ARTICLE

THERMODYNAMIC PERFORMANCE EVOLUTION OF AN INEXPENSIVE PROTOTYPE SOLAR COLLECTOR FOR 1 KW DOMESTIC STHW HEATING SYSTEM IN BOTSWANA

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ABSTRACT

The escalating and inflating energy costs, exhaustion of fossil fuels, recurring power deficits, and impacts on climate change have created the need for renewable energy sources for the purposes of saving energy, having a sustainable source, and protecting the environment. This paper is focused on the design and fabrication and testing of a prototype solar thermal hot water heating system for domestic market. A solar collector was designed, fabricated using available, affordable materials of acceptable standard and its performance evaluated in the Gaborone climatic conditions. Heating water by using solar water heater is a renewable energy heating technology used to process heat generation. Galvanized steel absorber plate of size 1.2m x 1.8m was painted black maximum absorption. Testing was carried out in the University of Botswana main campus premises by positioning the solar collector facing north, using solarimeter to get solar irradiance and a data harvester to get the temperatures. Within the cost of 1234 BWP the efficiency of the solar collector was found 33.1%.

KEY WORDS
Solar radiation, collector, thermal energy, PV, energy demand.

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INTRODUCTION

For many years of human existence human beings have utilized different sources of energy for various use. Commonly used sources of energy have always been non-renewable forms of energy which are fossil fuels. These fossil fuels have been formed from dead living organisms over millions of years ago and now we are reaping the rewards. Industrial revolution and advancement in standard of living has resulted in higher demand of energy [1]. This has resulted in inflation of energy costs, recurring power deficits and a great impact on the ozone layer as most power stations are powered by fossil fuels like coal and fuels like diesel emitting harmful gases into the atmosphere [2]. This opt for alternative sources of energy that can be trusted and still be environmentally friendly. A solar hot water system (SHW) is a conversion tool, which transforms sunlight into heat to produce hot water. Such technology is extremely cost efficient and can generate hot water in any climate. A solar hot water system will harvest more energy at a substantially lower cost than the high-tech solar-electric (photovoltaic; PV) systems. Most solar hot water systems consist of three basic parts: the solar collector with heat absorbing media, circulating system for the hot fluid (pipe system) and the water storage tank. Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium [3]. There are basically two types of solar collectors: non-concentrating (or stationary) and concentrating. A non-concentrating collector has the same area for intercepting (aperture area) and for absorbing solar radiation (absorber area), whereas a sun tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux.

The escalating and inflating energy costs, exhaustion of fossil fuels, recurring power deficits, and impacts on climate change have created the need for renewable energy sources for the purposes of saving energy, having a sustainable source, and protecting the environment. Therefore, this paper is focused on the design and fabrication of a prototype flat plate solar collector for powering a 1 kW solar thermal hot water heating system. This study is focused to energy savings, a sustainable source of energy will be harnessed, reliability and environmental protection and aims to- Analyze and design a 1 kW solar hot water systems (SHWS), Fabricate, and test a flat-plate solar collector using ISO standards. Test the fabricated flat plate collector for performance and efficiency, using the local irradiance in Gaborone, Botswana and Thermodynamic evolution of the heat transfer fluid (HTF).

The energy usage in a household may be consumed to heat cold water that is used in the shower, bathtub, wash-hand basin, and laundry. To satisfy these energy demands, fossil fuels such as natural gas are typically burned in a boiler to heat the fresh water from the mains supply [4]. Other configurations use an electric heating element in the hot water storage tank, where the electricity is usually supplied by a power plant that also burns fossil fuels. In 2008, total worldwide primary energy consumption was 132,000 terawatt-hours or 474 exa-joules [5]. In 2012, primary energy demand increased to 567 EJ [6]. Overexploitation has caused the depletion of non-renewable energy sources, such that, according to BP's 2014 annual statistical review of world energy there is only 113 years of coal production, 53.3 years of oil

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production and 55.1 years of natural gas flow left available [7]. Sunlight has the highest theoretical potential of the earth's renewable energy sources. Upon averaging the solar constant and subtracting the scattered and absorbed flux by the atmosphere and clouds, the final flux striking the earth's surface in Gaborone, Botswana is 469.9 W/m^2 [8]. The theoretical potential of solar power is: P= 469.9 x 4π r^2/2 and P= 120103 TW. Where, 4πr^2 is the earth's surface area and r = 6 378 000 m is the earth's radius. Surface area is halved based on the premise that only half of the earth will be receiving sunlight at any time. Tsao, Lewis, & Crabtree, 2006 [9] have estimated that the theoretical potential energy hitting the earth's surface in one and a half hours is: $E = P \cdot t$ (1)

$E = (120103 \times 10^{12})\,[W] \cdot (1.5 \cdot 3600)\,[s]$ Finally, $E = 649 \times 10^{18}\,J = 649\,EJ$ (2)

Solar water heating system

A typical solar water heating system, shown in [Fig. 1] consists of a distinct collector, designed to maximize solar absorption and minimize heat losses. The solar collector could be either a dark-colored absorber bonded to copper piping and covered with a transparent glass (flat-plate collector) or copper tubing surrounded with evacuated and selectively-coated glass tubes (evacuated-tube collector) [10].When solar radiation passes through the transparent glass and impinges on the collector surface of high absorption, energy is absorbed by the collector and then transferred to the Heat Transfer Fluid (HTF) to be transported in the pipes. The HTF is either pumped (active system) or driven by natural convection (passive system) through the collector to a storage tank where the heated water serves the building. The tank contains a backup auxiliary heater such as an electric immersion heater or conventional boiler.

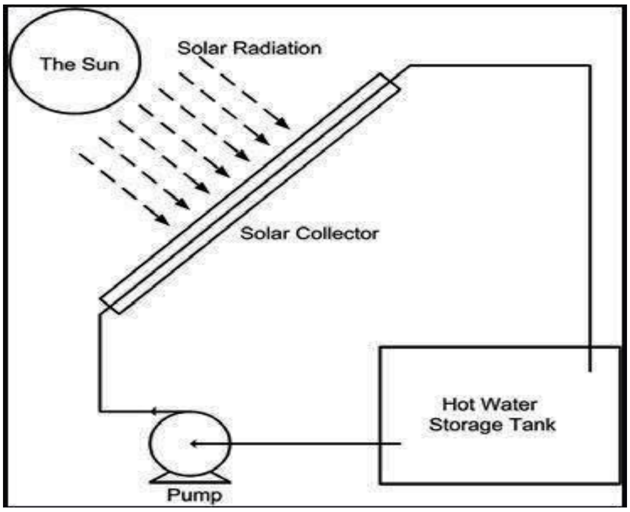

Fig. 1: Conventional solar water heating system [11]

Direct circulation systems

The pump circulates domestic water through the collector(s) and into the building. This type of system works well in climates where it rarely freezes. The direct pumped system has one or more solar energy collectors installed on the roof and a storage tank located somewhere within the building. A pump circulates the water from the tank up to the collector and back again. This is called a direct (or open loop) system because the sun's heat is transferred directly to the potable water circulating through the collector and storage tank [12].

Indirect circulation systems

Pump circulates a non-freezing, heat transfer fluid through the collector(s) and a heat exchanger. This heats the water that then flows into the home. This type of system works well in climates prone to freezing temperatures.

A heat transfer solution is pumped through the collector in a closed loop. The loop includes the collector, connecting piping, the pump, an expansion tank and a heat exchanger. A heat exchanger coil in the lower half of the storage tank transfers heat from the heat transfer solution to the potable water in the solar storage tank. An alternative of this design is to wrap the heat exchanger around the tank. This keeps it from contact with the potable water[12].

Passive solar water heaters

Passive solar water heaters rely on gravity and the tendency for water to naturally circulate as it is heated. Passive solar water heater systems contain no electrical components, are generally more reliable, easier to maintain, and possibly have a longer work life than active solar water heater systems[13]. The two most popular types of passive solar water heater systems are: Integral-Collector Storage (ICS) and Thermosyphon systems.

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Integral collector storage system

In an integral collector storage system, the hot water storage system is the collector. Cold water flows progressively through the collector where it is heated by the sun. Hot water is drawn from the top, which is the hottest, and replacement water flows into the bottom. This system is simple because pumps and controllers are not required. On demand, cold water from the building flows into the collector and hot water from the collector flows to a standard hot water auxiliary tank within the building. A flush_type freeze protection valve is installed in the top piping near the collector. As temperatures near freezing, this valve opens to allow relatively warm water to flow through the collect to prevent freezing as shown in [Fig.2].

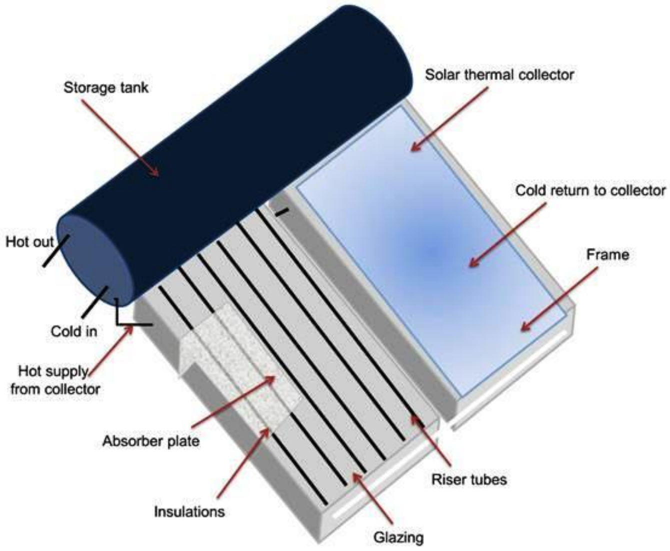

Fig. 2: Integral collector system [14]

Thermosyphon system

In a thermosyphon system [Fig.3] there is no need for a circulating pump and controller. Potable water flows directly to the tank on the roof. Solar heated water flows from the rooftop tank to the auxiliary tank installed at ground level whenever water is used with the building [15]. The thermosyphon system features a thermally operated valve that protects the collector from freezing. It also includes isolation valves, which allow the solar system to be manually drained in case of freezing conditions, or to be bypassed completely.

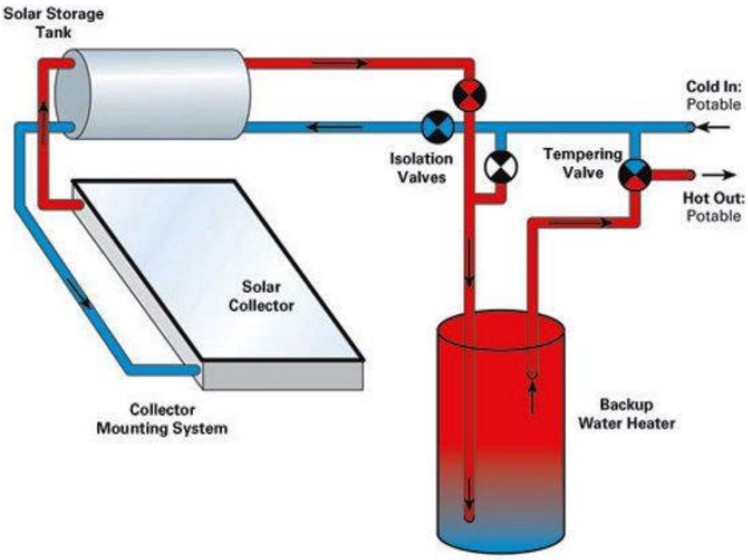

Fig. 3: Thermosyphon solar water heating system [16]

Solar collectors

According to Kalogirou, 2004 [17] the major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. A certain part of the incident solar radiation is lost due to reflection and heat transfer to ambient environment. The solar energy thus collected is carried from the circulating fluid (HTF) either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use.

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Mathematical analysis of solar water heaters

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors heat liquid or air at temperatures less than 80°C. If the rate of solar energy arriving on the collector surface area A, m², perpendicular to the line of the sun is I the solar radiation, in W/m², then the amount of solar energy being received by the collector is:

$$Q_i = I \cdot A \quad (3)$$

However, parts of this radiation is reflected back to the sky, absorbed by the glazing and the rest is transmitted through the glazing, reaching the absorbed plate as short wave radiation. Incorporating the rates of transmissions of the cover and the absorption rate of the absorber into Eq. 3, the equation below is formed:

$$Q_i = I \cdot \tau \cdot \alpha \cdot A \quad (4)$$

As the collector absorbs heat, its temperature becomes higher than its surroundings and a temperature gradient is created. This causes loss of heat to the atmosphere through convection and radiation. The heat loss rate Q_o is dependent on the collector overall heat transfer coefficient U_L, and the temperature difference between the collector t_c and ambience t_a.

$$Q_o = U_L \cdot (t_c - t_a) \quad (5)$$

$$U_L = \frac{1}{\frac{1}{h_n} + \frac{L_n}{k_n}} \quad (6)$$

Where, R_{total} is the total thermal resistance of the collector, and for the nth layer, h_n is the convective heat transfer coefficient, L_n is the thickness, and k_n is the conductivity.

Thus, the rate of useful energy extracted by the collector Q_u, expressed as a rate of heat extraction under steady state conditions, is the remainder after subtracting the heat lost by the collector to the environment Q_o from the energy absorbed by the collector Q_i.

$$Q_u = Q_i - Q_o = I \cdot \tau \cdot \alpha \cdot A - U_L \cdot (t_c - t_a) = [I \cdot \tau \cdot \alpha - (t_c - t_a)] \quad (7)$$

The useful energy extraction rate may also be expressed as the amount of heat carried away in the HTF passed through it:

$$Q_u = \dot{m} \cdot (t_o - t_i) \quad (8)$$

Where, $\dot{m}$ is the mass flow rate, c_p is the specific heat, and t_o & t_i are the outlet and inlet temperatures of the HTF, respectively. Due to the difficulty of measuring the mean collector plate temperature t_c, it would be more convenient to combine Eqn. 7 and 8 in order to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid temperature at inlet. A collector heat removal factor F_R is employed as this quantity. The F_R is the ratio of heat delivered to the HTF and heat in the condition that the overall collector plate temperature equals the inlet fluid temperature.

$$F_R = \frac{\dot{m} \cdot c_p(t_o - t_i)}{A[I \cdot \tau \cdot \alpha - U_L(t_i - t_a)]} \quad (9)$$

Introducing the collector heat removal factor to Eqn. 7 forms the widely used relationship for measuring collector energy gain known as the "Hottel-Whillier-Bliss equation [18]."

$$\boldsymbol{Q_u = F_R \cdot [I \cdot \tau \cdot \alpha - (t_i - t_a)]} \quad (10)$$

The performance of a solar collector could be measured using the collector efficiency η. This is the ratio of useful energy gained by the collector Q_u to the incident solar radiation on the collector during a specified period of time:

$$\eta = \frac{\int Q_u \, dt}{A \int I \, dt} \quad (11)$$

Since the solar collector could be characterized using a number of design parameters, Eqn. 11 could be simplified as given by [18]:

$$\boldsymbol{\eta} = \frac{Q_u}{AI} = \frac{F_R \cdot A[I \cdot \tau \cdot \alpha - U_L(t_i - t_a)]}{AI} = \boldsymbol{F_R}\left[\boldsymbol{\tau \cdot \alpha - U_L}\left(\frac{\boldsymbol{t_i - t_a}}{\boldsymbol{I}}\right)\right] \quad (12)$$

If it is assumed that F_R, τ, α, and U_L are all constant for a given collector and flow rate, then the efficiency will be a linear function of the following three parameters defining the operating condition; solar irradiance I, fluid inlet temperature t_i, and ambient air temperature t_a. The intercept with the $\Delta T/I$ axis. For well-insulated and concentrating collectors the stagnation temperature can reach very high levels causing fluid boiling and sometimes melting of the absorber surface [18]. The efficiency can vary depending upon the collector's characteristics and the combined factor of $\left(\frac{t_i - t_a}{I}\right)$. These variations are presented in [Fig.4] below.

METHODS

In order to construct a model suitable for a thermal analysis of flat plate collector, the assumptions were adopted as- The collector is thermally in steady state & the temperature drop between the two surfaces of the absorber plate is negligible. Heat flow is one-dimensional through the covers as well as through the back insulation. The headers connecting the tubes cover only a small area of the collector and provide

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uniform flow to the tubes. The conversion efficiency was assumed to be 45%. Therefore, the collector efficiency is given by equation (3) using Solar irradiance I = 469.9 W/m² [3] (average annual value for Gaborone at collector tilt 25° to the horizontal) [20]

As, $\eta = \frac{Q_u}{A\,I} = \frac{1000\,W}{A \times 469.9}$ or, A = 4.729m^2

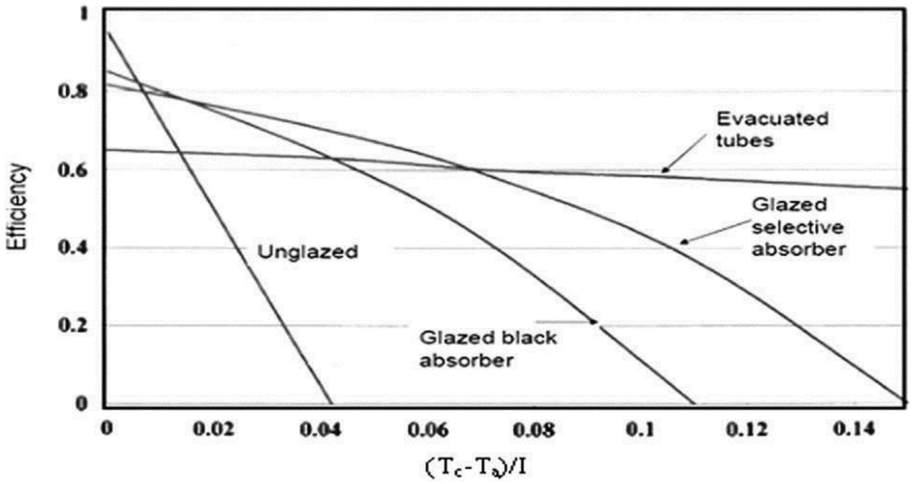

Fig. 4: Variations of the efficiency with the combined factor for a typical collector [19]

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A flat solar panel of area :(2.627 m x 1.8 m), which is in steady state at temperature T_c = 50 °C, is operating under -Outside ambient temperature T_a = 25°C, Working fluid H_2O : C_P=4.188 kJ /kgK, Convective heat transfer coefficient of the air above the glass cover, h_1=22 W/ (m²·K), Heat transfer coefficient of the glass, U_g =6.5 W/(m²·K), Conductivity of stagnant air under the glass, k_{air} =0.026 W/(m·K) [21, 22].

$$U_L = \frac{1}{\frac{1}{h_1} + \frac{L_{air}}{k_{air}} + \frac{L_{abs}}{k_{abs}} + \frac{L_{ins}}{k_{ins}} + \frac{L_{back}}{k_{back}} + \frac{1}{h_2}} + U_g$$

$$U_L = \frac{1}{\frac{1}{22} + \frac{0.05575}{0.026} + \frac{0.00025}{235} + \frac{0.04}{0.033} + \frac{0.012}{235} + \frac{1}{5.7}} + 6.5 = 6.7795\,W/m^2K$$

At the instant shown, the water enters the solar flat panel at an average supply temperature T_i =28°C. It is desired that after one pass through the collector, the water will exit at T_o =32°C. The amount of solar radiation in Botswana Q_i = IA = 469.9×4.729 = 2.2207 kW , the actual heat input into the flat-plate panel

using a variation of Eqn. 4: $Q_{i,\,act}$ = ταQ_i = 0.95×0.96×2.2207 = 2.0253 kW From Eqn. 5, the heat lost by the collector to the surroundings: Q_o =U_LA (T_c - T_a) = 6.7795×4.729(50-25) = 801.5 kW Using energy

$$\dot{m}C_P(T_o - T_i) = Q_i - Q_o$$

balance and Eqn. 8, and assuming that F_R=1: $\dot{m} = \frac{Q_i - Q_o}{C_P(T_o - T_i)} = \frac{1000}{4.188(32-28)} = \mathbf{0.0597\,kg/s = 3.582\,l/min}$

Therefore, in order to raise the temperature of water by 4 °C after every cycle, the HTF will have to flow at 2.3 l/min. The useful energy gained per second from the flat-plate collector: $Q_u = \dot{m}\,(T_o - T_i)$ = 0.0597 × 4.188 × 4 =1.0 KW

The efficiency of the collector: $\eta = \frac{Q_u}{AI} = \frac{1000}{2220.7} = 0.450 = \mathbf{45\%}$

A design with the lowest pressure drop is considered because after calculations because this system is naturally driven by the thermosyphon concept therefore low-pressure drop is necessary for easy circulation. The design chosen is the meander or snake design. From the CIBSE Guide C, [21] , for panel return bend k = 0.6 and also for flow of water at 75°C in copper pipes, for mass flow rate m =0.0597kg/s and diameter d = 15mm, equivalent length L_e is 0.4m and pressure drop per unit length $\Delta p/l$ is 178 Pa/m. Straight pipe 2.32(9) = 20.88 m Collector suction pipe = 0.05 m Collector discharge pipe = 0.05 m Panel return bend = 0.6 x 8 x 0.4 = 1.92 m Total equivalent length of straight pipe = 20.88 + 0.05 + 0.05 + 1.92 = 22.9m PRESSURE DROP Pressure drop = $\Delta p/l$ x l. Total pressure drop = 178 x 22.9 = 4076.2 Pa. The glass were chosen as per mechanical properties [23] with Density: 2500 kg/m³ ,Hardness: 470 HK, Compression resistance: 800 - 1000 MPa and Specific Heat: 0.8 J/g/K, Thermal conductivity: 0.8W/mK, Thermal expansion: 9.10-6 K-1, Emissivity coefficient: 0.92 - 0.94 [24]. The main characteristics of glass are transparency, heat resistance, pressure and breakage resistance and chemical resistance. The [fig.5] below shows the experimental testing set-up.

Fig. 5: Experimental testing set-up

RESULTS AND DISCUSSION

An open place (without shade) was chosen for the experiment. The true North direction was determined & then the SWH was fixed properly on mild steel stand supports facing the North direction while making an angle of 43 degrees with the ground for the first trial and 24 degrees for the second trial. The flow connections were made proper and the outlet and inlet temperature was measured at regular intervals of time. Major testing was done on 2 days, 30th April and May 1st. The first test was carried out with the tilt angle being 43°. On the 30th of April, the testing was ran twice, in the morning between 0930h-1230h and in the afternoon between 1500h-1600h. Temperature was recorded over a period of 3hours using 10 minute's interval. The graph 1 plots suggest that with a batch feed of water to the solar water heater, the temperature of water goes on increasing with time until a saturation level, after which there is no significant change in the outlet temperature. The maximum temperature recorded was 99 °C at which the time was 1230pm. From [Fig.6]. It can also be observed that the temperature gain increased with time and reached higher values of 74.9 °C at which the time was 1340 hours. And afterwards the temperature gain decreased as the inlet temperature increased. The temperature gain was steady for 60minutes and decreased with time. So, the efficiency of the solar water heater is maximum within the 60minutes and then later efficiency degrades.

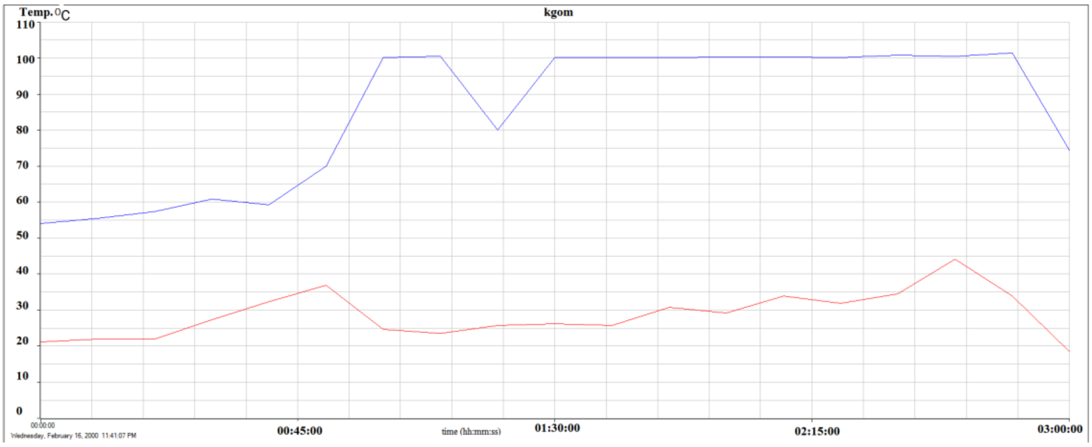

Fig. 6: Temperature-time graph for inlet (bottom) and outlet (top) flow 0930h-1230h on the 30th April

The same procedure was applied in the 2nd trial. The graph [Fig.7] shows high temperatures at the start of the session were recorded for the first 6 minutes reaching high temperatures of 97.6 °C after 4 minutes. The inlet and outlet temperature then became constant for the next 32 minutes with temperatures ranging between 48.2 °C and 51.8 °C as shown on the graph. The reason for this can be the low intensity of sun's rays in the late afternoon. So as the ambient temperature falls by a couple of degrees after 3:30 p m it must have affected the solar water heating equipment.

Another test [Table 1] was carried out on the 1st of May from 1030h-1230h with a few improvements made. These include lowering of the tilt angel angle to 24° to match the geographical latitude of Gaborone, Botswana. At this angle, more incident radiation perpendicular to the Sun will be received by the collector.

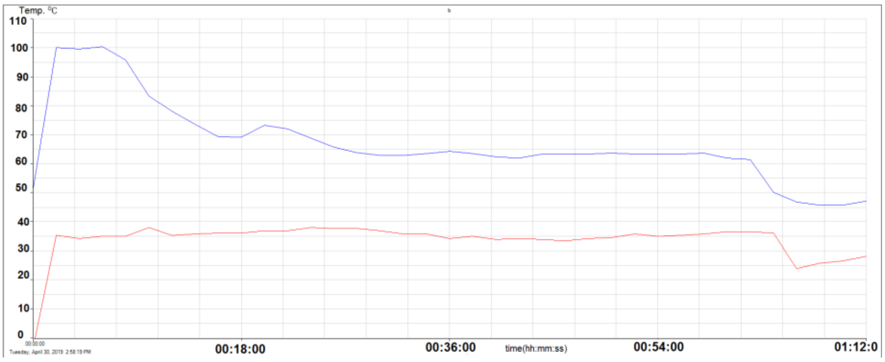

Fig .7: Temperature-time graph for inlet (bottom) and outlet (bottom) 1500h-1600h on the 30th April

Table 1: Results for 1st May from 1030h-1230h

Time (s)	Temperature (°C)			Solar Irradiance (W/m2)
	Inlet, Ti	Outlet, To	Gain, ΔT	
0	22	47.0	25.0	720
600	37	40.6	3.6	720
1200	36	39.3	3.3	734
1800	32	56.9	24.9	750
2400	36	63.5	27.5	734
3000	33	63.6	30.6	752
3600	32	36.4	4.4	734
4200	35	50.6	15.6	745
4800	36	59.6	23.6	736
5400	38	100.4	62.4	746
6000	36	99.5	63.5	761
6600	35	61.6	26.6	753
7200	35	68.6	33.6	757

Table 1 is arranged in intervals of 10 minutes. The overheating phenomenon of the solar collector at the beginning of the experiment was excluded by circulating the water until outlet water was at a similar temperature to inlet. Lowest T_i and T_o were 33 °C and 36.4 °C, respectively. Lowest ΔT was where T_i is approximately equal to T_o. Since solar intensity is almost same throughout the session, inlet temperatures are almost equal with different out temperature which is shown in the graph [Fig.8]. After 90 minutes the solar collector reached its peak recording temperatures of 38 °C and 100.4 °C for the inlet and outlet respectively.

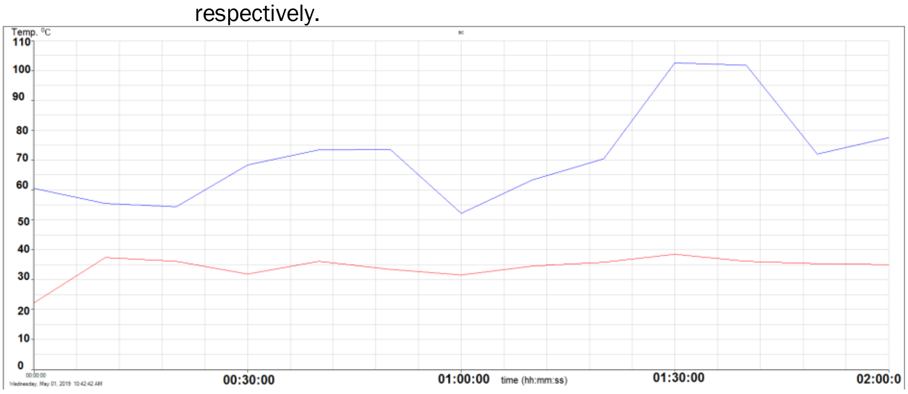

Fig. 8: Temperature-time graph for inlet (bottom) and outlet (top) for the 1st of May 1030h-1230h

Therefore the Heat input due to local irradiance: $Q_i = 820W/m^2 \times (1.8 \times 1.2m^2) = 1771.2W$

20 liters of water was used during testing. For the 0930-1230h on the 30th April, the test ran for 170 minutes which is equivalent to 10200s. Using the density of water of 1g/cm³, then 20 liters of water is

20,000cm³ which is equivalent to 20,000g or 20kg. The 20kg of water flew over 10,200s, therefore mass flow rate was: $\dot{m} = \frac{m}{t} = \frac{20kg}{10,200s} = 0.00196kg/s$ $Q_u = 0.00196kg/s \times 4.187kJ/kgK \times 71.5K = 0.587kW$

Efficiency =

$$\frac{\text{Heat input due to thermodynamic}}{\text{Heat input due to irradince}} \frac{587W}{1771\,W} = 33.1\%$$

CONCLUSION

An energy balance is based on measurement and calculation of input and output and the losses. This provides a true picture of the system performance and the opportunity to make changes for improvement. Energy balances should be developed for each process in order to define in detail the energy input, the amount of raw materials and utilities required, the amount of energy consumed in waste disposal, the amount of energy credit for byproducts, the amount of energy charged to the product and the amount of energy dissipated or wasted. The design and fabrication of the prototype solar collector for powering a 1kW solar thermal water heating system was achieved through analysis based on experimental study. The solar collector was designed and fabricated with materials that were readily available from the school workshops and affordable in builders hardware but to conforming to standards. Conversion of the abundant primary solar energy from the sun to other useable energy sources contribute to an increase in the variety of clean energy technology mixes. Solar energy input in one form to a system will produce an output in another form and the desired work performed. However there will be energy losses in different forms to achieve the required output. The flat plate solar collector was tested for performance and efficiency using local irradiance and thermodynamic properties of the heat transfer fluid being water. The efficiency of the solar collector was 33.1% which shows the good performance of the arrangement. Further studies can also be initiated using concentrated & other solar collection techniques but for the domestic use the cost should be relatively less.

CONFLICT OF INTEREST

None

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FINANCIAL DISCLOSURE

None

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