DESIGN AND PROTOTYPE DEVELOPMENT OF A SOLAR RECHARGE COOK STOVE

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APPROVAL SHEET

Certified that the contents and form of this thesis titled 'Design of a Solar Recharge Cook Stove' submitted by Ms. Mehrnoosh Khan, Ms. Najla Shafqat, Mr. Haider Ali Bukhari and Ms. Zara Azhar Khan have been found satisfactory for the requirement of the degree.

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ABSTRACT

The global population stands at 7 billion and counting, due to this continuous increase in population, the energy demand is also increasing and as a consequence available fossil fuels are depleting. Cooking is an essential part of life. All seven billion people need to cook food in order to consume it. Indoor emissions contribute 2% of global greenhouse gas (GHG) emissions. Cutting of trees for fuel leads to deforestation which results in soil erosion. There is a dire need of energy efficient technologies to cater for the aforementioned problems. Solar thermal energy is the basis of this project. The aim of this project is to design an energy efficient solar cook stove and to optimize the cost by using economical and locally available building materials. The project consists of design of various major components which are Solar parabolic dish, receiver, cooking pot, connecting pipes, phase change material – PCM, PCM storage unit, heat transfer fluid (HTF) and insulation. The HTF is heated in the receiver placed at the focal point of solar parabolic dish. The HTF heats up and flows on thermosiphon principle reaching the cooking pot and providing required heat for cooking. The same fluid flows through the PCM storage unit to recharge the PCM to be used as a backup energy source. Solar thermal energy has a wide range of applications besides cooking. The solar concentrating unit, that is the parabolic dish, can be used for various other purposes, including but not restricted to small-scale commercial water heating for temperatures up to 300°C, domestic water heating and domestic and office space heating. The functioning can be improved by use of inflexible pipes instead of flexible for better thermosyphoning and use of a small solar power pump for the flow of HTF from outdoor to indoor unit for high rate of heat transfer.

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Chapter 1

1.0 INTRODUCTION

1.1 Cooking Status

The global population stands at 7 billion and counting, due to this continuous increase in population, the energy demand is also increasing and as a consequence available fossil fuels are depleting.

Cooking is an essential part of life. It is the way of life, it always has been. All seven billion people need to cook food in order to consume it. Some people have the optimal resources for it while a large number of people suffer at the hands of resource unavailability.

1.2 Fuel Consumption

Nearly three billion people around the world utilize solid fuels in order to fulfill the cooking needs *(Environ Health Perspect, 2002)*. Wood, charcoal, animal dung, coal and crop residue is burned in open fires or by using inefficient stoves for daily cooking. Modern fuels are also being used for cooking purposes which include electricity, kerosene oil, LPG etc. *(Leach, 1987)*

1.3 Sustainability

The traditional solid fuels and modern fuels are available in a limited supply and soon there will be a time when the resources are exploited to the extent that there will be no more fuel available for the primary and basic human needs. The fact that the resources will be depleted is a matter of sustainability. If we keep this matter at bay and consider about the potential threat the traditional fuels have upon human life; we may cringe.

1.4 Environmental Impacts

Indoor emissions contribute 2% of global greenhouse gas (GHG) emissions *(Md. Danesh Miaha, et. al, 2009).* Cutting of trees for fuel leads to deforestation which results in soil erosion. A major impact of soil erosion is flash flooding *(Rashid M. Hassan, et. al, 1988)*

1.5 Health Impacts

Indoor air pollution caused due to fuel burning is the most important cause of death among children under 5 years of age in developing countries *(Bruce, et. al, 2000)*. Evidence also exists of associations with low birth weight, increased infant and perinatal mortality, pulmonary tuberculosis, nasopharyngeal and laryngeal cancer, cataract, and, specifically in respect of the use of coal, with lung cancer. Exposure to indoor air pollution may be responsible for nearly 2 million excess deaths in developing countries and for some 4% of the global burden of disease. (*Bull World Health Organ vol.78 n.9 Genebra Jan. 2000)*

1.6 The Problem

To identify a cost effective, sustainable and energy efficient solution to the prevalent condition of environmental and health impacts of Traditional Fuel consumption as far as cooking is concerned.

Chapter 2

2.0 LITERATURE REVIEW

2.1 Selection of PCM

Initially the following Phase Change Materials (PCM) were explored from literature that could be used for heat storage for the stove. These were selected depending upon their melting points and latent heat. A suitable PCM is one having melting point close to the required temperature (cooking temperature) and high latent heat so that minimum amount of PCM could store large amount of heat.

Table 2.1: List of Phase Change Materials

Sr. #	PCM	Melting Point (℃)	Latent Heat (kJ/kg)
1	Erythritol ($C_4H_{10}O_4$)	118	339
2	Acetanilide	118.9	222
3	KNO_3/$NaNO_3$ (30%/70%)	260	305
4	Lithium Nitrate	253	373
5	Sebacic acid	135.92	374.4
6	$ZnCl_2$ (31.9 %) KCl (68.1 %)	235	198
7	KNO_3	330	266
8	Li_2CO_3 (32%) K_2CO_3 (35%) Na_2CO_3 (33%)	397	276
9	Ammonium Alum ($NH_4Al\ (SO_4)_2.12H_2O$)	93.5	269
10	$MgCl_2.6H_2O$	117	169
11	$(NH_4)Al(SO_4).6H_2O$	95	269
12	Na_2CO_3-Na_2SO_4	330	474.81
13	LiCl (56%) KCl (40.5%) LiF (3.5%)	346	408.93
14	LiCl (55%) KCl (36%) NaCl (9%)	346	415.33
15	LiCl(58%)-KCl(42%)	348	405.77
16	LiOH (59.1%) K_2CO_3 (28.2%) Li_2CO_3 (12.7%)	350	534.76

Out of these we selected eutectic mixture of NaOH (50%) and KOH (50%) on the basis of following criteria:

- Melting point between 200 to 350℃ that can easily be achieved using parabolic trough
- High latent heat of fusion
- Hundreds of freezing and melting cycles
- Non-hazardous
- Inexpensive
- Easily available

2.2 Thermal Insulator

Table 2.2: List of Thermal Insulators

Insulation Material	Low Temp Range (℃)	High Temp Range (℃)	R-value (Per Inch)	Environmental Friendly	Flammable
Fiberglass	-30	540	3.1	yes	No
Mineral Wool, Ceramic fiber	n.a	1200	3.1	yes	No
Mineral Wool, Glass	0	250	3.14	yes	No
Mineral Wool, Stone	**0**	**760**	**3.1**	**yes**	**No**
Polyurethane Foam	-73	121	6.3	No	Yes
Polystyrene (EPS)	n.a	80	4	No	yes
Calcium silicate	-18	650	n.a	yes	No
Cellular glass	-260	480	n.a	yes	No

In order to control the heat losses the insulation of following parts was required:

- Heat Transfer Fluid Pipe
- Heat Storage containing HTF and PCM capsules
- Cover (lid) of Cooking pot

So a list of suitable insulation materials along with their specific characteristics were explored from the research papers and Stone wool is finally selected and used in the product because of it is environmental friendly, less expensive, locally available, and not flammable and has high temperature range.

2.3 Thermal Conductors

Table 2.3: List of Thermal Conductors

Materials	Thermal Conductivity (W/m.k)	Melting Point or Degradation (°C)
Silver	420	961
Copper	401	1083
Aluminum	237	660
Brass	150	900
Nickel	91	1455

These conductors are consideration for the following:

- Encapsulation of Phase Change Material
- Heat collector containing heat transfer fluid
- Hot plate for heat transfer from heat storage to cooking pot by conduction
- Cooking pot

2.3.1 Material Selection Criteria

- Excellent thermal conductivity
- High melting point
- Nonreactive
- Lightweight
- Inexpensive
- Availability

2.4 Heat Transfer Fluids

There are a number for heat transfer fluids that can be used for heat transfer within the range of $100°C\ to\ 400\ °C$ like DOWTHERM A and Therminol but we selected simple cooking oil for our product because of its availability. The Heat Transfer Fluid is selected on the criteria that its operating temperature should be within its boiling point and smoke point. Following is the list of cooking oils along with their smoke point and the one we have used is the mixture of all these.

Table 2.4: List of Heat Transfer Fluids

Oils	Smoke Point
Soybean oil	$257\ °C$ / $495\ °F$
Rice Bran oil	$254\ °C$ / $490\ °F$
Avocado oil	$271\ °C$ / $520\ °F$
Canola oil	$200\ °C$ / $400\ °F$
Sunflower oil	$271\ °C$ / $520\ °F$
Corn oil	$232\ °C$ / $450\ °F$

3.0 COMPONENTS AND WORKING MECHANISM

3.1 Energy Requirements

An estimate of how much energy is needed to cook a given amount of food is required to determine the amount of Phase Change Material and ultimately the size of heat storage or solar stove as per design. For cooking some food heat energy is provided to raise the temperature of the food to a point where cooking starts. Once the cooking starts we need to maintain that temperature till the cooking is over. Thus there are two phases in cooking food. In the first phase most energy is required to raise the temperature while the energy required maintaining the temperature is not too much.

The heat required (Q) to raise the temperature of matter is estimated using the following formula:

$$\boldsymbol{Q = mc_p \Delta T}$$

$Q = Amount\ of\ heat\ required\ (kj)$

$m = mass\ of\ food$ (Kg)

$c_p = specific\ heat\ of\ food$ (KJ/kg-°C)

$\Delta T = (temp\ required\ for\ cooking - ambient\ temp)$℃

Table 3.1: Specific Heat of Materials

Name	Specific Heat (Heat Capacity) KJ/kg-℃
Fresh water	4.18
Vegetable oil	1.67
Milk	3.93
Steel	0.39
Air	1.01
Potato	3.43
Chicken, Egg	3.2

Using the above equation we have calculated the energy required to cook the following:

- Fried Rice
- Fried Chicken
- Vegetables
- Fried egg/ Omelet
- Boiled Rice

Fried Rice:

$$Q_{boiling} = \left(m_{rice}c_{p_{rice}} + m_{water}c_{p_{water}}\right)\Delta T$$

$$Q_{boiling} = (0.3 \times 4.18 + 0.6 \times 4.18) \times (100 - 25)$$

$$\boldsymbol{Q_{boiling} = 282.15\ KJ}$$

$$Q_{frying} = \left(m_{rice}c_{p_{rice}} + m_{veg.oil}c_{p_{veg.oil}}\right)\Delta T$$

$$Q_{frying} = (0.3 \times 4.18 + 0.028 \times 1.67) \times (110 - 25)$$

$$\boldsymbol{Q_{frying} = 110.56\ KJ}$$

$$Q = Q_{boiling} + Q_{frying}$$

$$\boldsymbol{Q = 392.71\ KJ}$$

Fried Chicken:

$$Q = \left(m_{chicken} c_{p_{chicken}} + m_{veg.oil} c_{p_{veg.oil}}\right) \Delta T$$

$$Q = (1 \times 3.2 + 0.5 \times 1.67) \times (190 - 25)$$

$$\boldsymbol{Q = 665.78\ KJ}$$

Vegetables:

$$Q = \left(m_{veg} c_{p_{veg.}} + m_{veg.oil} c_{p_{veg.oil}}\right) \Delta T$$

$$Q = (0.6 \times 4.18 + 0.028 \times 1.67) \times (88 - 25)$$

$$\boldsymbol{Q = 160.95\ KJ}$$

Fried Egg/Omelet

$$Q = \left(m_{egg} c_{p_{egg}} + m_{veg.oil} c_{p_{veg.oil}}\right) \Delta T$$

$$Q = (0.26 \times 3.2 + 0.005 \times 1.67) \times (90 - 25)$$

$$\boldsymbol{Q = 54.62\ KJ}$$

Boiled rice:

$$Q_{boiling} = \left(m_{rice}c_{p_{rice}} + m_{water}c_{p_{water}}\right)\Delta T$$

$$Q_{boiling} = (0.3 \times 4.18 + 0.5 \times 4.18) \times (100 - 25)$$

$$\boldsymbol{Q_{boiling} = 250.8\ KJ}$$

Table 3.2: Heat Requirement for Four Person Meals

Meal	No. of Servings	Serving per Person	Total Required Quantity of Food	Cooking Temp. (℃)	Specific Heat of Food kJ/kg-℃	Energy Required per Meal (KJ)	Time Required to Cook the Meal (Minutes)
Fried Rice	4	75 grams	Rice: 300 grams Oil: 0.028kg (30 ml)	110	Rice: 4.18 Vegetable Oil: 1.67	392.71	10 – 12
Fried Chicken	4	0.25 kg	Chicken: 1 kg Oil: 0.5 kg	190	Chicken: 3.2 Vegetable Oil: 1.67	665.78	20 – 30
Vegetables	4	150 grams	Vegetables: 600 grams Oil: 30 ml/28 grams	88	Vegetables: 4.18	160.95	20
Fried Egg/ Omelet	4	63 grams	Eggs: 260 grams Oil: 1 teaspoon/5ml / 0.005 kg	90	Egg: 3.2 Vegetable Oil: 1.67	250.8	5
Boiled Rice	4	75 grams	Rice: 300 grams Water: 0.6 kg	100	Rice: 4.18 Water: 4.18	54.62	10

The maximum amount of energy that is required to cook a food is for fried chicken i.e. 665.78 KJ. So we are aiming for **1000kj** of energy that would be required to cook any king of food. This includes energy required to raise the temperature of cooking pot + cooking medium + food, to maintain that temperature and also energy losses.

3.2 Components

3.2.1 Solar Parabolic Dish

In order to provide sufficient heat for cooking, the mechanism that we have opted for in order to utilize the solar radiation is through a concentrating solar parabolic dish that will provide the necessary heat energy for cooking of meals.

We want to minimize the heat losses associated with solar radiation collection in the solar concentrators and aim to capture as much heat as we can in order to provide sufficient heating temperature to the heat transfer fluid – HTF. In order to avoid extreme complexity of design and keeping in consideration our budget constraints we have opted for a parabolic dish.

Design Considerations and Factors:

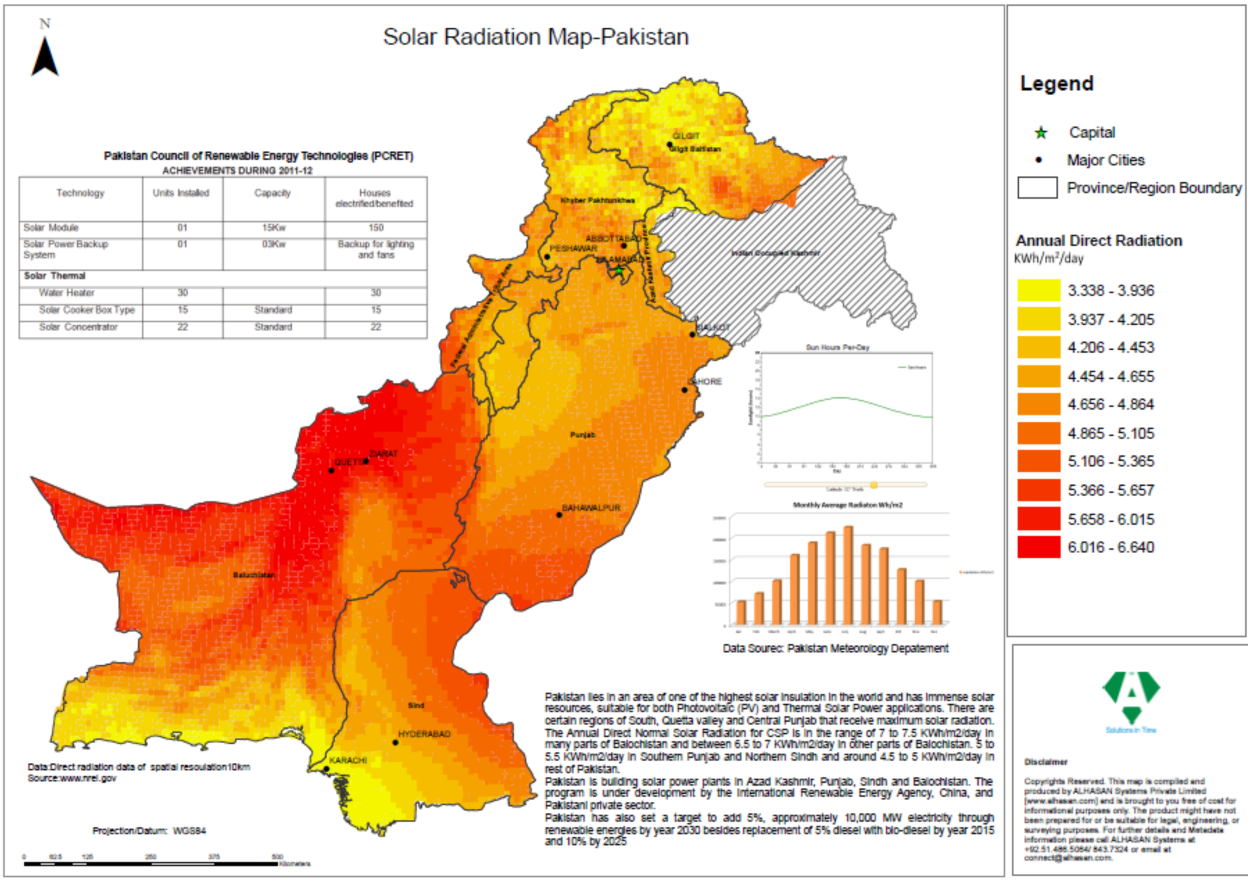
Solar Radiation:

Detailed information about solar radiation availability at any location is essential for the design and economic evaluation of parabolic dish solar power plants. *(Ricardo Vasquez Padilla, 2011)*

The average amount of solar radiation falling on a surface normal to the rays of the sun outside the atmosphere of the earth, extraterrestrial insolation, at mean earth-sun distance D_o is called the solar constant, I_o. Recently, new measurements have found the value of solar constant to be 1366.1 W/m^2. (*Ricardo Vasquez Padilla, 2011*)

Solar Radiation in Islamabad, Pakistan:

Our experimental setup is based in the city of Islamabad, Pakistan. The solar radiation data of Pakistan is detailed in the image below as provided by the MET department of Pakistan.



Pakistan Council of Renewable Energy Technologies (PCRET)
ACHIEVEMENTS DURING 2011-12

Technology	Units Installed	Capacity	Houses electrified/benefited
Solar Module	01	15Kw	150
Solar Power Backup System	01	03Kw	Backup for lighting and fans
Solar Thermal			
Water Heater	30		30
Solar Cooker Box Type	15	Standard	15
Solar Concentrator	22	Standard	22

Data:Direct radiation data of spatial resoulation10km
Source:www.nrel.gov

Data Sourec: Pakistan Meteorology Depatement

Pakistan lies in an area of one of the highest solar insulation in the world and has immense solar resources, suitable for both Photovoltaic (PV) and Thermal Solar Power applications. There are certain regions of South, Quetta valley and Central Punjab that receive maximum solar radiation. The Annual Direct Normal Solar Radiation for CSP is in the range of 7 to 7.5 KWh/m2/day in many parts of Balochistan and between 6.5 to 7 KWh/m2/day in other parts of Balochistan. 5 to 5.5 KWh/m2/day in Southern Punjab and Northern Sindh and around 4.5 to 5 KWh/m2/day in rest of Pakistan.

Pakistan is building solar power plants in Azad Kashmir, Punjab, Sindh and Balochistan. The program is under development by the International Renewable Energy Agency, China, and Pakistani private sector.

Pakistan has also set a target to add 5%, approximately 10,000 MW electricity through renewable energies by year 2030 besides replacement of 5% diesel with bio-diesel by year 2015 and 10% by 2025

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Figure 3.1: Solar Radiation Map of Pakistan

From the map we’ve concluded that the annual direct radiation in the city of Islamabad stands between 4.206 – 4.453 kWh/m^2/day.

Solar Tracking:

Solar tracking is an important factor which determines the efficiency of a parabolic dish. Large scale commercial parabolic dish use electronic solar tracking devices and systems that can track the sun and adjust the position of the parabolic dish to ensure maximum efficiency. Owing to cost constraints and complexity in design and also considering the scale of our project we have chosen manual tracking and movement of parabolic dish as the most preferred and feasible option.

Design:

As we’ve calculated the heat required for cooking food for 4 persons, incorporating the heat losses. For that, solar parabolic dish having dimensions of 8 feet diameter, 4.67 meter square aperture area and 2.66 feet focal length, is covered with glass mirrors to concentrate solar radiations at one focal point. Small pieces of 2 by 2 inch and 3 mm thick mirrors are glued as reflective material on the curved surface of parabolic dish with high temperature resistant and water proof silicon sealant. Mirror is not only the highly reflective material but also is cheaper than any other reflective material. In order to accommodate tracking adjustable stand is used.

Aperture Area of Parabolic Dish

$$\boldsymbol{A_{Aperture} = \frac{\pi}{4} D^2}$$

Where;

$A_{Aperture} = Aperture\ area\ of\ parabolic\ dish$

$D = Diameter\ of\ parabolic\ dish$

$$A_{Aperture} = \frac{\pi}{4}(8\ ft)^2$$

$$A_{Aperture} = 50.24\ ft^2$$

$$\boldsymbol{A_{Aperture} = 4.67\ m^2}$$

Focal Length of Parabolic Dish

$$\boldsymbol{f = \frac{D^2}{16h}}$$

Where;

$f = focal\ length\ of\ parabolic\ dish$

$D = diameter\ of\ parabolic\ dish$

$h = depth\ of\ parabolic\ dish$

$$f = \frac{(8ft)^2}{16(1.5\,ft)}$$

$$\boldsymbol{f = 2.66\,ft}$$

Parameters for Heat Received from the Concentrator

The rate of heat received from the concentrator to the receiver can be approximated by using an equation:

$$\boldsymbol{Q_{received} = A_{aperture} I \rho}$$

Where;

$D = diameter\ of\ parabolic\ dish$

$I = solar\ irradiance$

$\rho = reflectivity\ of\ reflective\ material$

$$Q_{received} = (4.67m^2)\left(\frac{4.55kwh}{m^2}/day\right)(0.98)$$

$$\boldsymbol{Q_{received} = 20.824\ kwh/day}$$

$I = \frac{4.55kwh}{m^2}/day$ (Average daily radiations of Islamabad)

Parameters for Solar Power Intercept by the Receiver

The value of solar power intercepted by the receiver (Kribus, 2002; Mendoza, 2012) can be calculated by using mathematical equation;

$$\boldsymbol{P_{in,rec} = I A_{aperture} \rho \varphi}$$

This equation shows that the value of solar power intercepted by the receiver depends on the amount of solar radiation I, the opening area of the concentrator aperture, reflective material and the intercept factor ø.

Generally, the intercept factor is between 90 and 99% (Bakos & Antoniades, 2013). Meanwhile, parabolic dish from the type of Wilkinson, Goldberg, and Associates, Inc or (WGA) have a high degree of accuracy with an intercept factor that is over than 99%. In this study, the intercepted factor used to calculate the receiver losses is in the range of 0.9 to 1.0.

Table 3.3: Solar Power Intercept by the Receiver

Intercept Factor φ	**For $I = 4.55 \frac{kwh}{m^2}/day$**		
	$Q_{received}$ (kwh/day)	$P_{in,rec}$ (kwh/day)	**Losses (%)**
0.9	20.824	18.741	10
0.91	20.824	18.949	9
0.92	20.824	19.157	8
0.93	20.824	19.366	7
0.94	20.824	19.574	6
0.95	20.824	19.782	5
0.96	20.824	19.991	4
0.97	20.824	20.199	3
0.98	20.824	20.407	2
0.99	20.824	20.615	1
1	20.824	20.824	0

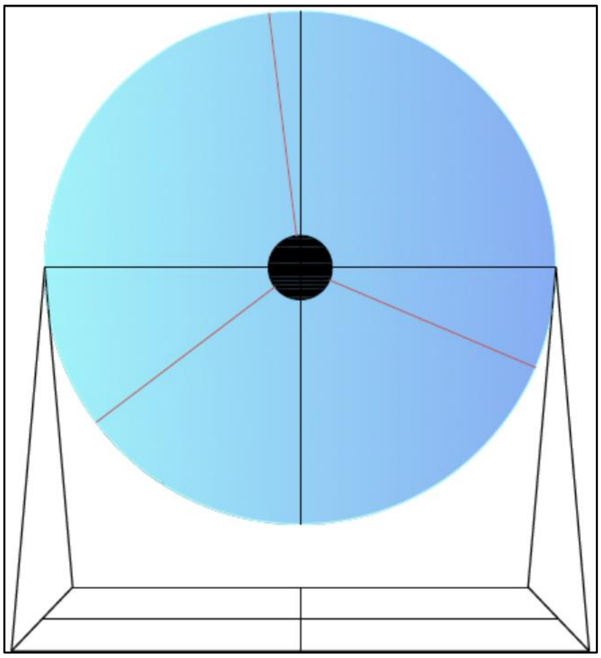

Figure 3.2: CAD Drawing of Solar Parabolic

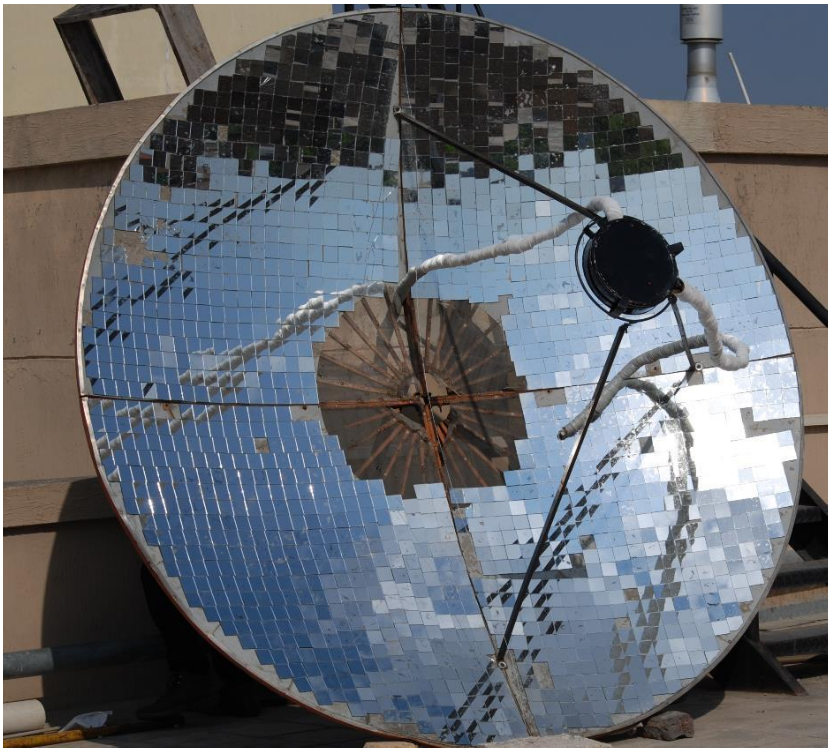

Figure 3.3: Solar Parabolic Dish

3.2.2 Receiver

Receiver made up of stainless steel, painted black and of 1 feet diameter having ½ inch inlet and outlet containing 3 liters heat transfer fluid is placed at the focal point of solar parabolic dish, supported on a stand, to receive the concentrated solar radiations.

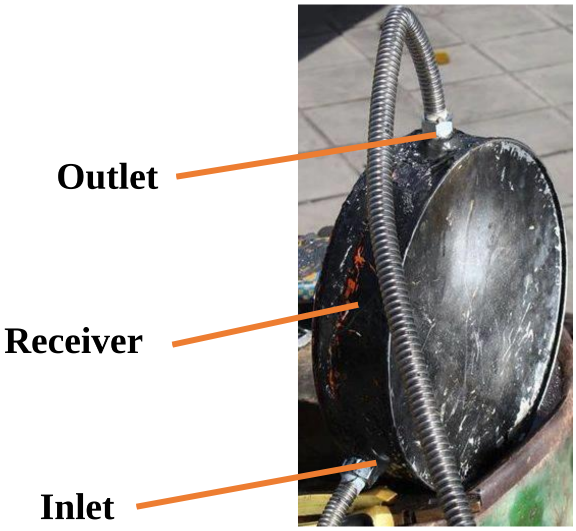

Figure 3.4: Receiver

3.2.3 Cooking pot

Our cooking pot is made of food grade stainless steel and has three layers. The heat transfer fluid heats up the inside layer of pot. This heat is slowly conducted to our removable pot and subsequently to the food. Cooking pot is insulated with rock wool and placed inside wooden box.

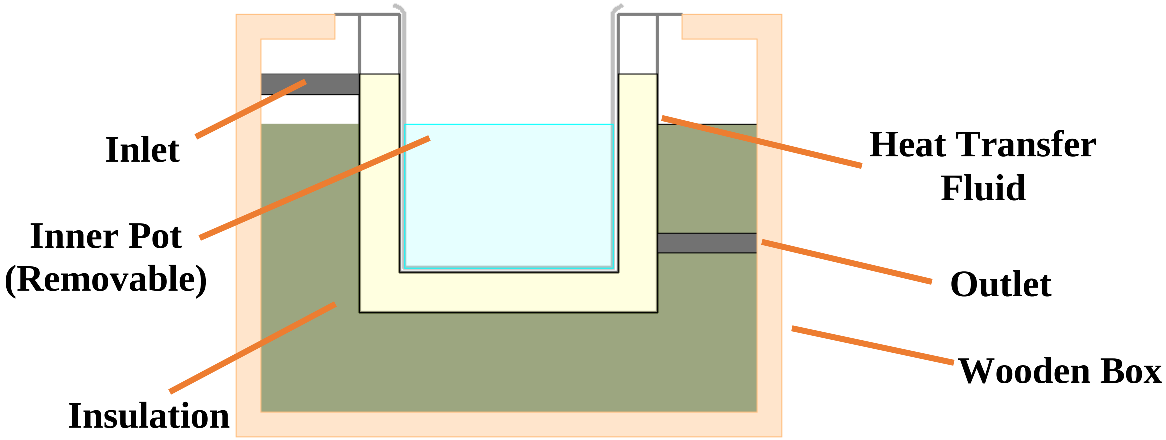

Figure 3.5: CAD Drawing of Cooking Pot

Figure 3.6: Cooking Pot

3.2.4 Phase Change Material

As the intermittent nature of the solar energy creates a mismatch between the energy supply and demand. This is where thermal solar energy storage comes into play. The PCM that we have used to store heat energy from the sun is a mixture of two hydroxides namely sodium hydroxide (NaOH) and potassium hydroxide (KOH). The mixture is a high temperature equimolar eutectic blend of a NaOH and KOH (50:50 mol. %). The melting point of the blend lies in the range of 169 – 178℃ and heat of fusion is found to be equal 202-213 J/g.

We've purchased the lab grade inorganic salts of sodium hydroxide and potassium hydroxide and prepared a eutectic mixture in laboratory. In order to prepare a 2.5 kg mixture, we've taken 1.25 kilograms of pellets of sodium hydroxide and 1.25 kilograms of pellets of potassium hydroxide separately in China dish. Then they're mixed in furnace by melting them together in a china dish. After that, the mixture is placed in an oven at 210 degree Centigrade where it melts in 45 mins. That's how 2.5 kg of eutectic mixture of PCM is prepared. Thermal cycles can be checked using Differential Scanning Calorimeter.

Figure 3.7: Preparation of Eutectic Mixture

3.2.5 PCM Storage Unit

The eutectic blend rests in a cylindrical stainless steel storage unit through which a helical coil of ½ inch thickness, 2.6 meter length and having 10 number of turns passes. The coil provides enough surface area for heat exchange between the PCM and the fluid. The fluid enters from the inlet and exits the storage unit from the outlet flowing under thermosiphon principle.

This unit makes it different from all other stoves available in market as it acts as a source of heat during night hours when there is no sun.

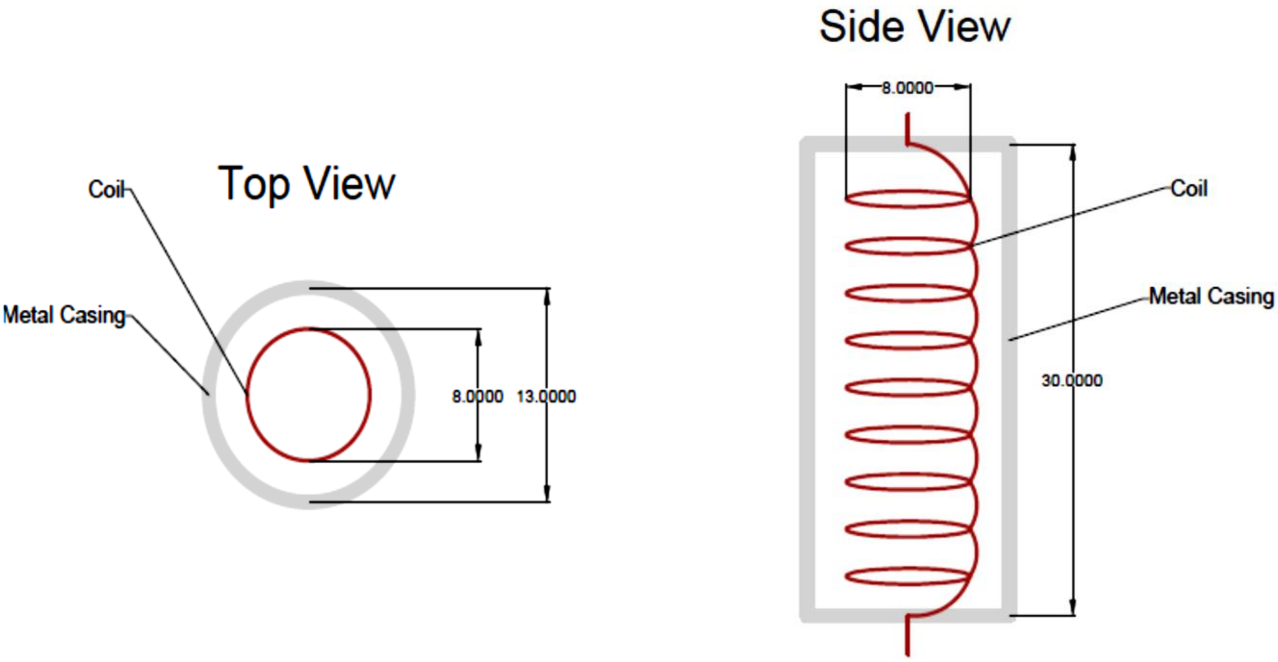

Figure 3.8: CAD Drawing of PCM Storage Unit

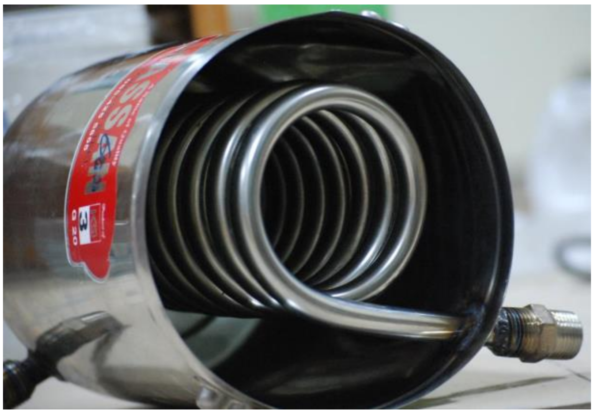

Figure 3.9: PCM Container

Designing the PCM Storage Unit

The calculations that were done to calculate the dimensions and specifications of the PCM container are as follows:

According to the heat requirements of our stove, we need 1000 kJ of energy for cooking the meals specified earlier. The following calculations were done to calculate the amount of our chosen phase change material, a eutectic mixture of KOH and NaOH (50:50), in order to cater to those needs of energy:

Specific Latent Heat of Fusion of PCM = 202 kJ/kg

Mass of PCM required =

$$\frac{\mathbf{1000\ kJ}}{\mathbf{202\ kJ/kg}} \approx \mathbf{5\ kg}$$

We'll add an additional 1 kg of PCM in order to cater for the possible energy losses from the PCM and also regarding the fact that 100% of the input energy cannot be extracted from the PCM.

Therefore,

Mass of PCM = 6 kg

Table 3.4: Volume Calculations for the PCM Salts

	KOH	NaOH
Mass	3 kg	3 kg
Density	2.12 g/cm^3	2.13 g/cm^3
Volume = Mass/Density	1415 cm^3	1410 cm^3

Total Volume of PCM =

$$\mathbf{1415\ cm^3 + 1410\ cm^3 = 2825\ cm^3}$$

Allowance for Expansion of PCM = 15%

Volume of PCM with Added Free Space =

$$\mathbf{(0.15)\ (2825\ cm^3) + 2825\ cm^3 = 3250\ cm^3}$$

For an estimation of the appropriate dimensions of the cylinder, we need to assume a diameter that would be suitable.

Assumed Diameter = 12 cm = D

$$\mathbf{V = \pi \frac{D^2}{4} H}$$

$$\mathbf{H = \frac{V}{\pi \frac{D^2}{4}}}$$

H = 28.8 cm ≈ 29 cm

If we take a ½ inch diameter pipe to form the coil inside the cylinder:

Area of the pipe's cross-section =

$$\boldsymbol{\pi \frac{d^2}{4} = \pi \frac{(1.27)^2}{4} = 1.27\ \mathrm{cm}^2}$$

Assuming diameter of coil to be 8 cm in a 12 cm diameter cylinder:

Length of 1 turn of coil =

$$\boldsymbol{\frac{2\pi d}{2} = \frac{2\pi(8)}{2} = 25.13\ \mathrm{cm}}$$

For optimum heat transfer, we'll take 1 turn of coil for every 3 cm of the height of cylinder. This would give us 10 turns of coil.

$$\mathbf{10\ coil\ turns \times 25.13\ cm = 251.33 \approx 252\ cm}$$

252 cm ⇒ Length of Pipe Required for the Coil

Total Volume of Pipe =

$$\boldsymbol{\pi \frac{(1.27)^2}{4}} \times \mathbf{252\ cm = 320\ cm^3}$$

Adding this volume into the total volume of the PCM, we get:

Total Volume of the Cylinder =

$$\mathbf{3250\ cm^3 + 320\ cm^3 = 3570\ cm^3}$$

Keeping the diameter of the cylinder constant, we'll now calculate the new height of the cylinder using the following equation:

$$\mathbf{H} = \frac{\boldsymbol{V}}{\boldsymbol{\pi \frac{D^2}{4}}}$$

H = 31.55 cm ≈ 32 cm

3.2.6 Connecting Pipes

The pipes we've used are flexible stainless steel pipes of ½ inch inner dimeter, to connect the components. They allow the HTF to flow throughout the setup. Hot fluid moves upwards in the pipes and colder fluid moves downwards according to the Thermosiphon principle. This flow occurs because of the density differences between hot and cold fluids.

Figure 3.10: Flexible Stainless Steel Pipes

3.2.7 Insulation

Rock wool is used for insulating receiver, cooking pot, PCM storage unit and connecting pipes. Cooking pot and PCM storage unit are further placed separately in wooden boxes to minimize conductive, convective and radiative losses.

Figure 3.11: Rock Wool Insulation

3.2.8 Heat Transfer Fluid

6 liter HTF used for effective heat transfer is everyday cooking oil, having a boiling point of 300 ℃ and smoke point of 350℃.

Figure 3.12: Heat Transfer Fluid

3.3 Working Mechanism

There are two units of our product. One is outdoor and the other one is indoor, just like air cons. Outdoor unit comprises of Solar parabolic dish placed on stand in order to accommodate solar tracking and a receiver placed at the focal point of dish. Parabolic dish concentrates the radiations on receiver which is filled with Heat transfer fluid. Hot fluid moves upwards in the pipes which ultimately heats up the inside layer of pot and heat storage unit, which are placed indoor. The colder fluid moves downwards according to the thermosiphon principle. This flow occurs because of the density differences between hot and cold fluids.

Heat storage unit containing PCM acts as a source of heat when there is no sun as it stores heat equal to their latent heat. Flow of HTF in the cooking pot and heat storage can be controlled through valves. Fluid circulates through these flexible pipes and transfer the heat from outdoor to indoor unit continuously during day time.

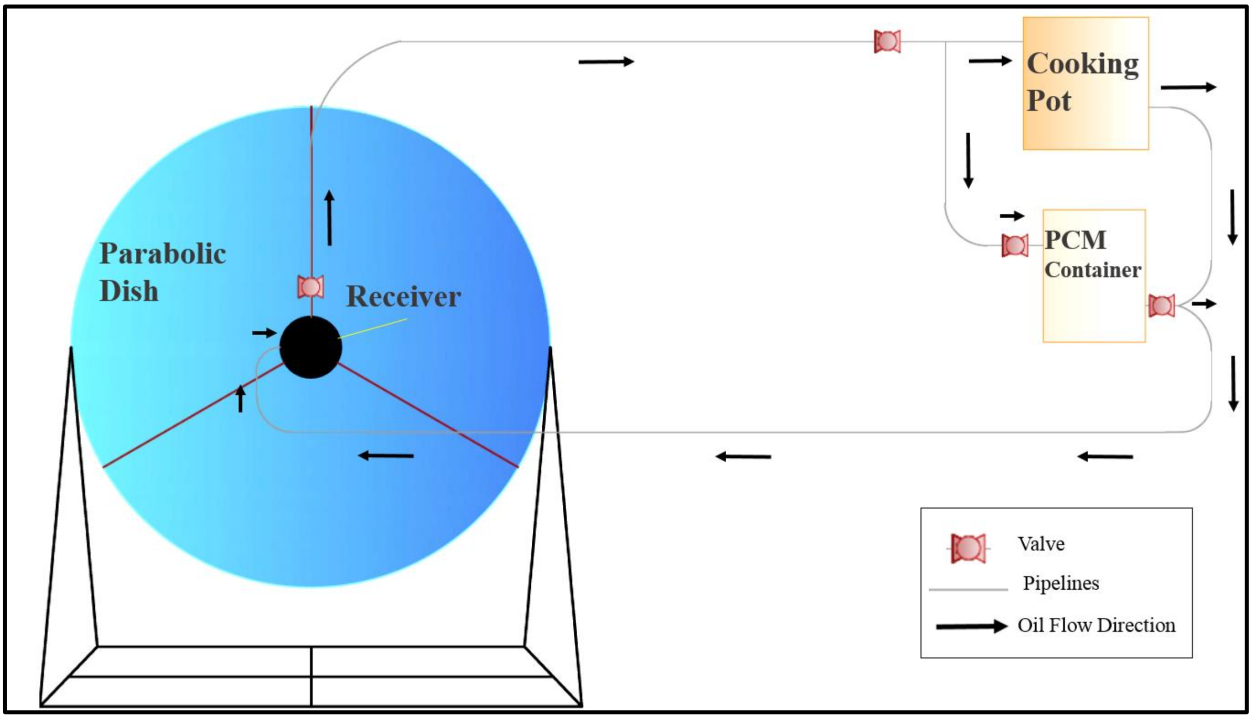

Figure 3.13: CAD Drawing of Solar Recharge Cook stove

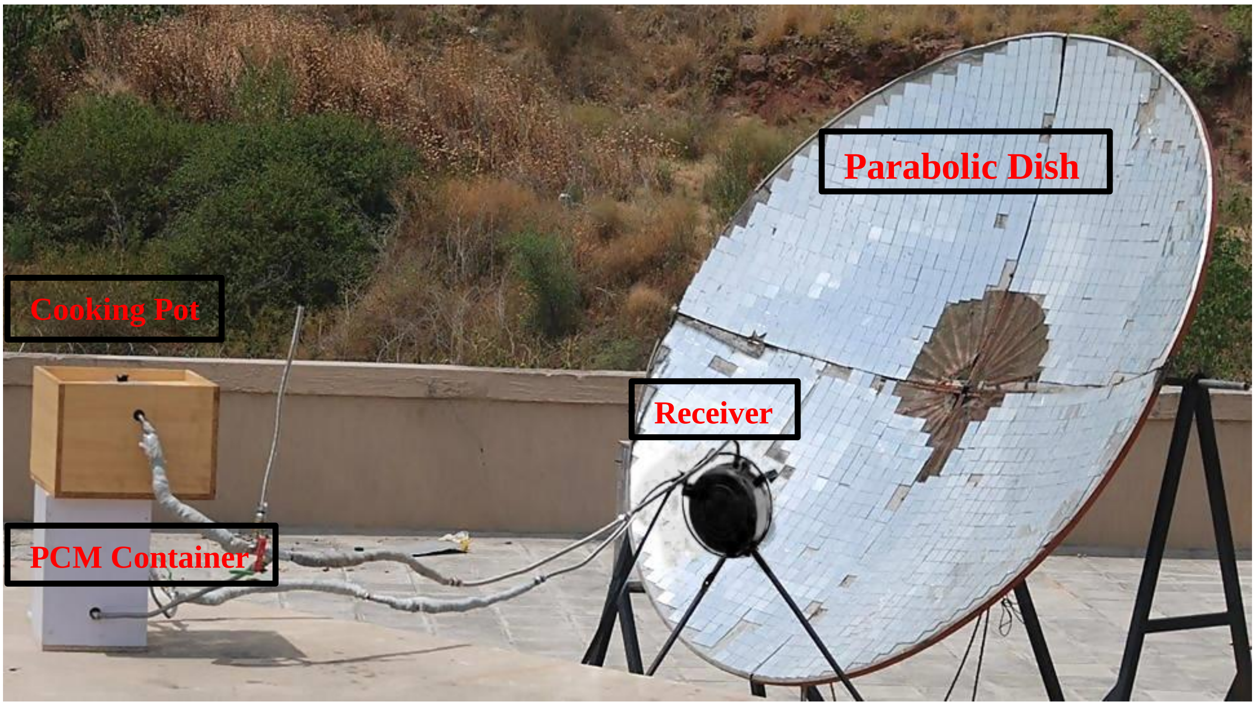

Figure 3.14: Solar Recharge Cook stove

4.0 RESULTS AND DISCUSSION

4.1 Temperature of HTF at Receiver

Table 4.1: Temperature of HTF at Receiver in Months of March, April and May

Sr. No	Initial Temperature (℃)	Final Temperature (℃)	Temperature Difference ∆T (℃)	Total Time (min)	Energy (KJ)	Month
1	26	120	94	45	433.26	March
	24	123	99	62	456.31	
	27	118	91	55	419.43	
2	29	155	126	68	580.75	April
	28	161	133	82	613.02	
	29	158	129	62	594.58	
3	32	188	156	55	719.03	May
	30	192	162	50	746.69	
	32	191	159	52	732.86	

This table shows the variation of temperature of HTF in the months of March, April and May. The readings have been observed by directly placing the thermometer in the HTF filled in the receiver through the valve opening. The receiver was fixed in the receiver stand and was entirely filled with HTF. The receiver was allowed to receive heat from the solar dish in order to heat the fluid in the months of March, April and May. The following observations were made for the aforementioned months:

March: The initial temperature of HTF varied between 24℃, 26 ℃ and 27℃, with the lowest being 24℃; correspondingly the final temperatures observed were 123℃, 120 ℃ and 118 ℃ with the highest temperature in March observed as 123 ℃. The time taken to achieve these temperatures is 62 minutes, 45 minutes and 55 minutes. The temperature difference ΔT noted for the month of March is 99℃, 94 ℃ and 91℃. The energy $Q = mc\Delta T$ comes out to be 456.31 kJ, 433.26 kJ and 419.43 kJ.

April: In the month of April the initial temperature remained close to 29℃ and 28℃ reaching a final temperature of 161℃ in 82 minutes providing energy of 613.02 kJ with a temperature difference of 133℃.

May: In the month of May the initial temperature remained close to 30℃ and 32℃ reaching a final highest temperature of 192℃ in 50 minutes providing energy of 746.69 kJ with a temperature difference of 162℃. The minimum temperature achieved for this month comes out to be 188℃ providing energy of 719.03 kJ in 55 minutes with a temperature difference of 156℃.

The variation in temperatures achieved is visible and evident because in March there was no insulation around the receiver containing the HTF to cater for convection losses. This is also due to the changes in solar insolation as the weather and climate of Islamabad escalates as we transcend in time from March towards May.

4.2 Water Boiling Test

Table 4.2: Temperature Variation of Water with HTF heated at Receiver

Sr. No	Initial Temperature (℃)	Final Temperature (℃)	Start Time (hh:mm)	End Time (hh:mm)
1	32	100	1:30	3:47
2	30	100	1:15	3:18
3	31	95	1:25	3:16
4	30	77	2:05	3:55
5	38	94.5	4:00	5:37

4.2.1 Heat Source – HTF heated at Receiver:

The efficiency of the stove was evaluated by conducting a series of water boiling tests. The results in the table above show that the initial temperature of water in the cooking pot varied from 30℃ to 38℃. The maximum final temperature of water achieved in the cooking pot by receiving heat from the receiver where HTF was heated by direct solar insolation is 100℃. The minimum temperature achieved in the cooking pot for water is 77℃.

The maximum temperature achieved in the cooking pot for oil is 125℃.

4.2.2 Heat Source – HTF heated by Phase Change Material:

Table 4.3: Temperature Variation of Water Heated by PCM

Sr.	Time Delay (h)	Initial Temperature (℃)	Final Temperature(℃)				Mass of Water Evaporated (g)	Heat Extracted (KJ)
			30 min Interval	60 min Interval	90 min Interval	120 min Interval		
1	0	32	61	100	90	35	60	415.2
2	1	30	56	100	83	34	36	373.7
3	2	31	49	95	62	31	18	332.2
4	3	30	42	77	49	30	7	290.6

Total Mass of Water used: 1 kg (equivalent of 1 liter in volume)

Mass of PCM used: 2.5 kg (at 178℃ in molten state after charging)

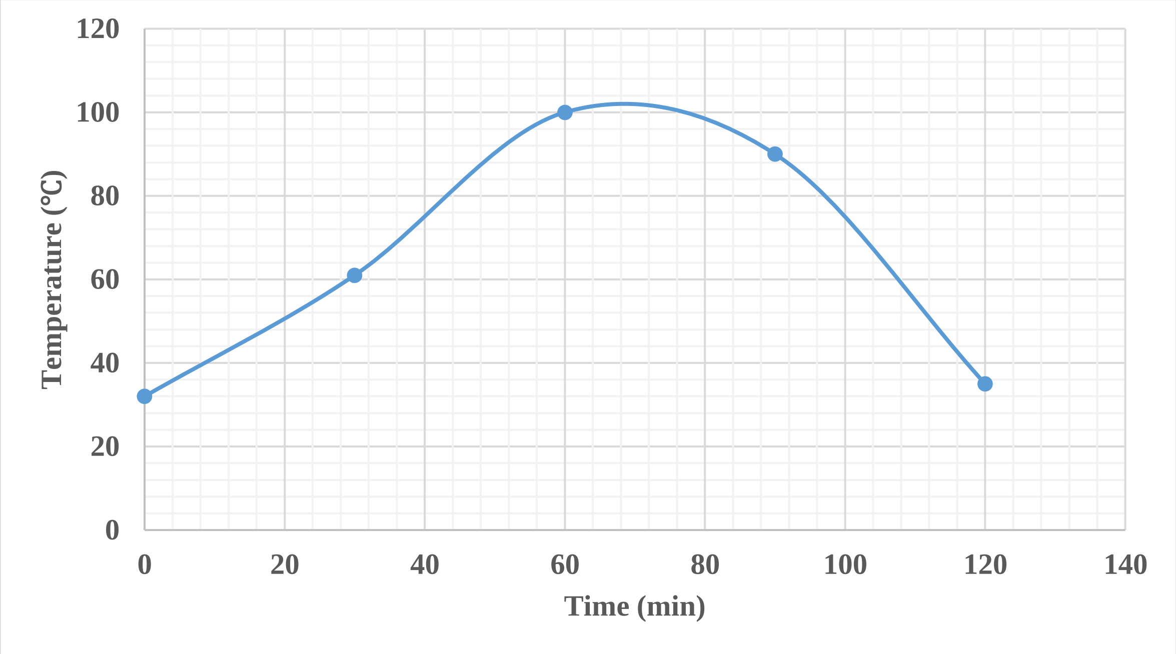

Figure 4.1: 0-hour Delay

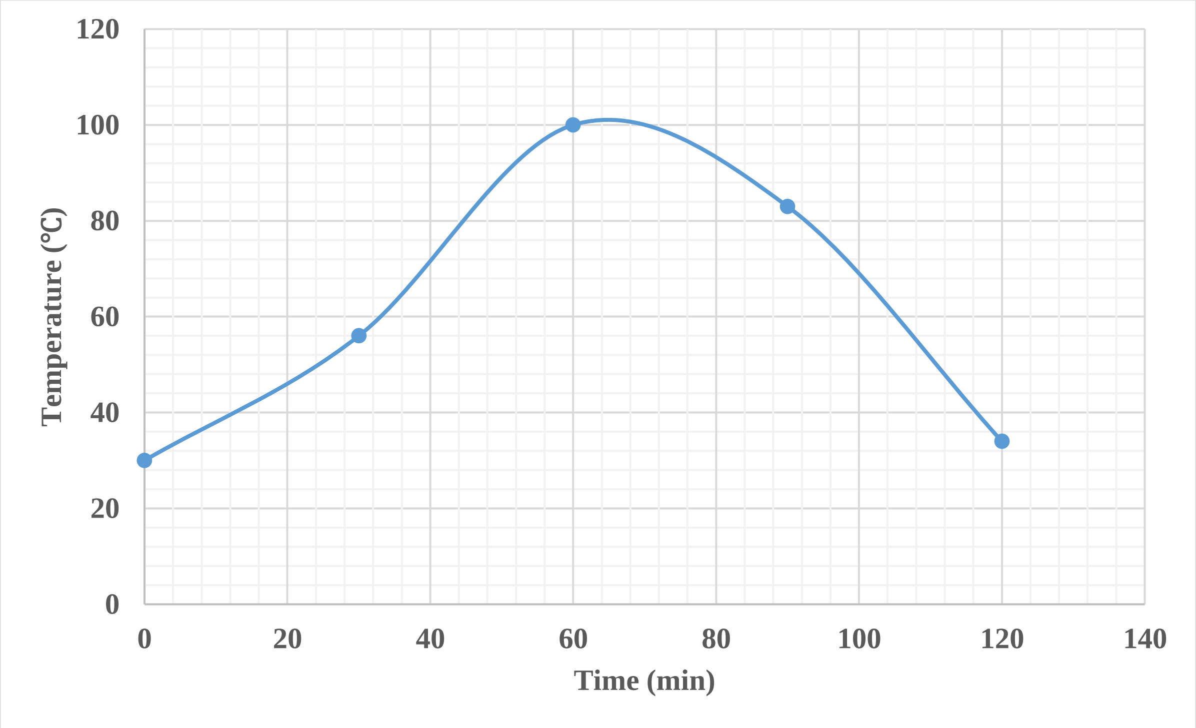

Figure 4.2: 1-hour Delay

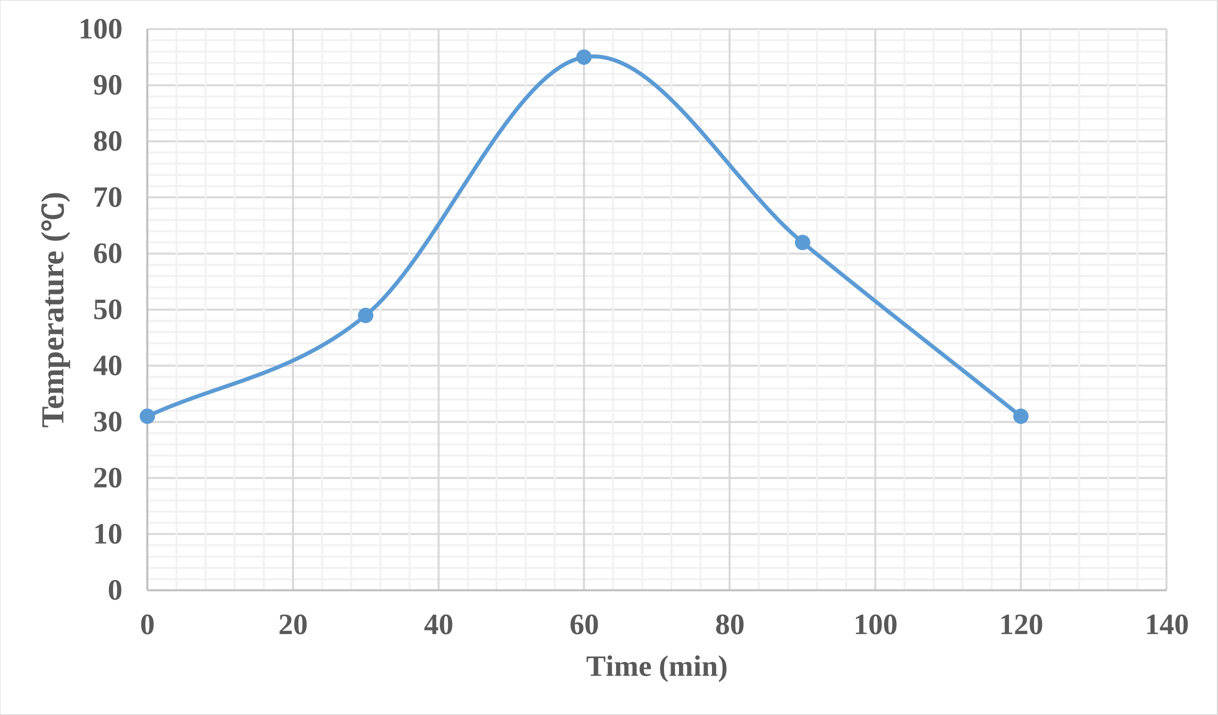

Figure 4.3: 2-hour Delay

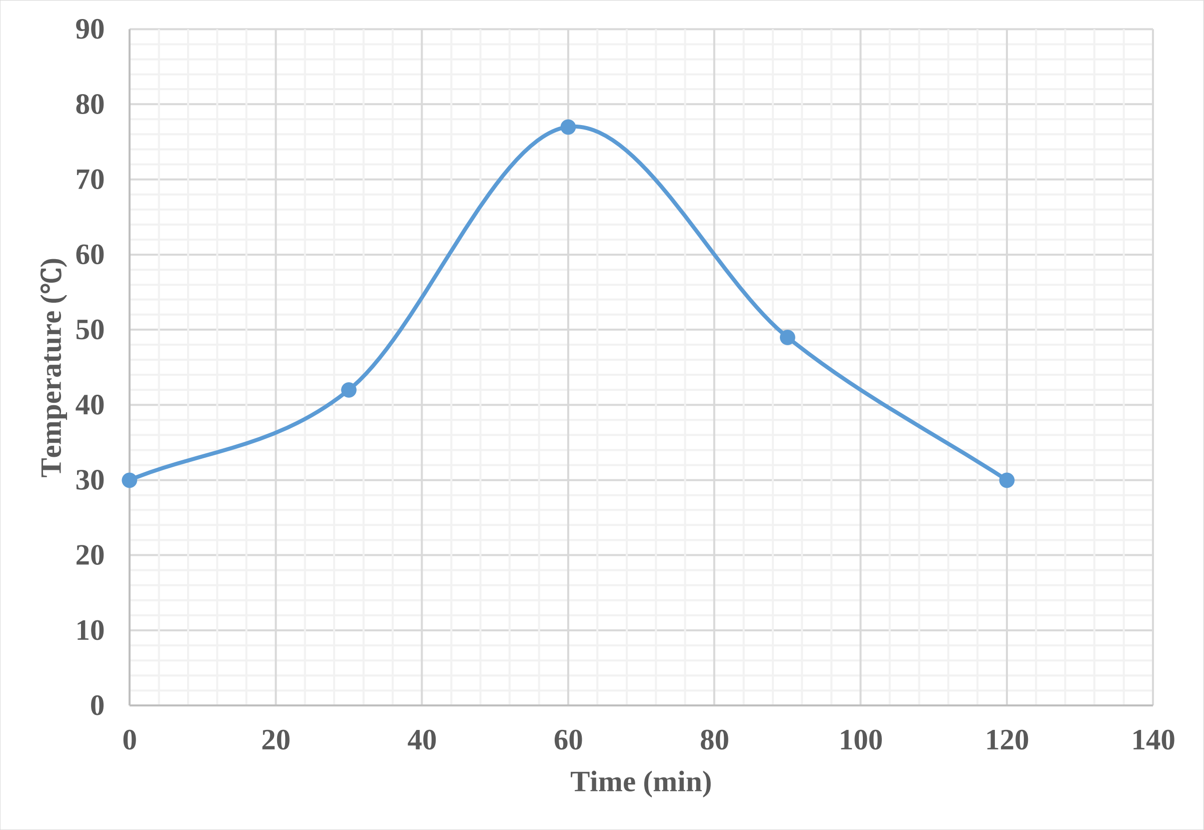

Figure 4.4: 3-hour Delay

The PCM storage unit was placed at the focal point of the solar dish, typically the point where the receiver is placed and with direct solar insolation the PCM was entirely melted and another water boiling test was conducted. The table shows discharging of PCM, effectiveness of its insulation and the heat transfer rate from PCM to the HTF. The mass of water used is 1 kg which is equivalent of 1 liter in volume, for this particular test.

The mass of PCM used 2.5 kg which correspondingly in ideal conditions processes a latent heat of 518.75 kJ. All of this heat cannot be extracted from the PCM due to convection losses and early solidifying of PCM around the coils.

Heat used in this test is the heat transferred from the PCM to the cooking pot containing water via HTF. The PCM delivers heat and exhausts with time.

The table represents delay time which represents the time duration between complete charging of PCM and experimentation. A delay time of 0 hours reflects that PCM has been used without any delay after complete melting. Similarly the delay time of 1 hour, 2 hours and 3 hours represent that correspondingly after complete melting and charging of PCM the experiment was conducted after 1 hour, 2 hours and 3 hours delay.

The table represents four cases corresponding to four serial numbers described below:

4.2.3 Case 01: With a delay time of 0 hours the initial temperature of water was at 32℃ . The rise in temperature was observed in time intervals of 30 minutes, 60 minutes, 90 minutes and 120 minutes. The temperature correspondingly rises initially to 61℃, 100℃ and then the PCM exhausts and temperature drops to 90℃ and 35℃. The total mass of water evaporated is 60g. The heat extracted from the PCM is 415.2 kJ where the rest is lost due to convection losses.

4.2.4 Case 02: With a delay time of 1 hour the initial temperature of water is at 30℃. It rises to 56℃ in the first 30 minutes and reaches a 100℃ in 60 minutes. As the PCM exhausts the temperature declines to 83℃ in 90 minutes and in 120 minutes it reduces to 34℃. The mass of water evaporated is 36g. The heat extracted from PCM is 373.7 kJ.

4.2.5 Case 03: With a delay time of 2 hours the initial temperature of water is at 31℃. It rises to 49℃ in the first 30 minutes and reaches a 95℃ in 60 minutes. As the PCM exhausts the temperature declines to 62℃ in 90 minutes and in 120 minutes it reduces to 31℃. The mass of water evaporated is 18g. The heat extracted from PCM is 332.2 kJ.

4.2.6 Case 04: With a delay time of 3 hour the initial temperature of water is at 30℃. It rises to 42℃ in the first 30 minutes and reaches a 77℃ in 60 minutes. As the PCM exhausts the temperature declines to 49℃ in 90 minutes and in 120 minutes it reduces to 30℃. The mass of water evaporated is 7g. The heat extracted from PCM is 290.6 kJ.

In case 04 the water is not boiling and it evaporates below boiling temperature. The observations also indicate that water boils before 60 minutes in case 01.

5.0 CONCLUSION AND RECOMMENDATIONS

According to our objectives of designing an energy efficient solar cook stove and to optimize the cost by using economical and locally available building materials, the results of our research on the product led to the following conclusions and recommendations.

5.1 Conclusion

The complete setup was installed and water boiling tests were run in the month of May in order to gauge the efficiency of our product.

Despite the damage that our solar parabolic dish sustained, it worked efficiently and provided us with very high temperatures, especially at the focal point. The highest temperature we got with insulation at the focal point was 192 degree Celsius.

However, this temperature is not enough to melt the Phase Change Material (PCM) that we chose for the purpose of storing heat. Our PCM is an equimolar (50:50 ratio) eutectic mixture of two salts, Sodium Hydroxide ($NaOH$) and Potassium Hydroxide (KOH), which melts at a temperature of 178 degree Celsius. The temperature of 192℃ at the receiver means that if we incorporate all energy losses, we cannot possibly expect a similar temperature to be reached at the point where the PCM is placed too.

It should be noted that the energy that can be extracted from the PCM is not a hundred percent of the energy provided to melt it, rather it is only a fraction of that energy, with the heat extraction efficiency varying from 75-85 %. This is because the phase change material that is closest to the coil in the container starts dissipating heat first and as a result, solidifies. Phase change materials are bad heat conductors, especially in their solid state and because of this, the solid PCM near the coil acts as an insulator and prevents the heat from the molten PCM underneath from reaching the coil.

From the water boiling tests we carried out to determine how efficiently our phase change material works, we found that by charging the PCM and discharging it immediately without delay, we can get the maximum energy output from it, whereas if we leave the PCM in the insulated box for intervals of 1, 2 and 3 hours subsequently after charging it, the extracted energy gets lower with the increase in the interval. This tells us that despite the insulation, heat is lost from the phase change material and the longer it stays in storage, the lesser would be the energy that can be extracted from it.

Another issue that we faced in the running of the setup was the thermosiphon principle which we were dependent on for the heat transfer fluid to travel through the entire setup and it was found to be too slow to be practical.

5.2 Recommendations

Following are some recommendations that might help improve the efficiency of the stove and the quality of the meals that are cooked in it.

- Installation of a pump can significantly improve the overall flow of the heat transfer fluid in the setup. This can mean higher temperatures achieved in the cooking pot and also, a higher rate of heat transfer meaning less heat losses in the system. The pump would be small and battery powered since we do not need very high flow rates because that would build up a high pressure in the pipes and we will have to face leakage problems. A small solar panel can be attached to the pump to make it into a solar powered pump. This way, we would not have to depend solely on the slow process of thermosiphon to make the fluid flow in the pipes.
- Better insulation would allow even less heat losses through the pipes, PCM container, cooking pot and receiver and thus more heat will be available for cooking. Also, the phase change material can be charged and stored for much longer periods of time

without heat losses affecting the amount of energy that can be extracted from it if the insulation is better and more efficient. We used rock wool as an insulating material and stuffed it inside the wooden box in which the PCM container was placed. In place of rock wool, we can use other better insulating materials that have a higher R-value.

- The phase change material we used has a high melting temperature and a relatively low corresponding latent heat of fusion, which makes it somewhat inconvenient for use in the stove. The relatively lower latent heat of fusion means more amount of PCM would be required to store larger amounts of energy and the high melting point is not suitable since the maximum melting point achieved at the cooking pot is 125 degree Celsius and the phase change material's melting point is 178 ℃.

There are other potential integrated applications of our solar concentrator as well. These include:

- Domestic and commercial water heating
- Solar water disinfection
- Domestic and office space heating
- Solar water distillation

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