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Construction of a High Temperature (~ 200 °C) Oil Pump for Solar Thermal Energy Storage System for Cooking Applications

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Abstract

In this study, a positive displacement (PD) oil pump capable of operating at temperatures about 200 °C was constructed using locally available materials. The oil pump was tested to circulate pre-heated refined sunflower oil in Thermal Energy Storage (TES) tank comprising of an oil only and rock pebble-oil system and cooking application. The oil pump was constructed of harden steel and mild steel materials driven by AC/DC electric motor rated 8000 rpm. Standard gear teeth cutting tool was employed to produce the spurs and the pumps' speed was varied using variable AC transformer connected to 220V AC main source. The performance of the pump was evaluated for maximum temperature during charging oil tank where the pump circulated hot oil through it and a temperature of about ~ 215 °C was achieved. In addition, when the oil pump was used to charge 5.5 litres of refined sunflower oil in TES tank by heat extraction through a boiler, an average temperature profile of 190 °C was achieved in 3 hours compared to the 74 °C attained by thermosiphoning in 6 hours of charging in the studies done by Mawire (2009). In addition, the TES cooking application fabricated demonstrated cooking of local foods such as bean and rice with a comparable cooking time. It was observed that the integration of the TES system with high temperature pump improved the performance of TES charging efficiency.

Keywords: High temperature, positive displacement pump, hard steel, heat extraction

Introduction

Effective utilization of solar energy around the World demands for indirect solar cookers that use Thermal Energy Storage (TES) systems for domestic cooking applications. This technology that uses oil as heat transfer fluid requires an oil pump that operates at high temperatures. Refined sunflower oil has good thermo-physical characteristics for high temperature applications (Okello et al. 2016).

One-third of the world's population burns organic materials such as wood, dung and charcoal for domestic and industrial cooking (Okello et al. 2014). Industrialized countries in the world are trying to reduce their carbon dioxide emissions by taking on renewable energy resources as part of their future strategy for a sustainable energy supply (Gullberg et al. 2014). Sustainable energy is crucial to virtually every aspect of the economy and social development. In most developing countries, providing affordable, adequate, reliable, and clean energy is a drive for a rapid growth (Birol 2010).

Uganda, a country in East Africa is blessed with an enormous solar energy with average daily sunshine hours of at least 8 hours and solar irradiance of about 5–6 kWm^{-2} (Biira and Geoffrey 2014) but still, it is unfortunate that, about 94% of the population depends on wood fuel for most domestic and industrial cooking (UBOS 2016). The use of solar energy for cooking would reduce deforestation and global warming (Prasanna and Umanand 2011). Solar energy has a lot of potential for the domestic and industrial cooking, lighting homes and in agriculture, but solar energy is intermittent, unpredictable, and only available during the day (Mussard 2013, Sedighi and Zakariapour 2014).

There are a number of solar cookers available in the markets which are categorized as direct solar cookers with maximum achievable temperature of 100 °C and the indirect solar cookers with a temperature potential of about 300 °C with TES integration (Sedighi and Zakariapour 2014). Most of the solar cookers available in the market are not capable of storing thermal energy (Kumaresan et al. 2016). Okello et al. (2016) and Chow (2010), recommended for the development of indirect solar cookers with TES system to contribute towards meeting energy demand for most cooking.

The potential heat transfer fluids (HTF) in TES system include; water, oil and air. Water is readily available and cheap but it needs a pressurizer for higher temperature applications above 100 °C; this makes water expensive and risky for rural applications. However, air has low thermal specific heat capacity compared to that of oil and sunflower oil is the most suitable heat transfer oil (Mawire and Taole 2014).

The use of oil as heat transfer medium indirect solar cookers demands for oil pump capable of operation at high temperatures preferable ≈ 200 °C to circulate the pre-heated oil in both the TES system and the cooking unit during heat extraction and thermal charging. The integration of pump in solar TES system will make solar cookers acceptable by many people therefore, making domestic cooking healthier with a smoky free kitchen and reduced use of wood fuel (Perez-padill and Schilmann 2011). This is in line with the United Nation goals for development of sustainable energy as reported by the United Nations (United Nations 2006, Birol 2010).

A pump is general machinery with varied technological applications that transfer fluid and slurry by mechanical action mainly driven by AC/DC electric motors as reported by Wang et al. (2017). Most of the available pumps in the markets operate best at low temperatures below 120 °C (Bertsch 2016) which are not suitable for high temperature applications suitable for most cooking. The aim of this study was to develop a pump capable of operating at high temperatures for indirect solar cookers as an alternative source of clean and sustainable energy for cooking.

Materials and Methods

The gear pump design

A Positive Displacement (PD) gear pump design shown in Figure 1 was modified from M-54D pump rated 10 psi (0.69 bars) oil pressure per every 1,000 rpm with a volumetric discharge of about 6 litres per minute was modified and constructed using local materials. The modification included re-sizing of dimensions and selecting appropriate materials for high temperature operation, and reducing number of teeth to eight (8). The pump consists of two spurs (driver and driven gear) each of the same dimensions and pump creates a partial vacuum as the gear teeth separate leading a discharge of a controlled volume of oil. This gear pumps is advantageous compared to other pump because it is self-lubricating, self-priming with high discharge pressure. In addition, the pump's costs of construction and maintenance are reasonably low due to few parts. Standard involute profile cutting machine whose profile angle is known was used produce the pump gears rotors and parts were assembled. Most of the internal parts were produced using hardened steel.

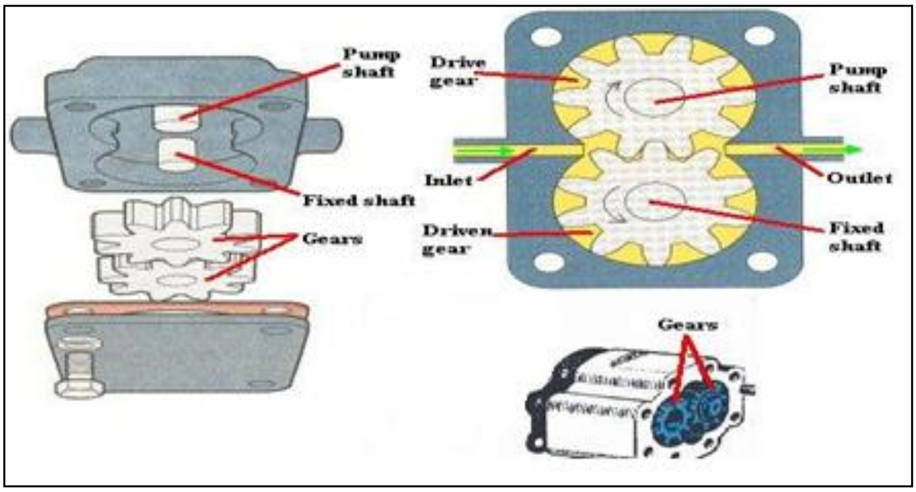

Figure 1: Geometrical design of the positive displacement oil pump.

Positive displacement gear pump construction procedure

The standard gear pump equations were used to calculate the gear pump parameters as cited by Saleem (2009) and Egbe (2013) and the results were then summarized in Table 1 as shown. The diametric gear pitch is given by the expression

$$P_d = {}^{n}/_{d} \quad (1)$$

The circular gear pitch is calculated from the expression

$$P_c = {}^{\pi D}/_{n} = {}^{\pi}/_{P_d} \quad (2)$$

The gear addendum, a and dedendum, d, respectively are given by the expressions

$$a = \frac{1}{P_d} = \frac{P_c}{\pi}, \qquad d = \frac{1.25}{P_d} \quad (3)$$

The pitch clearance, $C = \frac{0.25}{P_d}$, and D is the circular pitch diameter of the gear. According to Egbe (2013) and Ghionea et al. (2013) recommendations, the working depth should be $2/\mathrm{Pd}$ for good gear pump operation.

The outside diameter, d_o and whole depth, W_d of gear system are calculated from equations 4 and 5 (Laczik et al. 2014).

$$d_o = D + 2a = D + \frac{2}{P_d} = \frac{D(n+2)}{n} \quad (4)$$

$$W_d = a + d = \frac{2.25}{P_d} = \frac{2.25D}{n} \quad (5)$$

According to Liping et al. (2011), the volume of the fluid displaced per revolution is equal to the volume of the trapped within the space of the gear teeth and housing. The trapped volume of oil for displacement is given by;

$$V_p = \frac{\pi({r_a}^2 - {r_d}^2)b}{2} \quad (6)$$

where, r_a and r_d are the addendum and dedendum radii, respectively, b is gear face width, but the addendum and dedendum radii of a gear geometry is related by Equation 7 and Equation 8 (Pawar 2015, Zhao and Vacca 2017).

$$r_a = \frac{D}{2} + a = \frac{D(n+2)}{2n} \quad (7)$$

$$r_d = \frac{D}{2} - d = \frac{D(n-2.5)}{2n} \quad (8)$$

Combining Equations 7 and 8 results into

$$V_p = \frac{\pi(bD^2)(9n-2.35)}{8n^2} \quad (9)$$

Figure 2 shows the gear pump parts fabricated using local materials.

Table 1: Summary data extracted for construction of the gear wheels (driver and driven wheel)

Parameter	Symbol	Specification	Unit
No. of teeth	n	08	Teeth
Pitch	P	14.3	mm
Pressure angle	$\emptyset$	20	degree
Pitch diameter	PD	22.4	mm
Diametral pitch	D_p	0.36	mm^{-1}
Addendum	a	2.78	mm
Dedendum	d	3.47	mm
Circular pitch distance	C_p	8.80	mm
Pitch clearance	C	0.69	mm
Gear width	B	7.0	mm
Outside diameter	Do	28.0	mm
Whole depth	W_d		mm
Area enclosed	A	4.91×10^{-5}	m^2
Vol. displacement	V	4.14×10^{4}	m^3/min

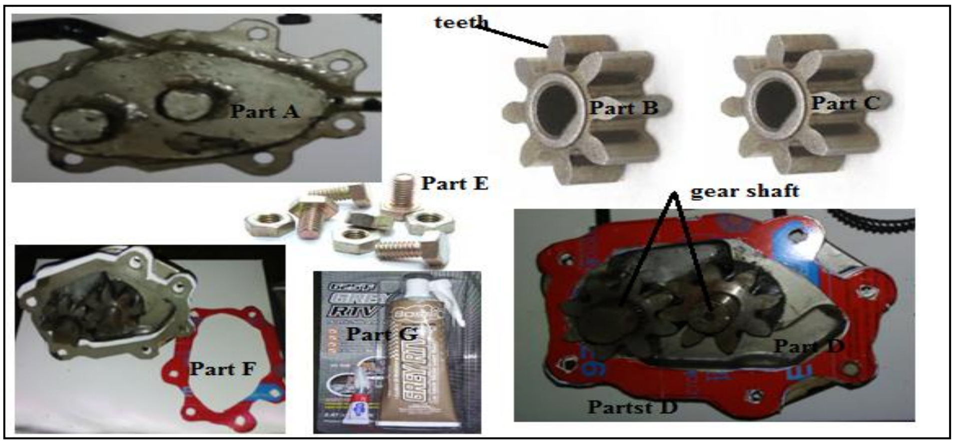

Figure 2: Gear pump parts fabricated using local materials.

Two pieces of 12 mm diameter fixed shaft rods made of mild steel were used to mount gears parts B and C firmly as shown in part D on one side of the pump casing and the other connected to a pulley since the pump was designed to be driven by an external belt- motor system whose speed was varied using a variable AC transformer (0 – 250 V).

The pump's parts were enclosed and highly compacted to give a better look and structures for periodic maintenance and to keep it trouble free. Most of the parts of the constructed pump can easily be dismantled using the right tools for easy servicing and the parts were carefully assembled as shown in Figure 3.

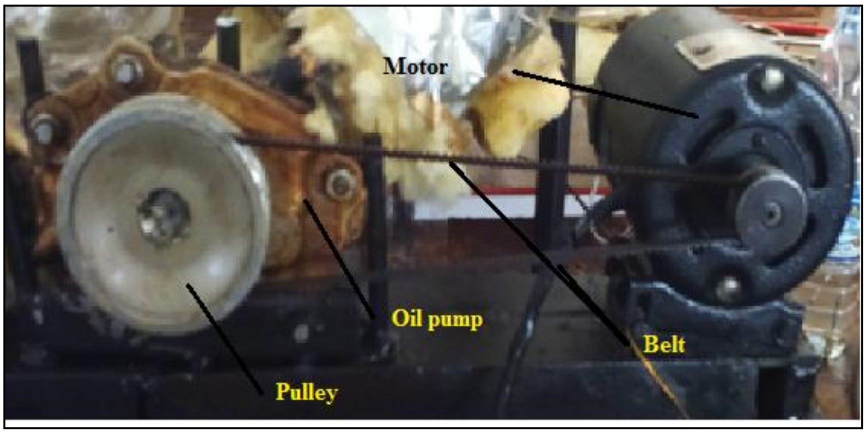

Figure 3: Assembled oil pump driven by an AC/DC electric motor.

An electric heater rated 1.5 kW connected to 230 V, AC power source was fitted and inserted into an oil TES tank containing 5.5 litres of sunflower oil whose smoke point is 235 °C (Esteban 2012) as shown in Figure 4. Thermocouples tips were inserted at different depth levels to record the temperature profile of the TES tank automatically using a TC-08 data logger interfaced with a computer during the charging process. The tips of three k-type thermocouples were arranged at 40 mm marked points from the top to the bottom of the TES storage tank. The tank was highly insulated using 30 mm thickness of glass wool as shown in Figure 5 B to minimize heat loss by radiation and conduction. Figure 4 is the schematic diagram for the test procedure whereby pre-heated oil is circulated by the oil pump for 3–4 hours in the loop.

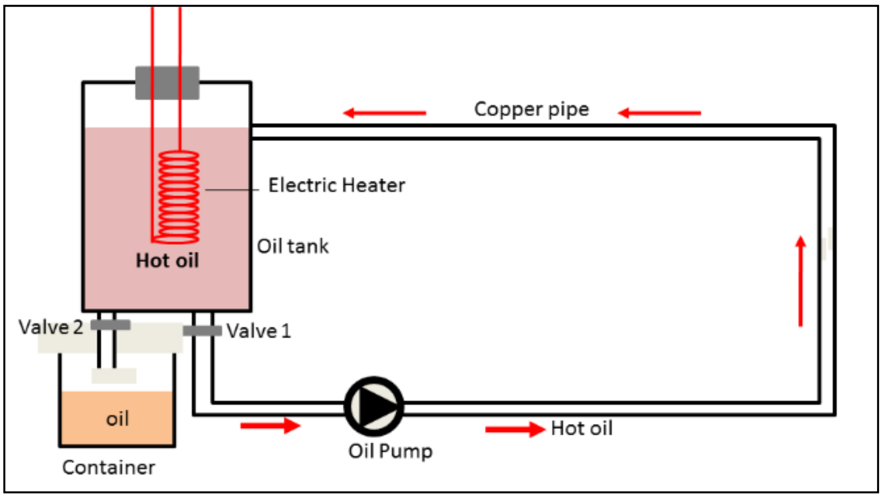

Figure 4: Schematic diagram to test maximum operating temperature of the pump: Performance of the pump for maximum operational temperature.

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The Figure 5 shows the TES tank constructed using a mild steel material of external diameter 200 mm and height of 250 mm with a provision on the lid to insert the heater.

An open cylindrical heat extraction zone (boiler) of internal diameter of 195 mm and height of 150 mm was fabricated of mild steel with holes on either side for inserting a copper pipe of diameter, 9 mm to pass through the heat extraction zone to join the hybrid TES tank via the oil pump on either side as shown in Figure 6. The experiment for testing the performance of the oil pump during charging of hybrid TES tank is shown in Figure 7.

Figure 5: Hybrid TES tank constructed using mild steel material and coated with aluminium paint.

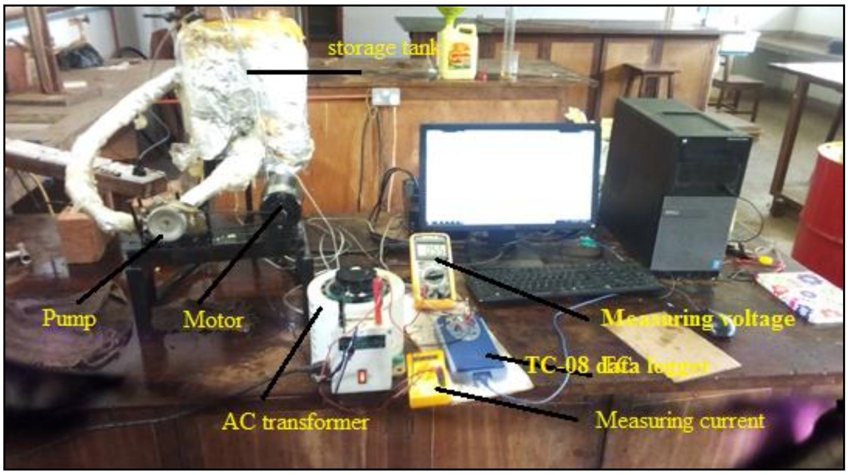

Figure 6: Experiment setup to determine the maximum operation temperature profile of the pump.

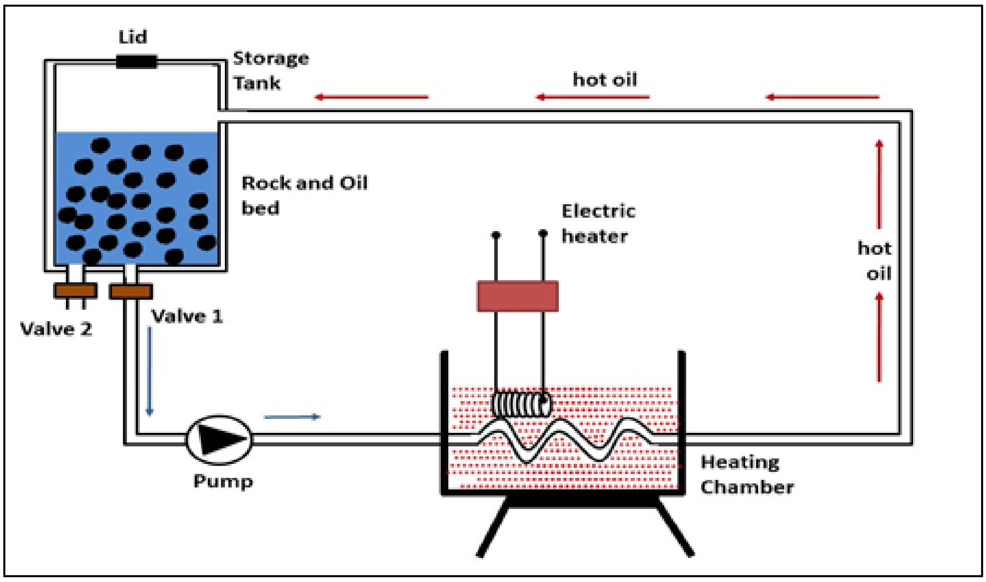

Figure 7: Schematic diagram for hybrid heat extraction pump experimental test: Performance of the oil pump during charging of hybrid TES tank.

The length of the heat extraction zone was 240 mm whose thermal heat absorption potential was varied by changing the speed of the oil pump circulated in the energy loop as in Figure 8.

The 1.5 kW electric heat was switched on and the pump was also started after 5 minutes of heating by the AC motor at voltage of 100 V to run with a constant speed for 30 minutes and then voltage varied from 100 V to 160 V using the variable transformer for a fast mixing in the TES tank as shown in Figure 9. The experiment was allowed to run in state for 3 hours without interaction. Meanwhile the temperature of oil in the boiler was manually maintained at 220 °C by switching off and on the heater with respect to the smoke point of the sunflower oil (235 °C). The temperatures were monitored and recorded using k-type thermocouples inserted in the TES tank and heat extraction zone (boiler) via TC-08 data logger interfaced with a computer. The data was collected in Excel sheet, sorted, and analyzed using MatLab programme. The pump was driven by a DC motor of 8000 rpm whose speed was varied using a variable transformer and multimeters were used to motor the voltage and current readings as shown in Figure 9.

Figure 8: The speed control component of the system to vary the speed of the oil pump.

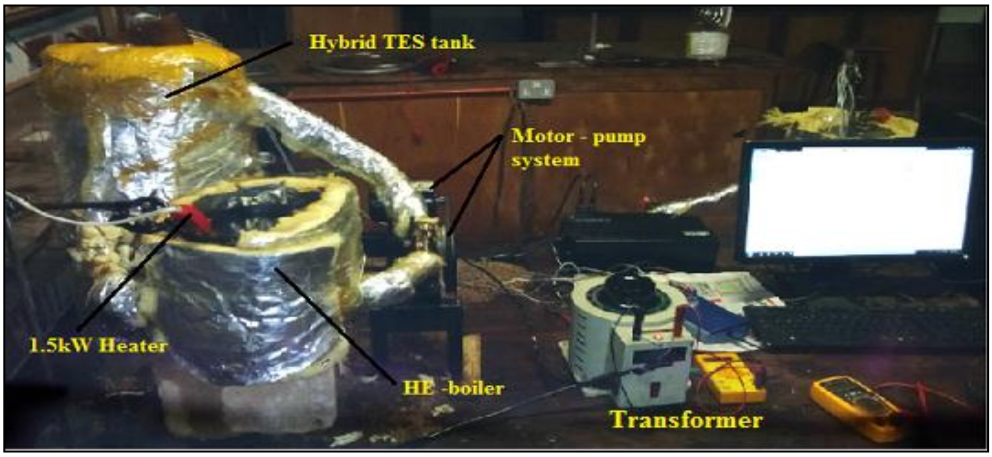

Figure 9: Setup to evaluate the performance of the pump in charging hybrid tank by heat extraction.

Results and Discussions

The performance of the pump at high temperatures

A 1.5 kW electric heater was used to heat 7.5 litres of oil in the tank using the set up in Figure 6 when the AC variable transformer was set at 100 V. The oil was heated for 3 hours and temperatures were recorded using thermocouples inserted into the tank. The pump was used to circulate the oil in the system.

Figure 10a shows the temperature profile obtained during the heating of oil in the tank. The oil was circulated using the pump as shown in Figures 4 and 6. During the first 40 minutes of heating and circulating oil by the pump, there was a rapid rise in the temperature of the oil in the tank up to an average of about 200 °C. Thereafter, the temperatures were maintained around 200 °C for further 40 minutes. The observed temperature spikes and peaks after 40 minutes are as a result of switching off and on the electric heater not to exceed the smoke point of sunflower oil used in the tank. Oil was observed to leak through the shaft point and around the bolts during the experiment which may be due to challenges in fabrications and machining of the pump.

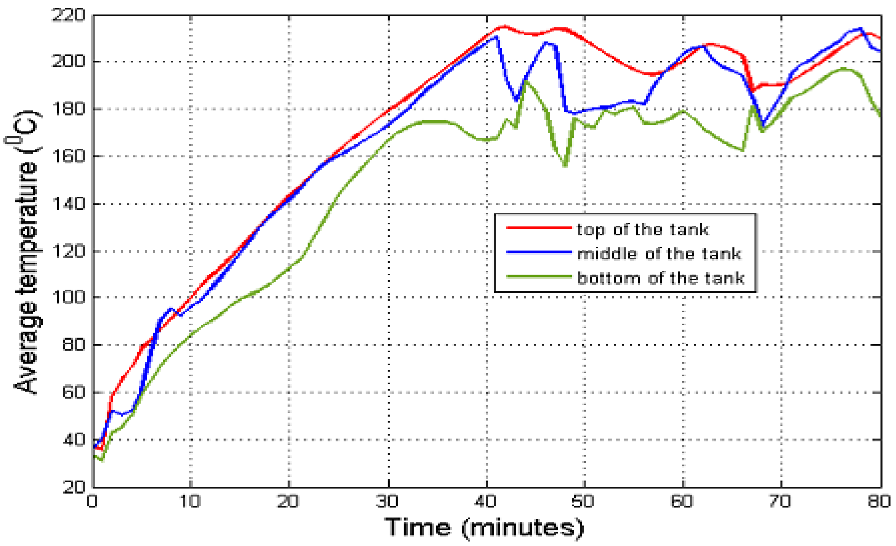

Figure 10a: Shows the temperature profile in the tank during heating of the Sunflower oil for 80 minutes. The pump was used to circulate the oil.

The average temperature at the bottom of the tank was about 180 °C. Ideally, the hot oil circulated through the pump was at high temperature of around 180 °C for a period of 1 hour as oil was circulated from the bottom of the tank to the top of the tank. In general, the temperature of the oil through the pump can be assumed to be the temperature at the bottom of the tank and the pump constructed was able to circulate hot oil at an average temperature of above 180 °C in the system for1 hour of the test period.

The motor used to drive the pump was heating up and therefore, the pump and heating was stopped for about 30 minutes but these had nothing to do with the pump except the motor which needed to be cooled. The heating element and the pump were switched on thereafter.

Figure 10b presents the temperature profile of the oil tank when heating was resumed at the 90th minutes. For the first 30 minutes the temperatures were nearly constant and smooth because there was no heating and no circulation of oil during this period.

The temperature of the oil tank was maintained around 220 °C by manual switching off and on the electric heater in order not to exceed the smoke point of the sunflower oil. The observed temperature spikes and peaks are more pronounced at the upper parts of the oil tank recorded by thermocouples placed at the top and middle of the tank with some abnormal peaks. This is mainly attributed to the position of the heating element being around the top of the tank.

In general, the temperature trend in Figure 10b shows that the oil circulated by the pump was at high temperatures up to around 220 °C in the tank in a period of about 3 hours of heating.

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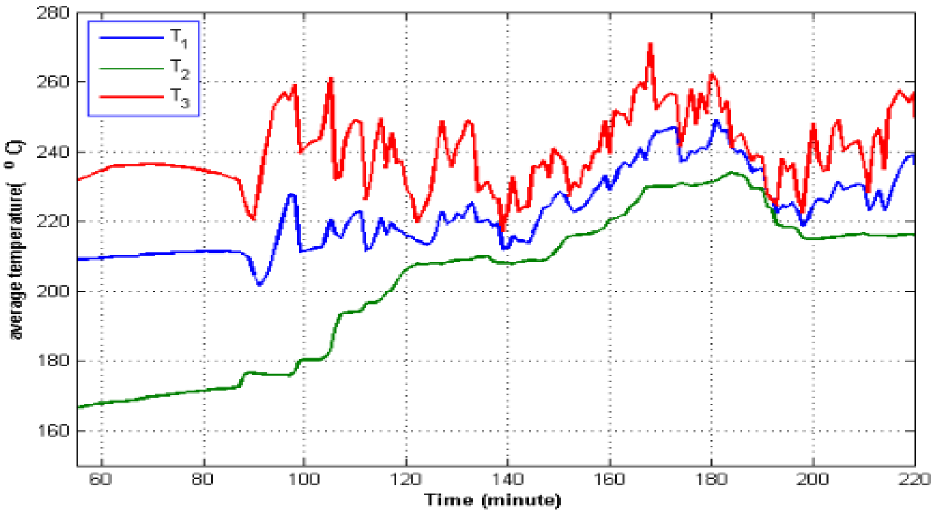

Figure 10b: The temperature profile of the tank during heating of an oil tank for a period of about 2.5 hours and the oil circulated using a pump. The temperatures T_1, T_2 and T_3 represent temperatures at middle, bottom and top of the oil tank.

Performance of the pump in charging the hybrid TES system

A thermocouple was placed in the boiler to record the temperature profile every minute as shown in the schematic diagram presented in Figure 9. Sunflower oil in the boiler was heated and the pump was used to circulate the oil from the hybrid storage through the boiler using copper tube. The process was carried out for 3.5 hours. The AC variable transformer was adjusted to a voltage of 140 V across the motor to increase the pump in order to overcome viscous drag due to the presence of the rock pebbles.

Figure 10c shows the temperature profile of the composite TES tank after charging the tank for 3.5 hours. The temperature increased to about 65 °C after 1 hour of charging. As the charging progressed for about 0.5 hours, a temperature of up to 80 °C was recorded as oil was circulated by pump through the boiler. In addition, there was a small temperature difference between the three thermocouples recordings in the first 2 hours.

However, after 2.5 hours of charging the storage tank, the variable AC transformer was adjusted to 90 V to reduce the speed of the pump to give maximum time for heat extraction by the oil being circulated through the boiler. A rapid rise in the temperature was observed up to about 120 °C in period of 30 minutes. However, at this flow rate, the temperatures increased rapidly with the tank attaining an average temperature of about 180 °C. The rapid increase in the temperature profiles was probably attributed to the lower flow rate allowing for maximum heat exchange both in the boiler and in the tank.

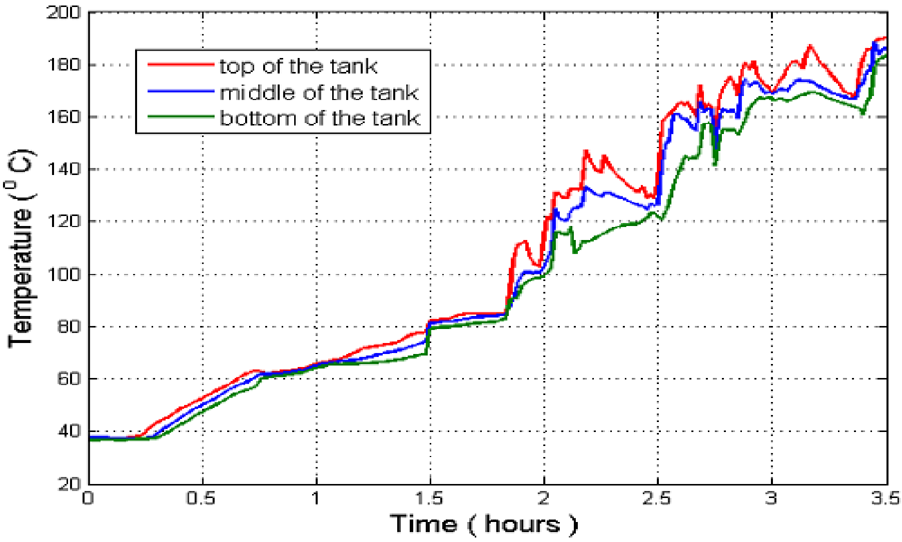

Figure 10c: Shows the temperature profile of the composite TES tank during charging. Heated oil was circulated using the pump for about 3.5 hours.

The average temperatures at the top, middle and bottom of the TES tank system recorded after 3.5 hours of charging were 190 °C, 180 °C, and 170 °C, respectively. The temperatures recorded in the hybrid TES tank are sufficient for most domestic cooking applications. The observed peaks were due to the manual switching on and off of the heater as shown in Figure 10d. In general, after 3 hours of charging, the pump was still able to circulate oil at high temperatures of about 180 °C for a period of 1 hour. Although there were oil leakages observed clearly showing that the pump was able to operate at high temperatures. Further still, the pump was able to circulate hot oil through the storage tank consisting of rock pebbles overcoming the viscous drag.

Figure 11 shows the estimated volumetric flow rate (discharge, Q) of the pump obtained using the data obtained from Table 2. From the graph, the volumetric flow increased as the speed of the pump also increased although at high speeds it was observed that the flow rate slightly decreased. This agrees with the theory of positive displacement external gear pumps since the gradient of the flow rate is positive as observed by Wang et al. (2017) during simulation of flow rate for PD pumps and the volumetric flow pattern obtained for burnt oil according to Dipen (2015).

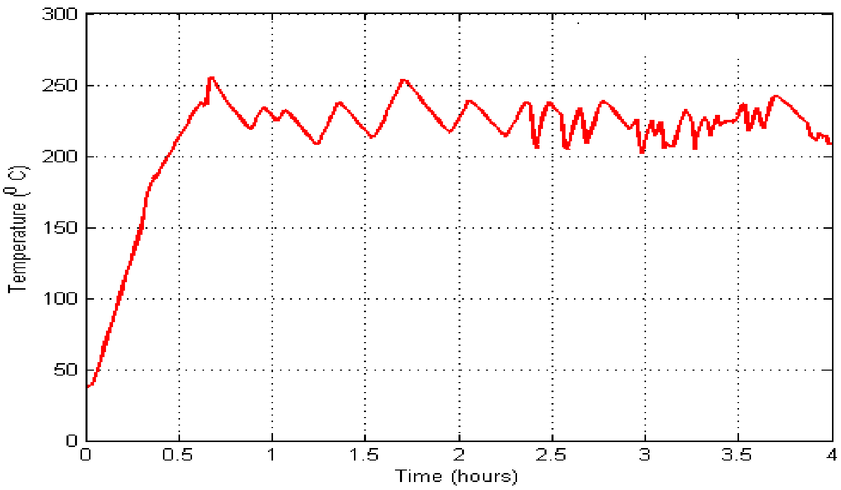

Figure 10d: The temperature profile of the boiler maintained by manually switching off and on the heater.

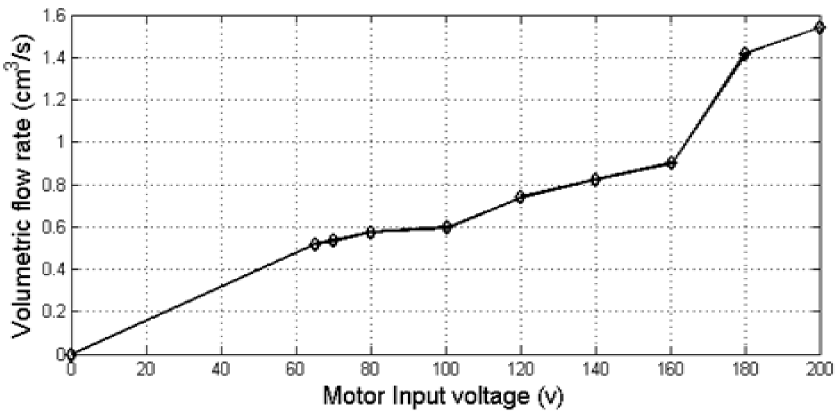

Figure 11: Volumetric flow rate and efficiency of the oil pump: The estimated volumetric flow rate of the pump generated using the data provided in Table 2.

The graph shows that the speed of the pump is directly proportional to the theoretical volumetric flow rate. However, after 4000 rpm, there was a light decrease in the volumetric flow attributed to the turbulent oil flow because the mechanical advantage of a pump decreases at high speed (Dipen 2015). In general, Figure 11 agrees with Figure 12, the volumetric flow rates of the pump at various rpm of the motor show clearly that the discharge increases as the motor speed increases as was demonstrated by varying the AC variable transformer. This result is in line with the theoretical discharge of an external gear pump which indicates that volumetric flow is directly proportional to the speed of the pump which agrees with Dipen (2015) using burnt oil, which had a positive gradient.

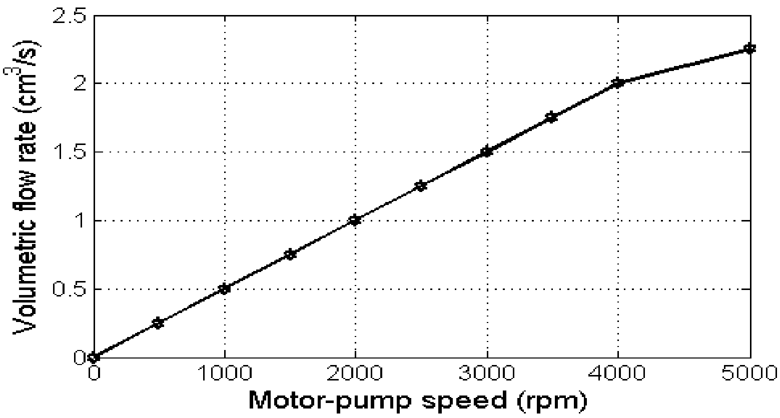

Figure 12: The MIT (2017) interactive gear pump interface was used to generate the graph.

Table 2: The results of the pump's volumetric displacement test

Voltage (V)	Current (A)	Volume (cm^3)	Time (s)	Q (cm^3/s)
65.5	0.55	185	236.0	0.78
70.0	0.65	185	224.0	0.83
80.2	0.68	185	201.0	0.92
100.4	0.76	185	181.0	1.02
120.2	0.87	185	170.0	1.09
140.1	0.99	185	145.0	1.28
160.7	1.08	185	125.0	1.48
180.2	1.12	185	90.0	2.05
200.0	1.21	185	80.0	2.31

Figure 13 shows the efficiency of pump generated using the gear pump interactive interface by MIT (2017). The pump specification parameters such as the numbers of teeth, profile involute angle and pitch diameter were entered in the interface.

The motor speed specification was also considered. In general, it is observed from the efficiency graph that the efficiency of the pump increased rapidly up to nearly about 100 percent speed at around 500 rpm; however, the efficiency remains nearly constant for further increase in the speed of the pump-motor system attributed to friction, noise, and weight of the moving parts as reported by Bilyeu (2006) and Dipen (2015).

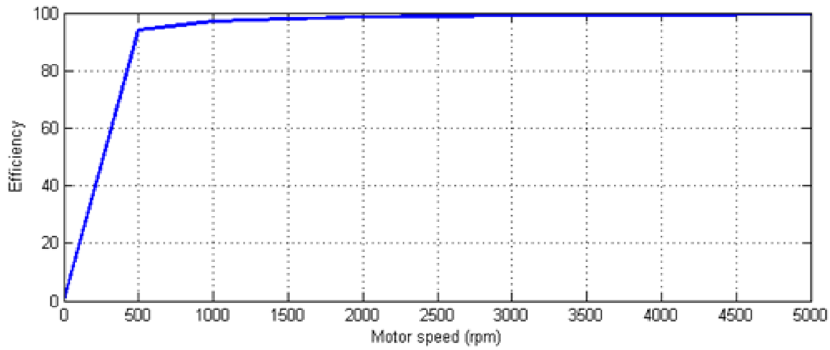

Figure 13: The efficiency of the oil pump evaluated with speed of the AC motor.

Conclusions

A pump capable of operating at high temperatures has been constructed using locally available materials. The suitability for high temperature operations of about the requirement for the TES system (~200 °C) was tested. The materials selected for the construction of the oil pump withstood high oil temperature up to about 230 °C during the test period. Furthermore, the pump constructed was able to circulate oil through a boiler and charge a hybrid TES tank consisting oil and pebbles to significant temperature of 190 °C in 3 hours. The TES cooking application has been constructed and demonstrated to show effective cooking of local foods such as beans and rice as compared to cooking time for improved stoves.

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