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Remodelling Operational Parameters on the Performance of a Modified Domestic Pressure Cooker

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ABSTRACT

Sub-Saharan Africa relies about 80% on biomass for cooking. Cooking by boiling is an energy-intensive method with glaring energy losses in steam escape and convection. This leads to forest resource depletion fueling climate change. The invention of pressure cooking significantly improved time and efficiency, resolving some of the challenges of ordinary boiling. However, pressure cookers have losses through whistling steam out and convection of heat from the surface to the environment. The current study main objective sought to evaluate the impacts of various factors on energy use, cooking time, and pressure cooker efficiency. The two primary factors, mass and heating rate, were modified from 1 kg to 6 kg and 800 to 2000 W for two scenario scenarios of ceramic wool insulation, while the control remained non-insulated. They were determined experimentally, and the findings were statistically examined. The results of the modified and original pressure cooker systems were compared. It was observed that the lowest energy use, highest standby cooking time, and highest efficiency were 0.16 kWh, 97 minutes, and 93%, respectively for the cooker. From the study findings, it can be inferred that insulation improved standby cooking time by 100% and efficiency by 1.07% - 9.09%. The mass and power rate variation improved pressure cooker efficiency by 12.05% - 14.67% and 10.84% - 19.4%, respectively. Lastly, the energy to cook was found to be directly proportional to mass and indirectly proportional to insulation and power rate. These findings will guide the design of energy-efficient insulated, non-steam release pressure cookers for domestic and industrial applications.

Index-words: *Remodeling operational parameters, Modified pressure cooker, Energy efficiency, Pressure cooking energy, Standby-cooking time.*

I. INTRODUCTION

Cooking energy is a necessity for some foods during preparation. In sub-Saharan Africa, cooking energy accounts for over 90% of all household energy consumption. Unfortunately, about 80% of the cooking energy used in sub-Saharan Africa is biomass-based [1]. This leads to severe deforestation, which mainly fuels climate change among other environmental challenges. About 2.9 billion people globally, mainly from developing countries, are exposed to indoor house pollution due to unclean cooking methods [1].

Biomass cooking has challenges in the low affordability and accessibility of clean cooking technologies like improved cook stoves, time wasted in collecting fuel wood that could accomplish meaningful work, and the uncontrollability of biomass flames during cooking[2, 3]. The unclean biomass cooking stoves are the only available cooking energy option for 781 million people in sub-Saharan Africa and 2.1 billion people in Asia [4]. Indoor house pollution is responsible for about 7 million premature deaths annually due to respiratory-related complications [2, 5, 6].

Few households in sub-Saharan Africa rely on electrical cooking due to low grid connectivity, unreliable power supply, and the high cost of power [7]. Among the domestic cooking methods, induction cooking is the most economical, followed by resistive electrical cooking and LPG gas cooking for many people in developing countries of Africa, Indonesia, and Ecuador among others [3, 8-11].

Electrical cooking is the cleanest and the most preferred due to its zero emissions during cooking

[12]. Among the two main electrical cooking methods, the induction method is the safest, cleanest, and fastest [13]. The induction cooking method uses the lowest possible energy. This has been the motivation behind several research studies on solar-powered induction cookers, which is the future of clean cooking [14-17]. Moreover, due to low energy usage, studies have explored the possibility of using batteries to power induction cookers. This is during seasons of low or no sunshine availability, especially at night [18, 19].

The induction cooker automation was successfully researched, enabling it to power off when the cooking vessel is not on or when the cooking food water is depleted[20]. Induction cookers are specific to the type of material of the cooking vessels. Ferromagnetic materials such as cast iron are the best, followed by stainless steel [21]. This calls for a change in cooking vessels for aluminum-based vessels besides the purchasing cost of an induction cooker. This poses a challenge and makes induction and electrical cooking an expensive method of cooking for rural households in developing countries [9]. Electrical cooking faces also the huddle of cooking unique traditional foods which some cultures and beliefs hinder its usage [12, 17]. Induction cooking shows great prospects, hence the reason why this research experiment uses an induction cooker to heat the modified pressure cooker.

Boiling is the main energy consumer compared with other cooking methods. Where simmering allows constant steam evaporation to the atmosphere. Steam undergoes a change phase from liquid to gas, an energy-intensive process. It has been reported that steam evaporation accounts for 90%, whereas conventional losses account for 10% of the total heat losses in a cookpot [22]. To overcome heat losses through evaporation, a study used sunflower oil in one of the vessels [23]. This improved heat transfer efficiency, by minimizing evaporation. On the other hand, the study used a shiny surface or an aluminum foil to reduce heat loss via radiation.

Insulation has been widely used to save energy during cooking on an insulated electrical cooker with positive results [24]. Also, insulation reduces energy intake in the cooking process on a photovoltaic-induction cooker [25]. Similarly, insulation using a low thermal conductivity wonder bag reduces heat loss by 30% [23]. A study on the characterization of heated and pressurized water from the pressure cooker indicated that the pressure level and volume influence of the amount of food ejected the lid with a departure speed following the lid opening. This demonstrates the influence of mass on heat loss [26].

The invention of the pressure cooker has solved the constant boiling evaporation challenge and provided other benefits, such as fast cooking and less energy consumption. The working mechanisms of the pressure cooker involve increasing the operational parameters of temperature to about 120 – 130°C and pressure to about 1.5 – 1.7 bar [26-28]. Research studies to improve the efficiency of the circular-shaped pressure cooker were invented by Hawkins; a pressure lid-locking system was invented by Chavich and Toronto, [29, 30]. This was followed by the invention of the rubber seal and the steam whistling vent for steam escape that revolutionized pressure cooking [30]. The modification of the lid to have a curved shape resulted in a 14.54% increase in surface area. This accommodated more steam and allowed faster cooling at the end of cooking [29].

Many studies have been conducted on pressure cooker direct steam and convection loss reduction, including non-steam release and insulation, the use of timers in cooking, and the combination of the pressure vessel and resistive element as one unit, as seen in current electric pressure cooker (EPC) [31]. This leaves a gap in understanding how the pressure cooker modifications that led to the creation of this EPC varied, and how the EPC using the induction cooker was powered. Research indicated that an ordinary pressure cooker with steam release had some losses and 33% efficiency, while one without steam release in an insulated box had very little energy losses and an efficiency of 85% [29] and open fire boiling has very high losses efficiency of 10% and 2-3 times more time than pressure cookers [12].

This research aims to address the unfulfilled gaps in pressure cooker energy losses caused by convection and direct steam losses. The novelty of this study is to fill a gap in the body of knowledge by determining how each specific modification and its variation of parameters impact the performance of household pressure cookers.

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II. MATERIALS AND METHODS

A. Experimental Set-Up

Modifications of insulation and holes were made on the pressure cooker to accommodate thermocouples and pressure sensors. They were sealed pressure-tight without compromising its operation and were ready for data acquisition. The Arduino Uno data acquisition system was coded and engaged. The equipment set-up assembly comprised a modified pressure cooker, weighing scale, wattmeter, induction cooker, a relay, data acquisition and storage system, and A.C. electrical power supply, as shown in Figure 1. The system was ready for experimentation.

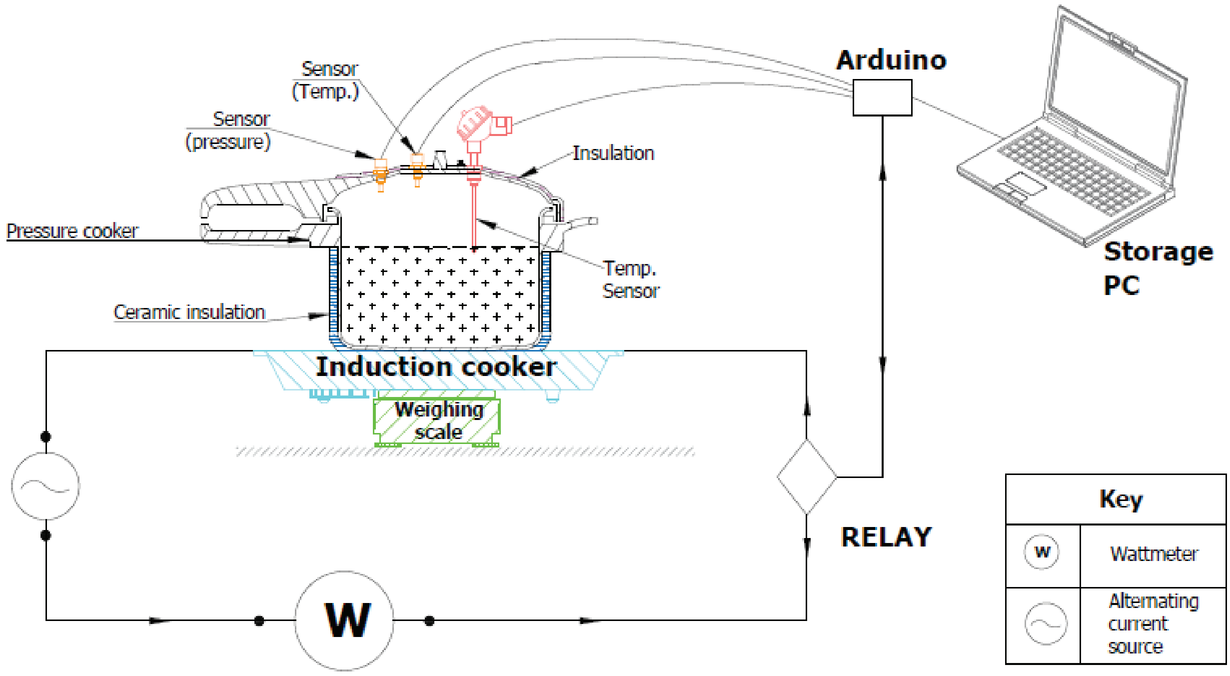

Fig. 1. Layout of the experiment

The insulation used was ceramic wool 25 mm thick, density of 128 Kg/M³, and a temperature grade of 1260 °C.

1. Experimental procedure

The mass was varied at 1, 2, 3, 4, and 6 kg. The power was set at 800, 1200, 1600, and 2000 W, for one case of ceramic wool insulation and another case of non-insulation. One kg of water was added to a non-insulated pressure cooker water at an 800 W power setting. The water was heated to boiling point on the induction cooker as per the experimental set-up in Figure 1.

It was heated to a full pressurization point where the relay put off the power at maximum pressure. The time it took to heat the water, boil the steam to full pressure, and condense all the steam back to water (standby cooking) was recorded. The energy used in heating and building up steam was also recorded. The efficiency of the pressure vessels was calculated using Equation 1.

$$\eta = \frac{\{(Mw-Ms)Cpw\Delta T1+(MsHvap)+(MsCps\Delta T2)\}}{(Energy\ consumed * 3600)} \ x\ 100$$

... Equation (1) [32]

where: Mw = Mass of water, Ms = Mass of Steam, Cpw = Specific Heat capacity of water = 4.187kJ/kg, $\Delta T1$ = Temperature of Water, (117-23) = 94K, Ms = Mass of Steam, $Hvap$ = Heat of vapourisation of Steam = 2257kJ/kg, Cps = Specific Heat capacity of Steam = 1.996kJ/kg, $\Delta T2$ Temperature change of Steam, (117-93) =24K and Energy consumed in kWh.

The same procedure was repeated for other masses (2, 3, 4, and 6 kg) at 800 W power setting. A similar procedure was replicated for the power settings (1200 W, 1600 W, and 2000 W) for all the masses in a non–insulated scenario and ceramic wool-insulated scenario. All the data were recorded, and sensitivity analysis of the model experiment

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was carried out. This was to investigate the main objective of finding out the effect of variables on pressure cooker operational parameters; on energy use, cooking time, stand-by cooking time, and pressure cooker efficiency.

The effect of mass on pressure cooker parameters concerning insulation was done by varying mass as the power setting. This was done while keeping insulation constant at a given point for a good comparison. The effect of the powering rate on pressure cooker parameters to insulation was achieved by varying the power rate, as mass and specific insulation were kept constant. Power rating varied from 800, 1200, 1600, and 2000 W at similar settings for mass and insulation. The effect of insulation on pressure cooker parameters was achieved by having two cases of non-insulation and insulation as mass and powering rate were kept constant at a given point.

III. RESULTS AND DISCUSSION

The results of the modified pressure cooking were analyzed using graphical methods and the trends were discussed and compared with the literature.

A. Effect of Mass on Heating Time to Insulation

Figure 2 shows the effect of the amount of food cooked and insulation on the heating time.

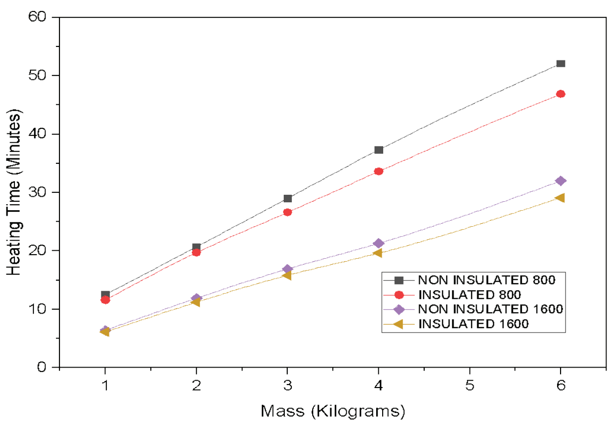

Fig. 2. Effect of mass and insulation on heating time

As the mass of food increases from 1 kg to 6 kg, the heating time increases from 7 minutes to 32 minutes for 1600 W insulated and 13 minutes to 54 minutes for non-insulated 800 W. This is because as mass increases, the number of particles to be heated also increases, hence takes more time. Therefore, a direct relationship exists between mass and heating time. The results agree with [26] who reported that the content in the pressure cooker is directly related to the amount of food ejected and the lid departure speed after opening the lid. This indicates that as the amount of food increases, the pressure increases. From Figure 2, the heating rate of 2000 W was the fastest, followed by 1600 W, then 1200 W, and lastly, 800 W was the slowest for both insulated and non-insulated cases. This is because the higher the power wattage, the higher the rate of doing the same work, resulting in less time than with lower wattages.

It can also be deduced that insulated vessels take less time compared to non-insulated vessels in all the power ratings. This is because as water is heated to near the boiling point, the non-insulated vessels lose heat to the environment faster than the insulated vessels. The ceramic wool insulation lagging increases thermal resistance, opposing heat flow to the environment. Therefore, when mass and heating rate are constant, the insulated vessel takes less time to boil and has less energy demand than the non-insulated vessel. These findings are congruent and comparable with previous studies that concluded that insulation in solar-insulated electric cooking reduces energy demand in cooking [24].

1. Effect of mass and insulation on average energy usage

Figure 3 illustrates the effect of mass on average energy use to insulation as the mass of food and water increases from 1 kg to 6 kg. The energy consumed increases from 0.16 kWh to 0.86 kWh and 0.17 kWh to 0.88 kWh for insulated and non-insulated, respectively. As mass increases, the energy consumption increases.

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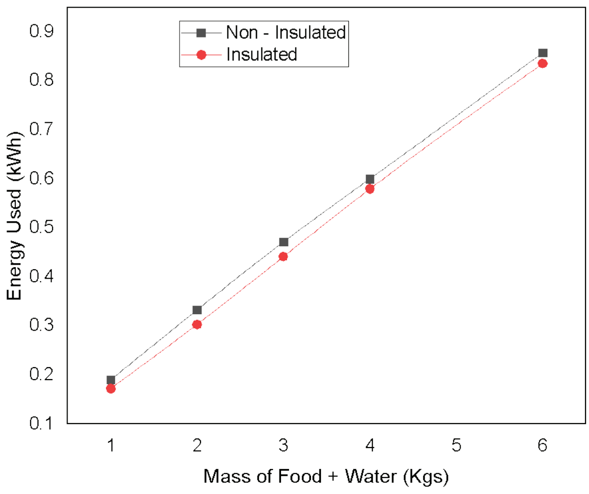

Fig. 3. Effect of mass on average energy use to insulation

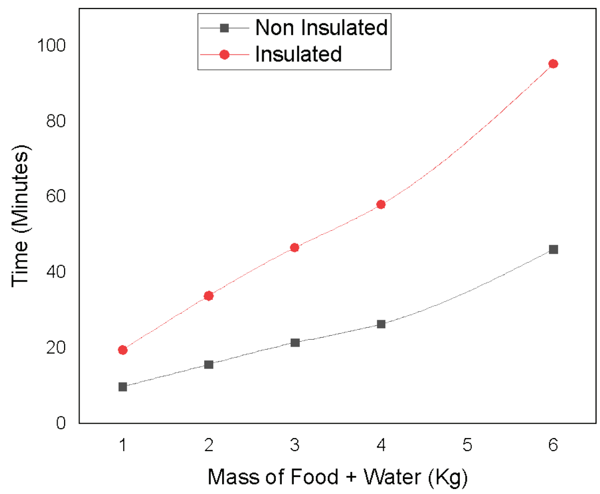

Fig. 4. Effect of mass on steam standby cooking time to insulation

This is because as mass increases, the number of particles to be heated increases; thus, needing more energy.

It can also be observed that the insulated cooker takes less energy when compared to the non-insulated for all the masses. This is because as heating continues, the non-insulated loses more heat to the environment due to natural air convection than the insulated. This takes additional energy to compensate for the loss, thus using more energy than an insulated vessel. This agrees with where insulation reduces energy demand [33].

2. Effect of mass and insulation on steam standby cooking

Figure 4 presents the effect of mass on steam standby cooking time to insulation.

From the Figure 4, it can be observed that the mass of food and water increases from 1 kg to 6 kg. There was an increase in steam standby cooking time from 10 to 48 minutes for non-insulated and 20 to 97 minutes for insulated vessels. This is an increment of 380% and 385% for non-insulated and insulated due to the increase in mass. This is because the surface area to volume ratio decreases as mass increases. This lowers the rate of heat diffusion to the environment compared with low masses that have a larger surface area to volume ratio. This causes a faster rate of heat diffusion to the environment. It can therefore be inferred that at higher masses, the rate of heat loss to the environment is higher than in lower masses.

Figure 4 shows standby cooking time changes from 10 minutes to 20 minutes and 48 minutes to 97 minutes for 1kg and 6kg, respectively. This is a 100%

and 102.1% standby cooking time increment for 1kg and 6kg, respectively, due to insulation. This shows that insulation doubles the steam standby cooking time for all the masses. This is due to the lagging that reduces the convection heat loss rate through the wall. Lagging increases resistance to heat flow, causing a delay in cooling rate. This reduced rate of cooling allows more time for food particles to interact with hot steam and water. It resulted in cooking with very minimal addition of external energy. This is the basis of this research to achieve cooking with minimal possible energy. It has also been reported that insulation in solar electric cooking prevents energy loss, thus attaining prolonged heat retention. This helped achieve effective cooking with minimal energy as also reported by [23, 34].

3. Effect of mass on average efficiency as per insulation

Figure 6 shows the effect of the increase of the mass of food and water from 1 kg to 6 kg.

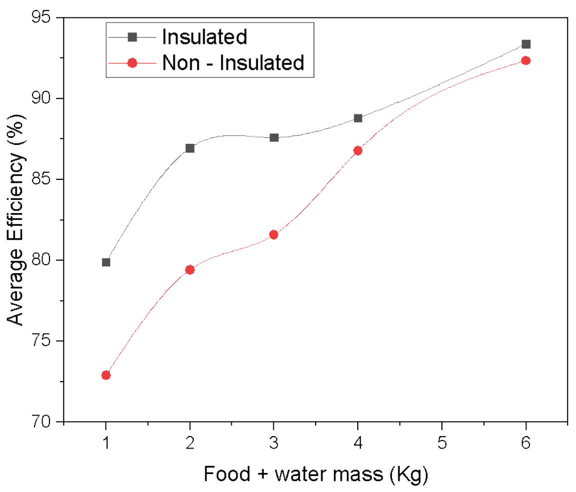

Fig. 5. Effect of amount of food on average and insulation on average efficiency

Efficiency increases by 19.4% - 10.84% due to an increase in the mass of food, while 9.09% -1.07% increase due to insulation. The increment in efficiency is attributed to the decrease in the surface area to volume ratio as mass quantity increases. This causes a reduction in the rate of heat loss to the environment by convection, thus achieving higher efficiency rates. The efficiency reported in this study agreed with cooking efficiency for rice potato beans and goat meat using a pressure cooker [32].

The insulated vessel demonstrated higher efficiency due to extra lagging, resulting in a reduced heat convection rate and lower energy consumption for the equivalent mass. These results were in agreement with Wonder Bag and photovoltaic-induction (PV-IC) experiments [23, 25].

4. Effects of powering rate on heating time and insulation level

The rate of heating increased from 800 W to 2000 W in Figure 6.

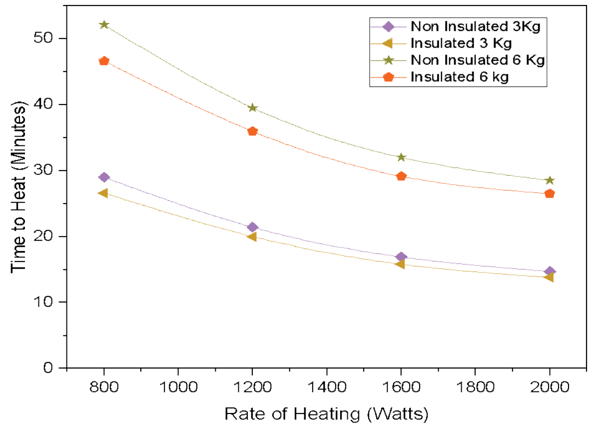

Fig. 6. Rate of heating and insulation on heating time

The time to heat decreased from 28 minutes to 13 minutes and from 29 minutes to 14.7 minutes for the 3kg insulated and non-insulated, respectively. For 6 kg, it is decreased from 53 minutes to 32 minutes and from 46 minutes to 26 minutes for the non-insulated and the insulated, respectively. There is a 50% decrease in heating time as the heating rate increases by 100%. It shows an exponential decrease in the total time to heat for a constant mass as the heating rate increases for all the cases. This is due to the increase in heat supply rate to do the same work, thus leading to less time. The exponential decrease is because as the powering rate increases the losses are constant, hence decrease in heating time is not linear it agrees induction cooking experiment [10].

The insulated vessels took less time for similar masses than non-insulated vessels. This is due to lagging in the insulated vessel, which reduces the rate of heat loss to the environment due to convection. Therefore, it takes less time to heat, unlike the non-insulated vessel, which loses heat

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to the surroundings and needs more time to replace the lost heat; hence, it is slightly slower.

5. Effect of power rate and insulation on average efficiency

As the rate of heat delivery drops, energy consumption rises somewhat due to the longer time required to heat the same amount, resulting in slightly greater loss and, thus, more energy. As illustrated in Figure 7, at higher power rates, the efficiency is higher than at lower power rates with the highest average efficiency reported at 2000 W. As the power rates increase, the efficiency increases.

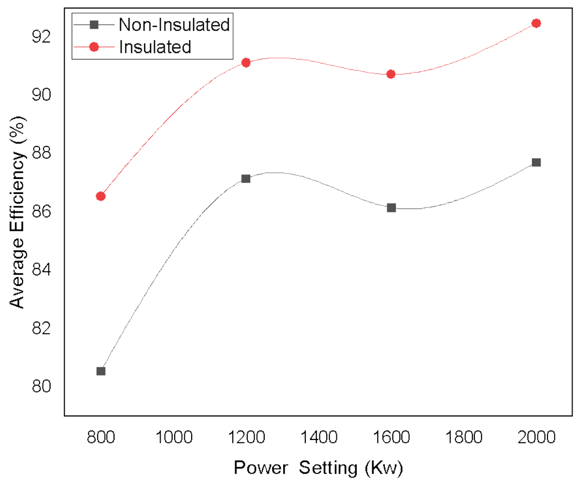

Fig. 7. The effect of power setting and insulation on efficiency

At medium power rates, the average efficiency is almost similar for both insulated and non-insulated vessels. This is because, at similar temperatures, the heat loss to the environment is the same over time. However, it takes longer to heat a fluid at lower power rates. This allows more heat loss to the environment, which needs to be replaced, resulting in slightly more energy use, making the system less efficient.

The insulated vessels were more efficient with an 83% to 93% average efficiency range. The non-insulated had an efficiency range of 75% to 86% for power rates of 800 W to 2000 W. This is an increase of 12.05% - 14.67% and 8.14% - 10.67% due to an increase in power rate and use of insulation, respectively. This is because the insulated vessel loses less energy to the environment due to lagging which reduces the convection heat loss rate to the environment. Insulation reduces energy loss by 30%, which improves efficiency. This is evident as found in the electric insulated cooker, insulation reduces the energy demand in cooking [24, 33, 34].

6. Effect of power rate and insulation on energy usage

Energy consumption varied depending on the power setting and the insulation state as shown in figure 8 below.

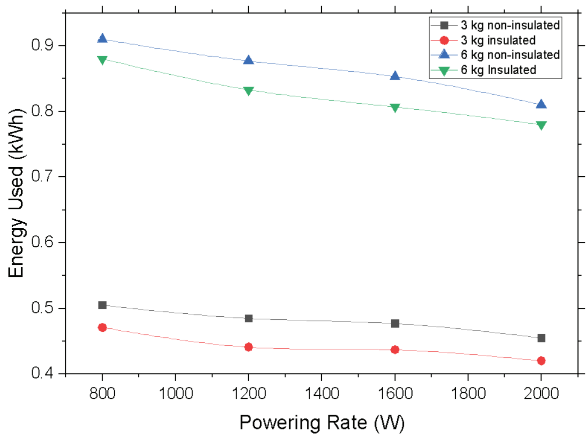

Fig. 8. The effect of powering rate and insulation on energy usage

From Figure 8, as the powering rate increases from 800 W to 2000 W, the energy consumption decreases by about 10% for both the insulated and non-insulated cases of 3 kg and 6 kg.

The decrease is because as the powering rate increases, the rate of heat loss to the environment is constant and the increase in rate of powering means less time available for heat loss to the environment, hence reduced energy consumption. The insulated has less energy consumption than the non-insulated, this is because insulation reduces heat loss to the environment this reduces the overall impact on energy demand hence less energy consumed.

Generally, it was observed that as mass increased from 1 kg to 6 kg, there was an increase of 19.4% - 10.4% and 380% - 385% in energy efficiency and standby-cooking time, respectively. As the powering rate increased from 800W to 2000W, energy efficiency improved from 12.05% - 14.67%. While as the powering rate doubled, the heating time decreased by 50%. The powering rate was independent of the standby cooking time. As insulation was introduced where there was none, the standby cooking time increased by 100% - 102%, while the efficiency improved by 8.14% – 10.67%. The use of insulation brought economy in energy usage by minimizing blatant energy waste, resulting in less energy consumption and saving resources. From the experimental results, it was seen that the highest possible amount of food and water (4 – 6 kg) and the highest power rate (2000 W) under ceramic wool insulation presented the best combination of the study parameters. These parameters minimized heating time and energy consumption while increasing energy efficiency and standby cooking capacity.

IV. CONCLUSION

It was observed that the introduction of insulation increased standby cooking time by 100%, and improved efficiency by 10.67%. It was also seen that cooking at higher power and higher mass of content had the best energy efficiency through the combination of factors and modifications of the domestic pressure. This research was only limited to the domestic pressure cooker with a maximum capacity of 10 liters. The novelty of this study was that it identified the most critical parameters influencing domestic pressure cooking, which were zero steam release and standby cooking experimentally. Future areas of interest for researchers and designers include zero steam release combined with standby cooking concepts for institutional and industrial pressure cookers that release steam. If this is accomplished, it will help to save energy that is lost while cooking, hence minimizing the climate change effect of cooking energy.

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Conflicts of Interest

The authors declare no potential conflicts of interest.

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