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Research Article

Performance Investigation of Ethiopian Local Drinking Alcohol Distillation System Using Solar Dish Concentrator

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In Ethiopia, in addition to the large quantity of biomass consumption per year for daily cooking, production of the traditional local "Areke" consumes large amounts of fire wood which further accelerates deforestation. This study introduces solar-based technology for distillation of the local "Areke" using an indirect heating system. A solar parabolic dish collector with an aperture diameter of 0.9 m and an improved truncated cone cavity absorber were installed. The heat transfer process is governed by the principle of natural circulation, boiling, and condensation between a receiver and a distillation column. The experiment was conducted in Debre Birhan city at 20°C ambient temperature and atmospheric pressure of 0.722 atm. The surface temperature of the truncated cone cavity absorber attained a maximum temperature of 300.3°C, and the thermal efficiency attained by the collector was 54.6%. The production efficiency of the solar thermal local alcohol "Areke" distillation system was found to increase by 1.67% compared to the traditional firewood distillation system.

1. Introduction

Energy is indispensable for human development in the present day civilization for reducing poverty and for achieving an improved standard of living. Nowadays, several researches relating to energy efficient devices and processes are being conducted. This is due to the fact that energy efficiency has gained considerable importance in the recent years. In developing countries, biomass has dominated the national energy consumption for many years. Majority of the population in developing countries rely on the traditional biomass sources such as wood, agricultural residues, and animal dung, exacerbating the problems of environmental and land degradation [1]. About 80.1% of the total population of Ethiopia is living in rural areas and only 44.98% of the total population has access to electricity [2]. Majority of the population in Ethiopia use biomass fuels at the household level which would account for 88% of the total national energy consumption. The industrial sector consumes 4%, transportation sector consumes 3%, and services and other sectors consume 5%. Nearly 50% of the urban households depend on the traditional biomass and almost all rural people depend on fire wood, dung and agricultural residues for cooking. Furthermore, a negligible percent of people use other alternatives such as kerosene [1].

According to the Ethiopian ministry of water, irrigation, and energy, the energy policy of the country broadly is aimed at ensuring energy supply for the development of agriculture and industry at reasonable prices, shifting from the traditional energy resources to modern ones, attaining energy self-sufficiency, improving the energy use and its efficiency, and ensuring the development and utilization of environmentally friendly, renewable energy resources derived from natural resources such as solar, wind, tides, and geothermal heat [3].

"Areke" is a traditional, homemade alcoholic drink of Ethiopia, and it is widely consumed in all regions of Ethiopia. The most famous "Areke" producing areas are Arsi Negele, Dembecha, and Debre Birhan. "Areke" is produced from a mixture of ingredients such as milled "Gesho"

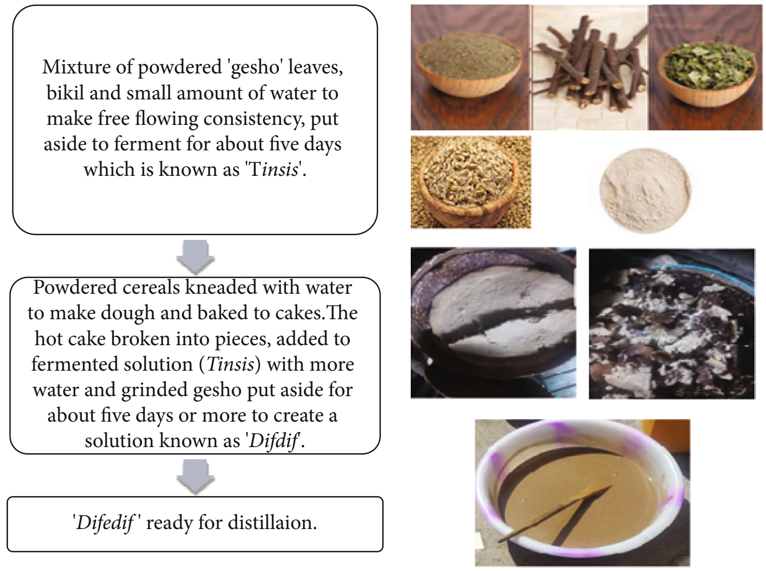

Figure 1: "Difdif" preparation process and its ingredients.

(Rhamnus prinoides), finely ground and baked cereals, malt, and water called mash (locally named as "Difdif"), followed by a distillation process [4].

Recent research findings revealed that around 3,500 households in Arsi Negele are engaged in the production of "Areke" which is sold in the market in colorful jugs across Ethiopia. It is also exported to neighboring countries like Kenya and Djibouti [5]. A household produces 150 liters of "Areke" in six working days with the traditional method that consumes an average of 450 kg of fire wood for the distillation process [5]. No substantial study has been conducted in Ethiopia towards improvement of the traditional, inefficient "Areke" distillation stoves by means of efficient modern stoves or use of alternative renewable energy sources like solar energy. Therefore, there is a strong motive for improving the efficiency of the distillation process either by developing energy efficient distillation stoves or by replacing fire wood with solar powered devices such as solar collectors and solar energy being a renewable, environmentally friendly, and pollution free energy source.

In order to substitute the fire wood with nonpolluting thermal energy source, Shewangizaw et al. [5] have conducted a numerical and experimental analysis of biogas stove for "Areke" distillation. The biogas flow rate was determined to meet the power input required for the distillation process. Here, 50% optimum biogas stove efficiency was obtained.

Various researches have been carried out using solar energy as a source of thermal energy for distillation processes. Some of them are listed as follows: Pablo et al. [6] have conducted the thermal analysis of solar distillation system for ethanol water solutions. Here, the effects of volumetric flow rates and thermal capacities of an ethanol distillation systems were studied. Jorapur and Rajvanshi [7] reported the successful use of solar energy for distillation of alcohol by using a flat plate solar collector system coupled to a pilot-scale distillation plant with a capacity of 1.8 l/h of 95% v/v ethanol. Ayuthaya [8] has developed a mathematical model for predicting the productivity of an ethanol solar basin. Mohamed et al. [9] studied the performance of solar dish concentrator for water heating. The dish was fabricated using galvanized steel, and its interior surface was covered by a reflecting layer with reflectivity up to (76%), and equipped with a receiver at the focal position. Pablo et al. [6] have conducted an experimental work on a small solar still and showed that solar energy can be used for alcohol distillation. Ibrahim [10] has reported the design and development of a parabolic dish solar water heater for domestic hot water application for which a thermal efficiency of 52–56% was obtained from the experimental test. Tesfay et al. [11] have experimentally studied a solar thermal stove which generates steam by concentrating sun rays using a parabolic dish collector. The steam was used to bake "Injera" using indirect steam at a temperature range of 135–160°C.

Figure 2: Traditional "Areke" distillation.

2. Materials and Methods

2.1. Local "Areke" Production Process. In the traditional "Areke" production system, the "Difdif" preparation process contains three phases as shown in Figure 1.

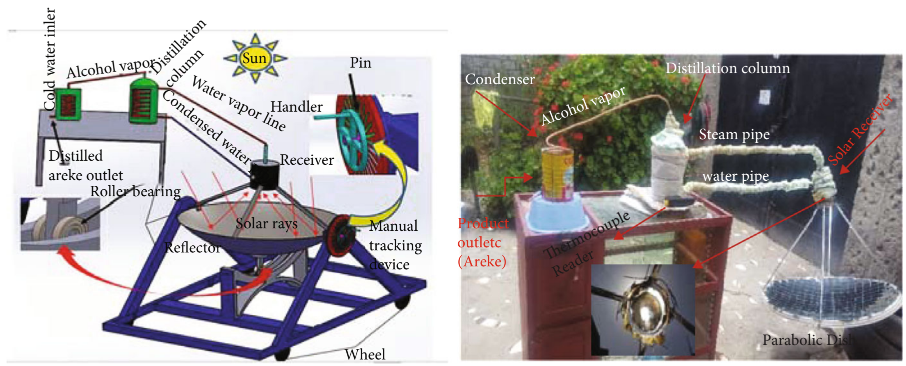

Figure 3: Schematic diagram (a) and experimental setup (b) of solar thermal local "Areke" Distillation system.

Table 1: Specification of parabolic solar dish collector.

Sr. no	Parameters	Unit	Value
1	Aperture diameter	m	0.9
2	Aperture area	m^2	0.64
3	Diameter of receiver	m	0.075
4	Diameter of distillation column	m	0.12
5	Depth of parabola	m	0.11
6	Diameter of copper coil	m	0.008
7	Focal distance	m	0.45
8	Rim angle	Degree	83.52
9	Concentration ration	—	144

2.1.1. Distillation Column. The traditional Areke distillation system (Figure 2) contains a distillation column, condensing pipe, and cooling tub. Heat is supplied to the distillation column by open combustion of firewood which has significant heat loss and hence consumes large amount of fire wood.

2.1.2. Condensate Pipe and Cooling Tub. In the traditional "Areke" distillation process, the condensate pipe made of bamboo and having a small opening at one end is inserted in the distillate collector flask, while the larger opening at the other end is inserted into the opening on the lid covering the distillation column. The condensation cooling tub is an open container filled with cooling water and the distillate collector flask. The distillate collector flask is immersed in the cooling water.

In this study, a solar parabolic dish collector is used as solar thermal energy concentrator for replacing fire wood. The solar parabolic dish collectors can provide high enough temperatures that can be used for various applications like boiling, cooking, and heating [10–15].

2.2. Description of the Study Area. Debre Birhan town is selected for the study area due to the fact that Debre Birhan is one of the leading "Areke" producing and consuming areas in Ethiopia. It is located in the north Shewa zone of the Amhara Region, about 130 kilometers north east of the capital city, Addis Ababa, on the paved highway to Dessie. Also, globally, the town can be located at a latitude of 9.633°N, longitude of 39.5°E and at an elevation of 2,750 m above sea level.

2.3. Experimental Setup. The schematic diagram of the experimental setup provided in Figure 3 shows that the local "Areke" distillation system uses solar energy as a source of thermal energy, collected by a parabolic dish concentrator fitted with a manual tracking system. The receiver converts the concentrated radiation energy into heat energy which is used to raise the temperature of the working fluid inside the receiver. The principle of boiling the "Difdif" and condensing of the "Areke" is demonstrated. The system uses naturally circulating steam as a heat transfer fluid between the receiver and the distillation column; i.e., the hot fluid is transported to the distillation column by density difference.

The distillation column is made from clay, and it is used to store the solution mixture called "Difdif." Inside the distillation column, there is a helical copper coil through which the hot fluid flows and transfers heat to the "Difdif" placed inside the distillation column in a manner similar to a shell and tube heat exchanger.

The temperature of the "Difdif" inside the distillation column rises until it reaches the boiling point of ethanol. Subsequently, the ethanol vapor collected from the distillation column enters into the condenser via the condenser pipe. The ethanol vapor releases its latent heat of condensation by exchanging heat with the cold water in the condenser and is liquefied; this liquid ethanol is locally called "Areke."

Polystyrene foam is used as a thermal insulator to reduce the heat loss from the pipe, distillation column, and receiver.

In order to concentrate the solar radiation, a standard Eurostar satellite dish of 0.9 m diameter and 0.45 m focal length is used with pieces of reflective glass pasted on the top surface to increase the reflectivity. The detail geometric parameters of the dish are given in Table 1 which is calculated in a fashion similar to Kalbande et al. [16].

The temperature readings from the experiment were taken by using K-type thermocouples installed at different locations as shown in Figure 4. Accuracy of the thermocouple reader is 0.015% rdg+1°C and uncertainty of 0.74%. The temperature data was taken every 5 minutes from each

FIGURE 4: Installation position of the thermocouple.

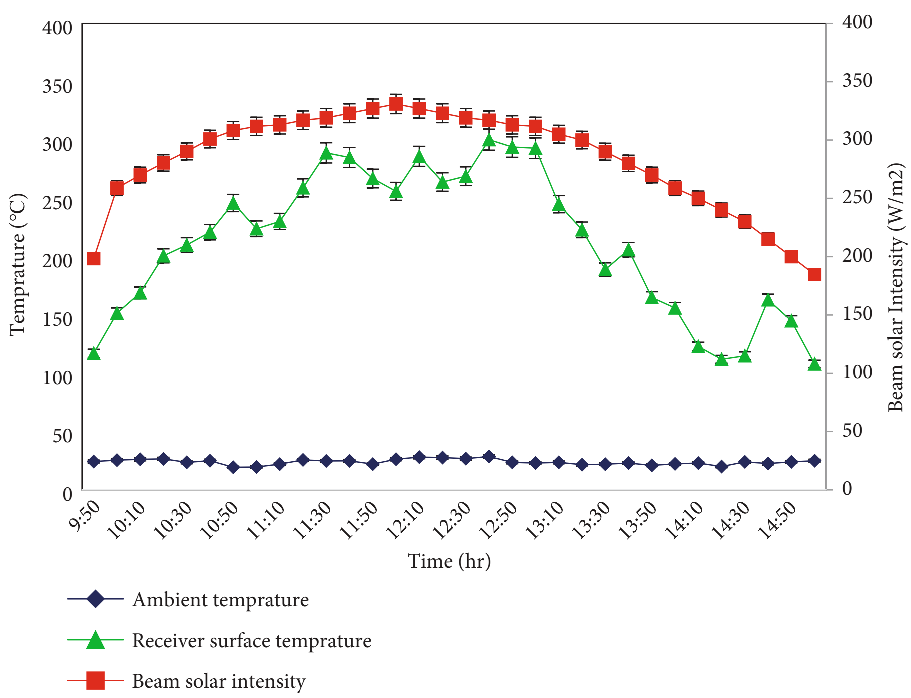

FIGURE 5: Temperature distribution over the receiver surface, ambient temperature, and solar radiation variation.

component. The input "Difdif" for each cycle distillation process is 2 liters.

2.4. Data Analysis. Useful energy required for the "Difdif" to evaporate the alcohol from water is given by

$$\dot{Q}_u = \dot{m}C_p(T_{\text{out}} - T_{\text{in}}). \quad (1)$$

The energy captured by the reflector is given by

$$\dot{Q}_s = I_b A_a. \quad (2)$$

Efficiency of the collector is determined by:

$$\eta_c = \frac{\text{Energy output}}{\text{Energy input}} = \frac{\dot{Q}_u}{Q_s}. \quad (3)$$

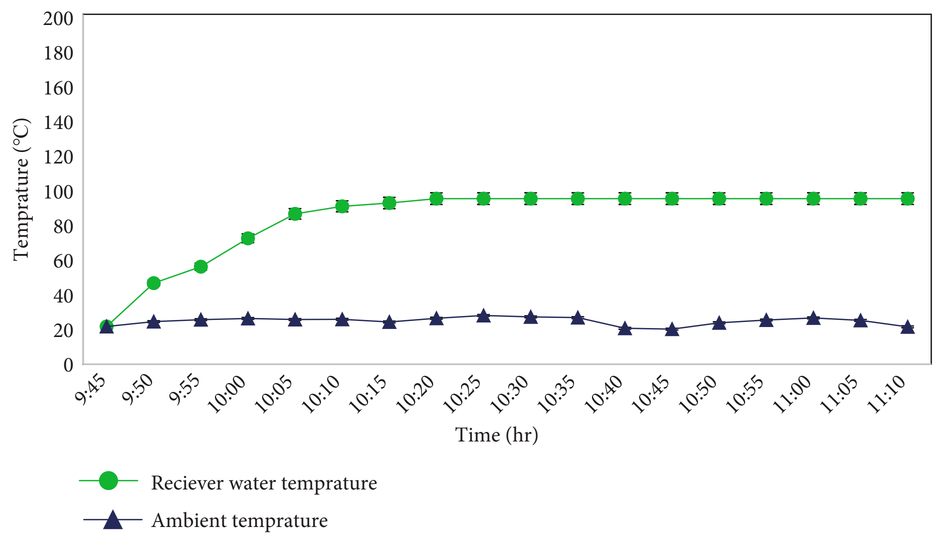

Figure 6: Receiver water temperature and ambient temperature.

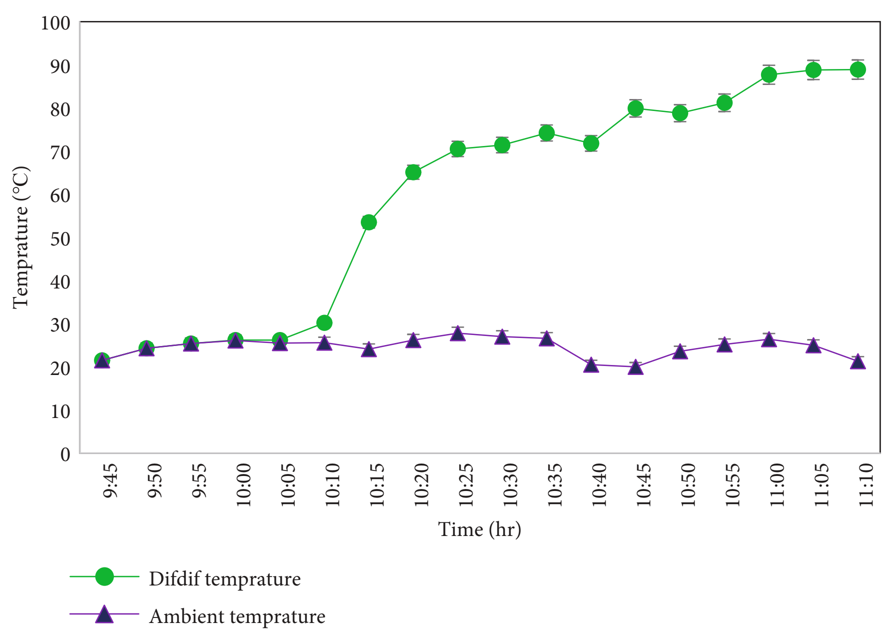

Figure 7: "Difdif" temperature distribution and ambient temperature.

Heat loss from the distillation column is given by

$$Q_{\text{loss}} = \frac{2\pi L(T - T_{\text{amb}})}{(\ln((r_{n+1})/r_n)/k) + (1/h_i r_n) + (1/h_o r_{n+1})} + 2\pi r_{n+1} L\varepsilon\sigma\left(T_{\text{sur}}{}^4 - T^4{}_{\text{amb}}\right). \tag{4}$$

The heat loss from the pipe line through conduction, convection and radiation is computed from

$$Q_{\text{loss}} = \frac{2\pi kL}{\ln((D_o + 2t)/D_i)}\left[T_p - T_a\right] + A_p\sigma\varepsilon\left[T_p^4 - T_a^4\right] + h_c A_p\left[T_p - T_a\right]. \tag{5}$$

3. Results and Discussions

The receiver surface temperature, ambient temperature, and hourly solar beam radiation incident on the horizontal surface throughout the day are shown in Figure 5. The solar beam insolation shows a parabolic path with the peak value attaining at the midday. Since the experimental testing has been conducted in the month of July which is in the rainy season of Ethiopia, the solar intensity is low. The maximum average surface temperature of the receiver reaches 300.3°C around midday; this maximum temperature is achieved due to the effective geometrical shape of the receiver and high reflectivity of mirror glasses pasted on the parabolic dish which increase the concentrated radiation reaching the receiver. Overall, the receiver surface temperature is

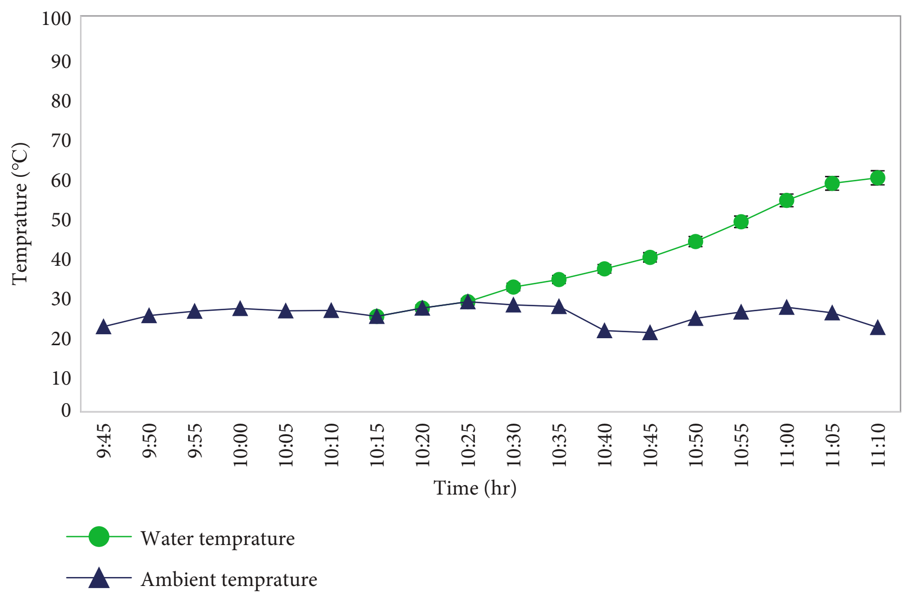

Figure 8: Condenser water temperature, ambient temperature, and solar radiation variation.

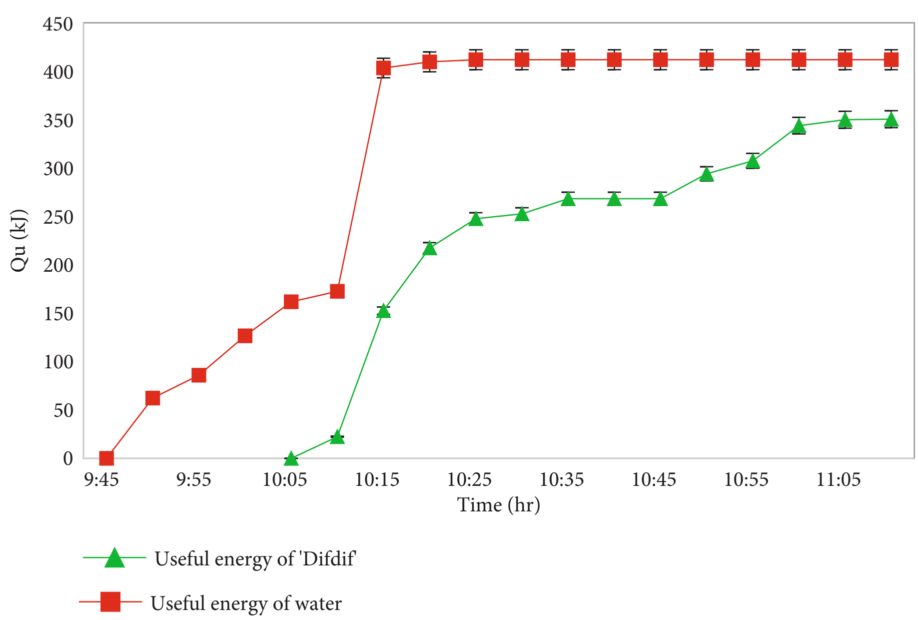

Figure 9: Useful energy gain by water in the receiver and "Difdif" in distillation column.

greater than 100°C throughout the testing period which is enough to boil the water inside the receiver.

The experimental result indicates that the boiling point of water is achieved at a temperature of 90.2°C while that of alcohol is at 71.4°C. It is obvious that if the solar intensity is low, it rises the time required for boiling. This study considered a truncated cone absorber to capture the solar intensity efficiently. In the graph (Figure 5), the uncertainties in each data points are indicated by "error flags," the vertical flags are for uncertainty in temperature. The lengths of this flags correspond to the uncertainty ranges as ±3%.

The water temperature variation inside the receiver with solar radiation and ambient temperature hourly variation are given in Figure 6. The temperature of water increases sharply at the beginning until the phase change occurs.

The experiment was started at 9:45 AM using 0.6 kg of water, the water boiled (phase change occurs) at 94.6°C, and the time taken to boil 0.6 kg of water was 25 minutes.

Figure 7 indicates the temperature variation of "Difdif" inside the distillation column. The "Difdif" starts to heat up after the water vapor inside the receiver flows through the coils inside the distillation column. The "Difdif" temperature was raised to 71.4°C, and at this temperature, the ethanol started to vaporize. The amount of "Difdif" poured into the distillation column is 2 L, and the total time taken to complete one cycle of distillation process is 65 minutes.

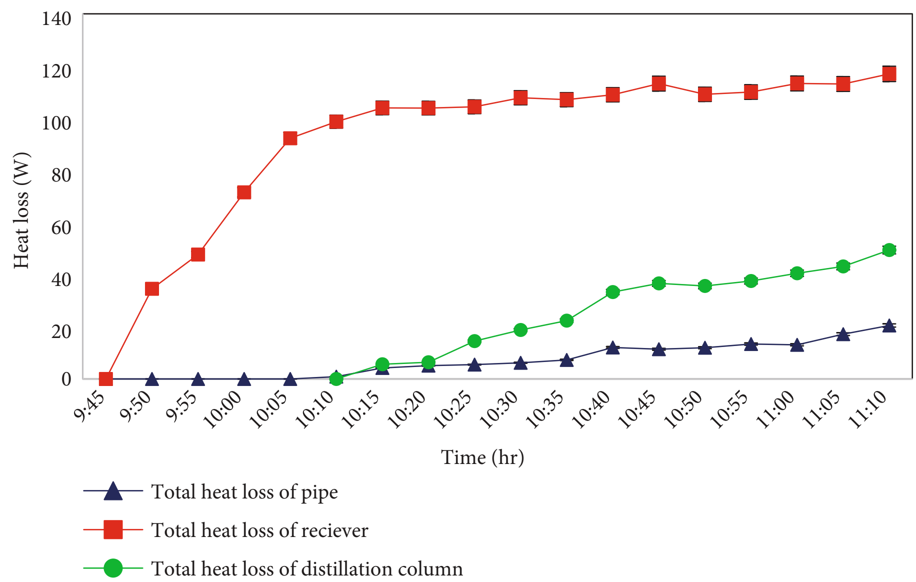

Figure 10: Total heat loss of the system.

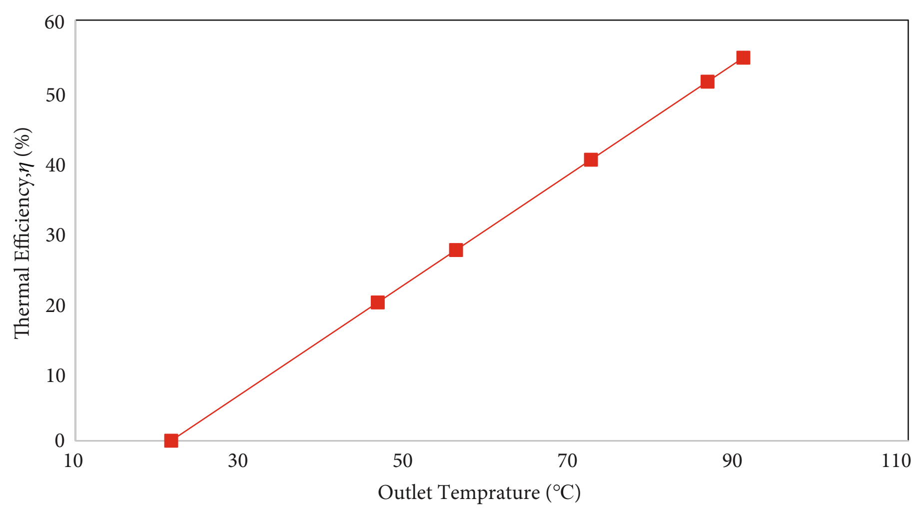

Figure 11: Thermal efficiency of the collector.

From the experimental result, 2 liters of "Difdif" provides 0.2 liter of "Areke". So the rate of production of "Areke" is a measure of the total distillation which is obtained as 0.185 l/h. The error propagation of "Difdif" temperature is determined as ±2.5%.

Figure 8 shows the temperature variation of water inside the condenser within a given time. The condenser water starts to heat up after the "Difdif" is boiled in the distillation column and the vapor of ethanol flows through the copper tube connecting the distillation column to the condenser. The ethanol vapor is condensed inside the condenser by transferring its latent heat of condensation to the cold water. This raises the temperature of water inside the condenser to 59.1°C.

The water inside the condenser is completely replaced by draining it for each cycle of operation since it is a batch method. The error propagation of receiver water temperature inside the receiver is determined as ±3%.

The useful energy required to boil water in the receiver and "Difdif" in the distillation column is indicated in Figure 9. The sensible energy required to boil 0.6 l of water is 172.5 kJ, and the sensible energy required to boil 2 L of "Difdif" is 249.5 kJ. The latent heat required to vaporize the ethanol from "Difdif" is 133.5 kJ, and the latent heat required to vaporize water is 226 kJ. In order to achieve the boiling temperature of water in the receiver, it takes around 25 minutes, and to complete one cycle distillation process, it takes 65 minutes.

Figure 10 shows that the total heat loss analysis of distillation column, solar receiver and fluid transport pipes. As seen from the graph, the maximum heat loss takes place from the receiver due its higher temperature and surrounding wind and minimum heat loss occurred on the condensate transport pipes which is insulated. The error propagation in receiver, pipe, and distillation column heat losses are: 2.5%, 3%, and 3%, respectively.

Figure 11 shows the thermal efficiency of the parabolic dish concentrator versus outlet temperature of the working fluid inside the receiver. The outlet receiver water temperature increases while keeping the inlet water temperature constant. This resulted in an increase of thermal efficiency.

A naturally circulating fluid flow is usually accompanied by pressure drop that is compensated by a hydraulic head between receiver and distillation column. The total pressure drop is the summation of pressure drop due to fluid flow through the receiver, vapor line, and condensate line. This was found to be 0.002 Pa.

The alcohol content of the distilled liquid "Areke" has been tested using alcoholmeter at Debre Birhan University, Debre Birhan-Ethiopia, and it was found that the alcohol content is 45% by volume.

4. Conclusions

In this paper, performance investigation of solar thermal local "Areke" distillation system has been carried out. The experimental results indicate that from 2 liters of "Difdif" it is possible to produce 0.2 liters of liquid "Areke" with a production rate of 0.185 l/h. The production efficiency of solar thermal local "Areke" distillation system is observed to be 10% which is a 1.67% increment when compared to the traditional production system using fire wood as a source of heat energy. Hence, this study shows that it is possible to use solar energy as a source of thermal energy for distillation process of local "Areke" production system with a better efficiency when compared to the traditional method using fire wood.

Data Availability

Data were deposited in a repository (http://etd.astu.edu.et/bitstream/handle/123456789/1530/Seyoum%20Getachew%20Nigussie.pdf?isAllowed=
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Disclosure

An earlier version of the manuscript has been presented as a thesis at Adama Science and Technology University, Adama, Ethiopia.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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