ANALYSIS OF THE EFFECTIVENESS OF SOLAR ASSISTED STEAM COOKING USING PARABOLIC TROUGH COLLECTOR

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Abstract - ***Solar energy is a permanent, none polluting and low running cost source of energy. Solar energy is the cheapest, inexhaustible and can be used for various domestic and agriculturical requirements including cooking, drying, dehydration, heating, cooling and solar power generation. In the present scenario of energy crisis an alternate cooking solution using renewable energy sources like solar energy or biogas is inevitable. The objective of this project is to develop a solar assisted steam cooking system.The experimental setup consists of parabolic trough collector. The reflected solar radiations are focused on absorber tube which was placed at focal length of the parabolic trough. In this setup, water is used as the working fluid which collects the heat from absorber tube. Water gets converted to steam and it is fed to the solar cooker where the heat energy of steam is used for cooking. This project also aims to analyze the performance of parabolic trough collector with different types of reflectors and also nutritional quality of steam cooked food is compared with conventionally cooked food.***

Key Words: *Parabolic trough; Solar cooker; Reflectors*

1. INTRODUCTION

World energy scenario is so encouraging for energy engineers in designing and implementing more and more energy efficient equipments in all walks of life. As energy bills around the world are increasing day today basis; India is no exception, so any steps taken towards reducing hydrocarbon based energy dependence is highly accepted. Apart from energy crisis, environmental factors also points towards importance of switching into cleaner and greener energy culture.

Though solar cookers are not entirely new idea, the integration of steam cooking with solar energy is considerably newer. Some plants are already operational for generating steam and using it for the purpose of cooking, but they are all large sized commercial installation. This work aims at a pioneering initiative which enables the households in the country to harness the solar energy and directly utilizing it for a healthy cooking practice; steam cooking. The impact of this work is such that it demands a change in mode of energy usage as well as in cooking practice.

The idea of steam cooking is always inspiring since it is far superior to the way how we cook at the present. In steam cooking, heat from the steam is directly condensed on the food material or heat transfer medium like a metal utensil is used, in the both cases there is no boiling water, which usually take away much of the nutrients from the cooked food in conventional cooking.

Cooking is an important transformation method for food which modifies both the sensory and nutritional quality of the food. Some foods do not need to be cooked; while others must be cooked otherwise they cannot be consumed. The main aim of cooking is to give the food an inviting look and colour; increase attractiveness as far as smells, flavors and aromas, soften the texture so it is softer and more digestible, destroy any bacteria, making the food safer and more hygienic. There are some negative effects to cooking, like the formation of harmful substances caused by heating the food, the destruction of thermo labile vitamins, which are sensitive to heat (vitamin C and vitamin B), the destruction of essential amino acids when cooking for a long time, and the dispersion of some vitamins and minerals in cooking water. Steaming is one of the best cooking methods to preserve the nutritional qualities, appearance and flavors. Steam cooked food is considered as the most healthy and nutritional.

Variety fuel likes coal; kerosene, fire wood etc are used as fuel for cooking purpose. But the cost of these fuels is increasing day by day and their contribution to global warming is also increasing at a rapid rate too. Labor and time involved in conventional cooking is immense. A solution for these problems is to use a solar steam cooking system which uses thermal energy of the sun to preheat the feed water to produce steam for cooking.

2. STEAM COOKING

Steam is the technical term for the gaseous phase of water, which is formed when water boils. In terms of the chemistry and physics, steam is invisible and cannot be seen; however, in common language it is often used to refer to the visible mist or aerosol of water droplets formed as this water vapour condenses in the presence of (cooler) air. At lower pressures, such as in the upper atmosphere or at the top of high mountains water boils at a lower temperature than the nominal 100 °C at standard temperature and pressure. If heated further it becomes superheated steam.

Steam is traditionally created by heating a boiler via burning coal and other fuels, but it is also possible to create steam with solar energy. Water vapor that includes water droplets is described as wet steam. As wet steam is heated further, the droplets evaporate, and at a high enough temperature (which depends on the pressure) all of the water evaporates and the system is in vapor–liquid equilibrium. Superheated steam is steam at a temperature higher than its boiling point for the pressure, which only occurs where all liquid water has evaporated or has been removed from the system.

Steam cooking is done by boiling water continuously, causing it to vaporize into steam; the steam then carries heat to the nearby food, thus cooking the food. The food is kept separate from the boiling water but has direct contact with the steam, resulting in a moist texture to the food. Steam cooking is most often done by placing the food into a steamer, which is typically a circular container made of metal or bamboo. The steamer usually has a lid that is placed on the top of the container during cooking to allow the steam to cook through the food. When a steamer is unavailable, a wok filled less than half with water is a replacement by placing a metal frame made of stainless steel in the middle of the wok. A wok is a versatile round-bottomed cooking vessel, originated from China. Some modern home microwave ovens include the structure to cook food by steam vapour produced in a separate water container, providing a similar result to being cooked by fire.

Overcooking or burning food is easily avoided when steaming it. Individuals looking to not increase their fat intake may prefer steaming when compared to other methods which require cooking oil. Steaming also results in a more nutritious food than boiling because fewer nutrients are leached away into the water, this is usually discarded. In 2007 United States Department of Agriculture (USDA) conducted a comparison study between steaming and boiling vegetables. The results showed that the most affected nutrients are folic acid and vitamin C when boiled. When compared to raw consumption, steaming reduces folic acid by 15%, and boiling reduces it by 35%. Steaming reduces vitamin C by 15% and boiling reduces it by 25%. Steaming, compared to boiling, showed 42% higher amount of Glucosinolates in broccoli cooked for medium firmness. Phenolic compounds with antioxidant properties have been found to retain significantly better through steaming than through boiling or microwaving. Steaming compared to boiling retained β-carotene in carrots.

2.1 Methods of Steaming

1. Atmospheric or low pressure steaming: food may be cooked by direct or indirect contact with the steam:
   a. Direct Contact: In a steamer or in a pan of boiling water.
   b. Indirect contact: Between two plates over a pan of boiling water.
   c. High pressure steaming: Equipment which does not allow steam to escape; steam pressure builds up, the temperature increases and cooking time is reduced.

2.2 Advantages of Steaming

1. Retention of nutritional value.
2. Some foods become lighter and easier to digest.
3. Low pressure steaming reduces the risk of overcooking.
4. High pressure steaming enables food to be cooked quickly, because steam is forced through the food, cooking it rapidly.
5. Labour-saving and suitable for large-scale cookery.

Economical on fuel (low heat is needed and a multi-tiered steamer can be used).

3. TYPES OF SOLAR CONCENTRATORS

A.Parabolic Trough

A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned directly above the middle of the parabolic mirror and filled with a working fluid.

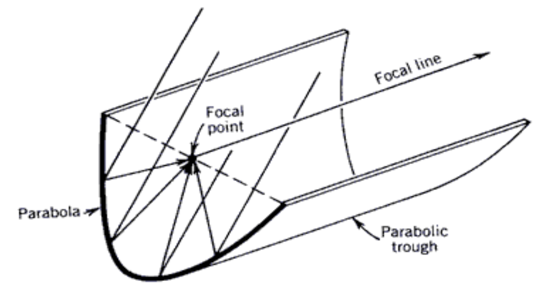

Fig-1: Schematic Diagram of Parabolic Trough

B. Enclosed Trough

Enclosed trough systems are used to produce process heat. The design encapsulates the solar thermal system within a greenhouse-like glasshouse. The glasshouse creates a protected environment to withstand the elements that can negatively impact reliability and efficiency of the solar thermal system. Lightweight curved solar-reflecting mirrors are suspended from the ceiling of the glasshouse by wires. Axis tracking system positions the mirrors to retrieve the optimal amount of sunlight. The mirrors concentrate the sunlight and focus it on a network of stationary steel pipes, also suspended from the glasshouse structure. Water is carried throughout the length of the pipe, which is boiled to generate steam when intense solar radiation is applied. Sheltering the mirrors from the wind allows them to achieve higher temperature rates and prevents dust from building up on the mirrors.

C. Fresnel Reflectors

Fresnel reflectors are made of many thin, flat mirror strips to concentrate sunlight onto tubes through which working fluid is pumped. Flat mirrors allow more reflective surface in the same amount of space as a parabolic reflector, thus capturing more of the available sunlight, and they are much cheaper than parabolic reflectors.

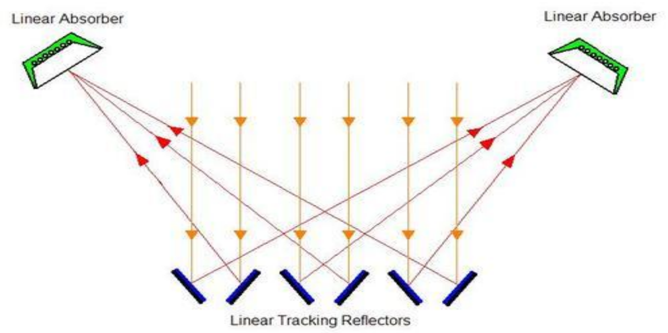

Fig-2: Schematic Diagram of Fresnel Reflectors

D. Dish Stirling

A dish Stirling or dish engine system consists of a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point. The reflector tracks the Sun along two axes. The working fluid in the receiver is heated to 250–700 °C. Parabolic-dish systems provide high efficiency (between 31% and 32%), and their modular nature provides scalability.

4. EXPERIMENTAL SETUP

In Experimental setup, parabolic trough collector having an aperture area 6 m^2, concentration ratio 33, and focal length 63 cm. The schematic diagram and experimental setup of parabolic trough collector are shown in Fig 3.

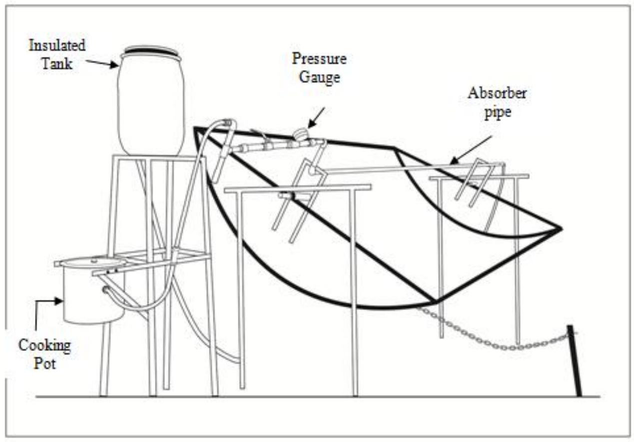

Fig-3: Schematic Diagram of Experimental setup

The system consists of following parts:

A. Insulated Tank

The insulated tank is placed above the parabolic trough collector to collect the water. Water is fed into the parabolic trough collector through the tube

B. Reflector

Reflector is one of the vital parts of the parabolic trough collector as it decides the fraction of solar irradiance to be collected by the absorber tube. A parabolic reflector reflects and concentrates all the sun rays on the absorber tube. The reflector is a parabolic shaped galvanized Aluminum sheet with a reflectivity at clean surface.

C. Absorber Tube

The absorber tube is placed at the focal length of the parabolic trough collector. The solar radiations reflected by the parabolic trough collector are collected by the absorber tube. Water is used as working fluid in the absorber tube.

D. Cooker

It is made up of stainless steel and it cooking region pipe is galvanized iron pipe with insulation.

5. SYSTEM OPERATION

The Solar assisted Steam Cooking consists of an insulated tank with a valve, reflector, absorber tube and a steam cooker. Water is first collected in insulated tank. Open the tank valve. Then it is passed to solar parabolic trough. The parabolic trough collector is manually tracked on each day before starts so that the solar radiation hits perpendicular to the plane of aperture area. When these solar radiations fall on the aperture area of the parabolic trough collector, these radiations are concentrated to the absorber tubes. This causes heat transfer between the surface of the absorber tube and the water flowing inside the absorber tube. Hence the water gets heated and converted to steam. Check for steam by opening all the valves. If the steam is formed, close the valve 2 & check for deflection in pressure gauge. At this time, valve 1 must be in open mode & valve 3 in closed mode. When the pressure comes around 2 bars, slightly open the valve 2 in such a way to keep steady flow of steam to the cooking pot. During cooking the outlet valve is adjusted to keep good quantity steam. Various food items such as potato, carrot, onion, beans etc can be cooked using this solar assisted steam cooker which helps in retaining texture & colour. This work also aims to have a comparison of nutritional quality of food cooked by the conventional cooking system and steam cooking.

6. DESIGN OFSOLAR COLLECTOR AND ABSORBER PIPE

Energy required cooking 1 Kg of Rice:

Specific heat of rice = 1.8 KJ/Kg ° C

Initial temperature of rice before cooking, T_1 = 20 ° C

Final temperature of rice to be attained, T_2 = 100 ° C

Amount of energy required, Q = m x Cp x ΔT

= 1 x 1.8 x (100-20)

= **144 KJ**

Energy required to cook boil 1.5 Kg of Water:

Specific heat of Water = 4.187 KJ/Kg ° C

Initial temperature of water, T_1 = 20 ° C

Final temperature of water, T_2 = 100 ° C

Amount of energy required, Q_2 = m x Cp x (T_2 -T_1)

= 1.5 x 4.187 x 80

= **502.44 KJ**

Energy required for heating cooking pot:

Mass of pot in which cooking is done, m = 1 Kg

Specific heat capacity of Stainless steel = 0.510 KJ/ Kg ° C

Initial temperature, T_1 = 20 ° C

Final temperature, T_2 = 100 ° C

Amount of energy required, Q_3 = m x Cp x (T_2 -T_1)

= 1 x 0.510 x 80

= 40.8 KJ

Energy required for vaporization of water:

Mass of water, m = 1.5 Kg

Latent heat of vaporization of water, h_{fg} = 2260 KJ/Kg

Amount of energy required, Q_4 = m x h_{fg}

= 1.5 x 2260

= **3390 KJ**

Total energy required for cooking, Q = Q_1 + Q_2 + Q_3+ Q_4

= 144 + 502.44 + 40.8+ 3390

= 4077.24 KJ

Assuming the loss is 1/3 of the required energy for cooking.

Loss, Q_L = 1/3 x Q

= 1/3 x 4077.24 KJ

= 1359.08 KJ

Therefore, Total design energy required for cooking 1 Kg of rice,

Q_D = Q + Q_L

= 4077.24 + 1359.08

= **5436.32KJ**

= 5.4 MJ

Calculation for Collector Area:

Amount of energy required to cook 1 Kg of rice = 5.4 MJ

Global solar radiant exposure over Kerala = 19 MJ/m^2 for 12 hours

Global solar radiant exposure for one hour = 1.583MJ/m^2

To find out the time required to cook:

Using above data,

For 1 m^2 collector area,

Time required = 5.4/ 1.583

= 3.41 hours.

Let the collector area be 6 m^2

Time required to cook with 6 m^2 = 5.4/ (6 × 1.583)

= 0.568 hours

~ 35minutes.

Hence, choosing area of collector is 6 m^2

Cooking time has to be limited to 1 hour maximum.

Hence,

Taking average energy requirement as 8 MJ.

Maximum temperature achieved – 150 ° C

Taking average temperature – 145 ° C

From steam table

At 145 ° C,

Pressure = 415.68 k Pa

Enthalpy for steam for 1 kg =2739 KJ/Kg

Amount of steam required = 8/ 2739

= 2.92 Kg

Length of pipe = 3m

Volume of water = Mass / Density

= 2.92/1000

= 2.92×10^{-3} m^3

Volume of pipe = Volume of water

$\pi \times r^2 \times L = 2.92 \times 10^{-3}$

$r^2 = 2.92 \times 10^{-3} / \pi \times L$

$= 2.92 \times 10^{-3} / \pi \times 3$

$= 3.1 \times 10^{-4}$

r = 0.0176 m

= 1.76 cm

Hence, choose three-fourth inch pipe for absorber tube.

7. MEASURING DEVICES AND INSTRUMENTS

The temperatures at different points are measured using infrared thermometer. The solar radiation intensity is measured during the day using a Pyranometer.

8. EXPERIMENTAL RESULTS AND DISCUSSION

Solar assisted steam cooking is placed in front of Automobile department, inside NCERC campus facing east west direction. A large number of parameters have various effects on the performance of the system. Cylindrical parabolic collector is manually tracked on each day before the reading starts so that the solar radiations fall on the aperture area. The major factor affecting the yield is the availability of solar radiation. A comparative study of different reflectors (Aluminum Sheet and Galvanized Iron Sheet) on parabolic trough collector is also conducted to identify more efficient reflective sheet for cooking purpose. Such a parabolic trough collector is used to check the performance of various reflecting sheets. And also nutritional quality of steam cooked food is compared with conventionally cooked food were analyzed. Experiments are performed from 9:00 hours to 17:00 hours.

8.1 Comparative Analysis of Various Reflecting Sheets.

Solar assisted steam cooking was developed and used to heat the water by manual tracking. Table-1 shows that the comparison results of various reflecting sheets on parabolic trough. Using this parabolic trough collector, the performance of various reflectors is found out to analysis feasible for steaming cooking purpose. Various experiments are performed to check the performance of various reflectors on parabolic trough collector. The concentrator has an aperture of length of 3 m. When the radiation falls on parabolic trough collector reflector then whole of the radiation will be collected on a line of absorber where the absorber is placed. Mass flow rate of water is 0.005 kg/s through the heat absorber pipe.

Table-1: Comparison of Various Reflecting Sheets

Time in Hour	Outlet Temperature for Aluminum Sheet(^{0}C)	Outlet Temperature for Galvanized Iron Sheet(^{0}C)
9:30 AM	68.4	45.2
10:30AM	82.1	51.2
11:30 AM	100.4	57
12:30 PM	127.7	64.4
1:30 PM	140.2	75.1
2:30 PM	120.5	65.4
3:30 PM	100.7	61.4
4:30 PM	85.8	52.5

8.2Variation of Solar Radiation at Different Times of a Day

The variation of solar intensity for aluminum sheet and galvanized sheet as reflector in different time of the day is plotted. The collector was exposed to solar radiation for half an hour before the start of reading and experimental data was recorded after regular intervals of an hour during the day time. From the graph shown in Fig-4 it is clear that the solar intensity is highest during the noon time.

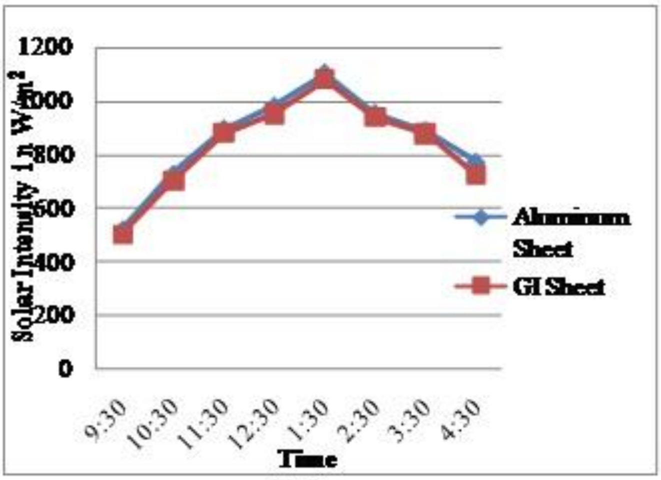

Fig-4: Solar Intensity vs. Time

8.3 Variation of Outlet Temperature at Different Times of a Day

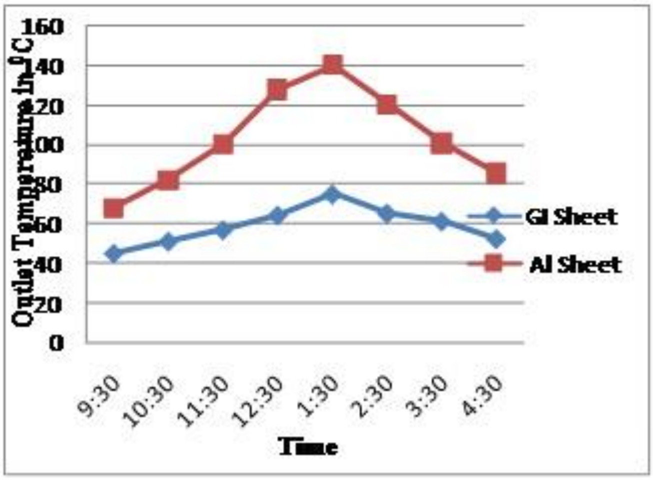

Fig-5: Outlet Temperature vs. Time

From the graph shown in Fig-5 it is analyzed that the outlet temperature of water is minimum at 9:30 hours which increases gradually with time. The maximum temperature is 140.2°C for Aluminum sheet and 75°C for Galvanized Iron sheet, this is because solar radiation falls perpendicularly on the trough and most of the radiations are collected on the given length of absorber. Again the intensity of radiation remains almost constant from 12:30 PM to 2:30 PM and due to unsteady flow of heat, temperature of pipe and temperature of water outgoing the pipe increases. The Outlet temperature was recorded using digital thermometer. It is noted that the outlet temperature with Aluminum sheet as reflector gives maximum temperature compared to Galvanized Iron sheet. This shows that Aluminum sheet can be used for steam cooking purpose because the outlet temperature of water should have above 100° C to reach the boiling point and hence water gets converted to steam. The steam will go directly to cooking pot, where the heat energy in steam is used for cooking. The product used for cooking is potato. Specific heat of potato is 1.72 kJ/kg^{0}C. Time taken to cook one kilogram of potato is two hours. This is because of solar intensity variation.

8.4 Variation of Efficiency with Time

Initially efficiency decreases and increases gradually.When using aluminum sheet as reflector, efficiency is greater compared to galvanized sheet. So it concluded that aluminum sheet can be uesd for cooking purpose.

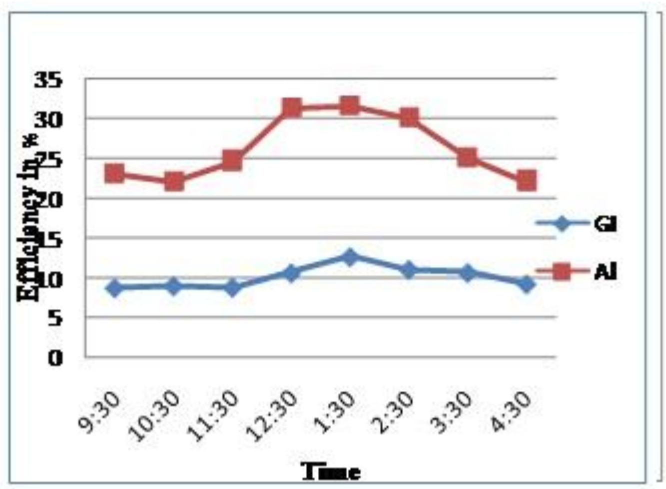

Fig-6: Efficiency vs. Time

8.4 Variation of Temperature with Atmospheric Temperature

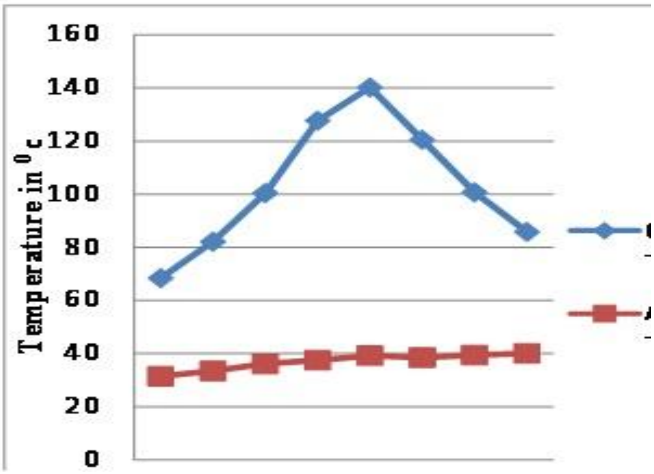

Fig -7: Temperature vs. Time

From the graph shows Fig-7 a typical day results of the hourly variation of the temperatures in the outlet temperature of water in absorber pipe compared to the atmospheric temperature. The absorber pipe is hottest about mid-day when the sun is usually overhead. The temperatures outside of the absorber pipe were much higher than the atmospheric temperature during most hours of the daylight.

8.5 Analysis Result

The two different food sample (solar steamed potato and boiled potato) were analyzed and results shown in Table 2. The results shows that the solar steamed potato contains more nutrition compared to the boiled potato.The study revealed that the solar steam cooking is more advantages compared to boiled cooking.

Table-2: Food sample

Parameters	Results	
	Solar Steamed Potato (mg/kg)	Boiled Potato (mg/kg)
Calcium as Ca	763.37	609.55
Magnesium as Mg	185.12	92.39
Iron as Fe	20.69	19
Phosphate	1098.04	310.08

Above table emphasizes the advantages of solar steam cooking over the other methods of cooking, since the retaining of different nutrients are considerably higher in steam cooking apart from retaining nutrients, the steam cooking also helps in retaining texture and colour.

8.6 Efficiency of the system

Efficiency was compute using equation as:

$$\text{Efficiency} = \frac{m_w C_p (T_{out} - T_{in}) + \frac{m C_p (T_{out} - T_{in})}{\text{Time taken for cooking in sec}}}{A I_b}$$

Where m_w = mass flow rate of water in kg/sec.

C_p = Specific capacity of water in kJ/kg/^{0}C.

T_{out} = Average outlet temperature of water in ^{0}C.

T_{in} = Average inlet temperature of water in ^{0}C.

A = Area of the collector in m^2.

I_b = Solar Intensity in W/m^2.

Mass flow rate of water = 5× 10^{-3} kg/sec.

Cp = 4.187 kJ/kg/^{0}C.

T_{out} = 103.22^{0}C.

T_{in} = 37.51^{0}C.

A = 6 m^2.

I_b = 851.375 in W/m^2.

In this project, product is used for cooking is potato. The weight of the potato is taken as 1kg.Specific capacity of potato is 1.72 kJ/kg^{0}C. To find out the amount of energy required, here assuming initial temperature is 20^{0}C and final temperature to be attained is 100^{0}C. Therefore,

Amount of energy required = 1 × 1.72 × (100- 20)

= 137.6 kJ

Time taken for cooking potato = 2 hours

= 2 ×3600

= 7200 sec

$$\text{Efficiency} = \frac{5\times 10^{-3}\times 4.187\times 65.71 + \frac{1\times 1.72\times(103.22-87.51)}{7200}}{6\times 851.375}$$

=0.2722

=27.22 %

9. CONCLUSION

In this experiment, we have found out the thermal performance of various reflectors (Galvanized Iron sheet and Aluminum sheet) on a parabolic trough collector. This research has its own special features. The collector cannot be easily tilted and oriented, as per the position of the sun with tracking mechanism and external power will be needed. The maintenance cost is minimum and hence economical. Running cost is nil. The labor cost is minimized on account of its simple design. The use of solar troughs is limited only to clear sunny days. The steam can produce scaling inside the metal absorber pipe and hence, non-corrosive coating should be applied in it. The manual tracking mechanism is of single Axis (East-West horizontal). Additional maintenance is required to clean the dirt absorbed on the surface. Periodic maintenance is necessary to avoid any complications.

As other forms of energy are fast depleting and polluting the atmosphere, non-conventional energy resources like solar energy are best suited to use. The solar concentrating collector is among the best way to use solar energy efficiently due to its advantages to convert abundantly available solar energy into effective and convenient form of heat energy which can be used for various purposes. Herein, this converted heat energy has been used for water heating. This work presents a comparative study of thermal performance of various reflectors (Aluminum sheet and Galvanized Iron sheet) on a parabolic trough collector in manual tracking. It concludes the following results: Use of Aluminum sheet as reflector, the maximum temperature at the outlet of water is 140.2° C which can be used for steam cooking purpose. This is because the outlet water of absorber pipe should be reach above 100^0 C to form steam for cooking purpose. Galvanized Iron sheet is not feasible for cooking purpose. Finally, it was concluded that concentration of Solar Energy on Aluminum sheet has been intensified when compared to Galvanized Iron sheet for cooking purpose.

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