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An Overview of the Development of Solar Water Heaters Systems in Côte d'Ivoire and Study of the Thermal Performance of a Locally Made Solar Water Heater

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Abstract:
Solar water heating systems (SWHS) in Côte d'Ivoire have a high share among the renewable energy sources in the total mix of the energy consumed. Studying the popularization of SWHS is significant for understanding Côte d'Ivoire's transition to green energy systems. The current number of installed SWHS in Côte d'Ivoire is negligibly small of all households. In this article, we compare the economic feasibility of an imported SWHS and an electric water heater, then SWHS designed locally versus the same electric water heater. A prototype of the study SWHS has been built and tested locally. The results show that the system is suitable for application in Côte d'Ivoire. The economic study confirms the viability and the real potential market of the locally manufactured SWHS. The purchase cost is 1.75 times lower than the imported ones

Keywords: *Côte d'Ivoire, Solar Water Heater System; Heat exchanger; Thermal performance; Efficiency*

1. Introduction

Solar energy technologies offer a clean, renewable and domestic energy source, and are essential components of a sustainable energy future (Bakirci, 2009). Despite this progress in harnessing solar energy, the success of a solar water heating system (SWHS) adoption has not been universal. The rate of adoption has varied widely, at the local level, characterized by highly successful adoptions in some regions yet low installation rates across other areas of the country. Water heating using domestic solar water heaters is the most feasible, economical and popular means of solar energy utilization in many countries in the world. The world market for their utilization has expanded significantly in recent years (Dehghan and Barzegar, 2011). With the development of economy, the demand of urban and rural residents in the world for living and bathing has increased substantially. Together with electric water heater and gas water heater, solar water heater becomes one of the major products supplying hot water for domestic use. Nowadays, SWHS is used more in centralized hot water supplying for hotels and schools (Hu et al., 2012). SWHS offer the most energy-efficient way to provide heating and cooling in many applications, as they can use renewable heat sources in our surroundings (Bakirci et al., 2011; Comakli et al., 2010). Energy consumption of a typical family, which lives in an ordinary house is less than the solar radiation energy, that reaches to the roof of the home from the sun. The relatively low temperatures required for heating and domestic hot water applications make solar collection efficiency relatively high.

There are many experimental and theoretical–numerical studies made on the performance evaluation of solar heating systems and storage tanks used on them under different operation or design parameters in the literature. A numerical model to study horizontal and vertical storages in thermosiphon solar water heaters was proposed by Morrison and Braun (1985). In this work, changes in the collector efficiency factor F', the overall loss coefficient U_L, flow rate and the dependence of U_L on the temperature has been neglected. The temperature of the collector and the storage and the resulting thermosiphonic flow rate were calculated and compared with the experimental data. Vertical storage tanks have lost popularity due to esthetic issues and to lesser extent due to higher aerodynamic resistance to blowing winds. Experimental investigation of temperature and flow distribution in a thermosiphon solar water heating system has been the subject of research done by Chuawittayawuth and Kumar (2002). They found that the temperature rise of the water as it flows through the riser tubes was 21–24°C for clear sky. On the heat transfer efficiency of load side immersed heat exchangers, earlier studies on testing and analysis in solar domestic hot water systems was done by Farrington and Bingham

(1987); they reported that a smooth coil with only 70% of the surface area of a finned coil performed better than the finned coil. Also, load-side heat exchangers can maintain and enhance stratification in storage tanks, permitting the use of control strategies that take advantage of stratified storage tanks to increase system performance. Increasing the heat exchanger flow rate and area resulted in higher heat transfer rates but not necessarily optimal performance; lower initial tank temperatures resulted in reduced tank stratification; the smooth heat exchanger outperformed the finned heat exchanger with the same outside surface area.

In comparison with these considerations, a further research on domestic hot water store with immersed exchanger is performed (Spur et al. 2006), the simulation results were validated by measurements obtained from experiment, and the conclusion showed that the inner configurations of the tank and the immersed heat exchanger can significantly affect the store performance; the stratified store can improve up to 32% more efficiency than the common commercial available store. In their experimental study, three different stores were used as shown in Figure 1. Store A is the novel-stratified store, which is chosen in order to determine the effect of an improved inner store design on the performance of the store. Store B contains a heat exchanger which is coiled upward from the bottom to the top of the store. Store C contains a heat exchange which is coiled upward from the bottom to the top of the store and downward from the top to the bottom of the store. Store C achieved less stratification compared with those in stores A and B. The maximum temperature difference between the top and the bottom of the store C hardly reached 8°C, whereas in stores A and B, stratification temperature differences of about 15°C occurred. The sophisticated inner configuration of the novel store improved its performance by up to 15%. The store with the downwards coiled heat exchanger pipe showed adverse effects and a decreased performance by up to 20%. According to these conclusions, the inner arrangement of the immersed heat exchanger and type of conduct pipe significantly, affects the stratification along the store height, the heat transfer and the recovery process of the immersed heat exchanger. The immersed heat exchanger position should be coiled upwards and located in the upper part of the tank in order to achieve a high rate of heat extraction. Ayompe and Duffy (2013) conducted their studies on a SWHS with an internal exchanger and studied the thermal performance of a solar water heating system with heat pipe evacuated tube collector using data obtained from a field trial installation over a year in Dublin, Ireland. An automated sub-system was developed and incorporated to control the hot water draw-offs and electric immersion heater to mimic the operation of solar water heating systems in domestic dwellings. Haltiwanger and Davidson (2009) conducted their studies on a SWHS with an internal exchanger and studied a discharge of a thermal storage tank using an immersed heat exchanger with an annular baffle. They studied and measured the temperatures at the inlet and outlet of the heat exchanger, the temperature difference across the heat exchanger, the mass flow rate through the heat exchanger storage water temperature distribution in order to calculate the heat exchanger effectiveness and heat transfer to the heat exchanger. Abu-Mulaweh (2006) studied the design and the performance of a thermosiphon heat recovery system that recovers heat rejected from an air conditioner and described it by presenting some experimental test data. In this study, he used a coiled heat exchanger in a storage tank. The coil consisted of loops. The inlet and outlet water temperature of the coiled heat exchanger and those of water storage tank are respectively studied. Results indicate that the thermosiphon effect can be used to recover some of the heat rejected from an air conditioner. Besides the possible savings in obtaining ‘‘free’’ hot water for the price of a small heat exchanger, employing the thermosiphon effect has an advantage over other heat recovery techniques. It eliminates a source of potential mechanical problems and noise, namely the circulating water pump.

The made researches showed that internal or immersed heat exchangers are for some placed at the bottom of the storage tank (Ayompe and Duffy, 2013; Cruickshank and Harrison, 2011; Pissavin, 1982; Michaelides and Eleftheriou, 2011) when others are placed on all the length inside this one (Spur et al., 2006; Abu-Mulaweh, 2006; Manuel et al., 2006; Ulrike and Simon,2005). In these different studied, almost all storage tanks are vertically disposed.

The thermal performance on some of those types of SWH has been improved by design improvement of absorber plate, fin efficiency, storage tank, selective coating of absorber, working fluid, thermal insulation, etc. However, no more information is given on the collector thermal performances and on the solar system thermal performance. But, studies on improvement of the thermal performance of SWHS with internal exchanger by increasing the convective heat transfer rate are limited. For these reasons, an experimental study of SWHS with natural circulation, including an original and innovative internal heat exchanger made of rolled copper tube placed diagonally in the storage tank is investigated. In this system, the service water passes through a coiled heat exchanger tube that is immersed in the stored fluid. The operating of the heat exchanger is translated by the thermal exchanges taking place inside the storage tank in the absence of racking. Those thermal transfers take place at the same time by conduction (due to the internal gradients) and by natural convection (movements engendered by the flow of thermal decrease). The convective transfers are translated by an action of immediate mixture as solar liquid flows through (the water) the heat exchanger, the heat stored by this one is thus transmitted in the water of the storage tank (by conduction and by convection) which warms up gradually. The use of the exchanger in the primary circuit has the advantage of lowering the temperature of the fluid at the outlet side of the exchanger that makes possible, increasing the effectiveness of the collector and, consequently, that of the system.

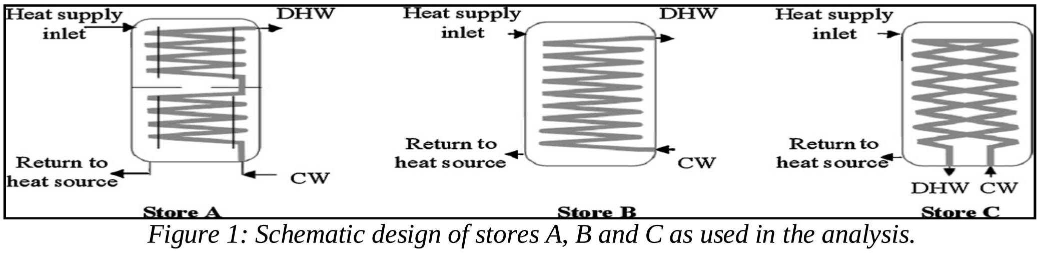

Figure 1: Schematic design of stores A, B and C as used in the analysis.

2. Solar Energy and Solar Water Heater: Inventory of Fixtures in Côte d'Ivoire

Côte d'Ivoire is a country of western Africa, situated in the intertropical zone, at the edge of the Gulf of Guinea and situated between 4°20 ' and 10°50 ' of north latitude and between 2°30 ' and 8°38 ' by longitude West. Its surface is 322 462 km² (Kadio et al., 2005). At the climatic level, the country undergoes two influences: the monsoon, the mass of wet equatorial air and the harmattan, the mass of dry tropical air with its drying wind. According to the latitude, four main climatic zones are distinguished: climates of mountain, attiéen, baouléen and soudano-Guinean. The vegetation is globally constituted by savannas in the North and by forest in the South. The geographical situation of Côte d'Ivoire confers him a varied climate, a wet tropical climate in the South and in the North a dry tropical climate. All these climates are characterized by four seasons: 2 dry seasons (big in December / March and small in August / September) and two rainy seasons (big in April-July and small in October / November). The average pluviometry is 2000 mm / year with an average temperature of 27°C and a relative humidity from 70 to 90 % (Kadio et al., 2005). The average daily solar radiation in Côte d'Ivoire is about 5.25 kWh/m^2, with a peak of sunshine being received March and April according to regions (Tiéné, 2004) and the SODEXAM reference (Seka, 2001). The sun is present almost all year long. The yearly hours of sun varies between 2 000 and 2 700 hours a year according to regions. The average sunshine ranges between 5 and 8 sunshine hours per day.

Côte d'Ivoire possesses a considerable potential for the development of the renewable energies, but have not of the strong energy policy, clearly defined and endowed with important financial means, for the promotion of these. A diversity of energy sources, including renewable energies, reduces dependency on conventional reserves or foreign imports and, thus, lowers the country's vulnerability. The country must optimize the utilization of all its available energy resources including solar, wind, and other forms. So, the sub-sector of the solar energy began to occupy a special place in the concerns of public authorities in 1995, with projects developed, in particular, in the punctual uses, such as the solar pumping, the telecommunications, the heating, the refrigeration, the lighting, etc. (Moulot and Sako, 1999). This solar potential can contribute widely to the satisfaction of the energy needs for the populations. We notice at present in the country, that all this solar capacity is averagely used in individual exploitations for the domestic lightings (photovoltaic solar energy), in installations deprived of solar water heater (thermal solar energy) and in installations deprived of drying solar collector for cooperatives of coffee, cocoa.

Several "obstacles" explain the weakness of a sustainable exploitation of the resources of the solar energy in Côte d'Ivoire. Today, the economic situation of the country is not totally favorable to an ambitious energy policy. The funds of research for development remain insufficient in spite of the efforts granted by the country. Even if it is true that the exploitation of most of the solar systems requires costs moderated except some loads of maintenance, the initial investment is still high compared to the traditional solutions. And thus the necessary equipments know the inverse effect of the economy of scale in which the rare products are expensive. Today, most of the used solar equipments are imported. The exploitation of the thermal solar energy, the heat production requires important investments, involving global cost of the technological tool. When it is made profitable, the times of return vary from 2 to 4 years. However, for houses using domestic use solar tools, it is necessary to count an amortization on a longer duration on the economy realized compared to fossil fuels (Christophe, 2010).The access to the credit is still one of concerns of the socioeconomic environment in the country. It is still very difficult even impossible for populations of sectors of society which are disadvantaged to have access to this. The absence of statistical data in Côte d'Ivoire stays one of the brakes in the development of these new technologies. Most of the time, the majority of the technicians who work in the field of solar energy have not formation. Indeed, solar energy is a speciality which requires a specific formation. So, generally, the first installations were badly made and this has compromised this new technology (Tiéné, 2004). Besides, the ignorance of the real needs for the concerned people often causes errors of sizing. So, the ignorance or no consideration of the specificities of solar equipments but also sometimes the too big technical confidence of certain installers technicians of the classic traditional systems concerning solar systems are often translated by bad realizations. In the absence of after-sales service, the realized installations are quickly out of order and sometimes for harmless breakdowns. That constitutes very bad references for the users and does not incite to the acquisition new solar systems. The prospects are thus wary of it. There is no real service after installation of solar equipments in countryside.

The distribution of new technologies requires upstream to studies of social impact and an association of the consumers in the development of the innovation in order to guarantee the penetration of products and an appropriation of the technologies by the users. Given that the solar water heater is a renewable energy and given that the sun, the gift of God, shines every day. This renewable energy will allow Côte d'Ivoire populations to benefit from a convenience in the international standards and especially to realize economies in financial gains because they will need no more electricity to warm the water. Hot water consumption is an important segment in the energy consumption in households in Côte d'Ivoire, where majority of households, heat water with electric resistance storage water heaters. A more appropriate alternative is installation of solar water heating systems (SWHS) in households. The current number of installed SWHS systems in Côte d'Ivoire is negligibly small. More appropriate way for water heating in households is to use solar water heating systems (SWHS): solar energy is free, SWHS are a mature technology. SWHS saves energy and reduces greenhouse emissions relative to conventional fossil fuel, water heating system (WHS) in the use phase and heavy metal emissions through displacing lignite burning in thermal power plants (Bakirci, 2011). However, a complete examination should include every stage of the life cycle of a SWHS, i.e. from raw material extraction to end of life disposal while considering energetic, economic and environmental performance comprehensively. The environmental impact of the SWH systems with natural gas heater backups is smaller than the impact of the systems with electrical heater backups (Tsilingiridis et al.,2004; Kalogirou, 2009) and the pure natural gas heaters have lower environmental impact compared to the SWH systems with electrical backups (Tsilingiridis et al.,2004).

With the development of the economy, the demand of urban and rural residents in Côte d'Ivoire for living and bathing has increased substantially. Together with electric water heater and gas water heater, solar water heater becomes one of the major products supplying hot water for domestic use. A study of SWH popularization can provide insights for Côte d'Ivoire's transition to greener energy systems, which has been widely recognized as a crucial step for lessening energy crisis effects in the long run. A diversity of energy sources, including renewable energies, reduces dependency on conventional reserves or foreign imports and, thus, lowers the country's vulnerability (Li, 2005). In particular, SWHS adoption is an important area for investigation given that solar energy is one of the key renewable energies for future greener energy systems, because it is abundantly available and can be transformed into other energy without causing much environmental pollution or greenhouse gas emissions (Scheer, 2004; Bradford, 2006).

3. Using of Solar Water Heaters in Côte d'Ivoire

There are less than five solar device companies in Côte d'Ivoire. It is only worth neither emphasizing that there is no local assembling nor manufacturing of SWHS. All companies in the SWHS business as NOA Trading Solar Energy and Hadep solar system are distributors for foreign made components**.** Despite the real need for hot water across economic groups and geographical boundaries, there is little use of SWHS in the country at the moment. Reliable statistics do not really exist, and only a rough estimate can be made on the quantity of SWHS installed in the country. Based on the Ministry of Planning and development data, import of SWHS nearly doubled every year between 1993 and 1995. These statistics data are decreasing because of the political military crisis that the country between 1999 and 2010 knew and of the high purchase cost and a lack of a dissemination policy. Although solar energy is free, a recent survey carried out by our care revealed that a large group of the families in Côte d'Ivoire are not installing SWHS at their households. That can be explained by the fact that a number of this group did not install SWHS because they felt that the initial investment of the SWHS is high for them. Some of them did not install SWHS because they did not think about it, and further others did not install SWHS because they thought that SWHS are unreliable.

Some studies were led on a number of water heater, solar energy existing in the country. A number of SWHS were visually inspected, and interviews with the owners of the SWHS were conducted. The majority of the inspected SWHS were defected: Among these, more half of the defected SWHS had collector problems, and others of the defected SWHS had piping problems. Moreover, practically all of the owners did not make any maintenance to their SWHS, and the insulation of the pipings of most of the inspected SWHS is defective. The primary factors that affect the life and efficiency of the Côte d'Ivoire SWHS are deduced from the study as in the following:

- Cracking of the cover glass is a widely occurring problem. It occurs mostly because of improper selection and/or fitting of the used silicon rubber between the glass and the metal. Many systems were not installed in the proper location whereby collector shading prevailed some times of the year.
- Corrosion of the absorber from the outside: Penetration of moisture, air, and dust into the collector casing, through gaskets and sealant, cause corrosion of the absorber from the outside.
- Degradation of gaskets and sealant is caused by high temperatures during the day, low temperatures during the night, and ultraviolet radiation.
- Consumer misuse: many owners were careless to clean the SWHS from the accumulated dust, and others were negligent of insulating the piping runs.

It seems that proper and supervised manufacturing, installation, and maintenance of SWHS in Côte d'Ivoire will lead to prolonging the operation life of the system and to maximizing its efficiency which in turn leads to increased demand on SWHS. Also, most of the research on SWHS in Côte d'Ivoire is directed towards experimental and theoretical areas. Little effort has been directed to investigate the aging manner of SWHS.

4. Comparative Study

The thermal system is used to produce hot water, but the problem of cost remains. To illustrate this purpose, we made an economic analysis of SWHS versus electric for a system with 100 liters storage capacity. The difference cost between these two energy sources is well illustrated on Figure 2. Compared with SWHs, the conventional electric water heater (EWH) costs on average 600 US$ for initial purchasing costs and installation. The electric consumption and the maintenance of the electric water heater are taken into account. The annual spending connected to its using are estimated for a duration of 20 years. For the imported SWHS; if we assume average installation and maintenance costs of SWHS are 1500 US$, the annual maintenance costs for SWHS are 120 US$, The annual spending connected to its using are also estimated for a duration of 20 years. Assuming SWHS and EWHS have similar life expectancy (15 years), the accumulated total costs of EWHS will exceed SWHS from the seventh year after installation (shown in Figure 2). Solar energy is so, more profitable than electricity after 7 years. The cost of SWHS is the best explanation. Figure 2 also shows that the sale costs of SWHS are away beyond the average income of most Ivoirians. Despite the payback period and the high sale cost, the advantages of SWHS are follows:

- → facilitate energy saving;
- → more environment friendly than firewood;
- → require less safety measures;
- → possibility of rural development improving.

A previous study of Moulot and Sako (1999) shows that locally manufactured low cost SWH company can arguably target at 25 to 30 % (economical, medium standing and good standing houses) of the housing market, which represents approximately 1500 to 1800 houses a year not including hotels and hospitals; which are also potential customers. The high price of the solar water heater imported added to the advantages that this one can have when it is conceived and realized by our care eventually convinces us to realize it and then to popularize it.

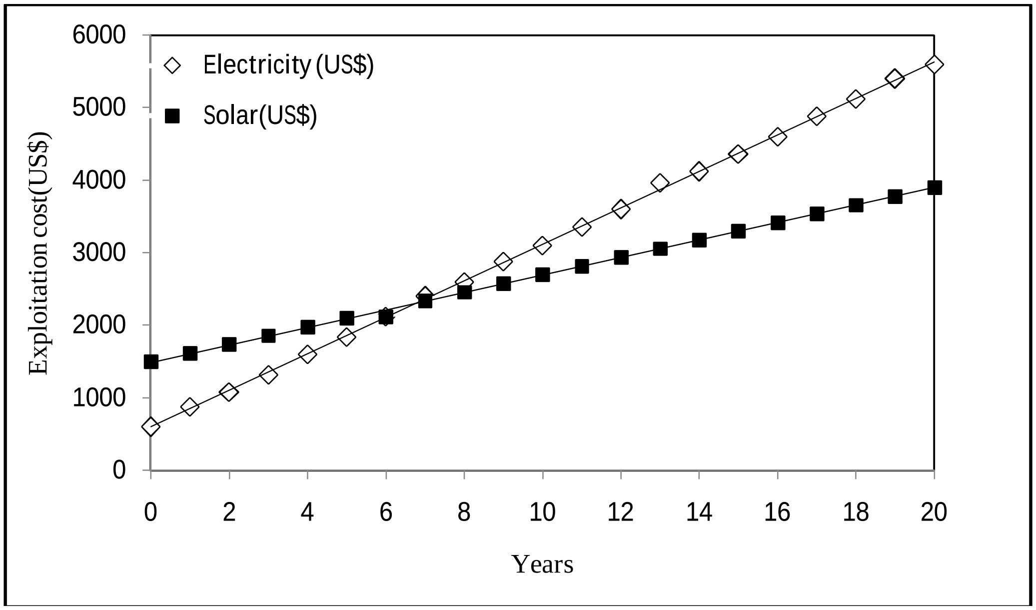

Figure 2: Comparative life costs for electric and imported solar water heater

5. Solar Water Heater Technologies, Materials and Methods Used

Solar Water Heating technologies are simple, reliable, and cost-effective methods of harnessing the sun’s energy to provide the energy needs for homes and businesses. Solar heating systems are generally composed of solar thermal collectors and a thermal fluid system to transfer the heat from the collector to its point of usage. The working fluid is either pumped (active system) or driven by natural convection (passive system). The system may use electricity for pumping the fluid, and have a reservoir or tank for heat storage and subsequent use. The systems may be used to heat water for a wide variety of uses, including home, business and industrial uses. Solar water heaters can also be classified as open loop or closed loop. The open-loop system circulates water through the collector while the closed loop system uses a heat transfer fluid to collect heat and a heat exchanger to transfer the heat to the storage tank (Garg and Holland, 1987). The collector could be made from a simple glass topped insulated box with a flat solar absorber made of sheet metal attached to copper pipes and painted black, or a set of metal tubes surrounded by an evacuated glass cylinder. In some cases, before the solar energy is absorbed, a parabolic mirror is used to concentrate sunlight on the tube. Sizing the solar water heating system basically involves determining the total collector area and the storage volume needed to meet the household’s hot water requirements. The orientation, size, mounted angle and efficiency of the collector will affect solar water heating system’s performance. Solar water heating systems use both direct and diffuse solar radiation.

The solar water heaters realized includes a solar collector of a 2 m^2, heat exchanger arranged in diagonal in the storage tank, a storage whose capacity is 95 liters and the piping of connections as the Figure 3 shows. The system has a glass wool insulation of thermal conductivity 0.040 $W.m^{-1}.K^{-1}$. The solar collector includes an absorber composed of 12 tubes separated from 58 mm and painted in matt black. Below these tubes, is a leaf of aluminum which reflects the thermal radiation received towards the absorber. The collector is covered with a glass which surface is 2 m^2 and 4 mm in thickness. The storage tank is arranged horizontally as shown in Fig 3. In this heat exchanger, the inner tube was formed into a coil. The coil consisted of loops. The heat exchanger is placed diagonally in the storage tank so that the hot fluid crosses a significant mass of stored water. The angle of optimal inclination of the solar collector to Yamoussoukro is between 0° and 10° (Nanga et al., 1998). The solar collector is directed in the South direction and titled by 10° regarding to the horizontal. The detailed technical specification of the system is listed in Table 1.

Design Materials/Parameters	**Specifications**
a. Solar collector	
Dimension	2200mm x1000mm x100 mm
Type	Flat plate
Lower header	d_i 20 mm, length 1100mm (copper pipe)
Upper header	d_i 20 mm length 1100mm (copper pipe)
Riser tubes	D 12mm, D 10 mm, length, 2000 mm(copper pipe)
Number of risers	12
Absorber plate	Copper tubes, length 2000 mm, distance between parallel tubes 58 mm
Insulation	Glass wool, thickness 50 mm
Collector glazing	Single transparent glass of 4 mm thickness
Frame	sheet galvanized, 1.5 mm

Tilt angle	10^0 to the horizontal
Orientation	South
b. Storage tank	
Disposition	*horizontal*
Height	490 mm
Dimension	Diameter 750mm x 390 mm
Material	sheet galvanized, thickness 3 mm
Insulation	Glass wool, thickness 50mm
Cover	Stainless steel, thickness 3 mm
Volume	95 L
c. *Heat exchanger*	
Length of tube	6000 mm (D 12mm)
Geometry	Inner tube is formed into a coil
Type of coil	loop (Diameter160 mm) (copper tube), coil spaced 45mm
Effective heat transfer area	0.226 m^2
c. Connecting pipe	
Tube situated between outlet heat exchanger and inlet solar collector	Length 2570mm (10 mm inside diameter) copper pipe
Tube situated between inlet heat exchanger and outlet solar collector	Length 1180mm (10 mm inside diameter) copper pipe
Bottom insulation	50 mm glass wool
Side insulation	30 mm glass wool covered by leaf of aluminum
Absorber plate coating absorptivity	0.95
Transmittance of glazing	0.88

Table 1: Specification of the SWHS used in the study

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. To avoid perturbing the fluid flow, one uses probes of small dimensions made of 1.6 mm diameter of diode 1N4148 in silicon, ± 0.5°C precision. Before using, the probes are calibrated using a digital thermometer which gives coefficients of conversion temperature/tension completely identical with a margin of 0.1. The schematic diagram of the experimental setup is presented at the Figure 4. 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 on the work fluid in the heat exchanger (the heat exchanger inlet and outlet), and the temperature of the absorber are measured in the system.

Figure 3: Schematic of SWHS studied with the coiled heat exchanger.

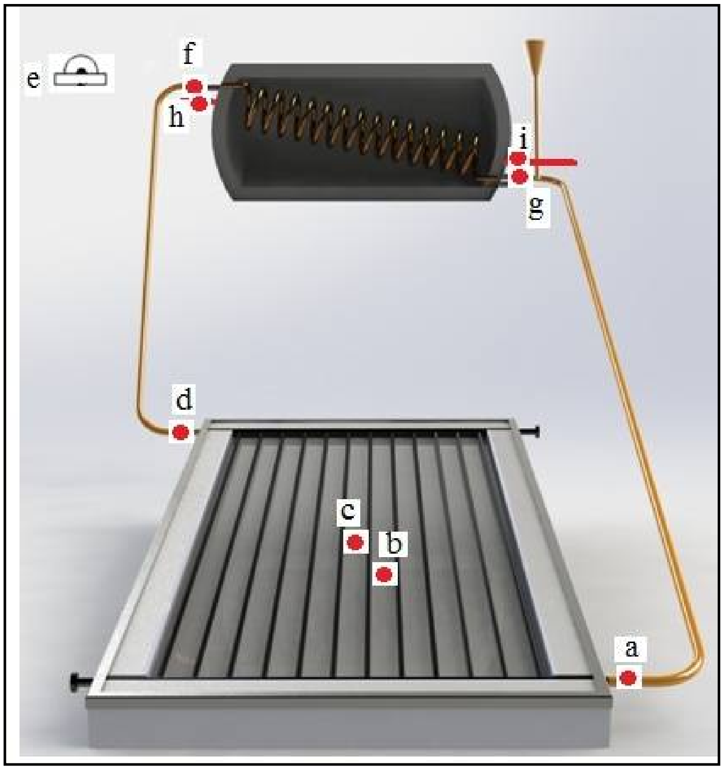

Figure 4: Schematic diagram of the experimental setup, (a, b, c, d, f, g, h, i) collector inlet, mean absorber plate, mean cover, outlet temperatures, heat exchanger inlet, heat exchanger outlet temperature, storage outlet and storage inlet temperature, (e) pyranometer.

6. Theoretical Analysis

Thermal analysis of solar collectors is covered in many solar thermal engineering texts (Duffie and Beckman, 1991; Howell et al.,1982; Lunde,1980). Therefore, only equations which describe the main parameters and their importance will be described in this paper. The top heat loss coefficient U_t is evaluated empirically (Malhotra et al.,1981).

$$U_t = \left[\frac{M}{\left(\frac{344}{T_{pm}}\right)\left(\frac{T_{pm}-T_a}{M+f}\right)^{0.31}} + \frac{1}{h_W} \right]^{-1} + \left[\frac{\sigma\left(T_{pm}^2+T_a^2\right)\left(T_{pm}+T_a\right)}{\frac{1}{\varepsilon_p + 0.0425M(1-\varepsilon_p)} + \frac{2M+f-1}{\varepsilon_C} - M} \right] \tag{1}$$

with

$$f = \left(1 - 0.04h_w + 5\times10^{-4}h_w^2\right)\left(1+0.058M\right) \tag{2}$$

and h_w is the heat-transfer coefficient due to convection at the top of cover due to wind. The h_w is calculated by the following relation suggested by McAdams as given in Duffie and Beckman (1991):

$$h_w = 5.7 + 3.8v \tag{3}$$

The bottom loss coefficient U_b, which accounts for the conduction heat loss through the back of the solar collector is calculated by:

$$U_b = \frac{k_{INS}}{L_{INS}} \tag{4}$$

The overall loss coefficient U_L is given by:

$$U_L = U_t + U_b \tag{5}$$

With initial estimates for T_{pm} and T_a, the value of U_L is computed using equations (1) and (2). Then, the collector efficiency factor *F*' can be calculated as follows:

$$F' = \frac{1/U_L}{w\left[\frac{1}{U_L\left[D+(w-D)F\right]} + \frac{1}{c_b} + \frac{1}{\pi D_I h_{FI}}\right]} \tag{6}$$

where F is the fin efficiency

$$F = \frac{\tanh m(w-D)/2}{m(w-D)/2}\text{, with } m = (U_L/kt)^{0.5} \tag{7}$$

h_{FI} is evaluated by the empirical equation of Sieder and Tate(1936) for a laminar flow.

$$Nu_{ct} = \frac{h_{FI} d_i}{k_w} = 1.86(Re.Pr)^{1/3}\left(\frac{d_i}{L}\right)^{1/3}\left(\frac{\mu_{mf}}{\mu_w}\right)^{0.14} \tag{8}$$

Knowing collector efficiency factor; heat removal factor F_R, which relates the actual useful energy gain of a collector to the useful gain if the whole collector surface was at the fluid inlet temperature, is estimated by (Duffie and Beckman, 1991) and is then calculated as follows:

$$F_R = \frac{\dot{m}c_p}{U_L A_C}\left[1 - e^{(U_L A_C F')/\dot{m}c_p}\right] \tag{9}$$

The only governing equation for the working fluid is the useful energy, which is transferred from the absorber plate, and that is: the incoming radiation minus energy loss when the collector temperature is assumed to be at T_{pm} (Duffie and Beckman, 1991).

$$Q_u = A_c F_R\left[(\tau\alpha)I - U_L(T_{f1} - T_a\right] \tag{10}$$

where (τα) represents the transmittance absorptance product for the glazing. In the calculation, the coefficients of α and τ were set as 0.95 and 0.88 respectively, according to the thermal properties of the material used in the collector (Koffi, 2008). So, for our study, τα = 0.836. Once F_R is calculated, the useful energy gain Q_u is calculated. MATLAB Simulink can be employed to study the efficiency of a solar collector during a day with certain weather conditions; exerting the environmental and physical properties, optimum condition of different parameters can be found.

The thermal efficiency of a flat plate solar collector can be depicted as the linear graph dependent on the outgoing useful energy of the collector, the amount of incoming sunlight and the thermal loss. The instantaneous efficiency of the collector is defined as the ratio of the gained useful energy to the radiated energy onto the collector surface:

$$\eta = \frac{Q_u}{A_c I} \tag{11}$$

The instantaneous efficiency of solar collectors is affected by many different factors such as the materials used in manufacturing the collector, the type and configuration of absorber plate and riser tubes, the properties of glass cover and the weather conditions; thereby, it can be written in the form of the following efficiency function (Duffie and Beckman, 1991):

$$\eta = F_R(\tau\alpha) - F_R U_L\left(\frac{T_{f1} - T_a}{I}\right) \tag{12}$$

where $F_R(\tau\alpha)$ determines how the energy is absorbed and $F_R U_L$ determines the way the energy is lost. η is the dependent variable and $\left(\frac{T_{f1} - T_a}{I}\right)$ is the independent variable. Therefore, in the efficiency diagram, $F_R(\tau\alpha)$ is where the curve intersects with y-axis and $-F_R U_L$ is the slope of the efficiency diagram. When sloped lines intersect the horizontal axis, it means that the outgoing useful energy from the collector is crosses and is called the stagnation status. The useful energy obtained from the collector can be calculated by measuring the flow rate of the fluid from the collector and the inlet and outlet temperatures.

$$Q_u = \dot{m}C_p(T_{f2} - T_{f1}) \tag{13}$$

Therefore,

$$\eta = \frac{\dot{m}C_p(T_{f2} - T_{f1})}{A_C I} \tag{14}$$

The experimental mass flow rate is obtained by calculation from the establishment of the heat and mass transfer balance between the inlet and outlet collector hot fluid according to the relation:

$$I(\tau\alpha)\eta A_C = \dot{m}C_p(T_{f2} - T_{f1}) \tag{15}$$

Substituting η, by its expression in Eq. (14), into Eq. (15), we obtain:

$$\dot{m} = \frac{I\ (\tau\alpha)A_C}{C_p(T_{f2} - T_{f1})}\left[F_R(\tau\alpha) - F_R U_L\left(\frac{T_{f1} - T_a}{I}\right)\right] \tag{16}$$

The temperature T_{f2} of the hot fluid at point d (Figure 5) is determined by the absorber thermal equilibrium equation.

$$I(\tau\alpha)dA_C - U_L(T_f(y)-T_a)dA_C = C_p\dot{m}\ dT_f \tag{17}$$

in which the elementary surface dAc (Figure 5) is defined by

$$dA_c = l_c\,dy = \frac{A_c}{L_c}dy \tag{18}$$

where $T_f(y)$ represents the water temperature in the collector at position y and dT_f represents the increase in the warm fluid temperature when it circulates in the element of surface dAc.

By introducing Eq. (17) into Eq. (18), one obtains a first order differential equation with second member.

$$\frac{dT_f(y)}{dy} = \frac{A_c}{L_c C_p \dot{m}}\left[I_T(\tau\alpha) - U_L(T_f(y)-T_a)\right] \tag{19}$$

whose boundary conditions are

$$T_f(0) = T_{f1} \tag{20}$$

$$T_f(L_c) = T_{f2} \tag{21}$$

After resolution, one obtains

$$T_{f2} = T_{f1} + \left[T_a + \frac{I(\tau\alpha)}{U_L} - T_{f1}\right]\left[1-exp\left(-\frac{U_L A_C}{\dot{m}C_p}\right)\right] \tag{22}$$

The collector outlet warm fluid temperature T_{f2} is, thus, defined. Moreover, the instantaneous heat balance of the pipe element dx as shown in (Figure 6) is written:

$$\dot{m}C_p\left[T(x) - T(x+dx)\right] = U_{ct}\times\pi\times D\times dx\times\left[T(x)-T_a\right] \tag{23}$$

It is a differential equation of order 1 having for condition at limits

$$T(0) = T_0 \tag{24}$$

$$T(L) = T_L \tag{25}$$

Having for solution:

$$T_L = T_o + (T_a - T_o)\left[1-exp\left(-\frac{U_{ct}\pi DL}{\dot{m}C_p}\right)\right] \tag{26}$$

Applying Eq. (26) to the pipe elements between points g and a of the system (Figure 6), one obtains the following equations:

$$T_{f1} = T_{f4} + (T_a - T_{f4})\left[1-exp\left(-\frac{U_{ct}\pi DL_{ga}}{\dot{m}C_p}\right)\right] \tag{27}$$

By neglecting the thermal wall resistance, the heat exchange coefficient between the connecting tubes and the ambient conditions (U_{ct}), referred to the external area of the tubes, can be determined by the equation:

$$U_{ct} = \frac{1}{\frac{D}{d_i}\times\frac{1}{h_{FI}} + \frac{D}{2k_r}ln\left(\frac{D}{d_i}\right) + \frac{1}{h_o}} \tag{28}$$

For this study, the calculated value of U_{ct} is 10 W/m^2 K ±1.5%. The set of differential equations are then represented in Simulink graphical user interface in the form of simulation blocks and connecting links. Due to its intricate structure and multiplicity of sub-systems, the block diagram has not been shown here. Simulations were run here for a sunny day.

An internal heat exchanger located in the tank room was used to separate the primary and secondary water circuits as shown in Figs. 3 and 4. This was provided to operate the system in heating mode by water in the primary circuit, which could not be allowed to mix with the tank water. The model used is based on a heat exchanger consisting of copper tubes immersed diagonally in a storage tank. The equation of thermal exchange taking place at the level of the heat exchanger is expressed by (Pierson and Javelas,1983; Sacadura,1993):

$$\dot{m}.C_p.(T_{f3} - T_{f4}) = U_e.A_e.[\Delta T_m] \tag{29}$$

With $$\Delta T_m = \frac{(T_{f3} - T_w) - (T_{f4} - T_e)}{\ln\frac{T_{f3} - T_w}{T_{f4} - T_e}} \tag{30}$$

The concept of the heat exchanger effectiveness, ε_{hx}, has been introduced by Nusselt to compute directly the rate of heat transfer from the inlet temperatures of the fluids [45].An evaluation of the heat exchanger effectiveness was made with the following equation [8; 44]:

$$\varepsilon_{hx} = \frac{T_{f3} - T_{f4}}{T_{f3} - \bar{T}_w} \qquad (31)$$

This parameter reduces the useful heat delivered by the solar collectors and is therefore desirable to be close to unity.

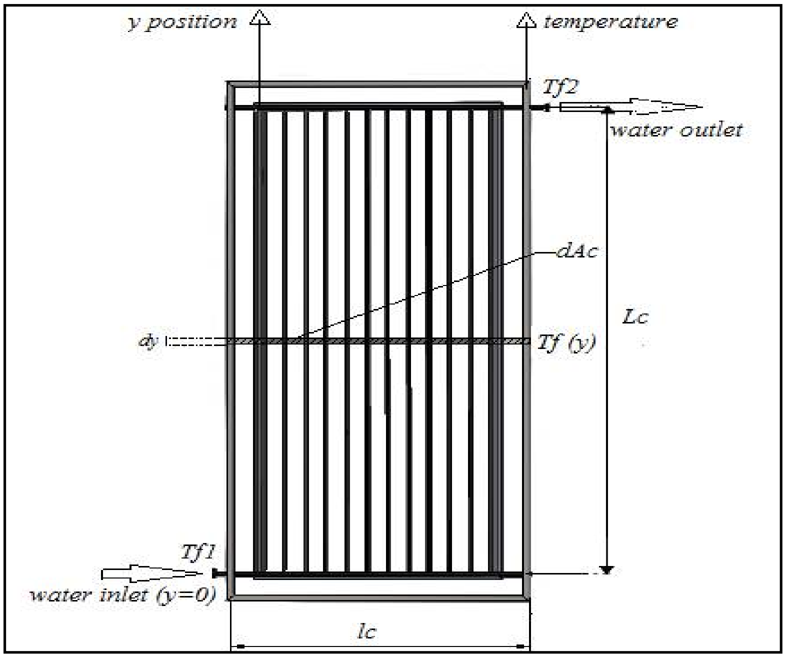

Figure 5: Schematic diagram of collector for calculation of fluid temperatures

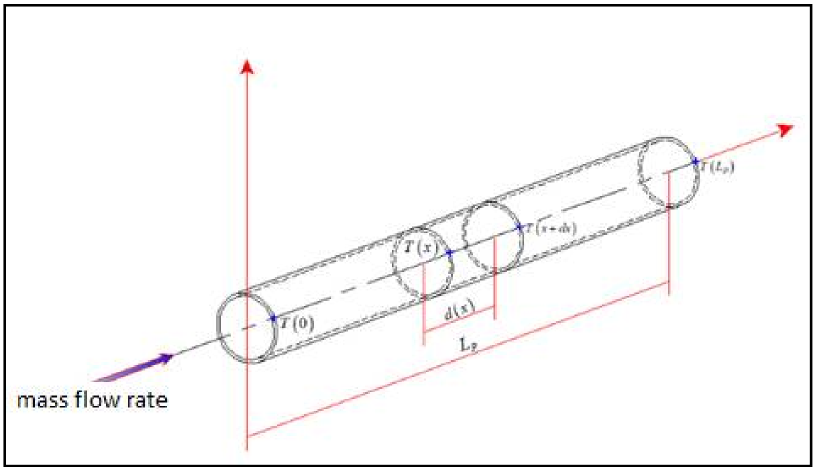

Figure 6: Pipe for calculation of fluid temperatures.

7. Experimental Investigation and Measurements

The particular performance tests of the solar collector have been carried, remotely, over two periods during 2 years. The selected system has been tested under normal weather conditions and at no load. During the testing the periodic measurement of associated climatic and operating parameters such as solar radiation, and ambient temperature has been made through a computer based data-acquisition system.

7.1. Statistical Analysis

The testing of the solar collector produced a good amount of data, and a statistical analysis has been carried out to determine inconsistencies and analyze it in a statistical manner. Along with the statistical analysis of the experimental results, calculations of the absolute error in the measurements were also carried out, to evaluate the boundaries in the system performance. The following sub sections describe the procedures followed and the calculation results.

7.2. Uncertainties on Calculated Parameters

The possible errors in the determination of the mass flow rate, the efficiency, collector efficiency factor, collector heat removal factor and overall heat loss coefficient and temperature fluctuations due to instrumentation error, has been estimated. For the determination of overall error corresponding to the instruments used the root sum square formula has been used. According to root sum square method, a quantity f is computed which is a known function of n independent variables x_1, x_2,…, x_n. It is assumed that x's are the measured quantities and have associated errors as $\pm \Delta x_1, \pm \Delta x_2, \ldots\ldots\ldots\ldots \pm \Delta x_n$ respectively; these errors will cause an error Δf in the computed result f. The error of the experimental results on the basis of the uncertainties in the primary measurements is performed using the Kline and Mc Clintock (1953) relationship as reported by Jia et al. (2006).

$$\Delta y = \left[\left(\frac{\partial f}{\partial x_1} \right)^2 (\Delta x_1)^2 + \left(\frac{\partial f}{\partial x_2} \right)^2 (\Delta x_2)^2 + \ldots\ldots\ldots . + \left(\frac{\partial f}{\partial x_n} \right)^2 (\Delta x_1)^2 \right]^{1/2} \quad (32)$$

where f is the given function of the independent variables, x is one of the variables of the function and Δx is the absolute error associated with the variable. The relative error is shown as

$$\frac{\Delta y}{y} = \left[\left(\frac{\partial f}{\partial x_1} \right)^2 \left(\frac{\Delta x_1}{y} \right)^2 + \left(\frac{\partial f}{\partial x_2} \right)^2 \left(\frac{\Delta x_2}{y} \right)^2 + \ldots\ldots\ldots . + \left(\frac{\partial f}{\partial x_n} \right)^2 \left(\frac{\Delta x_1}{y} \right)^2 \right]^{1/2} \quad (33)$$

The calculated parameters are the mass flow rate and efficiency calculated from the measured parameters. The analysis of the results indicates an overall accuracy of the mass flow rate as ± 6.5% and ±5% for the efficiency, 0.01% for collector efficiency factor, 1.15% for collector heat removal factor and 0.12% for overall heat loss coefficient.

8. Results and Discussion

Performance and testing of a hot water withdrawal was carried out in Yamoussoukro. The experiments were performed at different meteorological conditions in two periods:

- 1st period: from September 2010 to February 2011;
- 2nd period: from March 2012 to October 2012.

During the experimental period, measurements of the basic physical parameters that govern natural circulation by thermosiphon, total irradiation received by the collector, total daily irradiation, temperatures in various points of the system (connection piping, inlet and outlet of the hot fluid in the collector and in the heat exchanger) are reported with the aim of determining the mass flow rate and the thermal performances of this system. We have studied the system a sunny day (12/10/2012).The daily irradiation of this day is 4476 Wh/m^2 /day.

For any thermal system, it is important to know the energy quantity received and its distribution in time. Figure 7 presents the heat fluxes and the ambient temperature and the mass flow rate versus time with local time for a selected sunny day. The variation of ambient temperature is found to follow the solar radiation. During the test period, the minimum recorded ambient temperature was 20.3°C and the maximum recorded ambient temperature was 43°C at 3:30 p.m. The heat flux evolves according to time to reach its peak at 12:30 am and then begins decreasing. The reached maximal value is of 1130 W/m^2. These results are in perfect concordance with those of Sakhrieh and Al-Ghandoor(2013).

The solar radiation absorbed by the absorber plate increases the temperature of the system. Because of the natural circulation of water between the collector and the tank, temperatures at inlet fluid, outlet fluid temperature of solar collector, at inlet fluid, outlet fluid temperature of the heat exchanger and mean plate temperatures kept rising during the test time as long as the amount of energy gained from the sun is higher than the energy lost from the system. After that, those temperatures starts to decrease. At the morning times, the temperatures measured are relatively low due to the low flux of incident solar radiation.

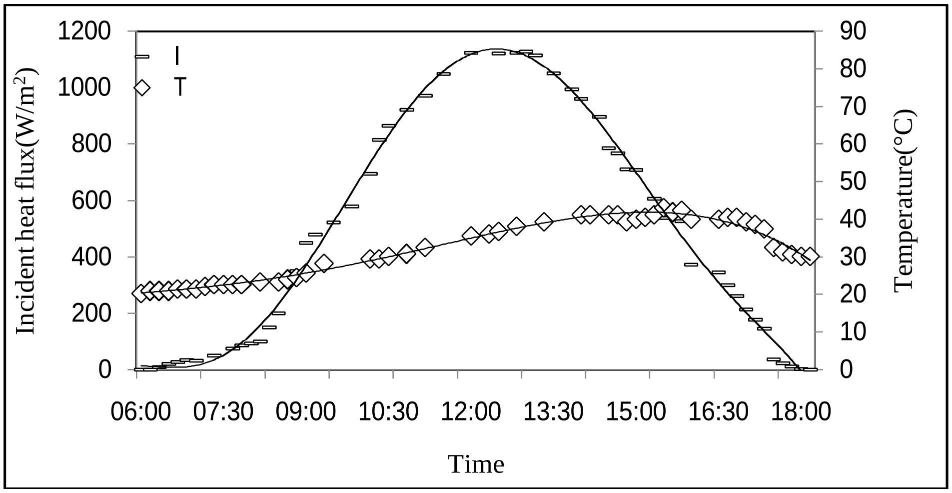

Figure 7: Instantaneous thermal heat flux and ambient temperature.

Figs. 8 present the inlet and outlet water temperature of the coiled heat exchanger. The figure shows that the inlet temperature of the heat exchanger is higher than the outlet one. This is due to the heat recovered from the working fluid. The figure show that the inlet heat exchanger temperature started to increase only after about 3h (6:00am to 9:00am) into operation. Practically similar at the beginning of the day (until 8:50am), inlet fluid temperature of the heat exchanger increases rather quickly during the day (between 8:50 am and 1:20 pm) translating thermosiphon effect. The maximal values are respectively obtained at 2:10 pm for a temperature of 68°C at inlet of the heat exchanger and at 5:00 pm (with a temperature of 46.8°C) at the heat exchanger outlet. Then, the received thermal flow becoming more and more low does not any more manage to warm suitably the fluid which temperature decreases.

Temperature in the storage water tank is a function of the buoyancy-induced flow of heated water in from the water heater. Due to the very slow buoyancy-induced flow rate, there will be a heated water front progressing downward through the tank. The rate of progression depends on the strength of the thermosiphon effect. The temperature variation in the water storage tank is shown in Figure 9. As can be seen from this figure, the temperature distribution rose during the operating time. Of 6:00 to 9:30am, the difference of temperature is almost nil. That is due to the relative weakness of the incident heat flux. The heat flux received by the system is not sufficient to overcome the inertia of this one. The effect thermosiphon starts actually later 9:30am. From this moment this variation increases until reach its peak to 4: 00 pm with a value of 11.1°C. After this moment, the received incident heat flux, becoming more and more low, the temperature decreases until achieve 5°C at 6: 00 p.m. This indicates that the thermal stratification retained well. It can also be clearly seen that only after about 3.5 h, the outlet storage tank temperature began to rise. Also, the figures show that the outlet storage tank temperature started to increase only after about 3.5 h into operation. This is because the temperature at the inlet of the heat exchanger began to rise only after about 3h in into operation as was stated above. The heat stored by the heat exchanger is gradually passed on in the water of the storage which warms up gradually. The maximal value of the temperature at exit of the storage is reached around 4:00 pm for an approximative value of 52°C before decreasing. It should be noted, as can be seen from Figs. 8 and 9, the water temperature at the outlet storage tank is slightly lower than the temperature at the heat exchanger inlet. This is because some heat loss occurs in the piping and heat losses from the storage tank. These results are in perfect concordance with those of Abu-Mulaweh(2006) and those of Rhee et al (2010).

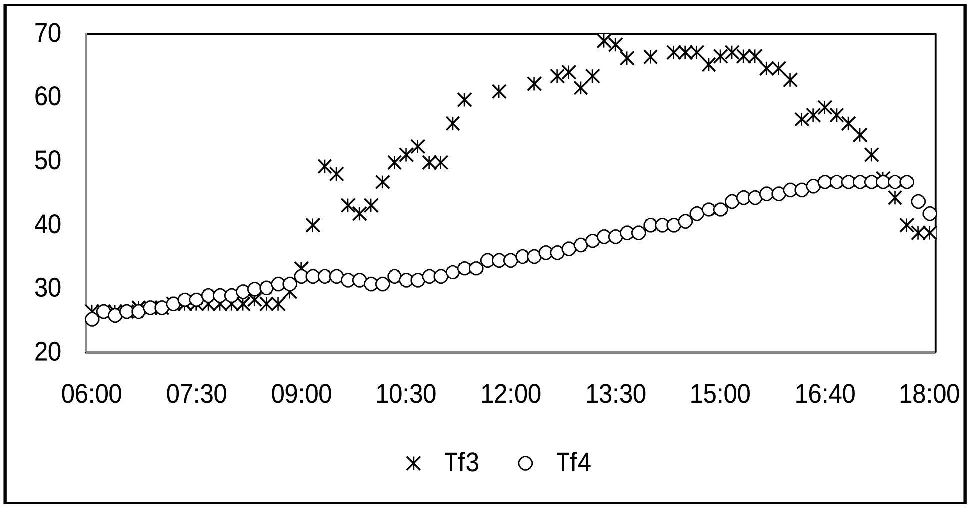

Figure 8: Coiled heat exchanger inlet and outlet temperature.

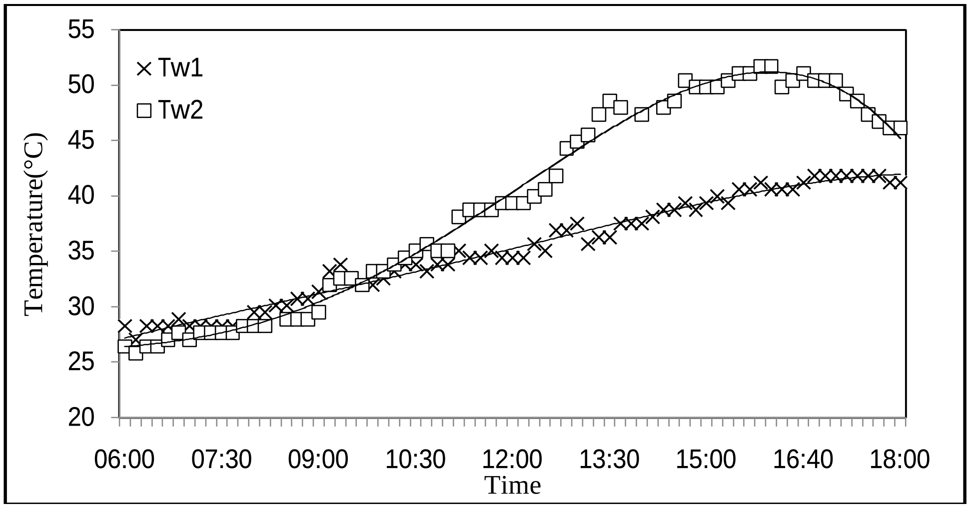

Figure 9: Temperature variation in the storage tank in heating water

Figure 10 shows the average temperature difference between the heat exchanger and the storage tank. During the daytime (from 8:50 am), the difference is positive, indicating an energy transfer from the heat exchanger in the storage tank. From 5:25 pm and during the night, the difference is negative, indicating energy transfer from the tank to the heat exchanger which is characteristic of the reverse flow. These results are in perfect concordance with those of Nahar (2003), those of Mertol et al. (1981). Incident radiation fluctuation can influence changes in the inlet and outlet temperatures of the collector as depicted in Figure 11. In this figure the discrepancy between the simulation and the experiment is lesser. In the experiment, the temperature increase in the collector is much less influenced by the incident radiation rise and fall periods. This can be attributed to a circulation halt in the collector when the radiation from the sun is small. Since flow is as a result of buoyancy force, when there is not enough solar radiation present on the surface of the collector, the flow stops and consequently the temperature difference between outlet and inlet remain high for a certain time. This was modeled well in theoretical in the full sunning period (9:00 am to 2:50 pm). The average fluid temperature rise in the collector over the entire day was estimated by theoretical with a small error. These temperature rises were 17.37°C and 18.2°C for the theoretical and the experiment, respectively. One can note that the average scattering recorded between the theoretical and experimental curves is 4.50 %. These are also qualitatively interesting because in good agreement with the conclusions of the studies of Ong (1976) and those of Chuawittayawuth and Kumar (2002). As previously mentioned, when the intensity of the sun radiation is suddenly decreased or increased, the fluid and the absorber temperatures do not go through sudden changes; which means they do not obey the changes in the radiation immediately.

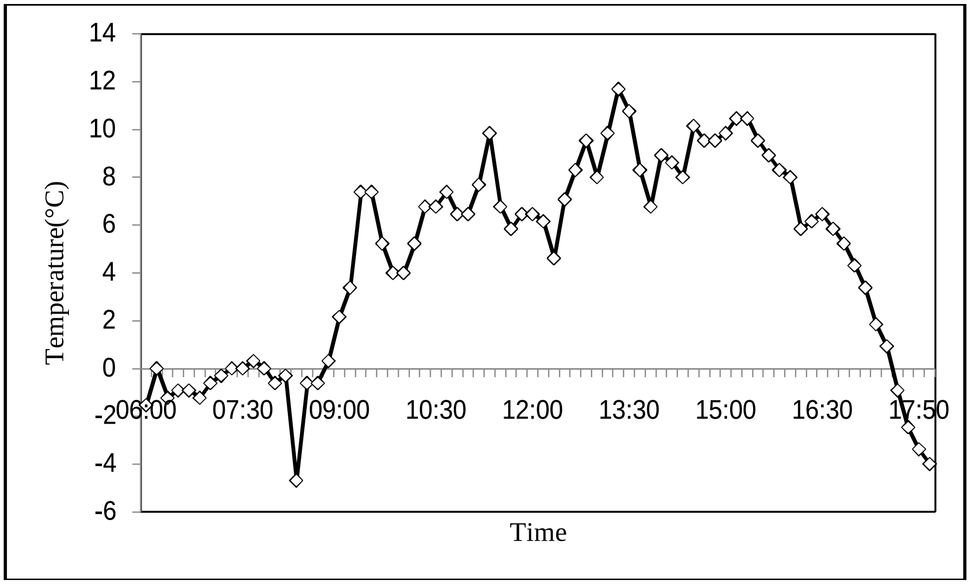

Figure 10: Difference between average heat exchanger and tank temperature

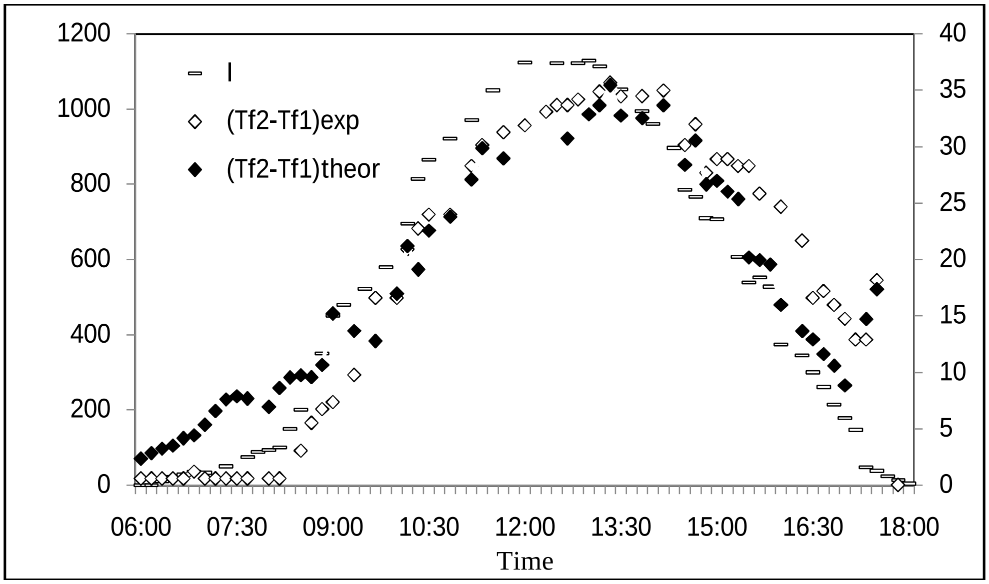

Figure 11: Variations of the experimental and theoretical temperature increase of the fluid passing through the collector on a typical sunny day.

In order to figure out how the working fluid (water) flow temperature affects the collecting efficiency, Figure 12 shows the variations of the instantaneous collecting efficiency with the measured working fluid temperature difference between the heat exchanger inlet and outlet. Globally, the temperature evolves with efficiency. The negative of temperature difference (Which is remarked generally at the beginning and at the end of the day) correspond to the onset of the reverse flow. Hot fluid in the riser reverses direction and enters at the outlet of heat exchanger while the cold fluid from the downcomer enters the heat exchanger inlet. During the day time, the onset of thermosiphon effect is translated by a positive difference of temperature (for efficiency between 28 % and 73.6 %). The efficiency curves of the flat plate collectors in TSWHS based on the inlet temperature of the fluid are shown in Figure 12. By linear curve fitting of the obtained data points, the experiments yields $-F_RU_L = 3.728$. Extending the lines to intersect with y-axis in the region of the maximum efficiency, the numeric amount of $F_R\ (\tau\alpha)$ will be obtained for the experiment as 0.765. These values are in good agreement with those of Pierson and Javelas(1983), those of Karaghouli and Alnasser(2001), those of Benallon and Bougard (1990) and those of Taherian et al. (2011).

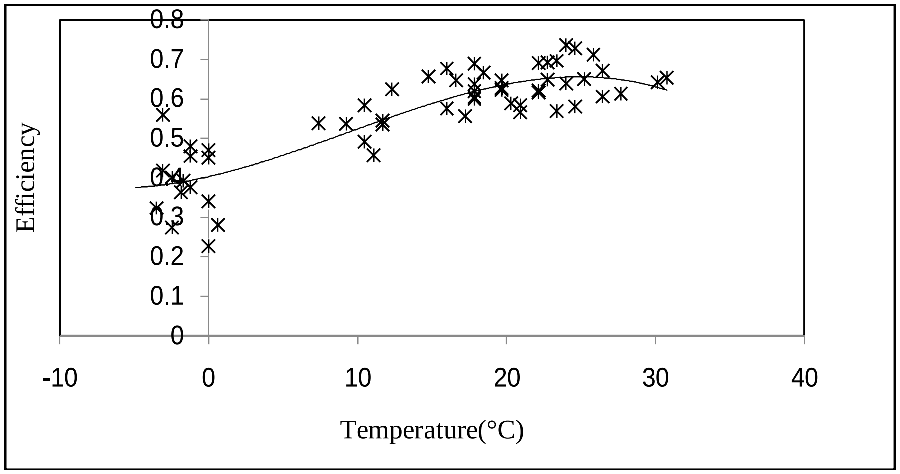

Figure 12: Variations of instantaneous efficiency with the heat exchanger temperature difference between outlet and inlet

According to the diagram, the instantaneous efficiency will decrease as the ratio of temperature difference to incident radiation increases. Therefore, it is recommended that the storage tank is designed in such a way that the incoming fluid to the collector has a temperature near the ambient temperature. The ratio of the nonlinear changes of the instantaneous useful energy obtained during the time the fluid passes through the collector to the instantaneous radiation energy incident on the collector is the mean momentary efficiency. If we consider that such a curve as in Figure 13 has been obtained in one day, then the average daily efficiency of 56.90 % is quiet considerable for such thermosiphonic system. Since the working fluid is water, T_{f1} increases restrictedly and therefore at noon, when the radiation is at its highest, the system efficiency is less than after and before solar noon. The coefficient of thermal exchange of the heat exchanger used, U_e, is determined using Eq. (29). The coefficient of thermal exchange of the heat exchange is estimated to be 149.15 W/m^2K. This result is in agreement with those found in the literature. According to Roulet (1988) and Wellinger and al. (1982), the transfer of heat taking place by natural convection in primary circuit and in the secondary circuit, the coefficient of transfer is of the order of 150 W/m^2K.

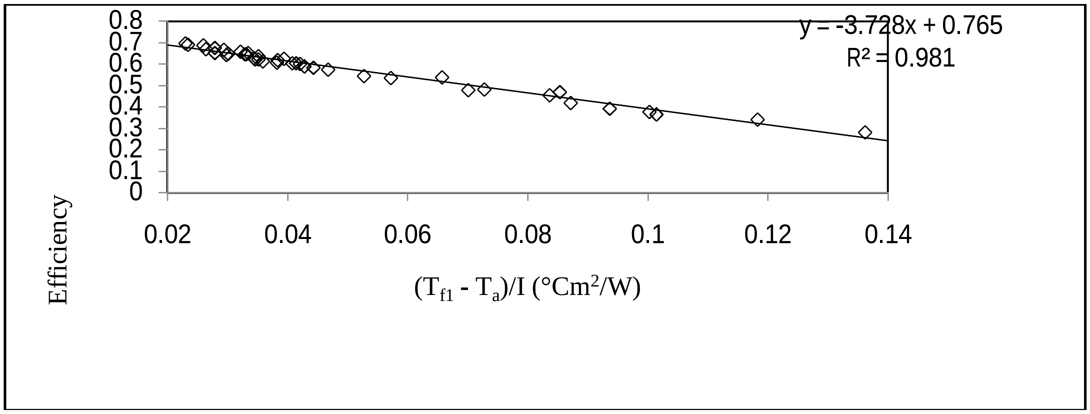

Figure 13: Collector efficiency with $T_{f1} - T_a \big/ I$

Figure 14 shows the variation of the heat exchanger effectiveness with solar time. The effectiveness varies with solar time, increasing and decreasing rapidly as the collector water temperature increases and decreases at the beginning and end of the day, respectively. For a major part of the period of heat input to tank on the day of measure, from 08:40am to 4:20pm, the effectiveness was found was found to be between 30% and 95% as shown in Figure 14. The average daily heat exchanger effectiveness obtained is 73.82%. This result is interesting compared to some values in the literature. Pierson [43] who worked with an external annular heat exchanger, obtained in the same weather conditions, efficiency included between 30.8 % and 95.1 % with an average daily heat exchanger effectiveness of 75.8 %. Roulet (1988) who made his study with an immersed heat exchanger showed that a good heat exchanger has to have a heat exchanger effectiveness superior to 50 %. Haltiwanger and Davidson (2009), which also used in their works an immersed heat exchanger, showed after one hour of measure that the efficiency of the used heat exchanger is understood between 61 % and 68 % with an average of 65.1 %. As for Syed et al. (2005), they showed in their works during the sunny day that, heat exchanger effectiveness was found to be between 60 % and 70 % with an average of 63 %.

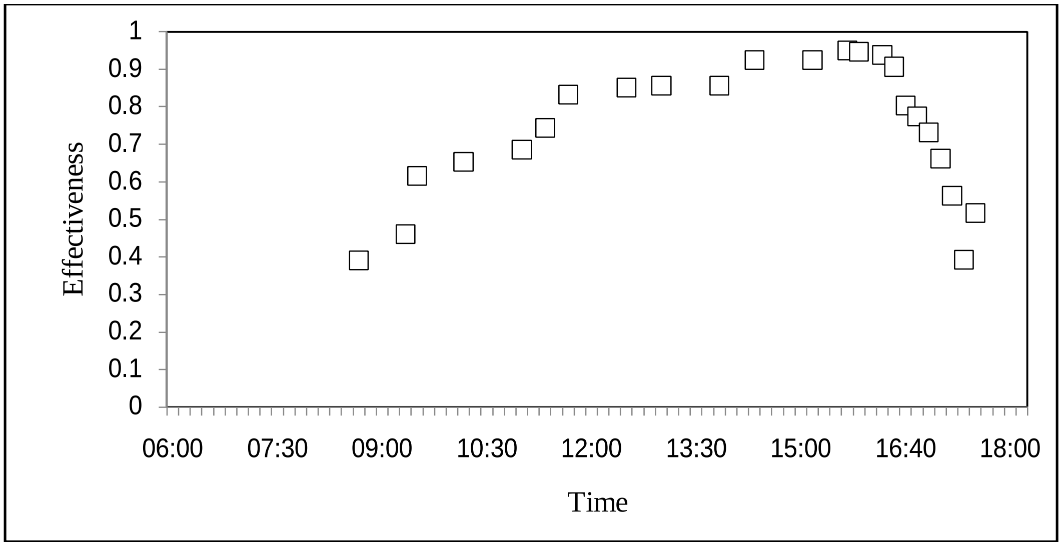

Figure 14: Time variation of heat exchanger effectiveness

A new economic analysis of the SWHS designed locally versus electric for a system with 95 liters storage tank is made (Figure 15). The results are obtained by using the current electricity rate and a 20 years period. The approximate unit sale value for initial purchasing costs and installation of this SWHS is estimated to US$ 858. According to this graph, SWHS locally made becomes more profitable than electric one less than two years. This result is better than those obtained with imported SWHS which is seven years. After two years, the solar system gives much lower specific energy costs than electrical system. So the SWHS locally manufactured using locals material, allows reducing the costs.

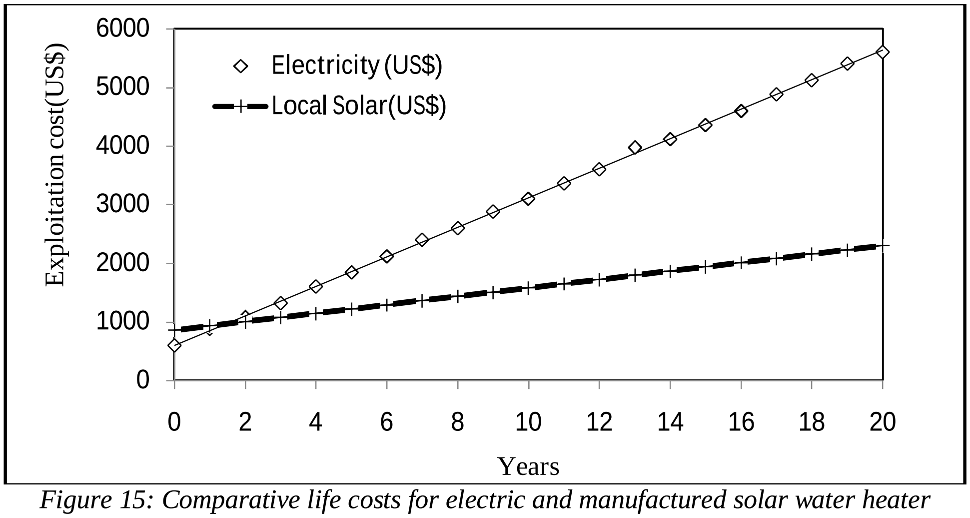

Figure 15: Comparative life costs for electric and manufactured solar water heater

9. Conclusion

This study aimed to assess the economics of adopting SWHs for urban households and to examine the institutional factors that have determined the various SWH adoption rates across Côte d'Ivoire. Surprisingly, up to now, no load industry deals with the manufacturing of SWHS. The main barriers to the dissemination of SWH nationally seem to be cost rather than trust in the technology, which, as shown in this study is relatively simple.

In this research, a thermal performance of locally made flat plate solar collector used as part of a domestic hot water system was experimentally studied a sunny day and was also compared with the theoretical data. During the experimental period, the following measurements were carried out on daily basis: total irradiation received by the collector, total daily irradiation, the ambient air temperature, temperatures in various points of the system. The daily irradiation of sunny day chosen is 4476 Wh/m^2 /day. The maximum ambient temperature and the maximum solar radiation during the test were 43°C and 1125 W/m^2 respectively. The obtained mean efficiency of 56.90 % is very remarkable for such thermosphonic systems. It has been shown that the instantaneous efficiency of the system decreases as the ratio of temperature to incident radiation increases. The storage tank designed and realized contains an internal heat exchanger in which circulates the working fluid. The highest temperature of the outgoing and the entrance fluid from the collector and heat exchanger respectively are seen in the afternoon. This causes an increase in the mean temperature of the working fluid, and therefore, the maximum temperature of the absorber is seen at this time. In the experimental results and when the radiation intensity is undergoing through more sudden changes, because of the working fluid properties (high heat capacity of water), the intensity of such sudden changes is less in the gained useful energy, and has a small time delay.

For various the sunny day studied, one observes that during the major insulation period, one obtains satisfactory qualitative and quantitative agreement between experimental and theoretical results of the collector outlet fluid temperature; when the coefficient of exchange thermal of the heat exchanger U_e found is 149.15 W/(m^2.K) and the average daily heat exchanger effectiveness obtained is 73.82%. These results prove the system is suitable under the weather conditions in Côte d'Ivoire. These performances added to the relative simplicity of the system manufacturing and the absence of moving parts; make it an interesting technological solution. The approximate unit sale value of the SWHS locally manufactured is US$ 858. This cost is 1.75 times lower than the imported one which shows the economical viability of the SWHS locally manufactured.

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