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Study, manufacture and testing of a hybrid Solar domestic water heater for a sustainable approach in West African climatic conditions

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Abstract

Sanitary hot water is needed in many industrial processes but can also be found in the habitat where it contributes to household comfort. In industrial applications, hot water is used in food processing or as a heat transfer fluid. It is sometimes used to operate machines such as absorption refrigeration systems for the production of cold for the preservation of foodstuffs, etc. Producing hot water from energy sources that are not harmful to the environment, such as solar energy, is a challenge to limit the negative impacts of the use of fossil fuels on nature. Despite the advantages of solar hot water production and the potential of solar energy in Africa, this technique remains little used in Sub-Saharan Africa due to the lack of equipment and its high price. The objective of the project is to help design, manufacture and test a local, efficient and affordable solar water heater for the African market. The first experimental tests on the hot water production showed that the hot water storage temperature in the equipment's tank can reach 80°C, on sunny days under the test conditions in Benin. On non-sunny days, the completed collector should operate with an electric booster to reach the hot water storage temperature of 80°C required for some industrial applications (absorption machines). These first tests are conclusive and this low environmental impact device can be improved and popularised for industrial and domestic applications in sub-Saharan climatic conditions.

Keywords: Flat plate heat collector, solar energy, sanitary hot water, sustainable development.

Introduction

With industrialisation, the planet's energy needs are decoupling explosively to support both industrial energy demands and the comfort needs of people's households[1,2]. Presently, the principle source of energy worldwide comes from fossil fuels, which combine two important negative aspects. On the one hand, these energy resources are present on earth in limited quantities; on the other hand, their extraction and combustion emit considerable greenhouse gases[3,4]. Faced with this situation, it is necessary to find alternatives and to rethink energy consumption patterns in all areas, as the planet's energy needs continue to increase with technological evolution, industrialization and demands for living comfort. As an alternative source, the use of renewable energies is a sustainable, reliable and environmentally friendly solution[1,5]. They are not new, and have been exploited on a smaller scale since the dawn of time[1-3].

Solar energy is a renewable energy that offers great potential for supplying energy needs. Solar radiation can be converted into heat and electricity, which can be exploited by a variety of technologies[2,6]. However, the technical feasibility and economic viability of these technologies at a specific location depends on the available solar resource and the cost of equipment[2,4,7].

The main element of a solar energy system is the solar collector that transforms solar energy into useful energy. There are several kinds of solar collectors, among them photovoltaic and thermal collectors[1,8,13].

Photovoltaic collectors convert solar radiation into electrical energy, while solar thermal collectors convert solar radiation into thermal energy. Thermal collectors are used for the production of valuable warm water in many industrial areas and also in the home. This is the case, for example, for solar thermal power plants for electricity generation or for refrigeration from absorption refrigeration systems[9-12,14].

This article reports the different stages of the study and manufacture of a flat plate solar thermal collector, as well as the different tests of solar hot water production in real situations in order to evaluate the performances.

Materials and methods

Dimensioning of the solar thermal collector: The correct dimensioning of solar collectors is a prerequisite for the environmentally friendly and optimised operation of domestic hot water and heating systems[3].

The hot water demand can be expressed as follows:

$$\mathrm{Q}_{hot\ water} = c_p.\rho.V.(\mathrm{T_c} - \mathrm{T_f})[\mathrm{kJ}] \quad (1)$$

The efficiency of the collector is written as following:

$$\eta_{\text{collector}} = n_0 - \left(\left(a_1 . \frac{(T_m - T_a)}{E_0}\right) - \left(a_2 . \frac{(T_m - T_a)^2}{E_0}\right)\right) \quad (2)$$

The collector area required for hot water production is calculated according to need:

$$S_{\text{collector}} = \left(\frac{1}{\eta_{\text{collector}}}\right) . Q_{hot\ water} / E_0 [\text{m}^2] \quad (3)$$

The volume of hot water storage tank is determined as following:

$$V_{\text{storage}} = 350 . E_0 . S_{\text{capteur}} / (T_c - T_f) [L] \quad (4)$$

Graphical modelling of the different elements making up the collector: The solar thermal collector is made up of several elements, such as the box, the absorber, the coil and the metal support on which the whole collector is mounted. Figures-1 to 3 show the box, the absorber and the coil respectively.

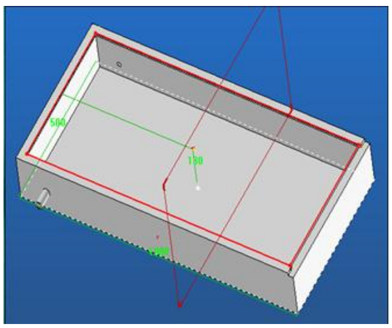

Figure-1: Box.

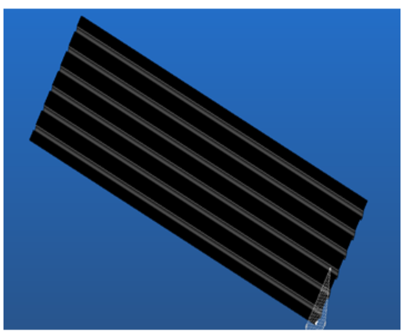

Figure-2: Heatabsorber.

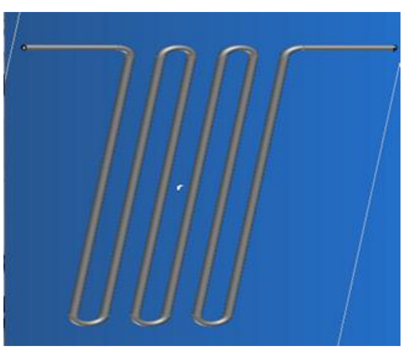

Figure-3: Copper Coil.

The box, absorber and coil assembly is shown in Figure-4. The metal support and the collector assembly are presented in Figures-5 and 6 respectively.

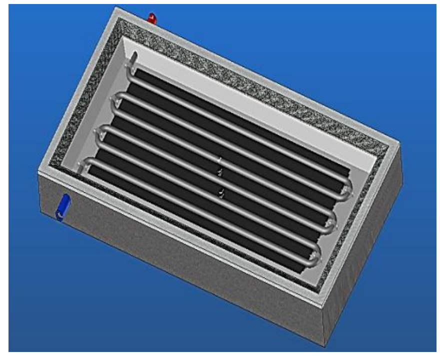

Figure-4: Box + Absorber + Coil.

Figure-5: Support.

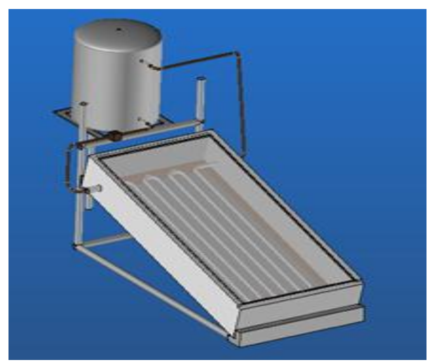

Figure-6: Flat plate solar heat collector.

Methodology

The collector is made up of a box insulated from below with 15 mm thick polystyrene to limit heat loss to the environment. A reflective aluminium plate is then placed on the polystyrene, followed by a copper coil painted black for better absorption of the solar energy transmitted by the glazing covering the top of the unit. The water to be heated circulates in the collector coil. These are ideally installed in a loop containing a hot water storage tank in which another exchanger is immersed.

The photos in Figure-7 show, in chronological order, the main steps in the implementation of such a thermal collector. The whole system is illustrated in Figure-8.

Figure-7: Main steps in the realisation of a plane collector.

Figure-8: Flat plate solar collector realised.

The whole device is controlled via an Arduino card which is a little electronic circuit outfitted with a microcontroller. This allows, on the basis of parameters sensed, to program and control the monitoring of devices. The most widely used Arduino Uno card, its low cost makes it an interesting ally. It can communicate with a Bluetooth card and allows the remote transmission of information (temperature measurements...) via a smart phone that remotely retrieves the temperatures read by temperature captures using the Arduino Bluetooth Controller application.

The measurements of the different temperatures of the heat transfer fluid at the inlet, outlet and inside the warm water storage tank, as well as the temperature of the collector absorber, are provided by LM35DZ type sensors installed in small watertight tubes, so as to be impermeable to water. The LM35DZ sensor is capable of measuring temperatures ranging from -55°C to +125°C with an accuracy of +/-2°C. Each sensor has been wired in parallel with a 100 micro Farad (100µF) capacitor to improve its performance.

The outdoor temperature is measured by a DHT11 type sensor. The DHT11 sensor is a sensor capable of measuring temperatures from 0 to 50°C with an accuracy of +/-2°C and relative humidity levels from 20% to 90% with an accuracy of +/-5. It should be noted that the DHT11 sensor has only been able to measure the outside temperature of the flat sensor. Figure-9 shows the wiring diagram of the assembly.

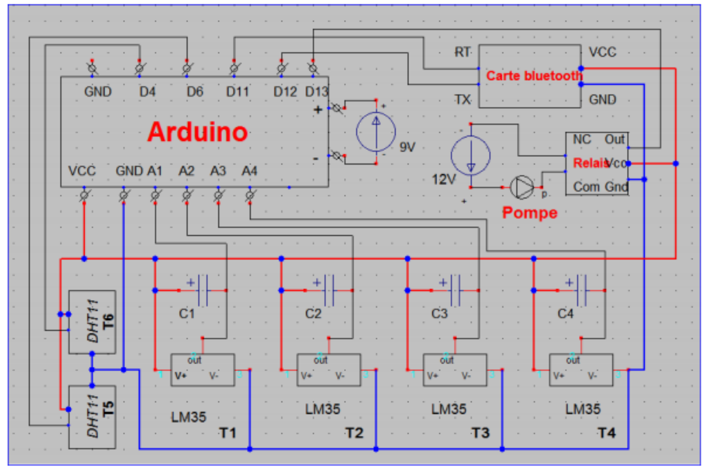

Figure-9: Wiring diagram of the control device.

In tropical countries, more precisely in Benin, there are three categories of sunshine: periods of very high sunshine, alternating with periods of medium or lower sunshine. The city of Lokossa was chosen for the experimental testing of the flat plate solar thermal collector. To ensure good use of the equipment, even in times of no sunshine, an electric heating booster has been installed in the storage tank. This booster is powered by 220V AC from a system of photovoltaic solar panels designed for the purpose (Figure-10).

Figure-10: (a) Flat plate thermal collector + Photovoltaic solar panels; (b) Solar power device (DC/AC).

Results and discussion

A series of experimentation series were carried out to test the efficiency and performance of the solar water heater based on temperature readings. The experiments took place under varying outdoor conditions. The performance test was limited only to the determination of the following parameters: i. The water temperature at the collector inlet T_e; ii. The water temperature at the outlet of the T_s collector; iii. The temperature of the water in the hot water storage tank T_r; iv. The temperature of the absorber T_{abs}; v. The outdoor temperature T_{ex}.

Dynamic characteristics of the flat plate sensor: The dynamic operating characteristics of the implemented sensor are displayed in the following Table 1.

Table-1: Dynamic features of the collector.

Collector efficiency	64 %
Collector surface	0.57 m^2
Hot water energy demand	8.360 kJ
Hot water storage volume	50 L
Average fluid velocity in the pipeline V	0.2 m/s
Linear pressure drop H_{pL}	$0.03.10^5$ Pa
Singular pressure drop H_{pS}	1.42. 10^5 Pa
Total pressure drop H_{pT}	1.45 10^5 Pa
Circulation pump output P_p	13.57 W

Experimental test on the collector without electric heating backup: All tests were carried out at the National Institute of Industrial Science and Technology in Lokossa (Benin). Several tests were done on the flat plate collector without electric heating support on sunny days. The tests of 21 May and 7 August 2019 are presented here for these cases.

Tests of May 21 and August 7, 2019 (good sunshine): This day of May 21, 2019 was a day of good sunshine without major disruption. Figure-11 shows the evolution of the different temperatures versus time, the maximum temperature recorded was 76°C at the storage tank (T_r) for a maximum outdoor temperature of 38.7°C (T_{ext}).

During the day of August 7, 2019, there were also no significant weather disturbances. Figure 12 shows the temperature profiles as a function of time. It can be seen that the temperature T_r reaches values greater than or equal to 80°C between 12:00 and 17:00, for a maximum of 88.9°C. This increase can be correlated with the temperature T_{ext}, which was high that day and was around 40°C.

Experimental test with booster: Several tests have been performed on the collector on days with little sunshine that require additional heating. The days of 02 and 03 October 2019 were chosen among these test days.

Tests on October 2 and 3, 2019: During the day of October 2, 2019, disturbances were observed. Indeed, it rained most of the day. The temperature T_r reached 80.69°C at 10h 50 min, 3h 50 min after the system was switched on. The maximum value of T_r (96.77°C) is reached around 15 hours with a maximum outdoor T_{ext} temperature of 27.6°C. The water demand was achieved by switching on the booster when the outdoor temperature T_{ext} is below 28°C.

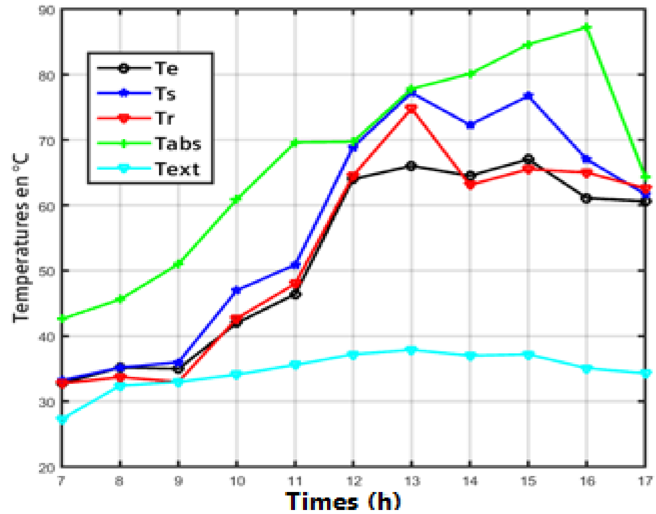

Figure-11: Temperature evolution (21 May 2019).

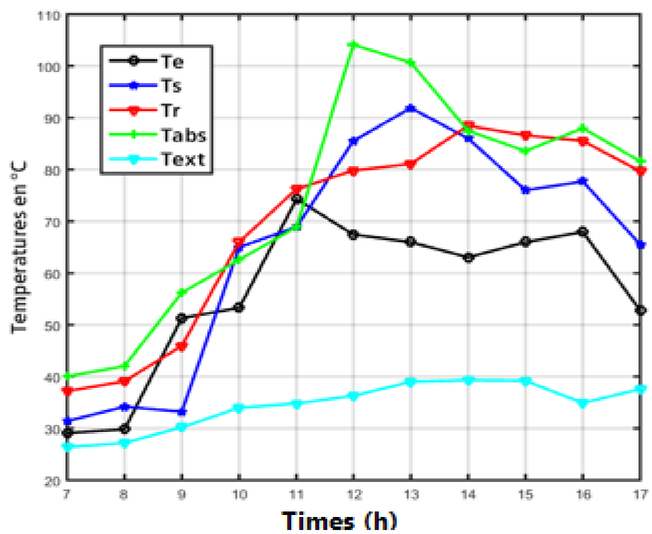

Figure-12: Temperature evolution (7 August 2019).

The day of 3 October 2019 was marked by rain in the morning. The T_{ext} outdoor temperature was below 28°C from 7h 00 to 13 h 00, during which time the top-up was switched on and off from 13h 00. Since the outside temperature at this time was 28.4°C, the electric booster was switched on during this time.

Figure-14 shows that the storage tank temperature T_r reached 80.3°C at 11h 00, four hours after the system was started. However, the maximum value of T_r (87.1°C) is reached at 14 h, with a maximum outdoor temperature of 28.9°C. T_r<90°C is achieved when the boosting system is switched off at 13 h 00 because the outside temperature T_{ext} had reached 28.4°C.

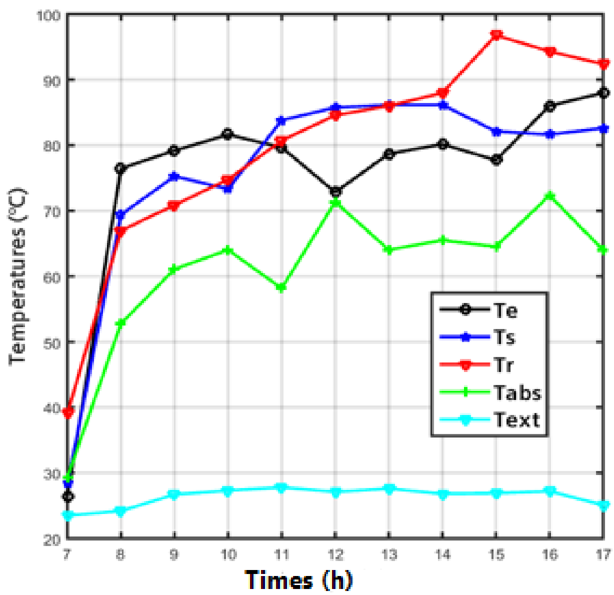

Figure-13: Temperature evolution (2 October 2019).

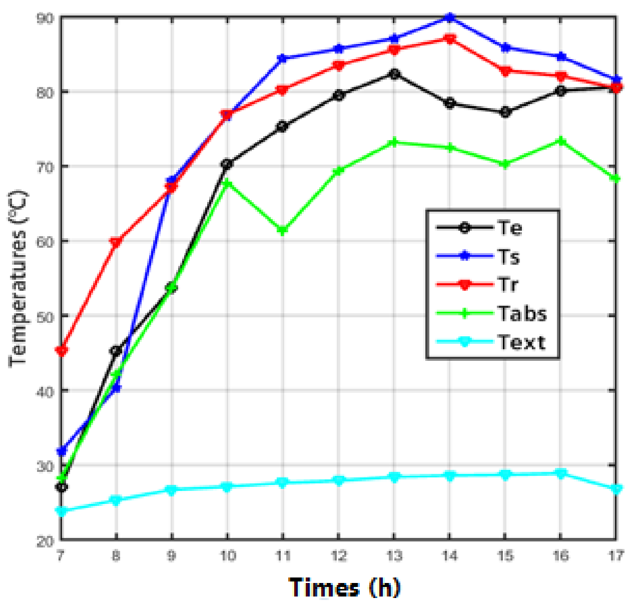

Figure-14: Temperature evolution (3 October 2019).

Despite the absence of solar radiation on this day, the maximum temperatures at the collector T_{abs}, at the T_e input and T_s output of the flat plate collector are 72.34 °C, 87.98 °C and 86.16 °C respectively. The thermal energy loss from the hot water tank to the outside environment is higher during periods when there is no sunlight. This reflects a poor insulation of the storage tank that needs to be improved for future prototypes.

Comparison of the device to an all-electric system (electric hot water tank): Table-2 shows a comparison between the 50 L the flat collector and an electric hot water tank of the same capacity.

Table-2: Estimated cost price of the designed solar thermal collector.

Designation	Quantity	Unit price [XOF]	Amount [XOF]
Glass	1	5000	5000
Aluminium sheet	1	4000	4000
Case	1	10000	10000
Copper rod	6	500	3000
Butane	4	1000	4000
Black paint	1	1000	1000
Rivets	12	50	600
Antenna	1	500	500
Temperature sensor lm35dz (0.01W)	4	1000	4000
Temperature and humidity sensor dht11 (0.0215 W)	2	2000	4000
100nF capacitors	4	250	1000
Connectors	25	50	1250
Arduino Card (0.048 W)	1	10000	10000
Bluetooth Card (0.68 W)	1	5000	5000
Electronic brochure	1	1000	1000
Pump (15 W)	1	35000	35000
Glue	1	1500	1500
Tank	1	26000	26000
Iron	1	8000	8000
Copper piping ½ (meter)	14	18000	18000
Metal sheet	1	7500	7500
Electrical heater (150W)	1	3500	3500
DC/AC converter (350W)	1	8000	8000
Solar panels (80 W)	2	9000	18000
VRLA Battery (12V - 18AH)	02	8000	16000
Charge regulator (10A)	01	7000	7000
Electric Wires	20 m	250	5000
Two-channel thermal relay	01	2000	2000
Total		209850	

Taking into account the cost of labour and a comfortable profit margin, this equipment could be sold, under Benin conditions, at 420 000XOF, that is about €640.

Electric power consumed by the solar collector: This electrical consumption amounts to 166W and is essentially limited to the consumption of the pump, the heating resistance and accessories (relays, electronic cards). The consumption of the latter are insignificant. It should be remembered that in the case of solar production, it is the batteries that power these devices. Therefore the costs are nil.

Electricity consumption of the electric storage tank (case of the all-electric choice): The receivers to be considered are mainly the heating resistance and the water pump, for a total consumption of 165W. For an average daily operating time of 10 hours and a cost of the electric kWh of 115 XOF in Benin, the daily expenditure in hot water energy would be 1150 XOF.

The payback time (or time of return on investment of the device) is calculated:

$$\mathrm{T_r} = \frac{\text{Cost of Solar Water Heater}}{\text{Cost of Electrical Consumption}}$$

$$T_r = \frac{420000}{1150} = 365\ days$$

The payback time is one year, which indicates a reasonable and profitable investment to adopt a solar water heater instead of an electric one, in addition to the ecological aspects already discussed.

Conclusion

Through this work, the design and the realization of a flat plate thermal solar collector (solar water heater) were made. Experimental tests carried out on the collector with and without a booster have shown that the temperature in the tank can easily reach 80°C. It is clear that the locally developed flat plate solar collector can provide hot water at a temperature that can exceed 80°C. The performance of this system is evaluated by data acquisition via a smart phone. This device for hot water production in all periods uses only solar energy, even for the electrical back-up, which is done by solar batteries. This device deserves to be perfected and produced locally. The popularisation and use of such equipment contributes to the protection of the environment.

Nomenclature: n_0: Optical factor, a_1: overall heat coefficient of the heat sensor, $W.m^{-2}.K^{-1,}$ a_2: global loss coefficient of the second order heat sensor, $W.m^{-2}.K^{-2}$, T_a: ambient temperature in the sensor environment, °C, T_m: average sensor temperature, °C, T_c: hot water demand temperature, °C, T_f: cold water temperature at heat sensor inlet, °C, E_o: power of solar irradiation measured in the plane of the collector, $W.m^{-2}$

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