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Experimental and simulation analysis for different pot-in-pot indirect heating scenarios for cooking applications

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Keywords

Oil medium;
Air medium;
Heat transfer coefficient;
Pot in pot indirect heating;
Heat transfer coefficient

Abstract

The paper presents simulation and experimental results to demonstrate heat transfer performance during cooking that can be practical in pot-in-pot arrangements for indirect cooking/heating. The cases included single pots, pot-in-pot with oil, and pot-in-pot with no oil. The aim was to optimize the heat transfer through conduction and the cooking process for a recently developed small-scale sensible heat storage system integrated with a cooking unit. Cooking experiments reported were carried out using an electric hot plate with a power rating of 1.8 kW, 220V. Temperature measurements were recorded using a TC-08 data logger. The heating rates were analyzed for the best option. Energy balance equations for heating the water were utilized to estimate the heat transfer coefficient for the cases of pot-in-pot with oil and that without oil (air). It was observed that boiling 1 L of water using aluminium pots in a pot with or without oil in between showed a faster heat transfer rate and quick temperature rise in comparison with a stainless-steel pot in pot. Water boiled to about 100 °C in a shorter period in an aluminium pot compared to a steel pot in all the scenarios. The heat transfer coefficient values were estimated to be 800 $Wm^{-2}K^{-1}$ and 500 $Wm^{-2}K^{-1}$ for the case of oil and no oil between the pots tested, respectively. This work presents a good learning resource for basic coding in MATLAB on heat transfer energy balance equations studies, and these results further affirm oil as a better heat transfer medium compared to air during indirect heating applications.

Introduction

The adoption of renewable energy sources, such as solar, for domestic cooking applications necessitates a heat storage component and an effective cooking unit.. Several cooking fuels can be used for indirect cooking, including solar, biomass, coal, wood fuel, and grid electricity (Argentina Guibunda et al. 2024, Hussein et al. 2008, Petrokofsky et al. 2021, Tabu et al. 2018). The use of solar energy for indirect cooking is promising as the solar resource is abundant in most African countries. However, most of these solar cookers face a challenge arising from their intermittent nature, since direct solar cookers do not store their energy as compared to indirect solar cookers, which can store energy for later use (Muthusivagami et al. 2010, Schindelholz et al. 2024). To overcome such challenges, studies have focused on the integration of Thermal Energy Storage (TES) with solar cookers (Aramesh et al. 2019). In addition, there is a need to develop solar cookers with efficient cooking units. Thermal energy storage systems integrated with cooking units have been reported and investigated experimentally (Kajumba et al. 2020, Mawire and Taole 2011, Tabu et al. 2018).

The performance of heat extraction from rock bed heat storage for high temperature applications was evaluated. The top part of the thermal energy storage was used as a cooking plate. The results revealed that a better contact between the cooking plate and the storage was necessary to reduce the heat losses (Okello et al. 2022b). A system of 12V DC-powered electrical cooker powered by a 450 W panel was reported. The cooking tests were performed with a pot inserted into a closed, insulated wonderbag to reduce heat losses (Mawire et al. 2024). A cooking unit integrated with oil-TES was studied for its thermal performance. It consisted of a double-walled unit where the cooking pot was inserted. The operation of the developed system was such that oil flow is controlled by a manual valve through connecting pipes to the cooking unit below the heat storage tank (Kajumba et al. 2020).

The charging of sensible heat storage materials, such as thermal oil, using the funnel method and performing indirect heat extraction through a cooking pot placed in contact with the heated oil was demonstrated. The system heating was varied by either raising the funnel height (Chaciga et al. 2024). Solar cooker with thermal energy storage experimentally investigated, showed that the maximum temperature of water temperature reached was about 355 K in 40 min due to heat losses according to (Wollele and Hassen 2019). Kumaresan et al. (2016) evaluated the heat transfer rate of a double-walled cooking unit and compared the results to those obtained from Computational Fluid Dynamics (CFD). Their

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analysis was further extended to analyze performance under various flow and geometric conditions. A detailed analysis of heat transfer mechanisms in a solar cooking pot with TES using CFD was undertaken. The results obtained showed that when oil is heated, it creates convective plumes, significantly enhancing heat transfer. Average values of heat transfer coefficient obtained improved by 1.6 $Wm^{-2}K^{-1}$ and 7.5 $Wm^{-2}K^{-1}$ for pot and TES, respectively.

A lot of emphasis has been put on designing and analysing different cooking units integrated with TES systems, and limited work has been done on the optimization of cooking units. This work, therefore, studies heat transfer for different indirect cooking unit cases as a way of optimizing solar cooking pots in terms of efficiently transferring heat to the cooking unit. Some studies on heat transfer mechanisms have been done based on conventional cookers. Heat transfer coefficient estimation based on heat energy balance between oil and sample during frying of the sweet potato as reported in the literature (Farinu and Baik 2007) . The results showed that the range of maximum heat transfer coefficient reached was between 710-850 W/m^2 ^oC. The convective heat transfer coefficient during deep-fat frying of potatoes at different temperatures was determined, and it was reported to range between 300 to 335 W/m^2 ^oC for the top, and 450 to 480 W/ m^2 ^oC for the bottom surface (Sahin et al. 1924). Experimental results on heat transfer during heating of four types of minced meat patties by contact with hot plates are given (HouSovzl and Topinka 1985). At hot plates power rating of 1600 W, the heat transfer coefficients measured were in the range 200 to 1200 Wm-2K-1, depending on product type, contact plate temperature, contact pressure and stage in the heat treatment. However, several studies have been done on heat transfer mechanisms during deep frying directly with mostly a single pot but not in a pot-in-pot (Farinu and Baik 2007, Hubbard and Farkas 1999)

The heat transfer mechanisms between pots with oil and air medium performance analysis provide information on future cooking unit designs, especially when using energy storage technology integrated with intermittent energy sources. Three typical scenarios are a pot inserted into another pot with some oil (storage material) between them, a pot in the pot without any oil between them, and a single pot. The results will inform the modification and optimization of cooking unit designs, especially the cooking pots for solar cooking applications.

Materials and Methods

Model diagram

The schematic in Figure 1 shows the model diagram and setup sensoria with and without oil in between the pot's simulation procedure. The thermal properties of the oil used were for refined sunflower oil, and that of air was for free atmospheric air, all initially at ambient temperature. Thermal conductivities of the medium were considered to be an important factor for the heat transfer mechanism between the metal boundaries. The model energy equations, Eqn. 1-6 were utilized with appropriate time-steps in a MATLAB programme code and run for temperature profiles with 1 L of water as a heating load.

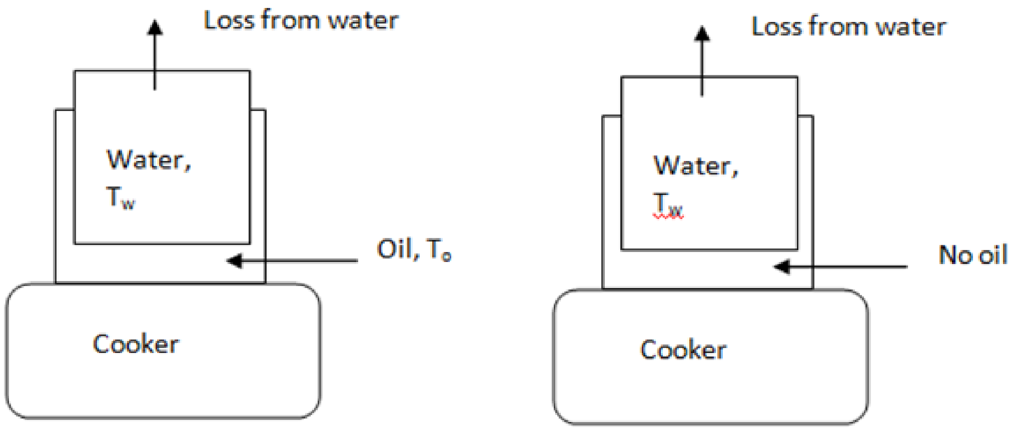

Figure 1: Schematic of energy balance model: left: two pots with oil in between, and right: is one pot without oil.

Model and energy balance equations

The Eqn. 1 here represents the quantity of energy supplied by the cooker as:

$$Q_{cooker} = Pt\ (kWh) \quad (1)$$

where, P is the power and t is the time.

The rate of heat gained by the water Q_{water} is given by Eqn. 2 as:

$$Q_{water} = mc_p \frac{dT}{dt} \quad (2)$$

Where, m is the mass of water (kg), c_p, the specific heat capacity of water (J/kg/K), and $\frac{dT}{dt}$ the water temperature rise rate.

The rate of heat loss, Q_{loss}, in the cooking pot is mainly transferred by conduction under steady state is given by Eqn. 3 as:

$$Q_{loss} = UA(T_w - T_{amb}) \quad (3)$$

where, U is the overall heat transfer coefficient (W/m^2K), A is the area of the surface (m^2) and (T_w) is the temperature of water (K) and (T_{amb}) is the ambient temperature (K).

The energy transferred to the water from the oil placed between the pot is given by Eqn. 4 as:

$$Q_{oil} = hA(T_o - T_w) \quad (4)$$

The energy balance for the cooking process is based on the schematic of Figure 3 and is given by Eqn. 5 as:

$Q_{cooker} = Q_{water} + Q_{oil} + Q_{loss}$ (5)

However, in coding in Matlab, the energy balance in Eq.5 can be rewritten as in Eqn. 6 below:

$mc_p \frac{dT}{dt} = P - hA(T_o - T_w) - UA(T_w - T_{amb})$ (6)

Apart from the atmospheric air used, a small volume of about 100 ml of heat transfer oil was used in the work. Refined sunflower oil, whose properties are related as follows was used: [3]

The density of the refined sunflower oil, ρ_s is given by Eqn. 7

$\rho_s = 930.62 - 0.65\,T$ (7)

The specific heat capacity, c_s of the refined sunflower oil, is given as in Eqn 8

$c_s = 2115 + 3.13\,T$ (8)

The thermal conductivity, k_s of the refined sunflower oil, is given by Eqn. 9

$k_s = 0.161 + 0.018e^{\frac{-T}{26.42}}$ (9)

Experimental set-up

To perform the cooking demonstration using the pot-in-pot, Figure 2 shows the image of the experimental setup. It consists of cooking pots, K-type thermocouples, a data logger and a computer. The experiments were conducted for three cooking scenarios: a single pot, a pot-in-pot scenario with oil between the pots, and a pot-in-pot scenario without oil. The pot-in-pot experiments were done with either aluminium pots, steel pots or aluminium and steel pots.

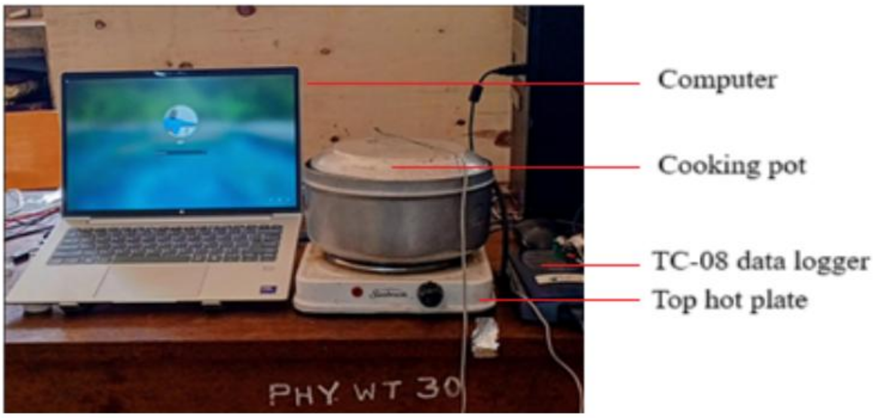

Figure 2: Experimental set-up showing the cooking pots, hot plate (1.8 kW, 220V, variable), TC-08 data logger connected to a k-type interfaced with a computer.

The pot-in-pot setup consists of a set of cooking pots designed to fit well inside one another, such that, in between them, either oil medium or air medium serves as a heat transfer medium. A conduction test was performed with about 100ml of sunflower oil added instead of air, as shown in Figure 3. This system of cooking can be suitable for our future work, where a heat storage system shall be integrated with cooking units and power supplied by a renewable energy system.

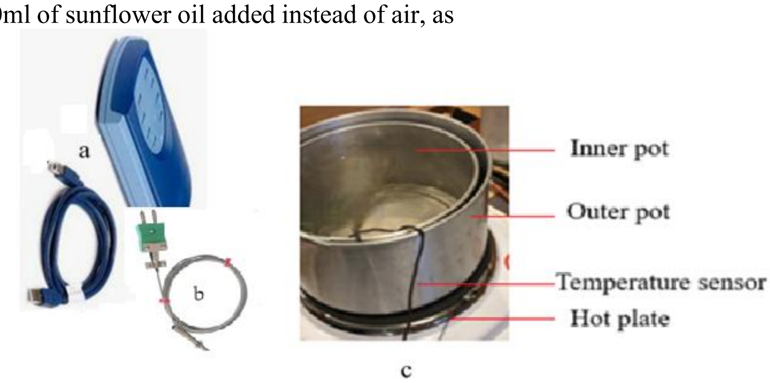

Figure 3: Image showing: TC-08 data logger, (a), k-type thermocouple sensors (b), and the arrangement of pots for both aluminium and stainless steel referred to as pot in pot (a) whereby one pot is inserted inside the other.

Experimental procedure

Initially, water boiling tests were done with single aluminium pots or steel pots to analyze the heat uptake rate for each type of pot. The pot with a given quantity of water was placed on the electric cooker rated 1.9 kW, 220 V. A K-type thermocouple was placed inside the cooking pot to measure the temperature of the water, which was then recorded by the TC-08 datalogger at 1-minute intervals. The water boiling tests were repeated with a pot inserted into another pot with air in between the pots. Finally, the water boiling tests were carried out with pot - in- pot-in-pot but with some oil in between the pots. In all the cases, the same quantity of water was heated using the same electric hotplate, up to the boiling point, while recording the time taken. In addition, the temperature of the cooker was measured and recorded over the same time interval. This was done to estimate the quantity of heat gained by the water from the cooker.

Results and Discussions

Comparison of heating by aluminium pots with oil and with air

In this experiment, a water boiling test was performed. One aluminium pot was inserted into another with initially no oil in between the two pots. 1 L of water was introduced in the inner pot, and the experiment was conducted until boiling was reached. The K-type thermocouples were used to measure the temperature that was recorded by a TC-08 data logger after a 1-minute interval

Another water boiling test was carried out by boiling 1 L of water using two aluminium pots with oil between the pots. Figure 4 shows a comparison of the temperature profile inside the cooking pot during heating for the case when there is oil, and with no oil in between the pots. It's observed that the temperature profile obtained while using a pot in pot with oil (blue color) between the pots increased quickly to about 96ºC in 42 minutes. However, while with air it took about 60 min. to attain 96ºC (shown by green color) during the water boiling test.

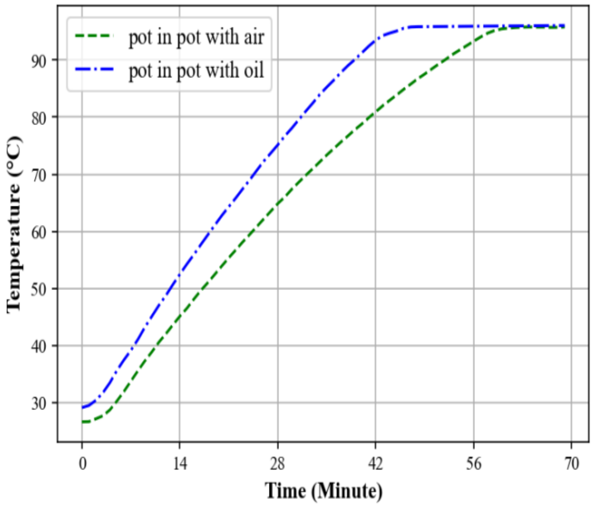

Figure 4: Experimental water boiling test when cooking with no oil in between the pots

The temperature increased significantly faster between the pots with oil as compared to the pots with air in between, as it took almost 18 more minutes for the same quantity of water to reach boiling temperature with the air medium. This is attributed to enhanced heat transfer from the oil to the cooking pot, as oil has good thermal conductivity as opposed to air as a heat transfer medium. This conclusion shows that with a material of good thermal conductivity, the rate of energy storage and energy release is high. This is particularly important for a cooking unit embedded with thermal energy storage in between the cooking pots.

Comparison of the water boiling test for a steel pot and an aluminium pot with an air medium

This experiment was carried out to observe the heating rate of a given quantity of water when using either a steel pot-in-pot or an aluminum pot-in-pot with air in between them, in separate experiments. The water added was at ambient temperatures initially

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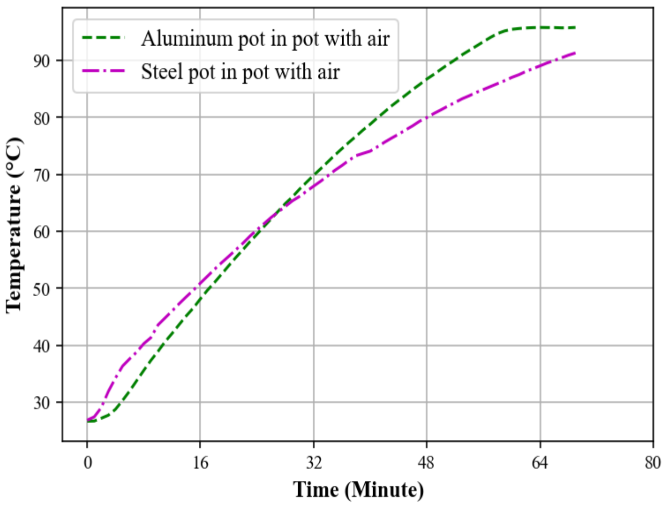

Figure 5: Experimental water boiling test of 1 L using different pot types for pot-in-pot with air in between the pots

Figure 5 shows the temperature profile inside the cooking pot when 1 L of water was heated. The temperature profile shows that generally it took about 25 min for the temperature of 1 L of water to reach 65 ºC when demonstrating the pot-in-pot with air as the medium between the pots. This is the warming temperature of water and could be used as a preheat for other applications. It was observed that initially, the temperature of the water in the steel pot was warmer than that in the aluminium pot. However, the water temperature in the aluminium pot reached the boiling temperature before that in the steel pot. This is clearly seen from the profile as the water in the aluminium pots reached the boiling temperature of about 97 ºC in about 56 minutes, while that in the steel pot was about 85 ºC at the same time. This is highly attributed to their superior thermal conductivity, and pure aluminium materials are better conductors of heat than steel or stainless material, as also demonstrated during deep frying (Alvis et al. 2009, Vanierschot and Mawire 2023). Therefore, aluminium pots could be recommended for fast cooking processes, while steel pots are recommended for slow cooking, like simmering processes.

Temperature profile during heating in a single aluminium pot and a stainless-steel pot

Figure 6 shows the MATLAB simulation results temperature profile of boiling 1 L of water for three different cooking scenarios, using an aluminium pot and a stainless pot. Initially, the aluminium pot was inserted into the stainless steel pot with no oil in between the pots. With the cooker temperature at about 250 ºC, the temperature of the water rose from 20 ºC to about 71 º C in about 800 seconds as depicted by the blue profile. The power of the cooker was then shut off (shown by red profile) and then switched on after 2400 seconds. An aluminium pot with 1 L of water was then placed on the cooker. The temperature of the water rose at a relatively high rate from 20 º C to 90 °C in only 400 seconds. The plot in Figure 6 shows the results of the experiment where the aluminium pot was inserted into the stainless pot, but with some oil in between the two pots. The addition of oil between the pots enhances the heat transfer, as shown in comparison with the pot-in-pot only. The temperature of the water rises from 20 º C to about 80 º C in about 600 seconds.

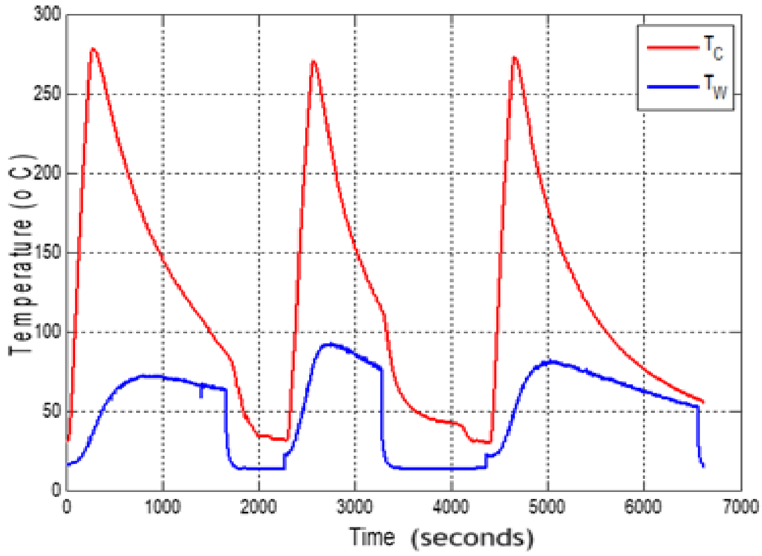

Figure 6: Temperature profiles for water and cooker for cooking with a single aluminium pot and a stainless-steel pot

The average values of the temperature rise rate of the water, $\frac{dT}{dt}$, were obtained as 0.06 º C/s for the first part (pot in pot with no oil), 0.21º C/s for the second part (single pot) and 0.09 º C/s for the third part (pot in pot with oil in between). This shows that the single pot solution has the highest temperature rate rise and that the pot-in-pot with air has the lowest. The pot in a pot with oil in between improves the temperature rise rate of the water. Assuming that the heat loss is similar for all the cooking experiments, the overall heat loss coefficient was obtained using Eqn. (3), as UA = 0.58 W/K for the first part (pot in pot with no oil), UA = 1.94 W/K for the second part (aluminium pot) and UA = 0.91 W/K for the third part (pot in pot with oil).

Using Eqn. (2), the rate of heat gain was obtained as Q = 0.12 kW for the first part (pot in pot with no oil), Q = 0.44 kW for the second part (aluminium pot only) and Q = 0.19 kW for the last part (pot in pot with oil in between the pots). The results indicate that the pot in pot with oil in between the pots has better heat transfer than the pot in pot with air. This can be attributed to the fact that the oil retains more heat than air is due to its higher thermal conductivity than air.

Temperature distribution equivalent of the heat gain and transfer rate for the aluminium pot

Figure 7 shows the simulated temperature profiles for the case of boiling with two aluminium pots (one fitting well inside the other). The hot plate was shut off at 250 º C as shown with the red profile (red). The blue profile represents the temperature of the water. In the first part, the inner pot is without oil, while in the second part, there is oil between the pots. It was observed that after the hot plate had been shut off, the temperature of water in the first part of the plot showed a rapid fall in profile as compared to the fall in the temperature of water in the second part of the plot. This may be due to the presence of oil between the pots in the second part of the plot, and therefore, the oil retains heat for longer periods as compared to air.

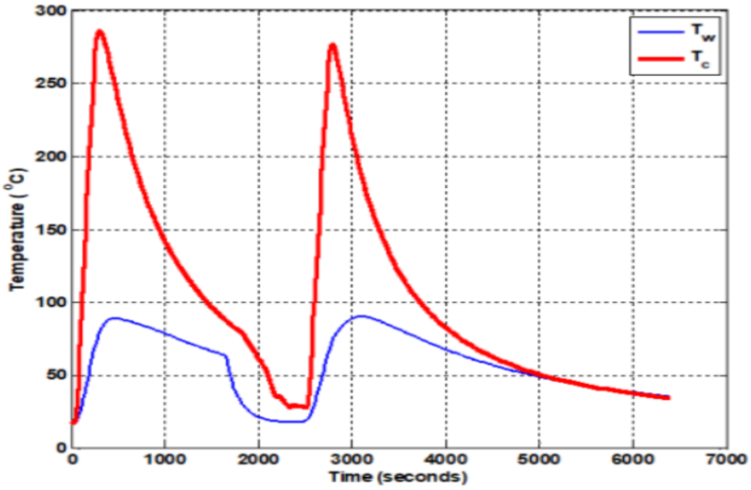

Figure 7: Temperature profile for water and cooker when cooking with aluminium pots

The average values of $\frac{dT}{dt}$ were obtained as 1.06 °C/s for the first part (with air between the pans) and 0.99 °C/s for the second part (with oil between the pans). The overall heat loss coefficient was obtained using Eqn. (3) as UA = 9.9 W/K for the first part and UA = 9.2 W/K for the second part. The results indicate that with two aluminium pots, the water temperature rise rate is generally higher than in the previous case of having an aluminium pot inserted into a stainless-steel pot. Further, the loss term values obtained reveal that having two aluminium pots not only gives a higher heat transfer but also a higher loss of heat to the ambient, as observed in the profile after 2000 seconds in Figure 7.

Estimation of the heat transfer coefficient

The model of the energy analysis of the cooking unit was validated using experimental results obtained earlier for boiling 1 L of water. Eqn. (6) was solved to predict the temperature of the water in the pot. The input parameters used were obtained from the experimental values, while the initial temperature of water was taken to be equivalent to the ambient temperature. The heat transfer coefficient, h, was then varied until the simulated water temperature profile was similar to the experimental profile.

Estimation of heat transfer coefficient when heating with oil.

Figure 8 shows the profiles obtained from the mathematical model run with the estimated values of the heat transfer coefficient and experimental results for heating water in two pots with some oil in between the two pots.

From the two plots, it was observed that the simulated profile and experimental profile have a similar trend. The average value of the heat transfer coefficient was obtained as 800 W/m^2/K for the case of having some oil in between the pots.

The convective heat transfer coefficients were estimated based on energy balances for temperatures ranging from 27 °C to about 68 °C. Previous studies give similar ranges of h-values, ranging from 722 to 827 W/m2/K at the top of the food surface and from 644 to 724 W/m2/K at the bottom (Farinu and Baik 2007).

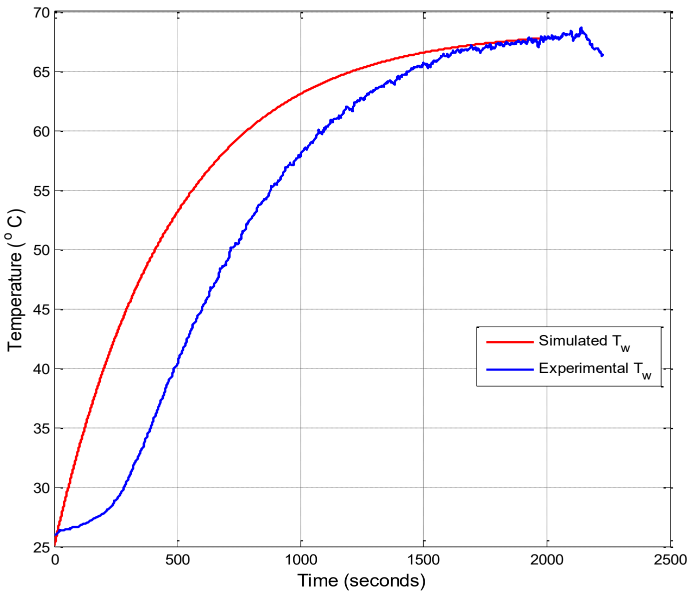

Figure 8: Experimental and simulated profile for water for pot in pot with oil in between the pots

Estimation of the heat transfer coefficient when heating with no oil

Figure 9 shows the profiles obtained from the mathematical model run with the estimated values of the heat transfer coefficient and experimental results for heating water for two pots without any oil between the pots. The average value of the heat transfer coefficient was obtained as 500 W/m^2/K. The value of the heat transfer coefficient with no oil between the cooking pots is therefore about 37% less than the value obtained with some oil in between the pots. This may be attributed to the fact that oil retains the heat and therefore enables higher heat transfer because oil has a higher thermal conductivity in comparison with air.

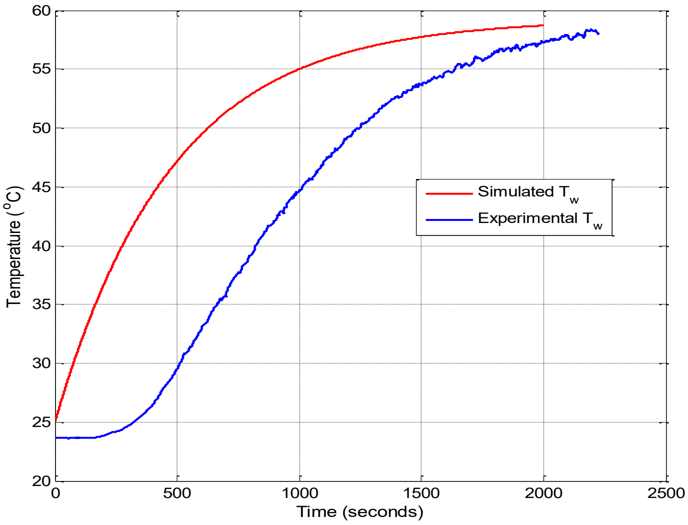

Figure 9: Experimental and simulated profile for water for two pots with no oil

The obtained results are comparable with previous works where the heat transfer coefficient values ranging from 600 to 895 W/m^2/ °C were recorded for potato cylinders cooked at temperatures ranging from 120 °C to 180 ° C (Hubbard and Farkas 1999). The results can inform the choice of heat storage material that can be integrated with cooking pots thus enabling better heat transfer for cooking applications.

Conclusion

The heat transfer mechanisms for pot-in-pot with oil and without oil were investigated in this study. The results showed that the single pot has the highest power rate gain of about 0.44 kW. Heating through water boiling tests with an oil test gave a heating power rate gain of about 0.19 kW compared to about 0.12 kW for pots without oil (with air medium). An aluminium pot was a better heat conductor than steel pots, as expected during simulation and validated by the experimental findings. Furthermore, the heat transfer coefficient was estimated from the energy balance equation as about 800 W/m^2/K with oil in between, as compared to about 500 W/m^2/K obtained for the case of no oil. Therefore, having oil in between the pots enhances the heat transfer compared to air. This work presents a useful practical learning and study resource in heat transfer media as well as an opportunity for our future research paper on the integration of heat storage with renewables for cooking applications.

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