectors.
- From Fig. 3, it emerges that the maximum temperature level of hot water leaving the coconut coir collector is 83 and 90°C for the glass wool collector for very sunny times, then 45 and 50°C for very cloudy times, respectively for the two types of collectors, for the same heat fluxes as in Fig. 2.

With this analysis, one can make two notifications. The first is that, after the setting in mode period of the system, the temperatures recorded for the glass wool collector are a little higher than those obtained for the coconut coir collector. This is normal if we take into account the fact that the glass wool has a thermal conductibility of 0.04 W m^{-1} K^{-1} (Bejan, 1993) which is lower than that of the coconut coir which is 0.074 W m^{-1} K^{-1} (Appendix 2), from where there is less thermal losses on the sides and at the bottom of the collector. The second notification is that in all

Table 2: Maximum values recorded from Fig. 2 and 3

Type of insulation	Heat flux (W m^{-2})	Ambient temperature (°C)	Collector average temperature (°C)	Outlet hot water temperature (°C)
Sunny time				
Coconut coir	1000	40	69	83
(CC) (time)	(12:00)	(13:40)	(13:00)	(13:00)
Glass wool (GW)	1000	40	75	90
(time)	(12:00)	(13:40)	(13:00)	(13:00)
Cloudy time				
Coconut coir	220	25.8	37	45
(CC) (time)	(12:30)	(12:50)	(14:50)	(14:50)
Glass wool (GW)	220	25.8	48	50
(time)	(12:30)	(12:50)	(14:50)	(14:50)

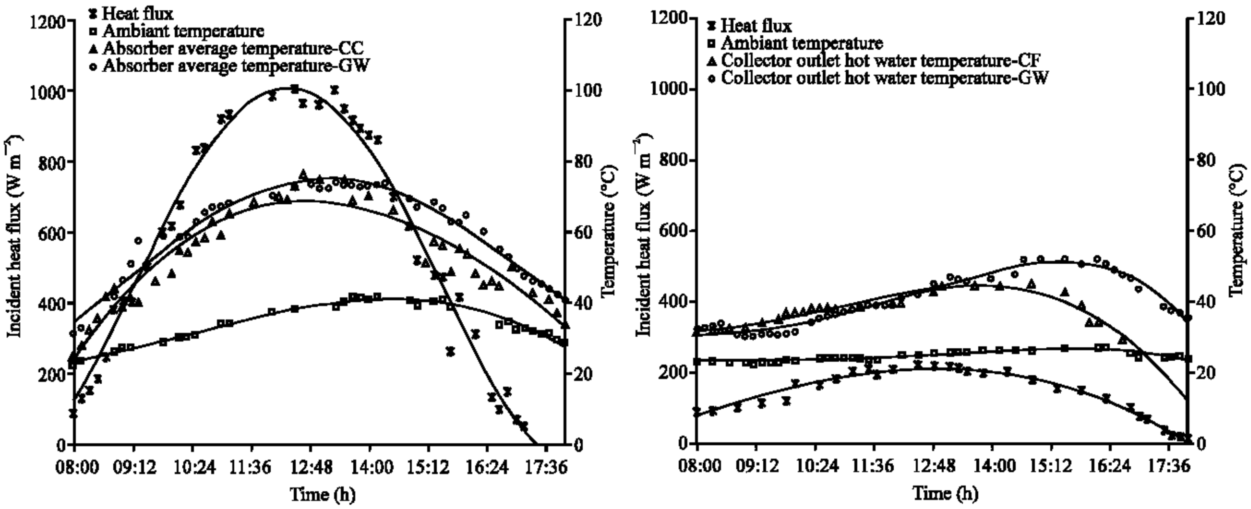

Fig. 2: Instantaneous average thermal heat flux, ambient and absorber average temperatures for the two types of collectors for a (a) very sunny time and (b) a very cloudy time

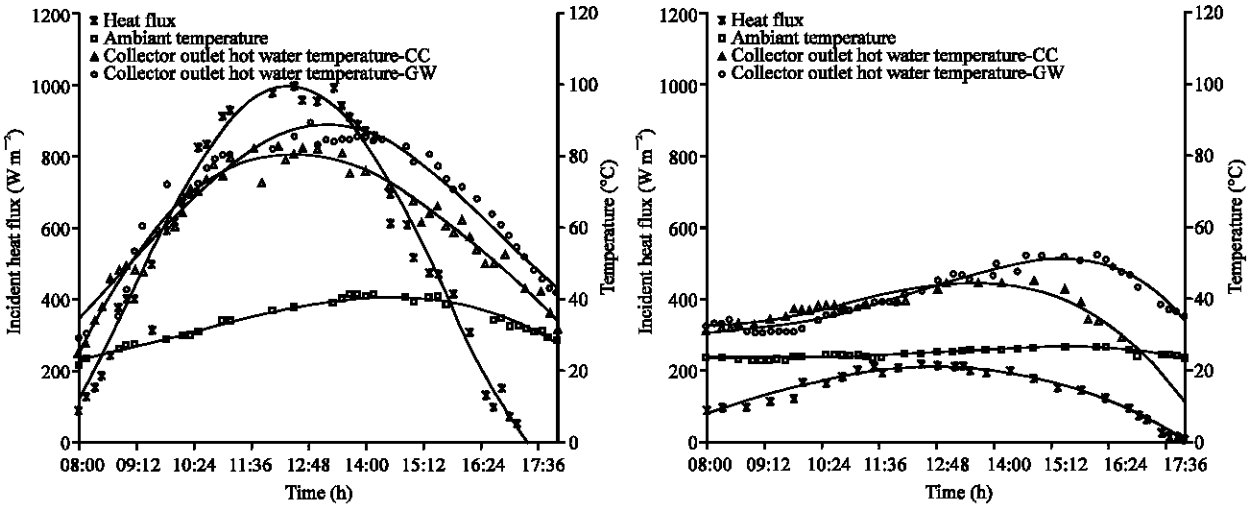

Fig. 3: Instantaneous average thermal heat flux, ambient and collector outlet hot water temperatures for the two types of collectors for a (a) very sunny time and (b) very cloudy time

Table 3: Comparative results of this study to previous ones of the literature

Study cite	Type of insulation (thickness)	Heat flux max. (W m^{-2})	T_{amb} (°C)	T_{ohf} (°C)	$\Delta T_{max} = T_{ohf} - T_{amb}$ (°C)
Chuawittayawuth and Kumar (2002)	Polyurethane (30 mm)	1140	20	76	56
Abdullah *et al.* (2003)	Polystyrene (15 mm) and glass wool (25 mm)	880	42	61	19
Hussein (2003)	Glass wool (25 mm)	880	38	57	19
Nahar (2002)	Glass wool (100 mm)	1055	32	58	26
Esen and Esen (2005)	Glass wool (100 mm)	1000	28	70	42
Present study (CC)	Coconut coir (50 mm)	1000	40	83	43
Present study (GW)	Glass wool (50 mm)	1000	40	90	50

these cases, whatever the meteorological conditions, the average difference temperature recorded, during sunny and cloudy times, does not exceed 7°C, which is interesting and shows that for an average difference of only 7°C between the glass wool collector and that of coconut coir, it is more economical and interesting to use a solar water heater of lower cost for the production of hot water.

In order to place this study in the perspective with previous works of the literature in the same field, Table 3 recapitulates a quantitative comparison between our results to numerical and experimental ones, for different types of heat insulations (polyurethane, polystyrene, glass wool). Analysing the results of this table, we have particularly privileged the results of the columns 3, 5 and 6 which relate the heat flux, the outlet hot water temperature levels (T_{ohw}) from the collectors and the difference between this temperature and the ambient one. So, for a difference of 43°C between the outlet hot water temperature and that of the ambient, one can note that the results of the coconut coir collector is one of the best, compared with that of Abdullah *et al.* (2003), Hussein (2003), Nahar (2003) and Esen and Esen (2005), knowing that the coconut coir is the lowest class of insulation.

Efficiency: The experimental results are also presented in the form of graphs and correlations that describe the collector efficiency (η) with the reduced temperature parameter

$$\frac{T_{abs} - T_a}{I_T}$$

for the two types of collectors during sunny days (Fig. 4a) and cloudy days (Fig. 4b). The experimental data are correlated in linear equations to provide the characteristic parameters of the collectors in order to establish comparison between these last one and that of previous works of the literature. Table 4 recapitulates equations of the four straight lines. The identification of these four straight lines equations to Eq. 4 allows the determination of the two collectors characteristic parameters. This comparison gives the y-axis intercept, F' ($\tau\alpha$) and the slope of the line F' U_G. The analysis of these results shows that the efficiency curves are close at low values of the reduced temperature parameter. As this parameter increases the curves diverge because the efficiency becomes more dependent on F' U_G and the efficiency decreases with the increase of the heat losses. One can note again that the two curves of the Fig. 4b are almost confused, which is normal taking into account the fact that on cloudy days, there is not direct radiation. The

Table 4: Collector characteristic parameters

Type of insulation	Efficiency equation	F'(τα)	F'U$_G$ (W m^{-2} °C)
Sunny time			
Coconut coir (CC)	$\eta = 79.820 - 599.76(\frac{T_{abs} - T_a}{I_T})$	0.798	5.977
Glass wool (GW)	$\eta = 80.340 - 540.16(\frac{T_{abs} - T_a}{I_T})$	0.803	5.40
Cloudy time			
Coconut coir (CC)	$\eta = 81.790 - 491.31(\frac{T_{abs} - T_a}{I_T})$	0.817	4.91
Glass wool (GW)	$\eta = 81.962 - 480.56(\frac{T_{abs} - T_a}{I_T})$	0.820	4.80

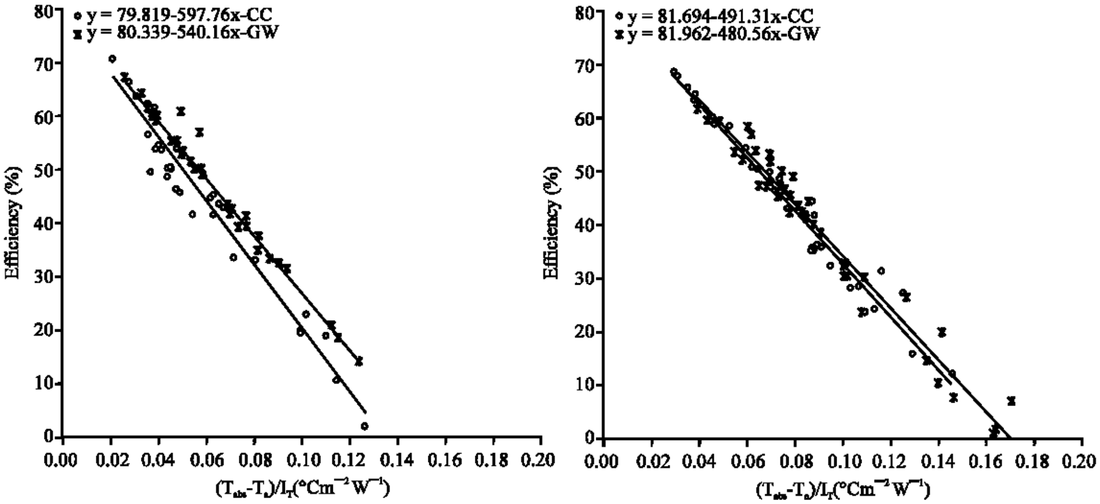

Fig. 4: Comparative efficiency of the two types of collectors for (a) sunny time with $\frac{T_{abs} - T_a}{I_T}$ and (b) cloudy time with

levels of temperatures and heat fluxes are then very low as confirmed by the curves of the Fig. 3b and b. It results from this a relatively weak thermal loss and thus a weak difference between the two curves. The data of this Table 4 show also that the glass wool collector has the highest efficiency and the lowest overall thermal loss, which is also normal. Whereas the thermal conductivity of the glass wool is 85% weaker than that of the coconut coir, the total average thermal loss is only 7.3% weaker for the glass wool collector. These results show that the coconut coir collector is a powerful thermal collector. Actually, according to Duffie and Beckman (1991) and Tiwari *et al.* (1991), the quality of a solar thermal collector is determined according to the pair of values of the intercept F' (τα) and the slope F' U$_G$. So, for a good collector, this pair of values is 0.8 and 4.5 W m^{-2} °C, respectively and 0.6 and 8.5 W m^{-2}°C, respectively for a poor collector. The calculated average values of this pair of values are 0.81 and 5.44 W m^{-2}°C, for the coconut coir collector and 0.81 and 5.10 W m^{-2}°C, for the glass wool collector. This shows undeniable qualities of insulation of this material that one can now take into account in the insulation of thermal solar collectors as well in the design of heating waters as in that of solar driers.

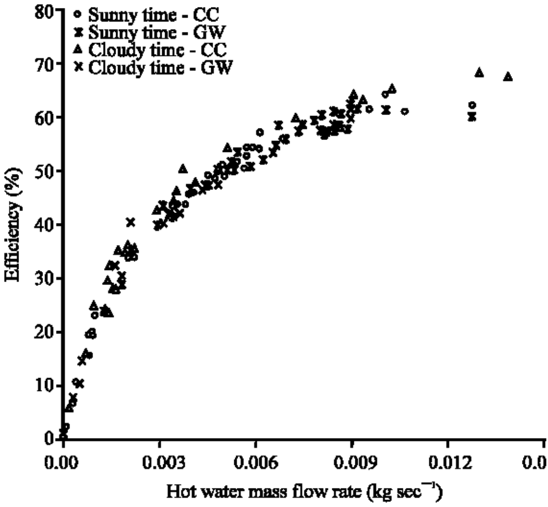

Fig. 5: Efficiency of the two types of collectors with hot water mass flow rate

Figure 5 presents the efficiency of the two types of collectors according to the mass flow rate of the hot fluid. The analysis of this network of curves shows that the efficiency increases quickly with the mass flow rate whatever the meteorological conditions and the type of collectors, then reaches 64% when the mass flow rate is 0.010 kg sec^{-1}. The uncertainty values of the $F'(\tau\alpha)$ and $F'U_G$ calculated is ±1.5%. This result is a very good one compared to those of Canellias and Javelas (1979) and that of Kalogirou and Papamarcou (2000) which are, respectively 40 and 50% at the optimum values of mass flow rate. It is also noticed that all these curves are almost identical whatever the meteorological conditions and the type of collectors. Which is normal and prove that the efficiency of a collector plate depends only on its physical characteristics (Nahar, 2003).

CONCLUSIONS

The performance of a solar collector using coconut coir as thermal insulation has been investigated. The experimental data are analysed and the correlations resulting are reported for all cases. Based on the experimental results reported herein, the following conclusions can be drawn:

- Wathever the meteorological conditions, it is possible to have hot water with very good temperature levels using solar water heaters with coconut coir as heat insulator.
- For a 25% manufacturing cost saving of the coconut coir solar water heater, the difference between outlet hot water temperatures of the two collectors is only 7°C, whatever the meteorological conditions, which is insignificant for the major benefit realized when buying this device.
- With a raising temperature in the collector of more than 40°C, a production of hot water at a temperature more than 80°C, there are some numbers which show that the thermal collector with coconut coir is a powerful one.
- The glass wool only represents 27.3% of the total manufacturing cost of the glass wool collector, while it is only 2.81% for the coconut coir in the total manufacturing cost of the coconut coir collector. In addition, the glass wool is not permanently available like it is for the coconut coir.
- All the results show that this system is quite suitable for application elsewhere and particularly in Africa, where there is a plentiful supply of coconut coir.

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Table 5: Cost of the materials needed, per SWH unit, in US$

Quantity	Part	Cost (US$) GW	Cost (US$) CC
4	Galvanized steel tubes of 0.5” diameter and 6 m long (standard length)	129.00	129.00
1	Galvanized steel tube of 1” diameter and 6 m long	19.05	19.05
3	Galvanized steel sheet (2×1 m standard dimensions) of 1 mm thick	94.05	94.05
3	Galvanized steel sheet (2×1 m) of 2 mm thick	194.10	194.1
1	Aluminum foil (2.5×1.5 m)	2.40	2.4
1	Roll of glass wool, or coconut coir of 0.2 m^3 (standard dimension)	220.00	17.0
1	Glass plate of 4 mm thick (2.2×1 m)	83.85	83.85
1	Tin (5 kg) of non glossy black paint + painting brush + thinner	20.70	20.7
1	Tin of silicone	17.85	17.85
1	Bag of Steel rivets	7.50	7.5
1	10 m flexible plastic hose and clips (for the piping)	19.50	19.5
	Total	808.00	605.0

Appendix 1: Comparative costs of coconut coir and glass wool collectors.

In Côte d'Ivoire, the coconut coir is a waste which poses environmental problems. Present study has consisted in recycling this waste by developing it. This recycling has been made in three steps: (1) collecting of nuts, (2) grinding of nuts, (3) drying of coir obtained, in the sun. All these operations cost only $17.

The glass wool which was used in present study was imported from France and has costed (transport charge included), $ 220. We awaited three weeks between the date of the order and that of the delivery. Table 5 presents the costs of materials having been used for the manufacturing of the two types of water heaters and the comparative total manufacturing costs of these two solar water heaters.

The comparative prices of the two types of collectors show that the coconut coir collector is 25% cheaper than the glass wool one. The glass wool only represents 27.3% of the total manufacturing cost of the glass wool collector, while it is only 2.81% for the coconut coir in the total manufacturing cost of the coconut coir collector. In addition, the glass wool is not permanently available like it is for the coconut coir.

Appendix 2: Determination of the thermal conductivity of the coconut coir.

The measurement of the coconut coir thermal conductivity has been realized in a laboratory of Poitiers University, in France.

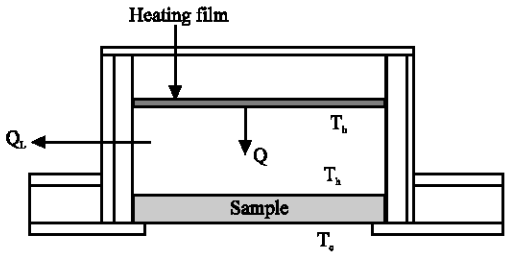

Fig. 6: Experimental set up of coconut coir thermal conductivity measurement

Principle of the measurement: The method used in our case is that known as method of the boxes. It consists in establishing an one-way heat flux, normal on the surface of the sample to be tested, as presented in Fig. 6.

With this intention, the sample is placed between a hot source and a cold one. The variation in temperature generates a heat flux proportional to the amplitude of this variation. Once the steady state reached, one records the average temperatures of the sample on the side of cold surface and also on the hot face. The temperatures of the hot box and that of ambient air are also measured. Knowing the power delivered by the hot source, it then becomes possible to calculate the thermal conductivity of the material by reporting the values obtained in the Fourier equation.

$$\frac{.dQ}{dt} = -kdS\frac{\partial T}{\partial n} \qquad \text{(A1)}$$

After simplification of the equation according to the experimental conditions, one obtains:

$$Q = \frac{k}{e}S(T_h + T_c) + Q_L \qquad \text{(A2)}$$

with:

$$Q_L = C(T_b\text{-}T_\alpha) \qquad \text{(A3)}$$

Q is the power provided by the hot source, Q_L corresponds to the lateral losses which occur at the level of the walls of the box, e is the thickness of the sample, k is the thermal conductivity of the sample, S is the surface of the sample, C is a constant of the measurement device. T_h, T_c, T_b and T_a are, respectively the temperatures of the hot surface of the material, the cold surface of the material, the box and ambient surrounding.

Experimental procedure: The characteristics of the sample tested are summarized in the Table 6.

Table 6: Characteristics of samples

Thickness	Surface	Volume	Mass	Volume mass
0.04 m	0.042 m^2	0.00168 m^3	0.037 kg	22 kg m^{-3}

- Installation of the sample; The material tested is very heterogeneous. So, we laid out 9 thermocouples. The thermocouples are fixed using an adhesive tape and the contact with the sample is optimized thanks to silicone grease
- **Results:** The result obtained after 10 hours of maintaining the devise in steady state is: k = 0.074 W/m.K, with a result precision of 5%.

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