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Thermal and economical study of two solar water heaters: the one using glass wool and the other vegetable fiber as thermal insulator

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Abstract

Two solar water heaters using a thermosiphon system and each one of them including an internal heat exchanger have been designed and realized at Yamoussoukro (city located at the latitude of 6.58° N and longitude 5.27° W). Each one is made of a solar collector of a 2 m^2 surface and of a storage tank of 95 liters capacity. A comparative study of both thermal performances is realized. The parameters taken into account in the same conditions for the two devices are: the total radiation received by the solar collectors, the ambient temperature, the storage tank hot water temperature, the hot water average temperature in the collector, the hot water average temperature in the heat exchanger, the hot water instantaneous mass flow rate and the instantaneous efficiency of the collector. The level of the average temperature in the storage tank, 45°C for the coconut coir insulation and 55°C for the glass wool insulation, added to the relative simplicity in the realization of these devices and the absence of pumps and other accessories, make them an interesting technological solution. Moreover, the results obtained with the solar water heater by using the coconut fiber as heat insulator show that this system is viable under the local climatic conditions and could be used as a basis for popularization of solar heating water by using local materials as heat insulator. An economic study shows that the solar water heater using coconut fiber makes possible in one year to be more competitive compared to the solar water heater using the glass wood whose gives two years when the imported solar water heater whose investment return ranges between fifteen and sixteen years.

Keywords: Solar water heater, solar collector, coconut coir, thermosiphon system, thermal performances.

Nomenclature/Latin notations: A: Surface (m^2); C: Specific heat (J/kg. K); G (i; b): global irradiance incident received by the inclined plane (W / m^2); K_G: coefficient of global heat losses of the solar collector (W / m^2. K); $\dot{m}$: Mass flow of the coolant (kg/s); T: Temperature (°C). **Number without dimension**: F ': efficiency of the absorber; FC: coconut matting; LV: glass wool. **Greek notations**: α: Factor of absorption of the absorber; η: solar collector immediate efficiency; ζ: Factor of transmission of the glazing. **Indicate**: Abs: absorber; A: Ambient; C: solar collector; E: Water; e, abs: inlet absorber; s, abs: outlet absorber; Exp: experimental; H1: inlet fluid of solar collector; H2: outlet fluid of solar collector; H3: inlet fluid of heat exchanger; H4: outlet fluid of heat exchanger; T1: inlet water temperature of the tank; T2: outlet warm water temperature of the tank.

Introduction

The study presented in this paper is essentially axed on the viability of solar water heaters locally made. The solar water heaters realized are of thermosiphon type with an internal heat exchanger placed diagonally in the storage tank. This arrangement already realized and studied by Koffi *et al*. (2008), permits to optimize the exchanges of heat between the primary fluid and the water to get warmed in the storage tank. Two type's solar water heaters were studied. The one uses the glass wool (imported product) as the heat insulator and the other one, the coconut coir, local material and in abundance. A study on the characterization and the use of the coconut coir as insulating material had already been made by Andoh *et al*. (2007) and showed its performances in the glances of the other studies made by Karaghouli and Alnaser (2001), Chang *et al*. (2004), Kudish *et al*. (2003), in the same domain. The parameters concerned in our study are the heat fluxes of the place, the temperature in diverse places of the system, the solar collector immediate efficiency, the fluid mass flow. In these previous studies, we complete the economic one, realized by Sako *et al*. (2007). From those works emerge that the solar water heater realized locally with the coconut coir can not only allow autonomy, but also will be very competitive on the African market.

Materials and methods

Each one of the solar water heaters realized includes a solar collector of 2 m^2, heat exchanger arranged in diagonal in the storage tank, a storage tank whose capacity is 95 liters and the piping of connections as the Fig.1 shows. One of the systems has a glass wool insulation of thermal conductivity 0.040 $W.m^{-1}. K^{-1}$ when the other one is isolated with a local vegetable fiber in this particular case the coconut coir of thermal conductivity 0.074 $W.m^{-1}. K^{-1}$. The solar collector includes an absorber composed of 12 tubes separated from 60 mm, from external diameter 12 mm and painted in matt black. Below these tubes, is a leaf of aluminum which reflects the thermal radiation received towards the absorber. The

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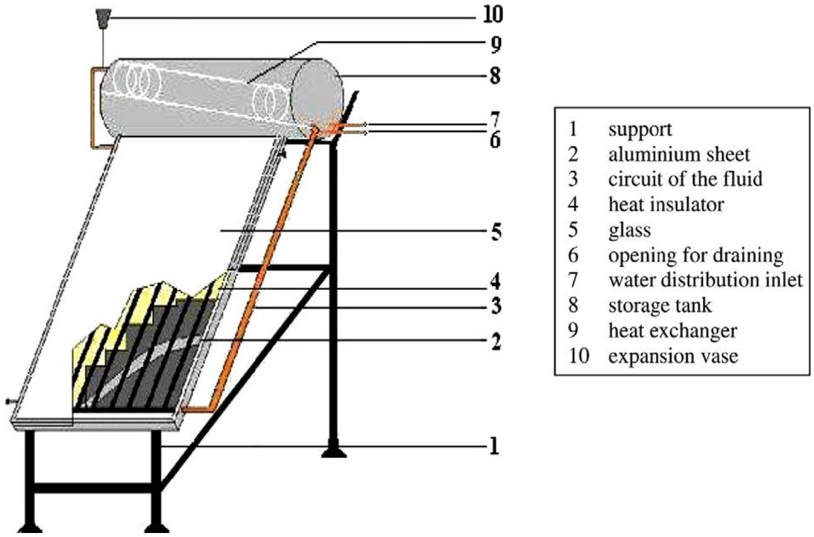
collector is covered with a glass which surface is 2 m^2 and 4 mm in thickness.

Fig.1. Model of the realized solar water heater



The work is made at Yamoussoukro, the capital of Côte d'Ivoire, situated in Sub-Saharan Africa between 5° and 11° north latitude. The latitude of the city of Yamoussoukro is about 6.58°N. The annual solar energy received in this region is, according to Benallou & Bougard (1990), between 1650 and 1950 kWh/m^2 a year. To find the optimal slope of the solar collector, preliminary works were made by Nanga *et al*. (1998). It emerges from these works that the angle of optimal inclination of the solar collector to Yamoussoukro is between 0° and 10°. Both solar collectors are directed in the South direction and tilted by 10° regarding to the horizontal. The made experimental studies consisted in the measure of the period of sunshine received by the solar collector and the temperature in diverse places of the system. The period of sunshine is measured by means of a KIPP and ZONEN pyranometer which relative uncertainties of ±2%. It is connected to a digital integrator, of the same mark, allowing the reading of the immediate received solar energy and the irradiation. The pyranometer is horizontally placed to get all the solar radiation. A data acquisition card, made by our care, allows recording the temperature in diverse places of the system. The sensor of temperature used for that purpose is a diode in the silicon 1N4148 of diameter 1.6 mm of precision ±0.5°C. The entire solar collector temperatures (16 all in all) used are calibrated before using. The average relative uncertainty of the moderate temperatures is ±4% (Koffi *et al*., 2008). The center of measure is presented at the Fig 2.

Besides the measure of the period of sunshine, the ambient temperature, the temperature of the work fluid in the solar collector (collector inlet, outlet), the temperature of the work fluid in the heat exchanger (the heat exchanger inlet, outlet), the temperature of the absorber and the temperature of the warm water of storage are measured in each of both systems. These data will permit to determine the immediate efficiency of the solar collector and its immediate mass flow. These parameters are obtained from the mathematical relations below. The immediate efficiency of the collector is influenced by factors such as the used material, the realized absorber, the properties of the transparent cover, the meteorological data and the conditions of functioning, according to Karaghouli & Alnasser (2001).

$$E_u = F'\left[G(i,b)A_c(\tau\alpha) - K_G A_c(T_{abs} - T_a)\right] \quad (1)$$

$$\eta = F'\tau\alpha - \frac{F' K_G (T_{abs} - T_a)}{G(i,b)} \quad (2)$$

The experimental mass flow is obtained from the relation below taking into account the thermal flow received by the collector, the difference of the temperature of the work fluid between the inlet, the outlet of the collector, and also the immediate mass flow of the work fluid, the surface and the optical properties of the collector:

$$G(i,b)\tau\alpha\eta A_c = \dot{m}_{\exp} C_e (T_{h2} - T_{h1}) \quad (3)$$

By replacing η by its expression in the equation (3), we obtain:

$$\dot{m}_{\exp} = \frac{G(i,b)(\tau\alpha)\eta A_c}{C_e(T_{h2} - T_{h1})}\left[F'\tau\alpha - \frac{F' K_G (T_{abs} - T_a)}{G(i,b)}\right] \quad (4)$$

Fig.2. Various points of measure of the temperatures and the protocol of acquisition of data

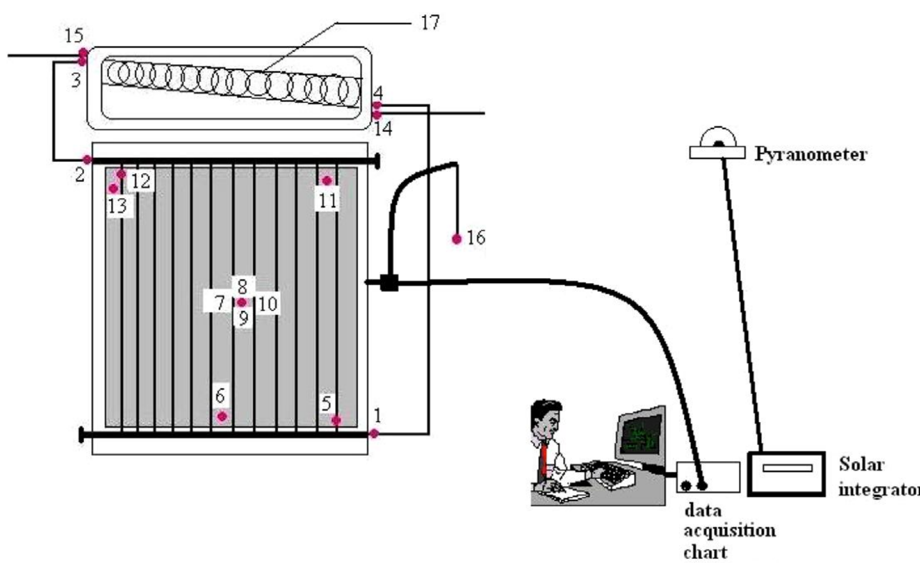


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Fig.3.Evolution of the solar flow and the ambient temperature according to time

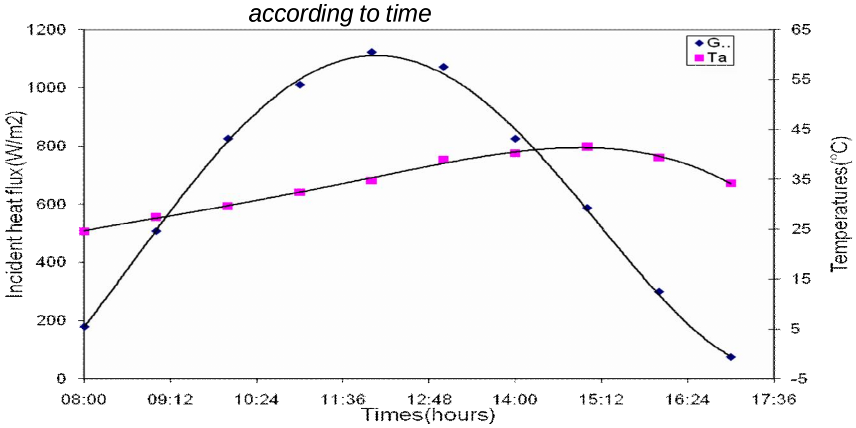


Fig.4. Evolution of the average temperatures of the solar collector

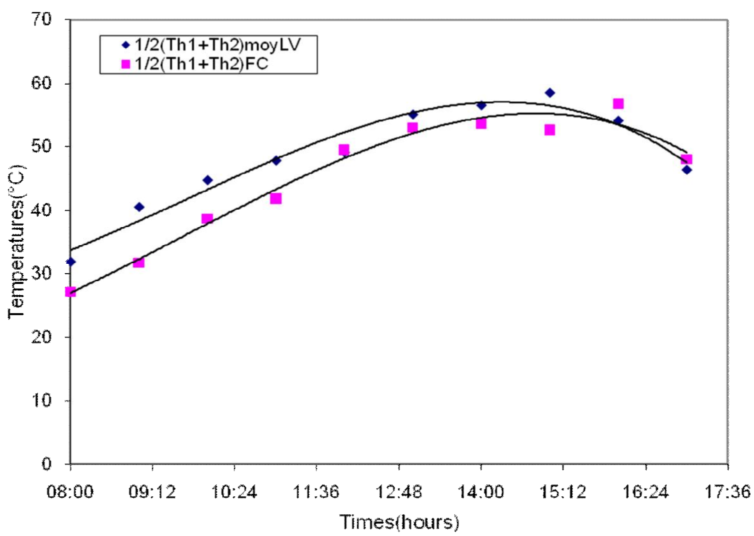
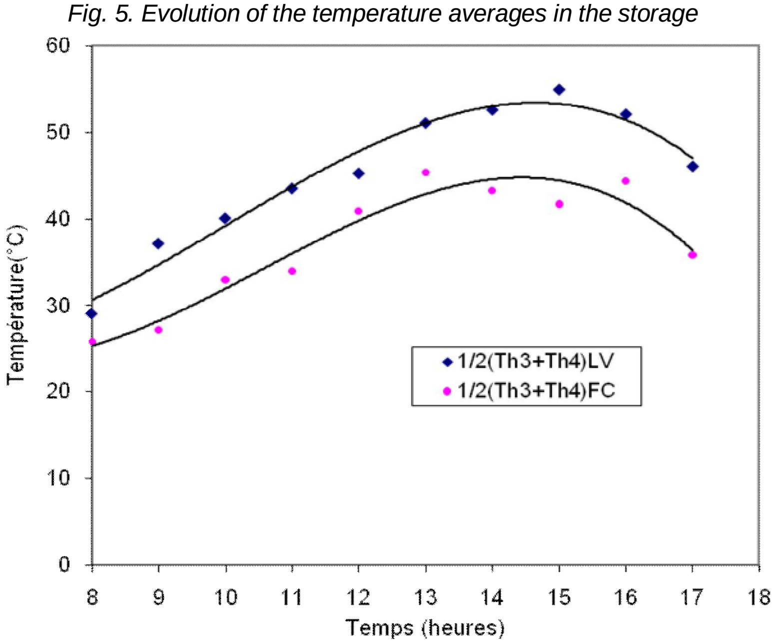


Fig. 5. Evolution of the temperature averages in the storage



Where:

$$T_{abs} = \frac{T_{e,abs} + T_{s,abs}}{2} \qquad (5)$$

Results and discussion

he experimental measures were made and recorded in the weather conditions on several days between the rise and the sunset every ten (10) minutes. Then, the hourly mean values are made. For this work, we decided to settle on a sunny day as it happens October 12th, 2004. For any solar system, it is important to know the solar energy received by the solar collector according to time. So the Fig. 3 presents the thermal flow received by the collector and the ambient temperature according to time. We notice that the solar flow and the ambient temperature evolve according to time. The thermal flow reaches its peak at 12 am true solar time, and then begins decreasing. As for the ambient temperature, it evolves slowly until reach hits maximal value at 3 pm. Then, it starts to decrease. The reached maximal values are respectively of 1123 W/m^2 for the solar flow and 41.5°C for the ambient temperature. These results are in perfect concordance with those of Pierson & Javelas (1983) and those of Nahar (2003). The continuation of the work is marked by a comparative study between both types of heat insulations used in both realized systems. This study concerns the comparison of their respective thermal performance.

Fig.4 shows the evolution of the average temperature of the solar collector. We can notice on this figure that for both systems the average temperature of the solar collector grows in time as the received solar energy increases. Both temperatures reach their maximal value at about 2:30 pm to cross themselves at about 4 pm. While the average temperature of the solar collector provided with the glass wool was over the one of the solar collector provided with the coconut coir, this trend is reversed after 4 pm. Someone can remark that the difference between the two average temperatures which was 6°C in the morning, decreases and becomes 0°C at 4 pm. Both systems have a close thermal behaviour one of the other one.

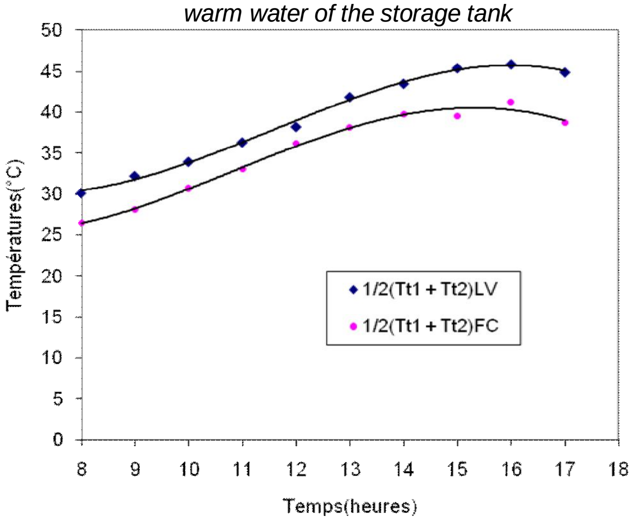


Fig.6. Evolution of the average temperature of warm water of the storage tank

Fig.5 presents the evolution of the average temperature of the water in the heat exchanger. We note an increase of this temperature for both systems which reach their maximal values at 2:30 pm. The maximal value of 55°C is reached for the system provided with a glass wool insulating material when it is 45°C for the system with the coconut coir. The difference between these two temperatures which was 5°C at 8 am in the morning racks itself to reach 11°C at the end of the day. However, we notice that the levels of temperatures reached by both systems stay in the range of the works made in this domain by Pierson & Javelas (1998) and also those realized by Kalogirou and Papamarcou (2000).

Fig.6 presents the evolution of the average temperature of the water in the tank of storage. We notice an increase of the average temperature of the water of the tank which reaches a maximal value of 47°C for the system provided with the glass wool and with 42°C for the one with the coconut coir at 4 pm. The temperature difference which was 3.5°C at 8 am narrowed to reach 2°C at about 12 am to increase then and pass in 6°C at 5

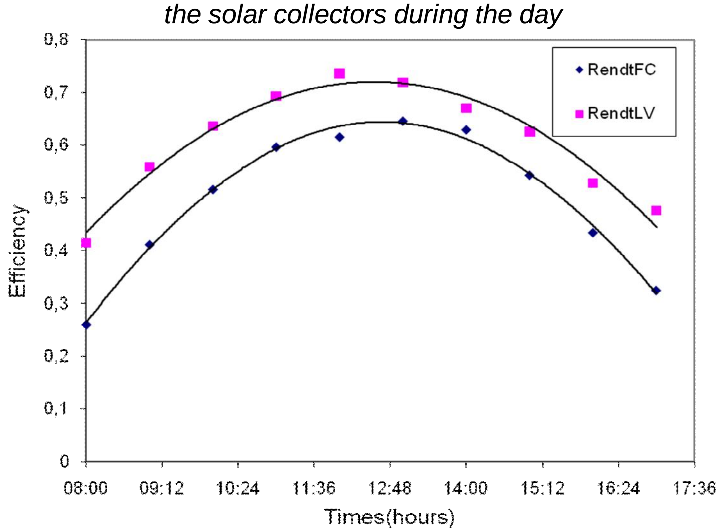


Fig. 7. Evolution of the thermal return on the solar collectors during the day

pm. However they reached levels of temperature are acceptable compared with those obtained by Bellesiotis & Mathioulakis (2002), Zerrouki *et al*. (2002) and the Ong (1974).

Fig. 7 shows the evolution of the efficiency on both systems. The thermal efficiency on the system with the glass wool reaches its maximal value of 72% at 12:30 whereas that of the system constituted of coconut matting is 65% during the same moment. The fork of thermal efficiency is situated between 42 and 72% for the system with the glass wool whereas the one the system constituted of coconut matting is between 26 and 65 % during the period going from 8:00 am to 5:00 pm. These levels of thermal efficiency compared with those of the works of Karaghouli & Alnasser (2001) and Kalogirou & Papamarcou (2000) is very acceptable for the solar hot water storage.

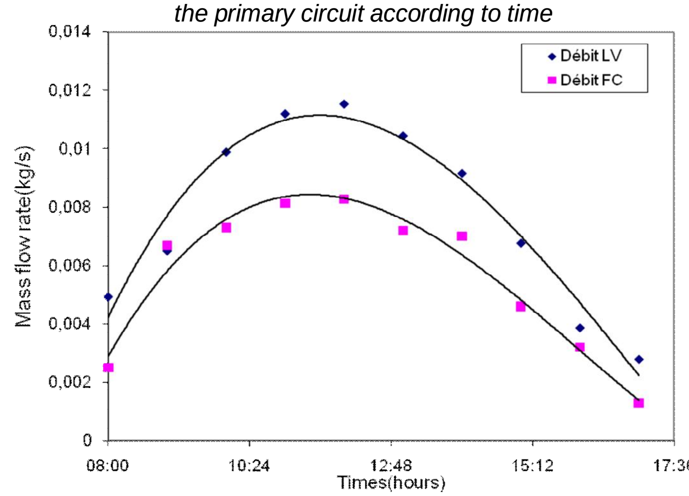


Fig.8. Evolution of the water mass flow rate in the primary circuit according to time

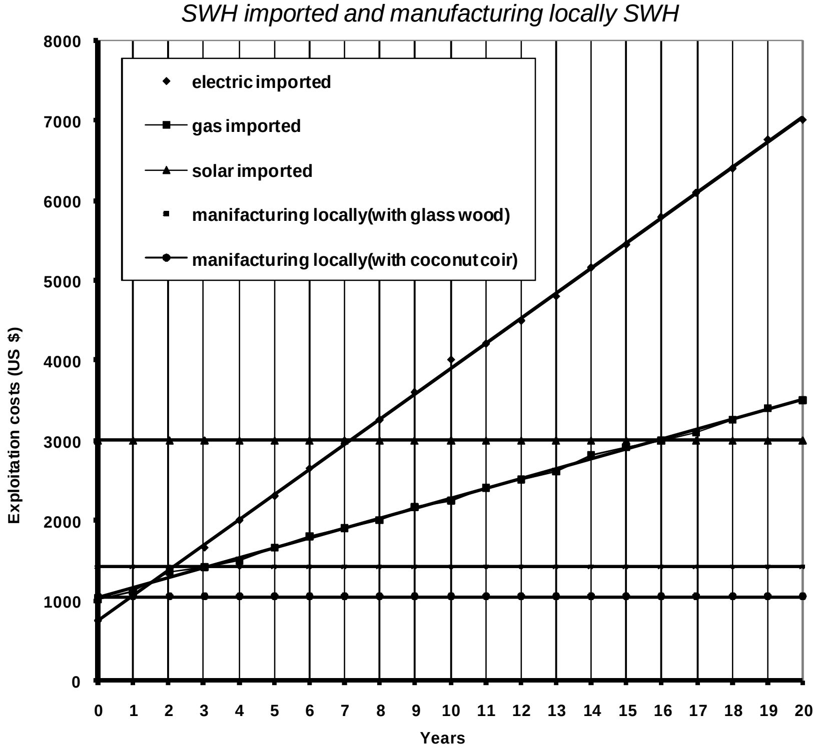
Fig. 8 presents the evolution of the water flow in the primary circuit of both systems. We notice that the water flow increases and reaches its highest level as the solar energy reaches its maximal value at 12:30. It reaches at this moment the value of 0.0175 kg/s for the system using the glass wool then that provided with the coconut matting is 0.0085 kg/s at the same moment. It is necessary to note that these values obtained for these two systems stay over those met in the previous works realized by the Ong (1974), Celentano & Kirchner (1988). These results are similar to those obtained by Zerrouki *et al*. (2002).

Economical study

A comparative economic analysis between three (3) different sources of energy used by water heaters is made. The sources of energy used are the electricity, the gas and the sun. So we have an electric water heater, a gas water heater and three solar water heaters. The study concerns five (5) water heaters among which three (3) are imported and two others (two solar water heaters) realized locally. These two (2) solar water heaters use the thermosiphon system and constituted the one, of the glass wool and the other one of the coco coir as insulations of heat. They are conceived and realized in the city of Yamoussoukro, in Côte d'Ivoire.

The price of realization of the solar water heater using the coconut matting as heat insulator is 696 US dollars. On the market, the approximate sale prices of realized solar water heaters would be respectively 1419 dollars of the United States for the system containing the glass wool and 1044 dollars of the United States for the system include the coconut matting as heat insulator. We notice that the solar water heater realized by our care is widely cheaper than that imported which costs 3000 dollars of the United States in Côte d'Ivoire. The solar water heater realized with the glass wool costs twice cheaper than that imported. This fact is particularly due to the rate of customs and also to the cost of the workforce of countries where comes from this solar water heater. The water heater realized with the coconut matting is the most economic according with the two others. It costs three times cheaper than the one imported. A new economic study of exploitation over 20 years is made by comparing them with the imported system. All the made studies are recorded in Fig.9.

Fig.9. Comparative life cycle costs for electric, gas, SWH imported and manufacturing locally SWH



According to the obtained curves (Fig.9), we notice that solar water heaters made locally are more profitable than the electric solar water heater after 2 years for the solar water heater using the glass wool as heat insulator, and on only 1 year for the solar water heater using the coconut matting as heat insulator.

With regard to the gas solar water heater, our solar water heaters made locally are more profitable after 3 years for the solar water heater using the glass wool and only 1 year for the solar water heater using the coconut coir. These results are better by comparing them to those obtained previously with the imported solar water heaters who were respectively of 7 years and 16 years for the electric and gas water heater. Solar water heater conceived and realized locally are successful and more profitable than those imported (solar, electric and gas) and it after a relatively short time of use.

The comparison of two (2) solar water heaters locally realized brings us to conclude that using the coconut coir as heat insulator is more economic than the glass wool one. It would thus be very interesting to turn to this type of process, local, available, cheap and cheaper heat insulator compared with industrial, imported and expensive classic insulations sold on our markets.

Conclusion

Our study was able to show that it is possible to make solar water heaters locally and with local materials. The thermal performances obtained with the solar water heater using the coconut coir as heat insulator are in the ranges of those found in the recent works. A mass flow of 0.0085 kg/s is obtained at 12:30 when the solar flux reaches its maximal value of 1123 W/m^2. The water heater provided with the coconut coir allows reaching levels of temperatures of current use in the field of the domestic hot water. So we obtain from some water in 42°C in the storage tank at about 4 pm. An economic study shows well the profitability of a water heater using of the coconut coir as the heat insulator. This study shows that in only one year the system is widely profitable. An improvement of this system is actually in progress. We estimate that we can exceed 60°C as temperature of the water in the storage tank and this with an additional spending reaching no more than 55 $ US.

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