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Design and Development of Electrical Energy Based Local Liquor (Areki) Distillation Unit

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Abstract

In Ethiopia, many people make their living by producing and selling Areki, a locally prepared liquor obtained through a distillation process. Traditionally, Areki distillation uses clay-based units heated by burning firewood, which results in poor thermal efficiency, non-uniform heat distribution, and significant environmental impacts. This study aims to develop an electrical energy-based stove and distillation apparatus for local liquor production to achieve uniform heat transfer and reduce environmental impact. Mathematical modeling and finite difference formulations were employed to design and analyze the prototype distillation apparatus. The system was developed based on both geometrical and thermal design analyses. Experimental results show that the 860W model distillation unit achieves higher efficiency, produces better-quality liquor, and reduces distillation time compared to conventional methods and the 750W model. The study concludes that the proposed system offers significant improvements in energy utilization, cost efficiency, and environmental sustainability.

Keywords: *Areki, difdif , Distillation unit, Electrical energy, Liquor*

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1. Introduction

One of the most culturally significant traditional beverages in Africa is Areki, a clear and colorless Ethiopian distilled alcoholic drink produced through the fermentation and distillation of grains, fruits, and/or vegetables. The distillation process is complex and time-consuming, requiring specialized equipment to produce a high-quality alcoholic beverage (Dersehilign et al., 2017; Getachew, 2015).

Areki distillation has become an important economic activity and a major source of income for many households in Ethiopia. However, the process is traditionally carried out using biomass fuel burned in open air, which leads to poor energy utilization, adverse socio-economic and environmental impacts, and indoor air pollution (IAP). Prolonged exposure to IAP is associated with respiratory illnesses such as acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), and an increased risk of tuberculosis and lung cancer (Adane, 2015; Agustin et al., 2010; Gezahegne, 2008).

Figure 1

A Conventional Areki Distillation Process

(Shewangizaw et al., 2016)

1.1. Areki Distillation Stoves

Recent studies have investigated alternative energy sources for Areki distillation, specifically parabolic dish solar concentrators and biogas-fueled stoves (Adane, 2015; Shewangizaw et al., 2016).

1.2. Solar and Biogas Alternatives

The parabolic dish solar concentrator uses direct solar energy, demonstrating the ability to reach the required boiling temperature within approximately two hours and produce up to 0.3 L of Areki from 2.5 L of ‘‘difdif’’. This technology helps reduce the environmental impact of burning firewood; however, its performance suffers from low efficiency, intermittency, and time constraints, as it only operates during daylight hours (Adane, 2015).

Research on a biogas-fueled distillation stove assessed its feasibility to reduce biomass dependency, minimize waste disposal issues, and enhance renewable energy utilization (Shewangizaw et al., 2016). Despite its benefits including lower pollutant exposure, cost-effectiveness over time, and a reduced environmental footprint biogas adoption is limited in Ethiopia, often supplying less than 10% of total distillation energy (Gaia et al., 2012).

Furthermore, its use requires significant initial investment for a large biogas digester (WHO, 2000). Performance tests showed a stove efficiency of 54.8% (high flame) and 43.6% (low flame), and reduced distillation time

(Shewangizaw et al., 2016). However, biogas cannot fully replace firewood, and its feasibility depends heavily on local conditions such as cattle ownership and water availability (WHO, 2000).

The conventional Areki distillation method is time-consuming and relies on open-fire stoves that fail to provide uniform heat distribution. This inconsistent heating can cause ingredients to stick to the pot bottom, resulting in a product with an unpleasant odor that is unfit for consumption, leading to material deficits. The open-fire method also results in inefficient energy use and high greenhouse gas (GHG) emissions.

The project, Design and Development of Electrical Energy Based Local Liquor (Areki) Distillation Unit, aims to address these issues by replacing firewood with electrical energy and substituting the clay apparatus with aluminum. The goal is to design an improved stove that consumes less fuel, saves time, reduces smoke/GHGs, and increases efficiency, safety, durability, and affordability compared to the traditional stove, while also ensuring consistent heat for higher quality liquor.

2. Materials and Methods

2.1. Thermal Design Analysis

The thermal design analysis is conducted to determine the thermophysical properties of the desired system, either numerically or experimentally, based on known or required inputs. It involves developing a mathematical model for the distillation unit, incorporating energy balance equations and finite difference formulations.

2.2. ''difdif'' Mass Balance

''difdif'', a fermented cereal, serves as the primary raw material for Areki production. The ingredient proportions by mass were determined from a household in Maychew town, Tigray Regional State, located 120 km south of Mekelle, whose primary livelihood involves distilling Areki and supplying it to local consumers.

Table 1

Composition of Ingredients Measured for a Single Batch in Conventional Distillation

Ingredients	Quantity by mass	Unit
Milled Corn	50	Kg
Malt (germinated wheat)	10	Kg
Milled Hop (hops)	6	Kg
Water	125	Liter

The total mass of the mixture ('difdif') m_{dT}, is then given by;

$$m_{dT} = m_g + m_m + m_c + m_w \quad (1)$$

The total volume of the 'difdif': (V_{dT}), is given by;

$$V_{dT} = V_g + V_m + V_c + V_w, \quad V_{dT} = 227 \text{ liters} \quad (2)$$

Based on previous studies (Adane, 2015), 8 kg of 'difdif' yields about 1.5 liters of Areki in 3–4 hours. A total of 227 liters of 'difdif' can thus produce approximately 40 liters of liquor in 28–33 distillation cycles.

The ethanol yield from a large-scale production plant is approximately 1 liter of ethanol per 2.69

kg of corn grain (Adane, 2015). Therefore, 50 kg of corn grain can produce approximately 18.6 liters of ethanol. In 227 liters of 'difdif', 45% consists of a mixture of corn meal, ground hops, and malt, while the remaining 55% is water. Consequently, one liter of 'difdif' contains 0.45 liters of the solid mixture (corn, hops, malt, and alcohol) and 0.55 liters of water.

2.3. Useful Energy of the Distillation Process

The average energy required for Areki distillation is the energy necessary to raise the temperature of 'difdif' (the mixture) from room temperature to the boiling point of alcohol and to evaporate the desired amount of Areki during the distillation process. This useful distillation energy can be estimated as the sum of sensible heat, required to heat the 'difdif' from room temperature to the alcohol boiling point, and latent heat, required to evaporate a portion of the ethanol and water content in the 'difdif'. The net useful energy in distillation is the sum of the following;

1. The heat energy required to raise the sensible temperature of mass of 'difdif' from ambient temperature to boiling temperature of alcohol (70 - 78°C) (Adane, 2015). given by;
   $$[m_{dTC} * C_{p(difdif)}(T_{boil,alcohol} - T_{room})]$$
2. Heat energy required to evaporate 0.522 kg of alcohol(ethanol) to vapour, $(m_e h_e)$
3. Heat energy required to raise the sensible temperature of the remaining mass of 'difdif' after 0.522 kg of alcohol distilled to boiling temperature of water (100℃ at atmospheric pressure) and is given by;
   $$[m_{dT1} * C_{p(difdif)}(T_{boil,water} - T_{boil,alcohol})]$$
4. And the heat energy required to evaporate 0.84 kg of water to steam: $m_w h_w$

Therefore, the net useful energy is given as:

$$E_{useful} = [m_{dTC} * C_{p(difdif)}\left(T_{boil,alcohol} - T_{room}\right)] + [m_e h_e] + [m_{dT1} * C_{p(difdif,1)}\left(T_{boil,water} - T_{boil,alcohol}\right)] + m_w h_w \quad (3)$$

The specific heat capacity data of the mixture ('difdif') is unknown hence it is determined by the equation given by;

$$C_{p(difdif)} = \sum X_i C_{pi} \quad (4)$$

$$C_{p(difdif)} = \sum (X_c C_{p,corn} + X_m C_{p,malt} + X_w C_{p,water} + X_g C_{p,gesho})$$

The heat losses by convection and radiation were estimated using standard correlations, with measured surface temperatures: bottom 135°C, side 120°C, top 105°C, and ambient 25°C.

Thus, the useful energy for boiling 12 litres of 'difdif' can be calculated as;

$$E_{useful} = [10.5\text{kg} * 4.172\, kJ/kgK\ (74 - 25)\text{K}] + [0.783\text{kg} * 846\, kJ/kg] + (9.717\text{kg} * 3.857\, kJ/kgK\, (100 - 74)\text{K}] + [1.26\text{kg} * 2256\, kJ/kg]$$

The useful power per cycle distillation for 12 litres of ‘difdif’ can be calculated by:

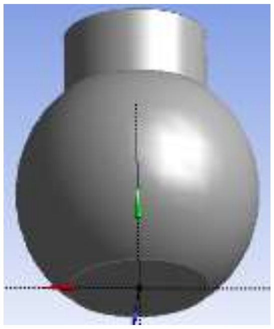
$$\text{Useful Power (P)} = \frac{E_{useful}}{Time\ taken} = \frac{6600.8kJ}{(3)3600s} = 600W \quad (5)$$

2.4. Geometrical Design Analysis

The research focuses on designing a new distillation unit based on the minimum working volume of the conventional apparatus, which is 8 Liters of ‘difdif’ per cycle.

Figure 2

Conventional Distillation Apparatus



For simplification in design and prototyping, the new unit is modelled as a cylinder with a fixed height of 300 mm. Assuming the minimum distillation volume is $0.016\, m^3$. The minimum internal radius (r) of the cylindrical unit is determined using the formula:

$$V = \pi r^2 h \quad (6)$$

The conventional clay distillation apparatus was replaced due to its poor energy efficiency, stemming from its unfavourable thermophysical properties. Clay is heavy, fragile, requires a long time to heat up, and absorbs excessive heat. Aluminium was selected for the new distillation unit because it addresses these drawbacks. Because, aluminium is abundant, lightweight, cost-effective, highly corrosion-resistant, non-toxic, and possesses excellent heat and electricity conductivity, ensuring better energy utilization and longevity compared to clay (Callister & Rethwisch, 2020).

2.5. Heat Losses of the Distillation Process

The heat transfer analysis for the distillation unit lies on energy balance. The rate of heat conducted from the electric heater must equal the rate of energy loss to the environment, which occurs through the combined effects of convection and radiation from the unit's surface (Asfafaw, 2016; Mesele et al., 2017).

To determine the total energy loss $Q_{TS,loss}$ from the surface of the distillation unit during the process, both convection and radiation losses are considered:

$$Q_{TS,loss} = Q_{T.conv,loss} + Q_{T.rad,loss} \quad (7)$$

The governing equation for the Convection heat transfer and the radiation heat transfer mechanism can be represented by basic heat transfer equations (Mesele et al., 2017; Asfafaw, 2016; Rajput, 2012).

$$Q_{conv} = A_s h_c \, \Delta T = A_s h_c (T_s - T_\infty)$$

$$Q_{rad} = \varepsilon\sigma A_s (T_s^4 - T_\infty^4) = A_s h_r (T_s - T_\infty)$$

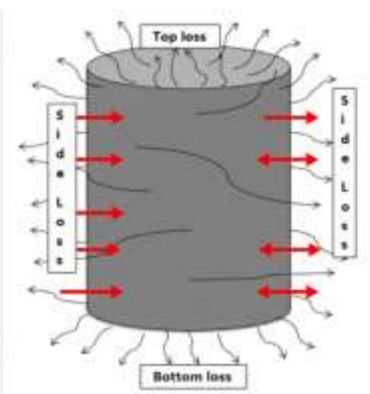
To determine the total heat loss of the system, the following assumptions were taken based up on the temperatures measured using a thermocouple from the surfaces of the conventional clay material distillation unit which is performed by burning bio-fuel in an open air.

Assumptions

1. Distillation unit bottom surface temperature (T_{bs}) 135°C
2. Distillation unit side temperature (T_{ss}) 120°C
3. Distillation unit top surface temperature (T_{ts}) 105°C
4. Ambient temperature (T_∞) 25°C

Figure 3

The Schematic Representation of Energy Loss from Distillation Unit



Thus, the total heat loss out of the surface of the distillation unit is the sum of the top, side and bottom convection and radiation heat losses.

$$Q_{TS,loss} = Q_{Tl} + Q_{SL} + Q_{Bl}$$
$$Q_{TS,loss} = 37.31W + 183W + 43W$$
$$Q_{TS,loss} = 263W$$

2.6. The Total Energy Input to the Distillation Unit

The total distillation input energy used for distillation of 12litres of 'difdif' was the sum of the total useful energy (E_{useful}) used to boil the 12litres of 'difdif' and the total energy losses ($Q_{TS,loss}$) out of that distillation pot.

$$Q_{T,input} = E_{useful} + Q_{TS,loss} \quad (8)$$
$$Q_{T,input} = 600W + 263W = 860W$$

2.6.1. Efficiency of the Distillation Unit

The thermal efficiency of the distillation stove for distilling 12 liters of 'difdif' is the ratio of the useful energy obtained to boil 12liters of 'difdif' and the total energy input to distillation process, and is given by the equation:

$$\eta_{du} = \frac{E_{useful}}{Q_{T,input}} \times 100\% = \frac{600W}{860w} \times 100\% = 70\% \quad (9)$$

2.7. Determining Size of the Stove

The aim of this study in addition to the design of distillation unit is to design an electrical stove which can provide the useful energy required for the distillation process. An electric stove was designed to provide the required energy, matching the distillation unit's dimensions (outer diameter 300 mm, thickness 10 mm). Heating coils were embedded in a clay base insulated with fiberglass. The stove was designed for operation at 750W and 860W under a 220V Ethiopian power standard. The minimum height of the stove can be obtained using the minimum volume of the 'difdif' to be poured on the distillation unit and the radius of the cylindrical pot and given by:

$$h = {}^{V}\!/_{\pi r^2} \quad (10)$$

By considering the minimum volume of the conventional cylinder = $0.008m^3$ and the external radius of the cylinder which is considered 150mm, the minimum height of the stove is given by:

$$h = {0.008m^3}/{\pi(0.15)^2} = 110.3mm$$

The stove is designed by wiring the heating coil (i.e., resistor wire) on the surface which is made up of clay. The total required input energy for the distillation process including those losses is taken in the range of (0.6-0.9) *Kw* and the line voltage in Ethiopia standard is 220V.

The heat energy generated by the heating system or stove, Q_{heat} is the input energy for the distillation process and it is a function of voltage (V) and the current (I) flowing across the heating element (Mesele et al., 2017).

$$Q_{heat} = \text{IV} \qquad (11)$$

$$q_{flux} = \frac{Q_{heat}}{Surface\ Area} = \frac{860w}{\pi r^2 + 2\pi rh}$$

2.8. Materials

The necessary materials used for this research are mainly 'difdif' which is a mixture of fermented cereals by their desired amount per batch process and fermented 3 to 5 days. Water is used for condensing purpose of the evaporated liquor.

Figure 4

'Difdif' Mixture

The study's instrumentation included a power metering device to measure electrical energy input in kilowatt-hours (kWh), and a Data Logger connected to a K-type thermocouple for temperature monitoring. The thermocouple, a sensor made of two dissimilar metal wires, transmits temperature data to the Data Logger, which subsequently transfers it to a computer for display as either tabular data or a graph plotting system temperature versus time taken.

Figure 5

Elucidates Power Meter and Data Logger with K-Type Thermocouple

Note. Power meter (a) and data logger with K-Type thermocouple

When the evaporation process starts the evaporated liquor coming through the condensing tube is stored in a condensate tank and further condensation takes place within this tank.

Figure 6

Condensate Tank

2.9. Experimental Setup

The comprehensive experimental setup, which is detailed in Figure 7, was designed to measure the heat distribution throughout the liquor distillation system over time using eight K-type thermocouples. These sensors were meticulously placed at key points: two monitored the side and bottom surfaces of the stove; two were positioned on the internal and external side surfaces of the distillation unit; two were submerged in the food mixture, recording temperatures at the bottom and midway points; and the final two measured the crucial vapor temperature at the condensing tube inlet and the final condensed liquor temperature at the outlet.

Figure 7

Experimental Setup of the Electrical Areki Distillation System

Steps Followed during Investigation of the Experiment are as follows:

1. Connect and verify the placement of all eight K-type thermocouples on the designated surfaces of the distillation unit and stove.
2. Ensure all eight thermocouples are properly connected to the Data Logger and that the Data Logger is communicating accurately with the computer.
3. Confirm that all thermocouples display a consistent and accurate reading of the ambient temperature before commencing the experiment.
4. Pour the food mixture (‘difdif’) into the distillation unit. Close the unit by attaching the condensing tube, and position the tube's outlet over the condensate collection tank.
5. Connect the electric stove to the power source and immediately start the Data Logger to begin capturing temperature readings from all eight thermocouples simultaneously. Then, activate the regulating switch to begin heating.
6. Stop the heating and stop the data capture once the target test temperature is reached and save the acquired data, then proceed to analyze and interpret the experimental results.

3. Result and Discussion

3.1. Results from the Thermal Design Analysis

Table 2 shows results obtained from numerical analysis and each result are indicated from the equation numbers at the numerical design analysis. These results are obtained from thermal analysis of the system starting from the total mass of the food item obtained during the mass analysis total mass of ‘difdif’ (total mass of ‘difdif’ ingredients $m_{dT} = 191Kg$ which is the total mass of the ‘difdif’ for a single batch distillation process and the by volume $V_{dT} = 227$ liters of ‘difdif’ were used.

Table 2

Results Obtained from the Thermal Design Analysis of the System

Parameter	Result	Equ.
Total mass of 'difdif'	$m_{dT} = 191K_g$	(1)
Total volume of 'difdif'	$V_{dT} = 227litres$	(2)
Specific heat capacity of 'difdif'	$C_{p('difdif')} = 2.7814\ kJ/kgK$	(4)
Useful energy of the system for 8L	$E_{useful} = 3632.75kJ$	(3)
Useful energy of the system for 12L	$E_{useful} = 6600.8.75kJ$	
Useful Input power for 8L 'difdif'	$Power = 337W$	(5)
Useful Input power for 12L 'difdif'	$Power = 600W$	
Total heat loss from the system	$Q_{TS,loss} = 263W$	(7)
Total input power to the system for 8L	$Q_{T,input} = 600W$	(8)
Total input power to the system for 12L	$Q_{T,input} = 860W$	
Efficiency of distillation unit for 8L	$\eta_{du} = 56.2\%$	(9)
Efficiency of distillation unit for 12L	$\eta_{du} = 70\%$	
Input power as heat flux	$q_{flux} =\approx 5000\ {}^{W}/_{m^2}$	(11)

Note. Equ= Equation number

The useful energy $E_{useful} = 3632.75kJ$ is the input energy applied to the distillation process which is considered with no losses to obtain the desired amount of distilled liquor.

The useful energy $E_{useful} = 3632.75kJ$ is the input energy applied to the distillation process, assuming no losses, to obtain the desired amount of distilled liquor. The power input for 8 liters of 'difdif' is 337 W, while 600 W is required depending on the useful energy of the process. The distillation process was assumed to take three hours per cycle. For the distillation of 8 liters of 'difdif', the total input energy to the system is the sum of the useful energy and the total heat losses (combined radiation and convection) from the surfaces of the stove and distillation unit. Based on the analysis, the thermal efficiency of the distillation unit for 8 liters of 'difdif' was calculated, whereas under similar conditions, the system achieved a higher thermal efficiency of 70% when distilling 12 Liters of 'difdif'.

3.2. Fabrication

The distillation unit shown in Figure 8 was fabricated based on the thermal design analysis using aluminium as the primary material. It has a height of 30 cm, an outer diameter of 30 cm, an inner diameter of 29 cm, and a wall thickness of 0.5 cm. The accompanying clay stove, insulated with fiberglass and covered with aluminium foil, is designed to ensure effective thermal integration during operation. With dimensions of 10 cm in height, 32 cm in outer diameter, and 30 cm in inner diameter, the stove incorporates two power input options (750 W and 860 W) to evaluate the effect of varying energy inputs on the distillation performance.

Figure 8

Fabricated Distillation Unit and Electric Stove

Note. Distillation unit (A), stove (B), and Stove and distillation unit (C) from left to right, respectively.

3.3. Experimental Findings

The experimental setup involved preparing the 'difdif' for the distillation process and assembling the distillation unit with the electrical stove. The experiments were conducted under varying power inputs, with eight trials in total—four using the 750 W model and four using the 860 W model. Each experiment utilized 8 liters of 'difdif', and parameters such as distillation time, energy consumption, and liquor quality were measured and analyzed.

Three experiments were taken for the 750W capacity model and results for energy consumption are indicated in table 3. It can be seen the system has consumed 3kWh electrical energy over one batch of distillation process. This process took 4.16hrs of distillation period giving an average heating capacity of 750W.

Table 3

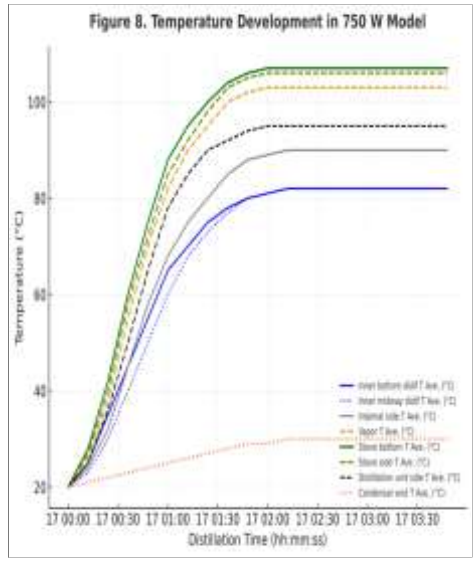
Power measurement readings for the 750W model stove

Time per sample (20 seconds/sample)	Power meter readings (kwh)
0:8'20	0.1
0:16'40	0.2
0:25'00	0.3
0:33'20	0.4
0:41'40	0.5
0:50'00	0.6
0:58'20	0.7
1:06'40	0.8
1:15'00	0.9
1:23'20	1.0
2:46'40	2.0
4:10'00	3.0

The graph shown in **Figure 8**, presents a comprehensive view of temperature variations across different sections of the distillation system throughout the distillation period. Each curve represents the temperature change in a specific location, illustrating the heat distribution and dynamic thermal behavior of the system as it progresses.

Figure 9

Temperature Profile Observed in the 750W Model



The Inner Bottom 'difdif' Temperature (blue dots) rises sharply, indicating efficient heat transfer from the stove to the base of the distillation unit, and stabilizes near the boiling point, signifying rapid thermal equilibrium. The Internal Side Temperature (green line) increases gradually, reflecting slower lateral heat conduction, while the Stove Bottom Temperature (light blue line) shows a rapid rise followed by a stable plateau, confirming consistent heat delivery. The Distillation Unit Side Temperature (dashed blue line) follows a similar pattern but at lower values, suggesting heat losses through the sides.

The inner midway 'difdif' Temperature (red dashed line) increases slowly and stabilizes at a lower level, indicating thermal stratification and delayed heat distribution within the mixture.

The Vapor Temperature (purple dashed line) rises steadily to a plateau, representing stable vaporization once boiling begins. The Stove Side Temperature (orange line) stabilizes below the stove bottom temperature, confirming lateral heat transfer with some losses. The Condenser End Temperature (brown dashed line) remains lowest, reflecting effective cooling and condensation. The system reaches a stagnation temperature of approximately 90°C within 2 hours and 40 minutes, while the bottom surface attains 100°C. These temperature profiles highlight the heat transfer behavior across the unit and confirm that steady-state conditions are achieved, ensuring efficient and continuous distillation.

Three experiments were conducted using the 860 W capacity model, and the results for energy consumption are presented in Table 4. The system consumed approximately 3 kWh of electrical energy per batch during the distillation process, which lasted 3.4 hours, corresponding to an average heating capacity of 860 W.

Table 4

Power Measurement Readings for the 860W Model Stove

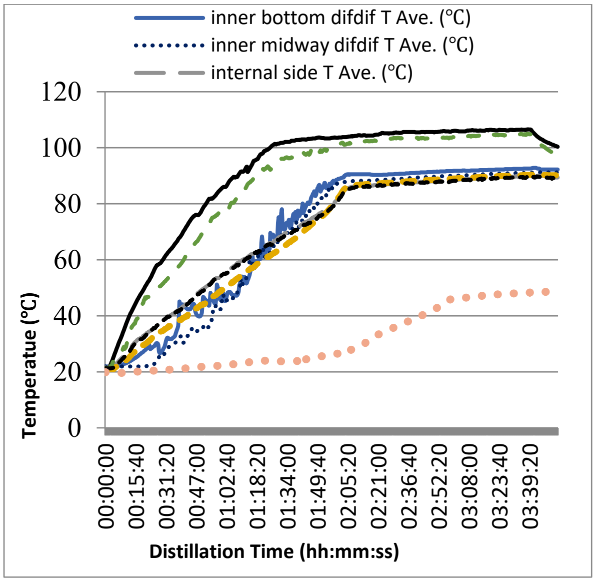
Time per sample hour (20 seconds/sample)	Power meter readings in kilo watts (kWh)
0:7’20	0.1
0:14’40	0.2
0:22’00	0.3
0:29’20	0.4
0:36’40	0.5
0:44’00	0.6
0:51’20	0.7
0:06’00	0.8
1:06’00	0.9
1:13’20	1.0
2:26’40	2.0
3:40’40	3.0

The figure illustrates the temperature evolution at various points within the distillation system throughout the distillation period. Each curve represents the average temperature recorded at a specific location, providing insights into the heating pattern, heat transfer efficiency, and overall thermal dynamics of the system.

The fluctuations occur due to density differences within the ‘difdif’ mixture, which consists of food components and water with varying densities. The denser portion settles at the bottom of the distillation unit, while the lighter mixture floats above. As the bottom surface is heated, its temperature and buoyancy increase, causing it to rise and exchange positions with the cooler upper layer. This convective circulation continues until the mixture reaches its boiling temperature.

Figure 10

Temperature Profile Observed in the 860W Model



The Inner Bottom ‘difdif’ Temperature (solid blue line) rises steeply in the initial phase, indicating effective heat transfer from the stove, and quickly reaches a steady state, allowing efficient boiling at the bottom. The Internal Side Temperature (green line) increases more gradually, reflecting slower lateral heat conduction, while the Stove Bottom Average Temperature (solid black line) climbs rapidly and remains high, highlighting the stove’s role as a continuous heat source.

The Distillation Unit Side Temperature (dashed black line) follows a similar trend to the internal side temperature but stabilizes slightly later, likely due to insulation effects or heat losses. The Inner Midway ‘difdif’ Temperature (dotted blue line) rises slowly and plateaus lower, suggesting thermal stratification and limited convection within the ‘difdif’.

The Vapor Temperature (dashed purple line) increases steadily to a plateau, representing consistent vaporization, while the Stove Side Temperature (orange dashed line) stabilizes at a high level, confirming lateral heat distribution. The Condenser End Temperature (dotted red line) rises gradually but remains much lower than other zones, indicating effective cooling and condensation. Overall, the system reaches an average stagnation temperature of approximately 95 °C within 2 hours, with the bottom surface peaking at 106 °C.

These profiles demonstrate efficient heat transfer and distribution, achieving steady temperatures in key regions for optimal vaporization and condensation while maintaining low temperatures in the condenser. Furthermore, experimental results show that from the 750W capacity model stove, one cycle took 4.2hrs with the input power of 750W per hour and 3000Whr per cycle which increases 50minutes as compared with the 860W capacity stove model.

The bottom surface of the distillation unit is exposed to electrical heat flux using an electrically powered stove. As indicated in **Figure 10** the temperature rises of the distillation unit from ambient (25℃) to its maximum temperature (equilibrium value 106℃) at 170minutes using 860W power or $5079W/m^2$ heat flux and from ambient (25℃) to its maximum temperature (equilibrium value 97℃) at 200minutes using 750W power or $4235.5W/m^2$ heat flux.

3.4. Energy and Economic Evaluation

3.4.1. 750W Model

The tariff off electricity is given in kilowatt hour (kWh), the formula to convert the Watt and Hour into kWh is given by:

$$\mathrm{kWh} = \frac{\mathrm{W\ x\ Hours}}{1000} = \frac{\mathrm{750w\ x\ 4.33hours}}{1000} = 3.247\mathrm{kWh}$$

According to the Ethiopian electricity tariff for low-consumption households (up to 50 kWh), the rate is 0.7571 Birr per kWh.

$$3.247 \mathrm{\ x\ } 0.7571 = 2.46\mathrm{birr}$$

Since the process typically operates during the daytime, about 5 cycles are completed per day. Therefore, the total electricity cost per day is:

$$2.46\text{birr x } 5 = 12.3\text{birr}$$

3.4.2. 860W Model

One cycle took 3:30’00 hours with the measured 860W input power per hour. The tariff off electricity is given in kilowatt hour(kWh), (~0.7571 ETB)

$$\text{kWh} = \frac{\text{W x Hours}}{1000} = \frac{860\text{w x } 3.5\text{hours}}{1000} = 3.01\text{kWh}$$

The price of electricity consumption is given by:

$$3.01 \text{ x } 0.7571 = 2.3 \text{ birr}$$

The price of electricity consumption per day is given by;

$$2..3\text{birr x } 5 = 11.5\text{birr}$$

Electricity consumption per cycle was 3.25 kWh (750W model) and 3.01 kWh (860W model). At a tariff of 0.7571 ETB/kWh, the cost per cycle was 2.46 ETB and 2.3 ETB, respectively far lower than the 25 ETB per cycle cost of traditional firewood use.

3.5 Liquor Characterization

Characterization of Areki liquor using the Anton Paar DMA 4500 M density meter and pH meter provided key insights into its ethanol content, density, and acidity. Ethanol levels ranged from 38% to 42% v/v, with a measured density of 0.94674 g/cm³, consistent with typical ethanol-water mixtures. The pH of 4.61 indicates slight acidity, likely from organic acids formed during fermentation. These results underscore the importance of quality control in traditional liquor production, supporting consistency, fermentation monitoring, and consumer safety.

4. Conclusion

This study was conducted to evaluate the suitability of an electrically powered stove as an alternative to traditional firewood for local liquor distillation. The distillation unit is made of aluminum to improve its physical and thermal properties for mini-household operations. Thermal analysis confirmed that aluminum provides better heat transfer and stability compared to traditional clay units, making it more suitable for efficient distillation.

The newly developed electrical distillation unit is more energy-efficient and cost-effective than traditional firewood-based methods. Traditional distillation consumes approximately 25 birr per cycle and over 4 hours and 30 minutes per batch, while the new unit operates at a cost of 2.45–2.65 birr per cycle and reduces the process time to 3 hours and 30 minutes. The aluminum unit can be operated using a 750 W stove, which lowers electricity costs to 2.456 birr per cycle but extends the distillation time to 4 hours and 30 minutes, or an 860 W stove, which achieves faster processing with a slightly higher cost of 2.65 birr per cycle. The 860 W model demonstrates superior thermal performance, balancing speed, temperature control, and cost-effectiveness.

Overall, the electrical system improves safety, product quality, and environmental impact while reducing health risks associated with smoke exposure. The distillation unit achieves efficient thermal management from heating and vaporization to condensation, with stable temperatures in critical regions. Thermal stratification within the 'difdif' was observed and may be optimized through improved internal heat distribution, ensuring consistent and efficient distillation for household-scale liquor production.

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Data Availability Statement

The original data in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Nomenclature

$C_{p(difdif)}$ Specific heat of 'difdif' $[J/(Kg.K)]$

D_i Internal diameter [m]

D_o Outer diameter [m]

E_{useful} Net useful energy $[kJ]$

m_{dT} Total mass of 'difdif' $[Kg]$

m_{dTC} Total mass of 'difdif' $[Kg]$

m_e Mass of ethanol $[Kg]$

m_g Mass of milled hops (hop flour) $[Kg]$

m_m Mass of milled malt (malt flour) $[Kg]$

m_w Mass of water $[Kg]$

q_{flux} Heat flux $[W/m^2]$

Q_{clc} Side convection heat loss $[w]$

Q_{rlc} Radiation heat loss $[w]$

$Q_{T,input}$ Total input heat energy $[w]$

$Q_{T.conv,loss}$ Total convection heat loss $[w]$

$Q_{T.rad,loss}$ Total radiation heat loss $[w]$

$Q_{TS,loss}$ Total heat loss $[w]$

T_a Ambient temperature [°C]

$T_{boil,alcohol}$ Boiling temperature of alcohol [°C]

$T_{boil,water}$ Boiling temperature of water [°C]

T_{bs} Distillation unit bottom surface temperature [°C]

T_f Mean film temperature [°C]

T_{room} Room temperature [°C]

T_s Surface temperature [°C]

T_{ss} Distillation unit side temperature [°C]

T_{ts} Distillation unit top surface temperature [°C]

T_∞ Surrounding fluid temperature [°C]

V_c Volume of corn$[l]$

V_{dT} Total volume of the 'difdif'$[l]$

V_g Volume of hops$[l]$

V_m Volume of malt$[l]$

V_e Volume of ethanol $[Kg/m^3]$

V_w Volume of water$[l]$

X_c Mass fraction of corn

X_g Mass fraction hops

X_m Mass fraction malt

X_w Mass fraction water

Greek letters

ρ_w Density of water $[Kg/m^3]$

ρ_m Density of malt $[Kg/m^3]$

ρ_g Density of hops $[Kg/m^3]$

ρ_c Density of corn, $[Kg/m^3]$

ρ_e Density of ethanol $[Kg/m^3]$

σ Stefan-Boltzmann constant= 5.67×10^{-8} $[W/(m^2.K^4)]$

ε Emissivity of the surface

μ Dynamic viscosity, $[kg/(ms)]$

ν Kinematic viscosity $[m^2/s]$

α Thermal diffusivity

β Thermal expansion $[K^{-1}]$

η_{ds} Efficiency of the distillation stove [%]

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