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Experimental investigation of a cooking unit integrated with thermal energy storage system

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ABSTRACT

The thermal performance of a newly developed cooking unit integrated with a thermal energy storage (TES) system suitable for solar thermal applications has been tested and analysed. The experimental set-up consisted of a TES tank, connecting pipes, a manual control valve and a cooking unit. Sun flower oil was used as both the heat storage material and heat transfer fluid. The heat transfer was such that hot oil flowed by gravity from the TES tank through a pipe to the bottom of the cooking unit, which was in contact with the oil. The flow of the oil was controlled by a manual valve fixed on the connecting pipe to the cooker unit. Cooking experiments were carried out by boiling known quantities of water and food items at different flow rate settings. The results showed that the heating rate increased with increasing flow rates, and the efficiencies of the cooking unit were obtained as 40%, 43% and 52% for flow rates settings of 4 ml/s, 6 ml/s and 12 ml/s respectively. The rate of heat loss in the cooking unit was determined, and the overall heat loss coefficient was found to be about 0.54 W/K. Energy balances were used to estimate the heat transfer coefficients between the hot oil and the water in the cooking pot at different flow rates. The results showed that a high flow rate setting of 12 ml/s gave the highest heat transfer rate while a very low flow rate setting of 4 ml/s reduced the heat transfer rate, but also retained heat for longer periods. The heat transfer rate was found to be on the average 120 W/m^2K. The manual valve makes it possible to control the heating rate and adjust the flow rate to suit the needs of a particular food. With a well-insulated cooker, a very low flow rate can be used for foods that require longer cooking times.

1. Introduction

Energy for cooking takes up more than 50% of the total household energy consumption on the African continent [1]. Around 94% of the rural and 73% of the urban households are dependent on wood fuels for their cooking energy needs [2]. According to a report from the Uganda Bureau of Statistics, about (90%) of households use wood fuel with 80% of rural households using firewood and 70% of urban households using charcoal [3]. However, the over dependence on biomass is a threat to the forest reserves and has resulted into negative environmental effects like climate change, limited control of floods, influencing rainfall patterns, less absorption of pollutants and effects on other ecosystem services [4]. Furthermore, the prolonged and inefficient use of wood fuels exposes the population to indoor air pollution that is linked to health issues like cancer, tuberculosis, and low birth weight among others [5]. Fortunately, Uganda is endowed with an abundant solar energy resource throughout the year. Existing solar data indicate a solar insolation of about (5–6) $kWhm^{-2}$ per day and an average of 6 sunshine hours [6].

Solar cooking is considered as one of the simplest, most viable and attractive options in terms of utilization of solar energy [7]. Solar cookers can provide a clean, alternative method for cooking in developing countries. Solar cookers are classified into direct and indirect solar cookers. In direct solar cookers, solar radiation is used directly in the cooking process and is mainly box type and concentrating type. Box type cookers are popular since they are easy to handle and operate, do not require tracking of the sun and are relatively cheap as compared to other types of solar cookers. However, the disadvantage of solar box cookers is their slow cooking process due to low temperatures and cooking time being limited to sunny periods of the day. Concentrating type solar cookers work with one or two axis tracking and can achieve higher temperatures of up to about 300 °C [8], but they have a challenge with requiring tracking of the sun, are not portable due to their big size and are relatively expensive. Indirect solar cookers use a heat transfer fluid

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Nomenclature

HTF	Heat Transfer Fluid
LHS	Latent Heat Storage
PCM	Phase Change Material
SHS	Sensible Heat Storage
SHSM	Sensible Heat Storage Materials
TES	Thermal Energy Storage
HTES	Heat Thermal Energy Storage
LMTD	Logarithmic Mean Temperature Difference
U_{loss}	Overall heat loss coefficient (W/m^2K)
h	Heat transfer coefficient (W/m^2K)
Q_{loss}	Heat loss (W)
$\dot{V}_o$	Volumetric discharge flow rate (m^3/s)
c_p	Specific heat capacity (J/kgK)
T_i	Average temperature at the top of the i th segment of TES tank (K)
T_{amb}	Ambient temperature (K)
T_B	Average temperature in the charging unit (K)
T_{in}	Temperature at the inlet of cooking unit/ outlet of TES tank (K)
T_{out}	Temperature at the outlet of cooker (K)
T_w	Temperature of water in pan (K)
T_o	Temperature of oil inside cooker (K)

to transfer the heat from the collector unit to the cooking unit. Indirect solar cookers may be with or without thermal energy storage and enable cooking to take place indoors. Solar cookers with thermal energy storage have an advantage that cooking can take place during periods of none or very limited sunshine. Therefore, some researchers have shown that having thermal energy storage systems coupled to solar cookers enhances their performance [9–11].

Thermal energy can be stored as sensible heat (SHS), latent heat (LHS), thermochemical or a combination of these. In sensible heat storage, thermal energy is stored by raising the temperature of a solid or liquid. Materials commonly used include water, rocks, iron or oil. These materials are cheap, chemically stable and easy to work with. Latent heat storage involves a phase transition at known temperatures. Thermo- chemical storage works by using energy from an exothermic reaction for the application and using endothermic reaction to recover the heat. Sensible heat storage materials (SHSM) are cheaper and usually have larger thermal conductivities when compared to phase change materials (PCM) and thermochemical reactions [12]. The low thermal conductivity of PCM materials slows down the time taken to absorb and release energy hence making them unsuitable for small scale applications like domestic cooking. Furthermore, some technological and economic aspects such as cost and availability make sensible heat storage superior hence making them suitable for use in small scale domestic applications like water heating and cooking [13].

Air as a heat storage medium and heat transfer fluid has been investigated by Laing et al. [14] and Lof & Hawley [15]. Air has low thermal conductivity and low thermal capacity and therefore a large sized heat exchanger would be required to cater for its high expansion hence making the system costly. The use of water as heat transfer and heat storage medium has been investigated [16–17]. Water does not stratify properly and special stratification devices are often included. Furthermore, the vaporization of water at temperatures of 100 °C limits its application for medium to high temperature ranges and necessitates use of pressurizing equipment which makes the system costly. Nahar [18] investigated the use of engine oil as heat storage medium in a solar cooker. The results showed the viability of engine oil as a heat transfer fluid but also noted that engine oil was quite expensive making it inappropriate for use in developing countries.

Vegetable oils have been studied as heat transfer fluids to replace the expensive commercial thermal oils [19–23]. Senthill and Cheralathan investigated experimentally the thermal performance of some solid and liquid sensible heat materials [19]. The sensible heat storage materials used were pebbles, sand, iron grits, steel balls, sunflower oil, olive oil and coconut oil. From the results it was observed that the thermal performance of the cooking pot could be enhanced with solid and even more so for liquid SHS materials respectively. Lugolole et al. [20] performed a thermal performance comparison of three sensible heat thermal energy storage (HTES) systems during charging cycles. The three sensible HTES considered were oil, small pebbles and large pebbles. The results showed that the oil only TES charges fastest, followed by the small pebble TES and lastly the large pebble TES. Mawire et al. [21] investigated the thermal performance of different oils available on the South African market during charging for domestic cooking applications. The results showed that sunflower oil had the highest charging power due to its high density and high specific heat capacity. Furthermore, its smoke point of about 250 °C makes it suitable for most cooking applications. In addition, sunflower oil is generally available as it is extracted from sunflower seeds that are locally grown in most African countries [22]. According to a review from the United Nations Food and Agriculture Organization, sunflower oil is characterized as nontoxic, generally edible and having tolerable fumes [23].

Utilization of thermal energy from charged thermal energy storage systems for cooking purposes has been studied [24–26]. A novel indirect solar cooker with outdoor elliptical cross section, wickless heat pipes, flat plate solar collector and integrated indoor phase change material (PCM) thermal energy storage was designed, constructed and tested by Hussein et al. [24]. The results showed that the solar cooker could cook successfully during the day and that it was possible to keep food warm at night and in the morning. The thermal performance of a prototype solar cooker based on an evacuated tube solar collector with PCM storage unit was investigated by Sharma et al. [25]. Commercial grade erythritol was used as latent heat storage material. The results showed that evening cooking using PCM was faster than cooking at noon. It was further recommended that a PCM material with lower melting temperature be used in periods of low solar isolation. Mussard [26] carried out experiments on charging heat storage coupled with a low-cost small scale solar parabolic trough for cooking purposes. The storage was coupled with a self- circulating solar parabolic trough filled with thermal oil (Duratherm 630). The heat transfer was oil based with nitrate salts to store latent heat. The results showed that the heat transfer to the cooking pot was rather poor, as the pot was positioned on the top surface of the heat storage with poor thermal contact.

An experimental set up for simultaneous charging and discharging experiments on oil storage for cooking applications was presented by Mawire et al. [27]. The results were presented for three cases of initially stratified, initially un-stratified and initially stratified at the top and un-stratified at the bottom. The results indicated that about 4.5 L water could be boiled within 2 h of charging/discharging cycle and a sufficient amount of energy could be stored in storage tank. A solar stove integrated on thermal energy storage tank for Injera baking in Ethiopia was investigated experimentally by Tesfay [28]. The experiments carried out showed the possibility of solar energy for Injera baking and its efficiency by including latent heat storage. Kumaresan et al. [29] carried out a performance evaluation of a newly developed double wall cooking unit integrated with thermal energy storage. The experimental set up consisted of a cooking unit, a storage tank and a positive displacement pump. Therminol 55 and D-Mannitol were used as heat transfer fluid and storage medium respectively. The results showed that the average rate of energy gained was 0.25 kW from 2.45 kW supplied from a thermal energy storage tank and that there was a considerable heat loss in flow circuit during discharging. Okello et al. [30] investigated experimentally the heat extraction from rock bed heat storage for high temperature applications. The top part of the thermal energy storage was used as cooking plate. The results showed that a constant airflow rate discharging gave a higher rate of energy extraction in a well stratified bed at the beginning but falls off with time and that the discharge rate can be increased and cooking time controlled by adjusting the air speed through the rock bed. Hazami et al. [31] presented an energy, exergy and economic viability of a heat storage system used for domestic supply of hot water in Tunisia. The daily energy efficiency ranged from 19%–27%. The results further showed that the system could meet 75% of the total hot water requirements. Experimental analyses of sensible heat thermal energy storage systems during discharging were done and presented by Lugolole et al. [32]. The results obtained show that the discharging times, discharging energy rates, exergy rates, exergy recovery efficiency and TES tank's de-stratification characteristics are all dependent on the heat transfer fluid (HTF) flow rates.

Solar heat storage systems have been modelled with various degrees of detail [33–35]. Anderson al. [33] developed a one –equation approach to thermal energy storage in a packed bed of alumina with air as heat transfer fluid. The model was used to solve the axial and radial temperature profiles in the packed bed, insulation and vessel. Discharging simulations of thermal energy storage (TES) system for an indirect solar cooker were carried out by Mawire et al. [34]. In their work, mathematical models for thermal energy storage and thermal energy utilization system were used to perform the simulations and validated with experimental results. Two applications of a numerical approach of heat transfer process with rock beds was presented by Coutier & Farber [35]. One of the applications presented was a new calculation method for the volumetric convective heat transfer coefficient using the compared results of theoretical modeling and experimental tests.

This study focussed on developing and evaluating the performance of a cooking unit integrated with thermal energy storage system. Hot oil from theTES tank flows into the cooking unit controlled by a manual valve. The cooking unit is placed below the TES and therefore, the flow of the oil into the cooking unit is driven by gravity. The system was demonstrated for boiling water, rice and beans. Boiling at different flow rate settings was analysed, and the energy balances considered. The aim is to develop an effective cooking unit for thermal energy storage that will make solar cooking competitive with conventional cooking methods, hence wider acceptability and applicability.

2. Materials and methods

The system description and methods of analysis are presented in the following sections.

2.1. Experimental set up

Fig. 1 shows the schematic diagram of the experimental set up. It consists of a thermal energy storage (TES) tank, charging unit, cooking unit, connecting pipes, manual valve and data acquisition unit. The thermal energy storage unit consists of a vertical cylindrical tank of diameter 0.20 m and height 0.40 m. The top part of the storage tank was covered with a movable circular lid. Both the storage tank and the lid were fabricated from mild steel material and were insulated with about 0.05 m thickness of fyre wrap insulation material. K-type thermocouples (accuracy: ± 2.2 °*C*) were placed inside the TES tank for temperature measurements. The positioning of the thermocouples was such that T_1, was at the top (a distance of 0.10 m from top level), T_2, was in the middle (0.20 m from top level) and T_3, at the bottom (0.30 m from top level) as shown in Fig. 2. Thermocouple, (T_B) was placed at the exit of the charging unit while thermocouple, T_{in} was placed at the exit of TES tank to monitor temperatures in the charging unit and oil inlet temperatures to the cooking unit respectively.

The charging unit consisted of a circular casing of diameter 0.05 m and height 0.15 m where a heating element of rating 800 W and 220 V was inserted. The charging unit and the connecting pipes were insulated with about 0.05 m thickness of fyre wrap. During charging, sunflower oil flowed by self-circulation through a pipe of diameter half inch and height 0.06 m. After the oil was heated, its density reduced, and it then flowed to the top of thermal energy storage tank through a pipe of

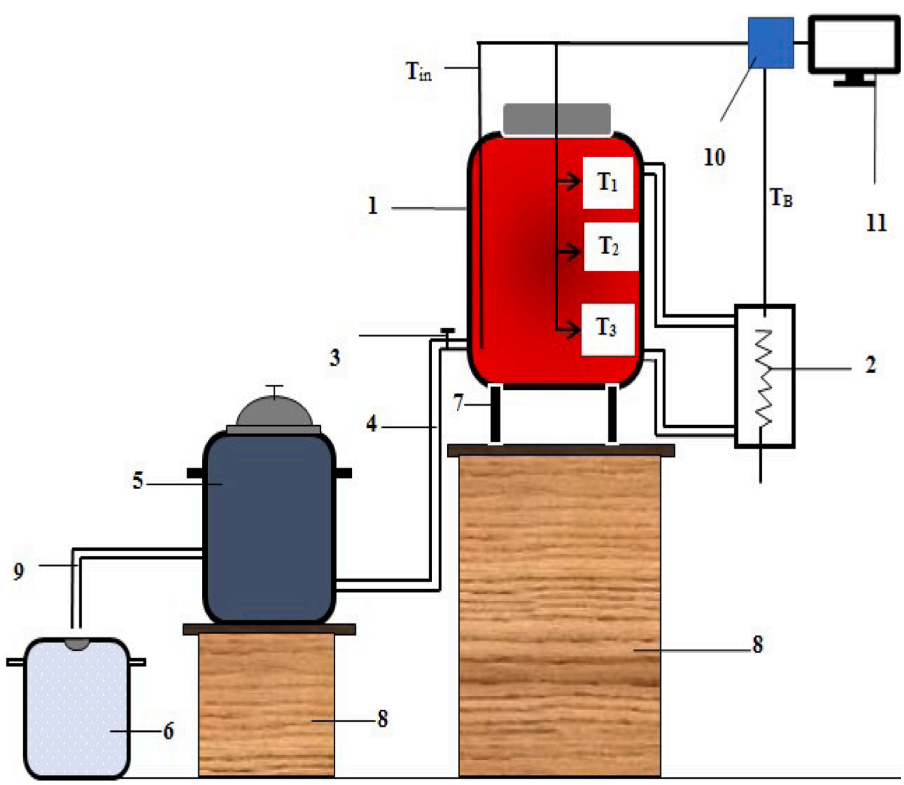

Fig. 1. Schematic of the cooking unit integrated with thermal energy storage system: (1) TES tank (2) charging unit (3) manual valve (4) oil inlet pipe (5) cooking unit (6) reservoir (7) support stand (8) table (9) oil outlet pipe (10) Pico data logger (11) computer.

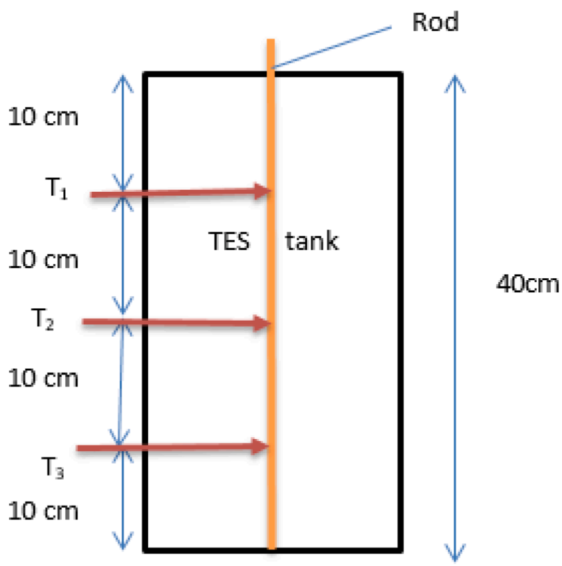

Fig. 2. Arrangement of thermocouples on a rod placed inside TES tank at distances of 10 cm apart.

similar thickness and height 0.25 m. As the hot oil flowed from the charging unit to TES tank, the denser cold oil at the bottom of storage tank was moved by gravity to the charging unit. The charging cycle continued until temperatures in the TES tank were within the temperature range (100 – 220 °C) that are suitable for most cooking applications. After the charging cycle, the heating element was switched off and then the cooking process was started. The data during charging and cooking was recorded after in intervals of 1 min by a Pico data logger. The data was then retrieved and stored on a computer interfaced with the data logger. An image of the experimental set up consisting of an insulated TES tank, insulated charging unit, insulated connecting pipes and the cooking unit is shown in Fig. 3.

2.2. Cooking unit

The cooking unit shown in Fig. 4 consisted of a double wall fabricated from galvanized steel of inner diameter 0.28 m and outer diameter

Fig. 3. Constructed experimental set up system showing an insulated TES tank, insulated charging unit, insulated connecting pipes and the cooking unit.

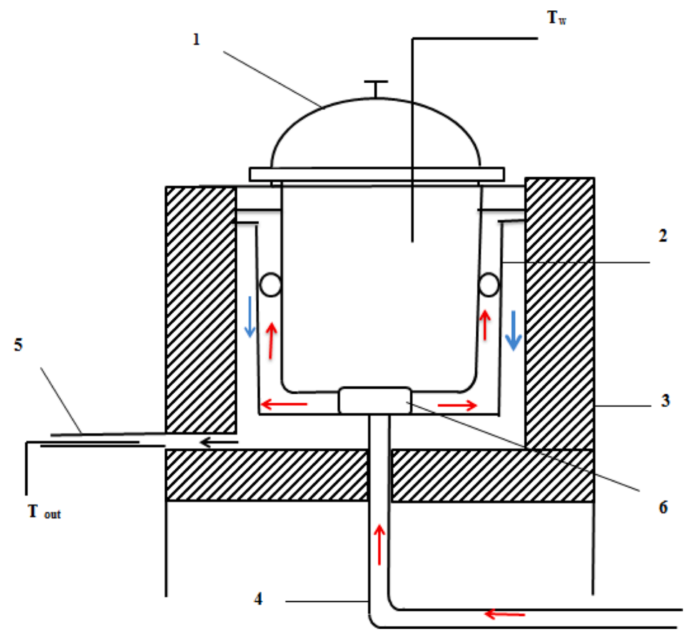

Fig. 4. Schematic of the cooking unit: (1) cooking pan with cover (2) perforated pan (3) double wall with insulation (4) oil inlet pipe (5) oil outlet pipe (6) adjustable screw.

0.38 m. The space between the inner and outer wall was filled with 0.05 m thickness of fyre wrap insulator. This was done to reduce heat loss during the cooking process. A copper pipe of dimension ¾ inch was fitted with a manual valve and connected from TES tank to the bottom of the cooking unit. The size of pipe was selected to avoid restriction of oil flow to the cooking unit. The flow of hot oil was from the TES tank to a perforated pan fitted inside the cooking unit. The perforated pan was connected in such a way that it was screwed to the hot oil inlet pipe. This was done to ensure flexibility in adjustment. Fig. 5(B) shows the cooking unit with the perforated pan.

During the cooking experiments, a cooking pan covered with a lid and containing a known quantity of water was placed in the perforated pan in contact with the hot oil as shown in Fig. 5(A). The manual valve was then opened to ensure that the hot oil flows and transfers heat to the pan placed inside the cooking unit. With the valve opened, there was a continuous flow of hot oil to the cooking unit which exited through the perforations and was then replaced by hotter oil from the TES tank. The flow of hot oil to the cooking unit was purely controlled by opening and closing of the valve. A K-type thermocouple, $T_{in}$was placed at the exit of the TES tank to monitor the temperature of the hot oil as it entered the cooking unit while another thermocouple, (T_w) was placed in the cooking pan containing the food items being cooked to monitor the temperature. In addition, a thermocouple, (T_{out}) was placed at the out let of cooking unit to monitor the temperature of the oil as it exited. The flow rate of oil during cooking was obtained manually by measuring the time taken for a given volume to flow at the outlet of the cooking unit using a Pyrex beaker and a timer. A reservoir tank was placed at the outlet of the cooking unit to collect the oil which was later recycled since there was no pump.

A photograph of the cooking unit that was designed, developed and tested is shown in Fig. 5.

2.3. Experimental tests

Experimental tests carried out consisted of charging the TES until it attained medium temperatures (about 200 °C) that are suitable for most cooking applications. Cooking tests were carried out by boiling a known quantity of water or cooking a given quantity of foodstuff. The cooking tests were done for two different conditions of constant flow rate and

Fig. 5. Images of the cooking unit (A): with the cooking pan inserted and (B) with the cooking pan removed.

varying flow rate. For the charging process, three thermocouples were positioned in TES tank as shown in Fig. 2, while another thermocouple was placed in the charging unit to monitor the temperature of the oil inside the charging unit. For the cooking experiments, a thermocouple was placed at the exit of TES tank T_{in}, to monitor the temperature of oil as it entered the cooking unit. Thermocouple T_w was placed in the cooking pan to monitor the temperature of the water inside the pan while another thermocouple T_{out} was fixed at the outlet of cooking unit for oil outlet temperature measurements. The thermocouples were connected to a data logger which was interfaced with a computer.

2.4. Experimental thermal analysis

Neglecting heat loss from the connecting pipe, the rate of energy, P_o delivery from the hot oil to the cooking unit is expressed as;

$$P_o = \rho_o c_{p,o} \dot{V}_o (T_{in} - T_{out}) \tag{1}$$

where ρ_o and $c_{p,\ o}$ are the density and the specific heat capacity of sunflower oil, respectively and $\dot{V}_o$ is the discharge flow rate. The density and specific heat capacity are expressed as functions of the inlet and outlet temperatures $T_{in}$and T_{out}, respectively, as summarized in Table (2). The temperature at the inlet of cooking unit was assumed to be the same as that at the exit of TES tank.

With the term "heating rate", P_w we mean the power required for changing the temperature of a given amount of water in time. The average heating rate for a finite time Δt to bring the water from a given initial temperature, T_{ini} to final temperature, T_w is:

$$P_{wav} = \frac{(\rho_w V_w) c_{p,w} (T_w - T_{ini})}{\Delta t} \tag{2}$$

where, V_w, is the volume of water, ρ_w, the density, $c_{p,\ w}$ the specific heat capacity of water and $(T_w - T_{ini})$, the change in temperature of the water. The instantaneous heating rate is:

$$P_w = (\rho_w V_w) c_{p,w} \dot{T}_w \tag{3}$$

The efficiency of the cooking unit is calculated as the ratio of power to heat water, P_w to the power, P_o delivered from the TES tank. This is expressed as:

$$\eta = \frac{P_w}{P_o} \tag{4}$$

Assuming that there are no heat losses to the ambient, the quantity of oil, V_{oil} used to bring a given quantity of water, V_w, from T_{ini} to T_w is obtained as:

$$V_{oil} = \frac{(\rho_w V_w) c_w (T_w - T_{ini})}{\rho_o c_o (T_{in} - T_{out})} \tag{5}$$

The rate of heat loss in the cooking unit to the ambient was evaluated for a case when there was no more oil flowing to the cooking unit. This was done to determine the heat retention capacity of the cooking unit. A known quantity of water that had boiled was allowed to cool from the boiling temperature to a lower temperature in a given time interval and the rate of heat loss to ambient is then:

$$Q_{loss} = m c_p \dot{T} \tag{6}$$

where Q_{loss}, is the rate of heat loss (W), m, is the mass (kg), c_p, is the specific heat capacity (J/kgK), $\dot{T}$, the time rate of change of temperature.

The overall heat loss coefficient, U, in the cooking unit is computed basing on expression:

$$U = \frac{Q_{loss}}{A\ LMTD} \tag{7}$$

where Q_{loss} is the rate of heat loss in cooking unit obtained from Eq. (6) above, A is the area of the double wall and $LMTD$ is the logarithmic mean temperature difference. $LMTD$ was calculated for temperature differences for water at the boiling point and the ambient for a given time interval and is expressed as;

$$LMTD = \frac{\Delta T_{w1} - \Delta T_{w2}}{ln\left(\frac{\Delta T_{w1}}{\Delta T_{w2}}\right)} \tag{8}$$

where ΔT_{w1} is the temperature difference of water at the boiling point and at the ambient temperature, and ΔT_{w2} is the temperature difference between water at a lower temperature (slightly below the boiling temperature) and at the ambient temperature. The density of water and specific heat used in this study are ρ=1000 kg/m^{-3} and c_p=4200 J/kgK respectively. The temperature dependent properties of sunflower oil

Table 1
Design Specifications of components of the cooking unit integrated with TES.

Component	Specifications
Storage tank	ϕ =0.20 m, height = 0.40 m
Heater casing	ϕ =0.05 m, height = 0.15 m
Heater	Power = 800 W, 220 V
Thermocouples	K-type
Data logger	Pico TC-08 USB
Cooking unit	inner diameter =0.28 m, outer diameter =0.38m
Perforations	ϕ =10 mm, height from bottom = 0.06 m

used in this analysis were obtained from Esteban et al. [37] and are summarized in Table 2.

2.5. Experimental uncertainty

The uncertainty associated with the experimental measurement of temperature is estimated to be ± 2.2 °C basing on standard K-type thermocouple accuracy. The accuracy of Pico TC-08 USB data logger used to record the data is given as ± 0.2% from the datasheet [36]. The Pyrex beaker used has an accuracy of ±5% while the timer has an accuracy of ±0.001 s. The uncertainty analysis was done basing on the standard error propagation relation for a function F, the uncertainty is evaluated according to $x_1, x_2, \ldots x_n$ as:

$$\partial F = \left[\left(\frac{\partial F}{\partial x_1}\right)^2 (\partial w_1)^2 + \left(\frac{\partial F}{\partial x_2}\right)^2 (\partial w_2)^2 + \ldots + \left(\frac{\partial F}{\partial x_n}\right)^2 (\partial w_n)^2\right]^{\frac{1}{2}} \quad (9)$$

where ∂w_1, $\partial w_2 \ldots$, ∂w_n represent the uncertainty in the independent variables. For purposes of computations in this work, $\partial \rho_{av} = \pm 0.069 g/cm^3$, $\partial C_{p,av} = \pm 0.021 J/gK$ and $\partial \dot{V} = \pm 1$ % ml/s. Therefore, the uncertainty obtained for the calculated parameters was within 0.5% to 4.5%.

Systematic uncertainties are associated with the local positioning of the thermocouples and the fact that the flow rates will change in time as it is gravity driven from a heat storage tank above the water.

2.6. Mathematical model for the cooking unit

A model for energy analysis of the cooking unit was developed to simulate the oil and water temperatures. The energy balance equations for oil and water were solved and used to estimate the heat transfer coefficients. Fig. 6 shows the schematic diagram of model cooking unit. It consisted of a hot oil tank, cooker and cooking pan. The flow of hot oil was from the TES tank at a temperature, T_{in} into the cooking unit where the oil attained a temperature, T_o. A covered pan containing a known quantity of water was placed in the cooking unit where the water temperature, T_w was monitored. The oil exited the cooking unit at a temperature, T_{out} through perforations to a reservoir as hotter oil replaced it from the TES tank. An energy balance process was applied for the heat transfer from the hot oil to the water.

The energy balance for the oil is expressed as:

$$V_o \rho_o c_{p,o} \dot{T}_o = \rho_o c_{p,o} \dot{V}_o (T_{in} - T_{out}) - [(hA)_w (T_o - T_w)] - [(UA)_o (T_o - T_{amb})] = RHS_o \quad (10)$$

The term on the left represents the oil temperature rise rate, the first term on the right represents the power in the cooker, the second term on the right is the energy transferred to the water and the last term on the right is the loss term.

The energy balance for the water is expressed similarly:

$$V_w \rho_w c_{p,w} \dot{T}_w = [(hA)_w (T_o - T_w)] - [(UA)_w (T_w - T_{amb})] = RHS_w \quad (11)$$

Where, the term on the left represents the water temperature change rate, the first term on the right is the energy transfer to the water and the second term on the right is the loss term from the water.

Eqs. (10) and (11) are discretised and solved with an explicit time integration:

Table 2
Temperature dependent thermal properties of sunflower oil as given by Esteban et al. [37] (T in degrees C).

Parameter	Unit	Value
Density (ρ)	kg/m^3	930.62–0.65T
Specific heat capacity (c_p)	J/kgK	2115.00+3.13T

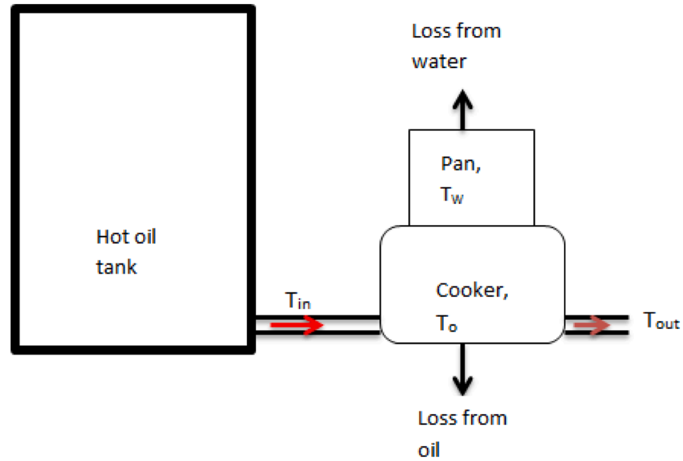

Fig. 6. Schematic diagram of model of energy analysis of the cooking unit consisting of TES tank, cooker and cooking pan.

$$\Delta T_o = \frac{\Delta t RHS_o}{V_o \rho_o c_{p,o}} \quad (12)$$

$$\Delta T_w = \frac{\Delta t RHS_w}{V_w \rho_w c_{p,w}} \quad (13)$$

The assumptions made were (i) the temperature does not change along the pipes (ii) the loss term is assumed as the same for the water and oil (iii) the specific heat capacity and density of the oil and water are assumed to be constant. The overall heat loss coefficient, UA was estimated from the experiment using Eq. (7) while other input parameters used were obtained from the experimental data.

3. Results and discussion

In this section, the experimental results of the cooking process and thermal performance analysis are presented. Estimated values of the heat transfer coefficients obtained by solving the energy balance equations for oil and water are also presented and discussed.

3.1. Charging temperature profiles

The results for temperature profiles in the TES tank during charging are shown in Fig. 7. The TES tank was filled with 10 litres of sunflower oil. Three thermocouples were placed inside the thermal energy storage tank as shown in Fig. 2 with T_1, 10 cm from the top, T_2 in the middle and T_3, 10 cm above the bottom while another thermocouple, T_B was placed inside the charging unit. The insulated TES tank was covered with an insulated movable lid. To start the charging process, the heating element was switched on and temperatures during the charging cycle monitored. The temperature profiles show a relatively high temperature, T_B rise in the charging unit as temperatures peaked to 155 °C in first 5 min of charging. A decrease in temperature, T_B inside the charging unit occurred when cold oil started to flow from the TES tank to the charging unit. Temperature, T_1 at the top of the TES tank started to rise after the circulation started and temperature, T_2 in the middle somewhat later as the thermal front propagated downwards in the storage. This also shows that there was high stratification in the beginning which began to fall as charging progressed.

The heater temperature varies little until the hot oil front reaches the lower part of the TES tank. As hot oil then starts to enter the heater, the temperatures out of the heater also starts rising. After 2 h of charging, the TES tank is still stratified with temperatures of 230 °C, 200 °C and 170 °C at the top, middle and bottom respectively. These temperatures are considered to be in the range suitable for most domestic cooking

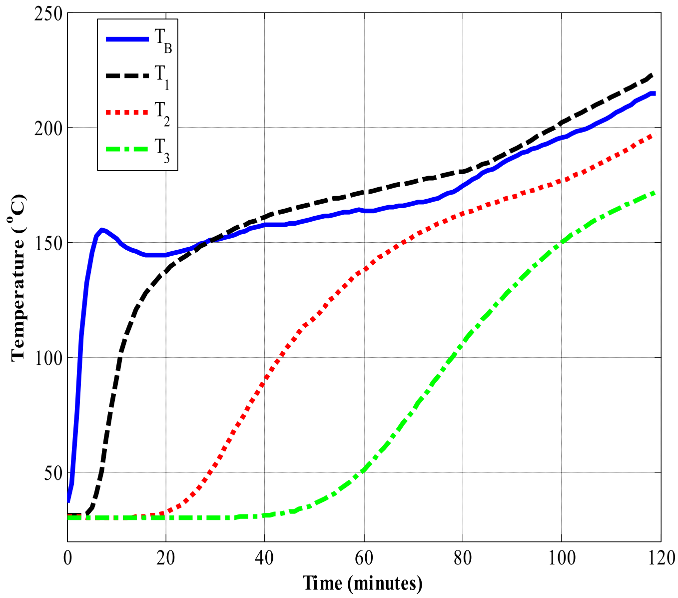

Fig. 7. Temperature profiles for oil during thermosiphon charging in the storage tank.

applications [30]. The discrepancies in the temperature of the oil exiting the heater, T_B and the oil entering the TES tank, T_1, is attributed to effects of precise location of the thermocouple in the heater (wall effects).

3.2. Cooking unit temperature profiles

During the cooking process, hot oil from thermal energy storage (TES) was allowed to flow to the cooking unit through an insulated connecting pipe. The flow of the oil was controlled by a manual valve. As soon as the valve was opened, the flow rate was measured and the cooking process monitored by recording temperatures at the inlet of the cooking unit, in the cooking pan and at the outlet of the cooking unit. Cooking experiments were performed for two different flow regimes i.e. varying flow rate settings and constant flow rate settings.

3.2.1. Varying flow rates

Varying the flow rate is necessary for most cooking processes and is usually applied in actual cooking. The results for cooking at varying flow rates are shown in Fig. 8. Initially, when the valve was opened at a flow rate setting of about 4 ml/s, it was observed that the temperature of the water, T_w increased at a slow rate as it took about 15 min for the temperature to reach about 50 °C. The flow rate was then increased to 6 ml/s and it was observed that there was a fairly high temperature increase to about 80 °C attained in 13 min. When the flow rate was adjusted further to 12 ml/s, the temperature of the water increased at a relatively higher rate from 80 °C to 96 °C in only four minutes. Two litres of water took a total of 32 min to boil as shown in the profile of water.

It was further observed that at flow rate settings of 4 ml/s and 6 ml/s, the temperature of water, T_w was slightly higher than the oil outlet temperature, T_{out}. This can be attributed to the positioning of the oil outlet thermocouple and local thermal loses at the outlet pipe. The decline of the oil outlet temperature in time, after shutoff, is quite large, and the rise also after the second shutoff shows some thermal inertia

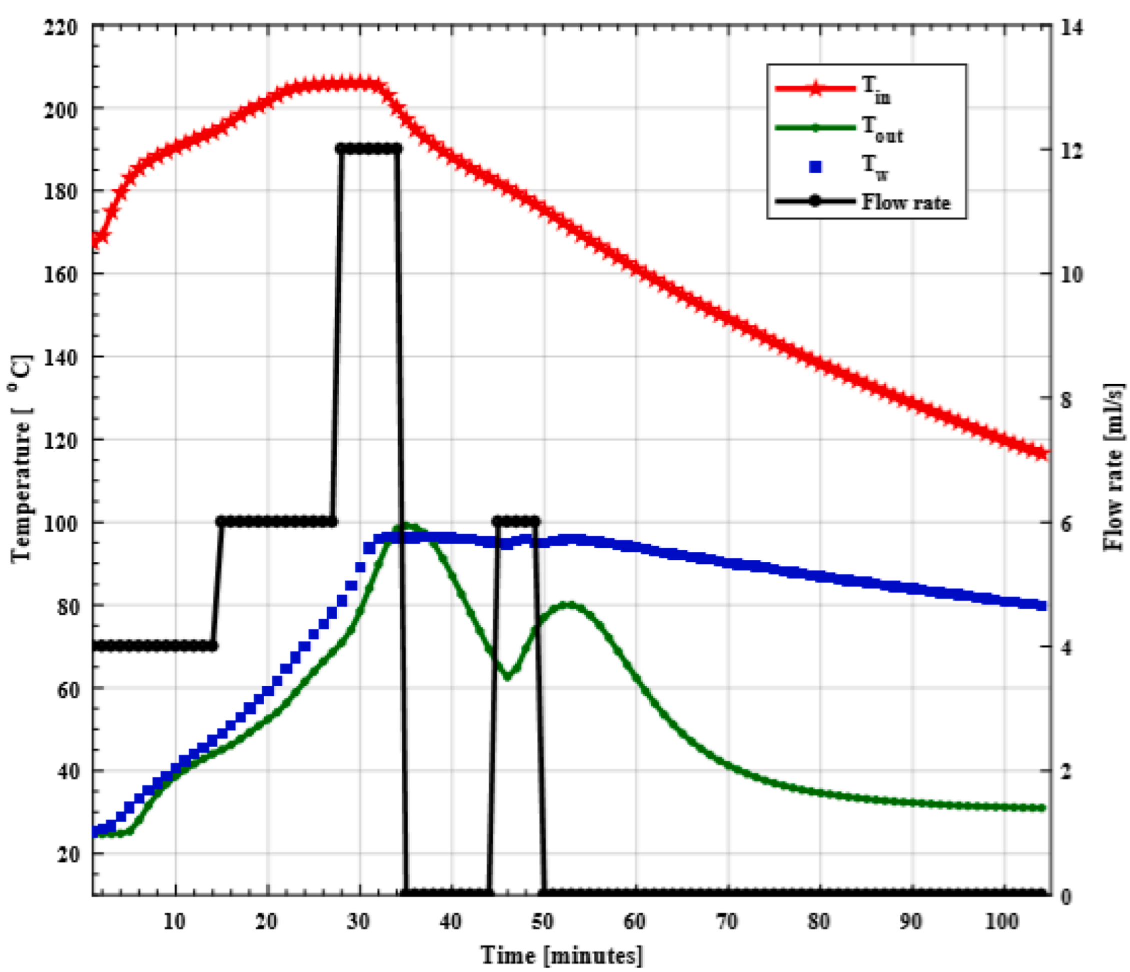

Fig. 8. Temperature profiles for boiling 2 litres of water, T_w, inlet oil temperature, T_{in} and outlet oil temperature, T_{out}.

effects. When the flow rate was increased to 12 ml/s, the oil outlet temperature and the water temperature increased rapidly. The flow of the oil was stopped after about 35 min and it was observed that boiling was maintained for almost 10 min. After 45 min, a flow rate setting of 6 ml/s increases the boiling again. At about 50 min, the valve was closed and temperatures close to boiling were maintained for another 40 min. This shows that food that requires simmering can be cooked at very low flow rates and keep boiling temperatures for long times after the flow of oil is stopped.

Using Eq. (3), the power gained at a given flow rate setting was obtained as 0.2 kW at the flow rate of 4 ml/s, 0.3 kW at the flow rate of 6 ml/s and about 0.5 kW at a flow rate of 12 ml/s. The equivalent amount of oil used for this energy exchange up to the point of boiling would be 3.5 L using Eq. (5). The actual amount used was about 7.0 L due to the thermal losses.

3.2.2. *Constant flow rate*

Fig. 9 shows the experimental results for cooking at a constant setting of the flow rate. Initially, when the flow rate was set to 4 ml/s, the temperature profile of the water shows that the temperature, T_w increased at a very low rate as it took about 94 min for 2 litres of water to reach the boiling point. After reaching the boiling point, the valve was closed and boiling was maintained for about 10 min. When the temperature of the water started to drop after 107 min, the valve was opened and flow rate set back to 4 ml/s hence a slight increase in temperature T_w. The profile for outlet temperature shows that T_{out}, was lower than the temperature of water, T_w for the whole duration of the cooking process. This can again be due to the positioning of the outlet sensor and heat loss from the cooking unit. It was observed that after initial boiling, temperature, T_w remained close to the boiling temperature and that it was maintained even after the valve had been closed.

The averaged power gained was obtained as 0.09 kW using Eq. (3). The minimum amount of oil needed for the energy exchange would from Eq. (5) be 4.0 L but due to thermal losses about 8.0 L was used during the experiment.

3.2.3. *Increasing volume of water after initial boiling*

This experiment was carried out to demonstrate actual cooking processes where water is added as the cooking progresses. Fig. 10 shows the profiles for the inlet oil temperature, T_{in} water temperature, T_w and outlet oil temperature, T_{out}. Initially, when the valve was opened and set to a flow rate of about 8 ml/s, T_{in}, dropped from about 220 °C to about 100 °C. Due to the fairly high flow rate, there was increased heat transfer

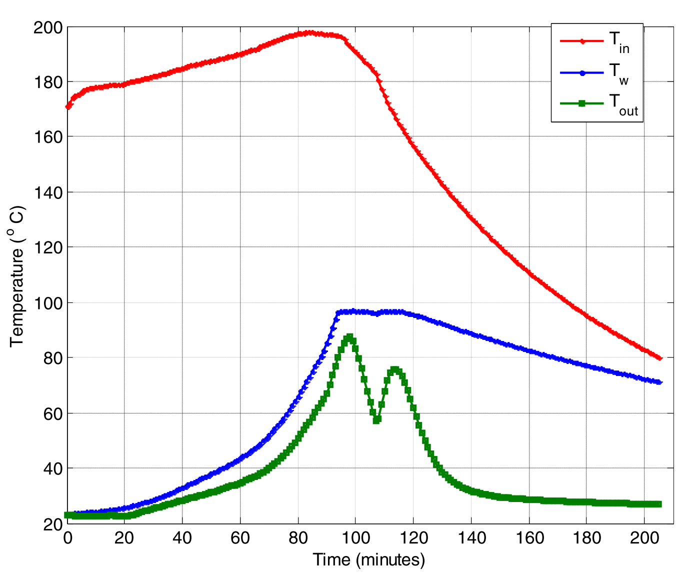

Fig. 9. Temperature profiles for oil and water for a case of constant flow rate.

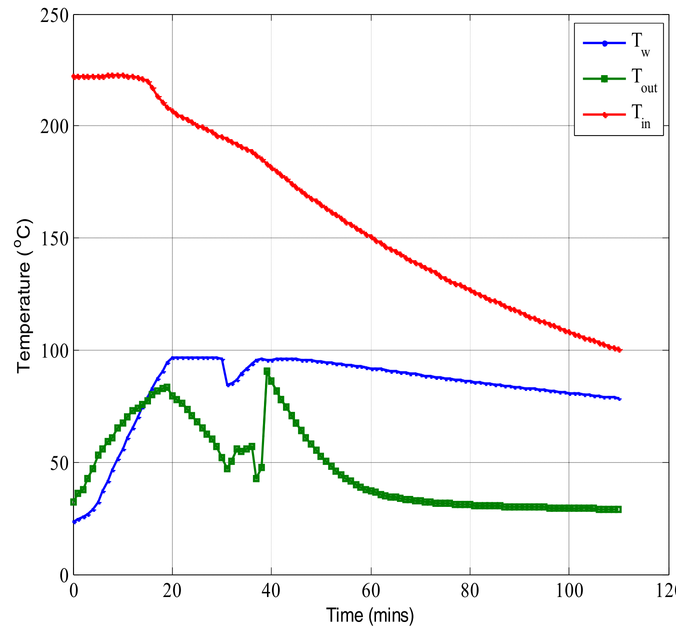

Fig. 10. Temperature profiles for oil and water for a case of water added after initial boiling is reached.

between the oil and the water depicted by fast increase in T_w. This is evident as one liter of water boiled after 19 min. After initial boiling of the water, the valve was closed. It was noticed that boiling was maintained for about 15 min even though the valve had been closed. When the water temperature, T_w started to drop, a liter of water was added and the valve opened again. It took about 6 min to boil and the boiling was maintained for at least 10 min. It was observed that addition of water did not affect the boiling process as the temperature of water remained close to the boiling point. The insulation of the cooker means that maintaining cooking temperatures can be made with small oil flow rates.

The averaged power gained was calculated as 0.5 kW using Eq. (3). Using Eq. (5), the quantity of oil needed for the energy exchange until the boiling point for one liter of water would in the ideal case be 2.5 L. The measured volume used was about 5 L due to the thermal losses.

3.3.4. *Boiling of rice experiment*

The results obtained from the cooking experiment where 0.250 kg of rice was boiled in 0.80 litres of cold water are presented in Fig. 11(A). Initially, the oil flow rate to the cooking unit was set to 12 ml/s and the valve setting was maintained until the rice started to boil. The rice boiled after about 17 min and then the flow rate was reduced to about 2 ml/s to allow simmering of the rice. It was observed that although reducing the flow rate to 2 ml/s reduced the heating rate, the rice was fully cooked after 30 min. Due to high flow rate of 12 ml/s, there was an evident high oil out let temperature, T_{out} depicting higher heat wastage from the system.

A previous study by De et al. [38] investigated the minimum energy required to cook 1 kg of rice in 1.6 litres of water. The stove was rated about 626 W and the total energy transferred to the rice was about 0.40 kWh per kg. Carlson et al. [39]. carried out experiments for the energy required to cook rice, wheat, barley, pasta, spaghetti and potatoes. The study showed that 0.55 kWh was required to cook 1 kg of rice using a hot plate of rating 1 kW.

The energy needed to cook various food items will depend on the amount of water used especially if it is done by boiling. The energy used in this cooking unit can be estimated from the temperature rise until the cooking point, whereafter the flow rates was reduced to a very low value. Using the heat capacity of water alone, an estimate for the power gained using Eq. (3) is then 0.29 kW. In 17 min this amounts to 0.08 kWh

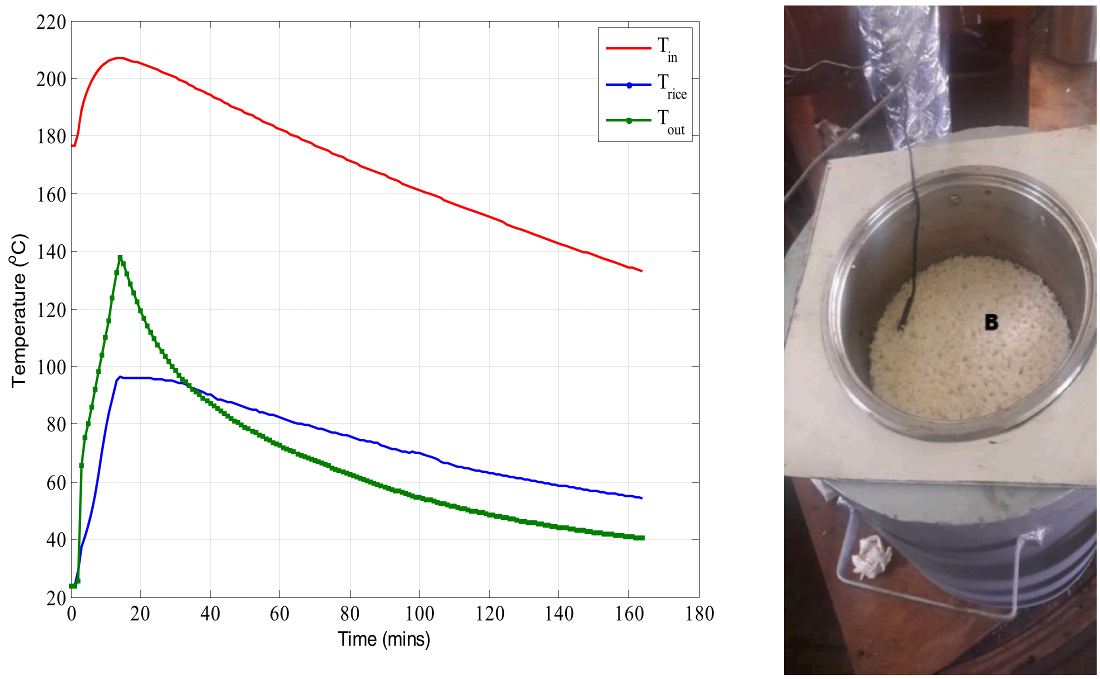

Fig. 11. (A) Temperature profiles for cooking unit, rice and outlet of cooking unit during cooking process; (B). Cooked rice in the pan.

giving 0.33 kWh per kg rice. This is a lower estimate, but shows that the insulation makes the cooker to be quite energy efficient.

3.3. Energy analysis for cooking unit

3.3.1. Profiles for energy rates

During the cooking experiments, the power delivered from the hot oil to the cooking unit was obtained using Eq. (1). The density and specific heat capacity of sun flower oil were taken from expressions given by Esteban et al. [37] as summarized in Table (2). Profiles for energy rates for varying flow rate settings of 4 ml/s, 12 ml/s and 6 ml/s are shown in Fig. 12. It was observed that at a low flow rate setting of 4 ml/s, the rate of energy delivery from the hot oil is almost constant as shown in profile A. The drop in the rate of energy delivered to the cooking unit from about 0.7 to 0.4 kW, occurred at about the time the water came to boiling. At a high flow rate setting of 12 ml/s, the energy extraction rate from the TES was fairly high as shown in profile B. The profile shows a rapid drop in the energy rate from 2.4 to 1.1 kW that occured in only 20 min. This was the time taken to boil 2 L of water at the flow rate of 12 ml/s. At a meduim flow rate setting of 6 ml/s, the drop in the energy rate from about 1.7 to 0.8 kW occured during a period of about 30 min as depicted in profile C.

According to the profiles, it is evident that the rate of energy extraction is relatively fast at high flow rates and almost constant at lower flow rates. This means that at low flow rates, energy is retained for longer periods of time and thus foods that require longer cooking times can best be cooked at low flow rates. Consequently, food that requires fast cooking should be cooked at fairly high flow rates as there is no need to retain heat for long periods of time.

3.3.2. Overall heat loss coefficient

The rate of heat loss in the cooking unit was calculated when there was no more oil flowing to the cooking unit. This was done to determine the heat retention capacity of the cooking unit. Basing on the temperature profile of Fig. 10, boiled water was allowed to cool for a time duration starting from 40 min to 110 min. Using Eq. (6) the average heat loss rate was obtained as Q_{loss} = 0.03kW for a volume of 2 litres of water and specific heat capacity, c_p=4200 J/kgK. The Logarithmic mean temperature difference (LMTD) was calculated using Eq. (8) for temperature differences from 96 °C to 25 °C and 80 °C to 25 °C. The result of LMTD was obtained as 62.74 K. Using this value of LMTD, the overall heat transfer coefficient (UA), in the cooking unit was calculated as 0.54 W/K using Eq. (7) for the temperature range 96 °C to 80 °C. From the estimates, it was observed that the cooking unit can retain heat for a relatively long duration as the rate of heat loss to the ambient is relatively low implying that after initial boiling, there is less energy required so simmering is possible.

3.3.3. Efficiency of the cooking unit

The efficiency was calculated as a ratio of the rate of energy transferred to the water to the rate of energy released by the hot oil. The power released by the hot oil was calculated using Eq. (1) while the heating rate of water was calculated using Eq. (3). Values of density and specific heat capacity of water used were ρ=1000 kg/m^{-3} and c_p=4200 J/kgK respectively. Temperature dependent values of sunflower oil were obtained from expression shown in Table (2). The heating rates that were obtained for the different flow rates are summarized in Table 3.

The highest efficiency occurred while cooking at the highest flow rate setting of 12 ml/s as this gives a high rate of energy transfer. At low and medium flow rate settings of 4 ml/s and 6 ml/s respectively, the rate of energy transfer was reduced and cooking occurred over long periods of time. The cooker efficiency increases with increasing flow rates but the overall system efficiency reduces with increasing flow rates as the oil leaves the cooker with higher temperatures. The cooking unit efficiency can be improved if the energy of the hot oil leaving the cooker is recovered by recirculation, but this requires a pumped system.

The efficiency estimates have uncertainties related to the positioning of the thermocouples and the overestimation of the flow rates. The measured outlet temperature is less than the actual oil temperature due to the positioning of temperature sensor, the inlet temperature to the cooking unit is taken as the measured outlet temperature from the storage and the flow rates will decrease in time as the level in the storage is decreasing. All these effects will give higher efficiency values than the ones given in Table 3.

3.4. Estimated heat transfer coefficient

The model of the energy analysis of the cooking unit was validated

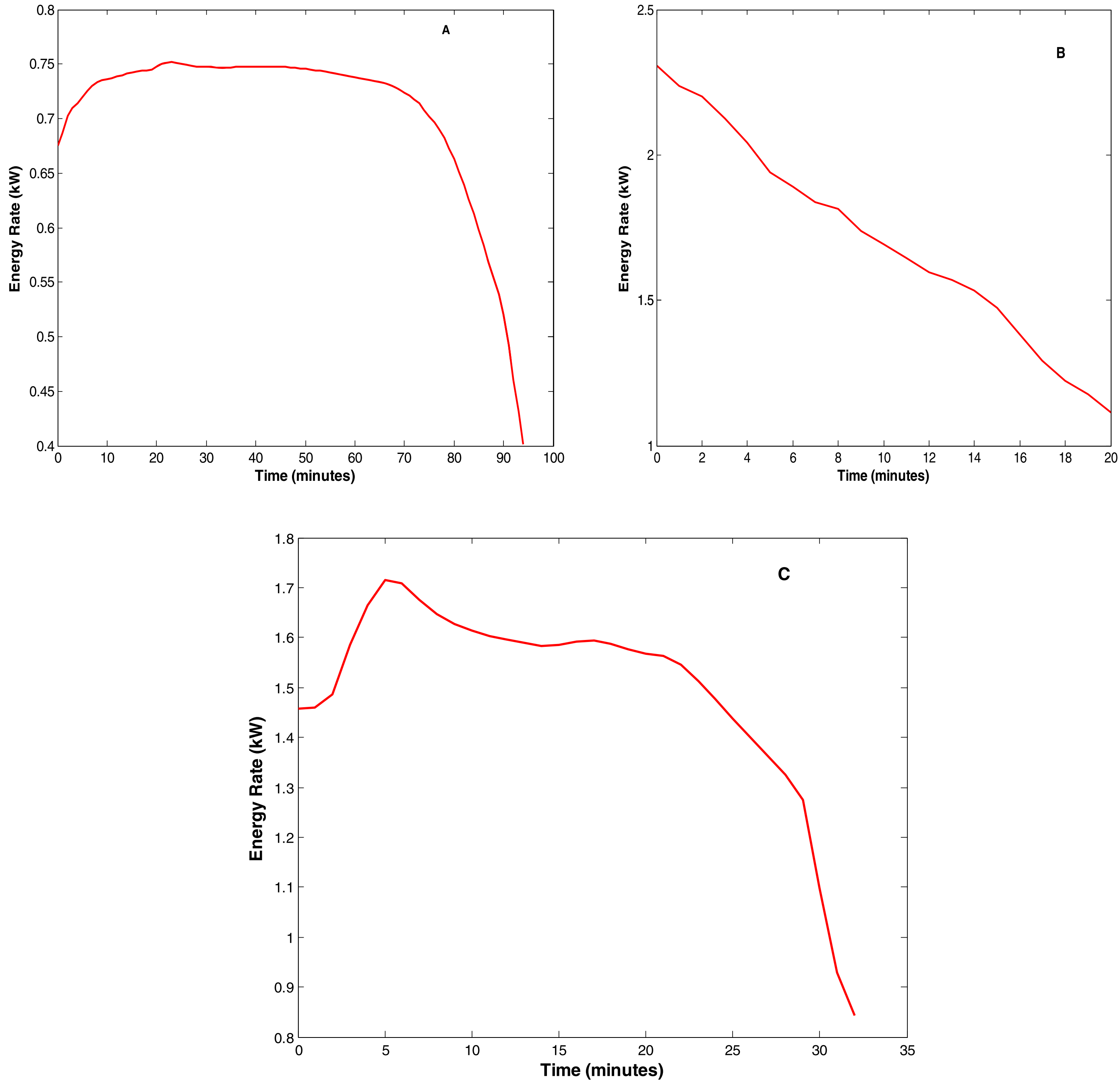

Fig. 12. Energy rates for oil in the cooking unit as a function of time for varying flow rates: A. 4 ml/s, B. 12 ml/s and C. 6 ml/s.

Table 3
Summary of the efficiency value for a given value of flow rate.

Flow Rate (ml/s)	P_o (kW)	P_w (kW)	Efficiency (%)
4	0.40	0.16	40
6	0.82	0.35	43
12	1.10	0.57	52

using experimental results obtained earlier for boiling 2 L of water at varying flow rates of 4 ml/s, 6 ml/s and 12 ml/s. Equation (14) was solved to predict the temperature of water in the cooking unit. The volume of water was taken as 2 L, the overall heat transfer coefficient, (*UA*) was taken as 0.5 W/K as obtained earlier. The initial temperature of water was taken to be equivalent to the ambient temperature while the temperature of the oil was taken from the experimental values obtained. The heat transfer coefficient, *h* was then varied until the simulated water temperature profile was similar to the experimental profile for a given value of flow rate. Fig. 13 shows the profiles obtained from the mathematical model run with the estimated values of heat transfer coefficient and experimental results for a flow rate of 6 ml/s. A comparison between the experimental and simulated water profile shows that there is some discrepancy between the two profiles but they follow a similar trend. According to the profiles, the temperature of the water increased initially until it became constant after the boiling point. The deviations could have been brought about by uncertainties in measuring the experimental values that were used in the model.

The heat transfer coefficient was found to range from 100, 110 and 150 W/m^2K for flow rates of 4, 6 and 12 ml/s respectively. Fig. 14 is a plot of the variation of the heat transfer coefficient with flow rates. From

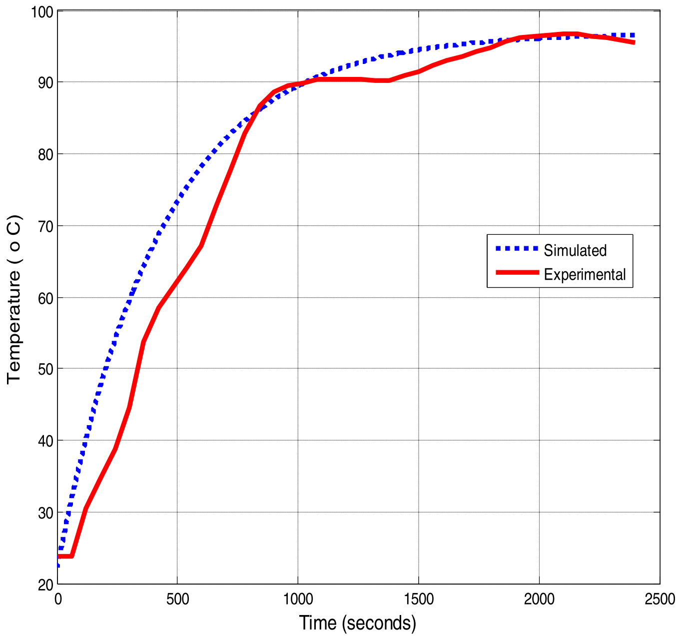

Fig. 13. Experimental and simulated profile for water over time for a flow rate of 6 ml/s.

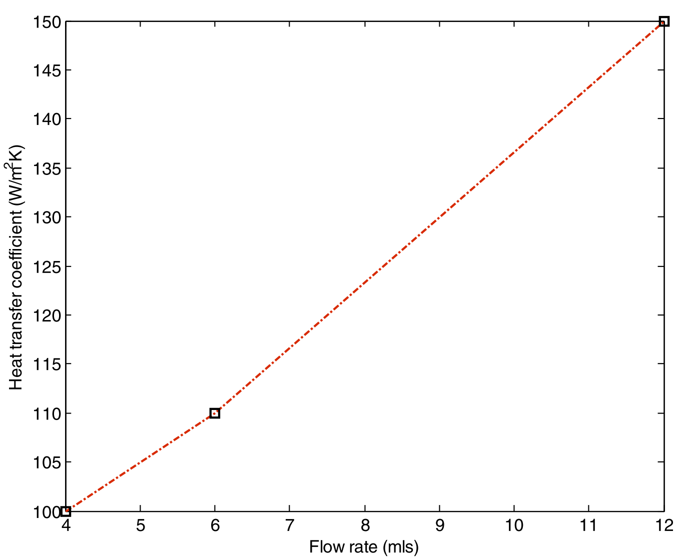

Fig. 14. Heat transfer coefficient for a given flow rate.

the plot, it was observed that there was almost a linear relationship between the flow rate and the heat transfer coefficient. The average flow rate was computed and was obtained as about 120 W/m^{2}K which is in the range of values given for fluid flow in free convection mode. Furthermore, Mawire & McPherson [40] in their previous work used an estimated heat transfer of about 80 W/m^{2}K while Lof & Hawley [15] showed that there is a linear relationship between heat transfer coefficient and air flow rate.

4. Conclusion

An experimental set up consisting of a double walled cooking unit positioned below a hot oil based thermal energy storage (TES), was developed and its thermal performance investigated. The developed system was able to boil 2 litres of water in about 19 min at the highest flow rate setting of 12 ml/s. High flow rates give rapid cooking times, but also higher rates of energy losses from the TES tank. The total system efficiency of the heater, storage and the cooker can be improved by introducing a pump to redirect the oil flow from the cooker back to the storage.

The overall heat loss in the cooking unit was estimated from cooling recordings and it was found to be about 0.54 W/K. The efficiency of the cooking unit was obtained as 40%, 43% and 52% at flow rates settings of 4 ml/s, 6 ml/s and 12 ml/s respectively. These are conservative estimates, due to the positioning of the temperature sensors and due to the assumption of constant flow rates during the cooking tests.

The heat transfer coefficient between the flowing oil and the water in the cooker was estimated from energy balances. The average value was 120 W/m^{2}K, increasing with increasing flow rates. The direct contact between the cooking pot and the flowing hot oil gives efficient heat transfer and the cooking power can be effectively controlled by operating the valve. As the cooker is insulated, a small flow rate is sufficient to keep food simmering for long periods of time.

CRediT authorship contribution statement

Pamella K. Kajumba: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Denis Okello:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation. **Karidewa Nyeinga:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation. **Ole J. Nydal:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation.

Declaration of Competing Interest

The authors declare that there is no conflict of interest in the undertaking of this research.

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