International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

Theoretical Analysis and Thermal Design of Solar Cooking Unit with $NaNO_3$+KNO_3 Phase Change Material

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Abstract: ***The increasing levels of greenhouse gases and the scarcity of fossil fuels are the primary driving forces behind the utilization of conventional energy resources. Among the various conventional resources available worldwide, solar energy emerges as a promising source. It is abundantly present in nature and completely free from pollution. Solar cooking, both for household and commercial purposes, offers numerous benefits. This study focuses on the theoretical analysis and thermal design of a solar cooking system using a kitchen box, also known as a solar cooking unit. The design considerations were made for cooking two meals, including rice, pulses, and vegetables. This required 50 kg of phase change material (PCM) salt, along with three solar parabolic reflectors, to harness the required 5.4MJ of solar energy. To transfer the heat energy from the storage tank to the kitchen box, the study suggests using Thermia b heat transfer oil. As an efficient PCM salt, a mixture of NaNO3 and KNO3 eutectic is recommended. This salt mixture stores latent heat energy at a temperature of 222°C, with the potential to reach temperatures as high as 350°C, enabling efficient energy utilization. The estimated cost saving for cooking food for four persons by conventional means is Rs.360 per month, while the approximate cost of the solar cooking unit (SCU) is Rs.20, 000. Furthermore, the incorporation of a kitchen box ensures continuous cooking in the kitchen, providing convenience to users throughout the day and night. Solar cooking systems offer numerous advantages and have the potential to gain popularity, contributing to a sustainable and energy - efficient future.***

Keyword: solar cooking, phase change material, heat storage tank, Renewable energy, Solar energy, Solar cooker, Socio - economic analysis

Abbreviations

M_s= Mass of PCM salt (Kg)
M_n = Mass of $NaNO_3$ (Kg)
M_k= Mass of KNO_3 (Kg)
M_o = Mass flow rate of heat transfer oil (Kg/hr)
SCU= Solar cooking unit
L_s= Latent heat fusion of PCM salt (KJ/kg)
Cp_n= Specific of $NaNO_3$ (KJ/Kg. K)
Cp_k= Specific heat of KNO_3 (KJ/Kg. K)
Cp_o= Average Specific of heat transfer oil (KJ/Kg. K)
T_2= Temperature of cooked food (^oC)
T_1= Ambient Temperature (^oC)

1. Introduction

Currently, the availability of non - renewable energy is declining, emphasizing the need for renewable alternatives like solar and wind energy. Solar energy is abundant in nature and comes at no cost, making it a cost - effective solution. Cooking is a vital energy - consuming activity, particularly in India where firewood is widely used, along with LPG and other sources. Solar energy presents itself as a viable alternative for traditional cooking methods, especially in rural areas where firewood is predominantly used. Solar cookers are efficient devices that utilize solar energy for cooking, making them ideal for reducing fuel consumption and minimizing the risk of accidental fires. They offer a safer and more environmentally friendly alternative to conventional cooking methods, which often have significant health and environmental consequences (Ghodake 2016).

This review paper aims to provide a comprehensive understanding of solar cooker to eradicate the problems faced by persons involved in cooking. As per the discussion among 20 people of urban and rural region, the following major problems of solar cooking have been identified, which is a hindrance for its popularity. Let's elaborate on each of the given major problems:

Solar cooking is slow: One purpose of solar cooking is its slow cooking process. Solar cookers utilize the heat from the sun to gradually cook food, which can take longer time compared to traditional cooking methods. This slow cooking can be advantageous in certain situations, such as when you have ample time for food preparation or when you want to simmer dishes for an extended period, allowing flavors to meld together.

Solar cooking is not available in the kitchen: This purpose highlights the fact that solar cookers are not typically found in conventional kitchens. Solar cooking requires specific equipment, such as solar cookers or solar ovens, which are designed to capture and utilize solar energy effectively, it is a viable option for outdoor cooking, camping trips etc. It is required to make available solar energy in kitchen.

Solar cooking is only available during sun hour: Since solar cooking relies on the sun's energy, it is limited to daytime hours. Solar cookers are most effective when exposed to direct sunlight. Therefore, after sunset or during cloudy weather conditions, solar cooking is impractical.

While solar cooking offers numerous benefits, it is important to consider these problems and develop the system to eradicate these problems to fulfill the cooking requirements and circumstances.

2. Literature Review

Solar energy is a freely available and abundant source of energy in the universe. It surpasses other conventional sources such as wind energy and water energy in terms of availability. In India, solar radiation is accessible for approximately 8 - 9 months throughout the year. The figure 1 illustrates the Climate Variation Zones for Jalgaon District.

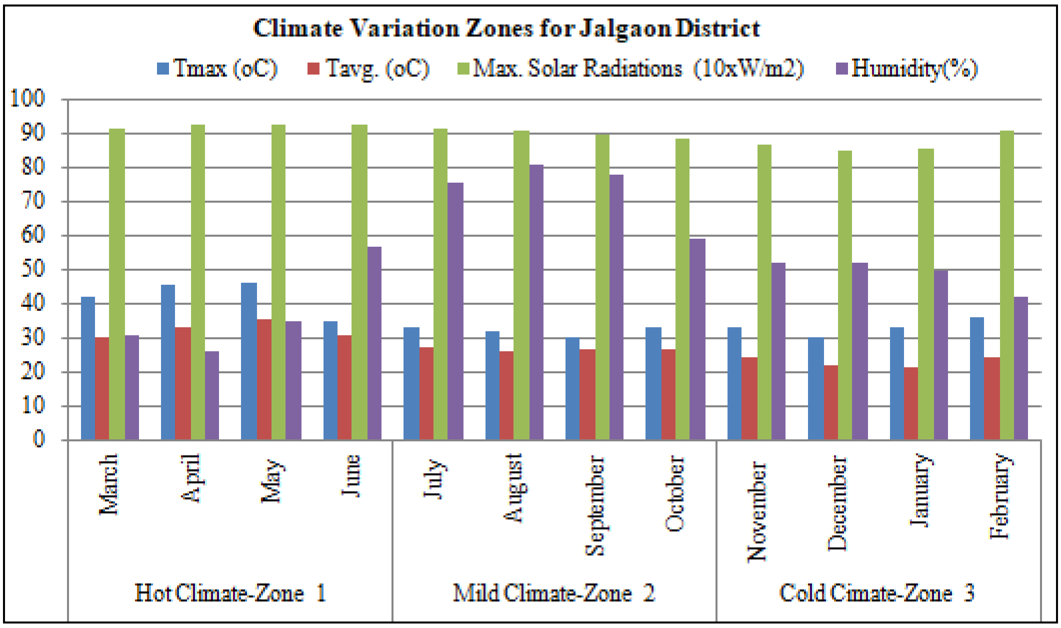

Figure 1: Climate Variation Zones for Jalgaon District

The graph clearly demonstrates that the intensity of solar energy in Jalgaon city ranges from 800 to 1000 W/m^2 between 11: 00 am. To 1: 00 pm. prior to this time frame, solar energy gradually increases, while after this period, it linearly decreases. Based on this observation, it can be concluded that if we focus and concentrate this energy to a specific area using any means, solar energy can serve as a significant and abundant energy source (Jaszczur 2018).

Solar radiation is widely recognized as a highly promising energy source in various regions across the globe. Efficient thermal energy storage becomes crucial in situations where there is a disparity between energy supply and consumption. One particularly appealing approach involves the use of phase change materials (PCMs) for latent heat storage, as they offer high storage density while minimizing temperature fluctuations (C. Thirugnanam 2020). Solar cooking during evening hours or when sunlight is not available can be achieved through the utilization of auxiliary power or the integration of phase change materials (PCMs) in solar cookers for thermal heat storage. An experimental study conducted on a basic box - type solar cooker examined the effectiveness of stearic acid (commercial grade) as a suitable latent heat storage material. A comparison was made between the performance of this solar cooker with PCM and a similar design solar cooker without PCM (Saxena Abhishek 2013). However, Solar cookers cannot be utilized when sunlight is scarce. To overcome this drawback, the integration of phase change materials (PCMs) as thermal storage has significantly enhanced the performance of solar cookers. This improvement enables the possibility of cooking in the evening or during periods of sunlight shortage. Additionally, the geometric features of PCM contribute to enhancing the cooking behavior, further supporting its usage in solar cookers (Omara 2020). Solar cookers offer the possibility of cooking during evening hours or when sunlight is not available by utilizing auxiliary power or incorporating phase change materials (PCMs) in their design. By using PCMs as a storage medium, solar cookers can effectively store thermal energy and use it for cooking even when sunlight is limited. This feasibility of utilizing phase change materials in solar cookers enhances their performance and extends their usability beyond direct sunlight availability (Bharat aher 2018).

A solar cooker with a thermal storage system incorporating a phase change material (PCM) has been developed specifically for cooking food for 2 - 4 individuals. In this design, paraffin is utilized as the PCM for energy storage. The solar cooker underwent testing following standardized procedures to assess its performance. The figures of merit were determined to be 0.3102 for the cooker with thermal storage, while a cooker without thermal storage had a lower figure of merit at 0.2946. The payback period for the solar cooker was calculated to be 7.87 years, resulting in a reduction of carbon footprint by 80.541 kg CO2 per year (S. Mallikarjuna Reddy 2017).

Solar cooking after the sunshine hours can be employed by using the phase change materials in the vessel subjected to the sunrays, which melts the phase change materials and in turn absorbs heat up to maximum temperature of 372.5^{o}C. It provides flexibility in cooking (Dr. S. Selvakumar 2020).

It is reviewed that still attention is required to develop a SCU with thermal storage system using phase change material to facilitate cooking at the kitchen and also in the night or in cloudy days.

The objective of this study to theoretically analyzed the thermal aspect of SCU with thermal storage system inside the kitchen.

Theoretical Analysis of Solar Cooking Unit

Solar Cooking Unit components

The solar cooking unit (SCU) consists of several major components that work together to harness and utilize solar energy for cooking purposes.

Solar Collectors: The SCU typically includes solar collectors, such as solar parabolic reflectors or solar panels, which are responsible for capturing sunlight and converting it into usable heat energy.

Heat absorber tank: The SCU incorporates a heat absorber tank, which consists of a storage tank or container that holds a heat transfer fluid, such as Thermia b heat transfer oil. This fluid absorbs and stores the thermal energy generated by the solar collectors.

Kitchen Box: The kitchen box is the cooking chamber of the SCU. It is designed to accommodate the cooking utensils and food items. The heat energy from the heat absorber tank is transferred to the kitchen box to cook the food.

Phase Change Material (PCM): A phase change material is often used in the SCU to store and release heat energy efficiently. PCM salt, such as a mixture of $NaNO_3$ and KNO_3 eutectic, is commonly employed. It can store latent heat energy at high temperatures, enhancing the energy utilization efficiency of the system.

Duration and Heat Release: The PCM gradually releases the stored heat over an extended period, allowing for slow and steady cooking. This ensures that the food is cooked evenly and thoroughly.

By combining the solar collector positioned outside the kitchen with the PCM - based thermal storage system connect with suitable heat exchanger containing heat transfer fluid. The SCU effectively utilizes solar energy to generate and store heat, enabling cooking activities within the kitchen area.

Solar Cooking Unit Working

Solar cooking units (SCUs) commonly use parabolic reflectors to capture solar energy, which is then used to heat a heat transfer fluid in an absorber tank. The heated fluid transfers the energy to a heat storage tank, also known as the kitchen box, located in the kitchen. A heat exchanger, typically using thermal oil, facilitates the transfer of energy from the absorber tank to the kitchen box. The kitchen box incorporates phase change material (PCM) that absorbs and stores the latent heat of melting. This stored heat can be utilized during cloudy days or in the evening, providing energy for cooking even when direct sunlight is unavailable.

In the solar cooking unit (SCU), the hot heat transfer oil from the heat absorber tank is pumped through insulated piping to a heat exchanger, which is surrounded by phase change material (PCM) in the kitchen box. The PCM absorbs the heat from the oil, and the cooled fluid is then pumped back to the heat absorber tank. This cycle is repeated until the desired temperature is reached. To monitor the temperature, a temperature sensor is installed at the outlet of the hot oil from the absorber tank. The flow of thermal oil from the absorber tank to the kitchen box is controlled by a solenoid valve. Additionally, a solar pump is used for the continuous circulation of the heat transfer fluid and facilitating the heat transfer process.

Hence the objective of this paper is to provide energy in the kitchen and in the night or cloudy day also may be achieved. The schematic diagram to demonstrate the working of SCU is illustrated in figure 2.

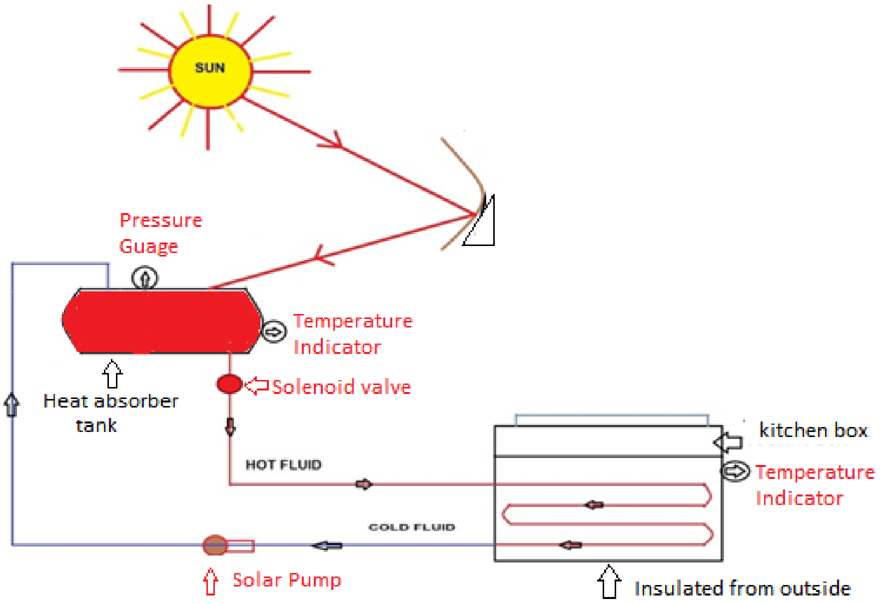

Figure 2: Schematic diagram of working of SCU with kitchen box

Heat Transfer fluid

Heat transfer fluid used to transport heat from solar collector to thermal storage tank is significant. This study focused on the thermia b as a thermal fluid (Atiş 2013). The Physical properties of heat transfer fluid thermia b are illustrated in table 1 and the figure 2 illustrates the variation of specific heat with change of temperature.

Table 1: Physical properties of heat transfer fluid thermia b (Atiş 2013)

Properties	Unit	Value
Density at 15°C	Kg/m^3	0.868
Falsh Point (PMCC)	°C	220
Fire point (COC)	°C	255
Pour Point	°C	- 12
Kinamatic viscosity		
at 0 °C	mm^2/s	230
at 40 °C	mm^2/s	25
at 100 °C	mm^2/s	4.7
at 200 °C	mm^2/s	1.2
Initial Boiling Point	°C	>355
Auto Ignition Temperature	°C	360
Neutralization Value	mgKOH/g	< 0.05
Average Specific heat of oil	KJ/Kg. K	2.5

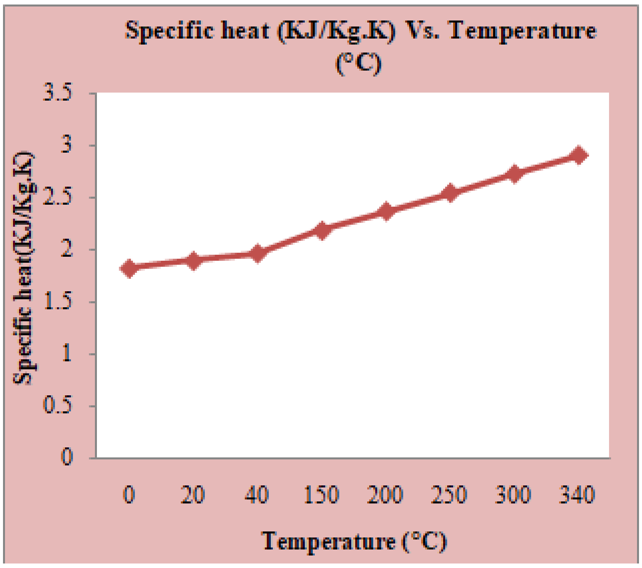

Figure 3: Specific heat (KJ/Kg k) Vs. temperature (°C) for Thermia b heat transfer fluid (Mitra 2015)

Phase Change Material (PCM)

As per the laboratory analysis conducted (Wagari 2016) it was determined that a salt mixture consisting of 60% $NaNO_3$ and 40% KNO_3 by mass exhibited promising thermal characteristics. An experiment was subsequently carried out to assess the suitability of this selected salt mixture for cooking applications. The findings of the experiment revealed that a total of 2.38 kWh of energy was needed to cook both meals for a family of five members, considering lunch and dinner. To store this required amount of energy, 4 kg of the PCM was found to be necessary. Based on the experimental results, it was determined that for 1.4 kg of the PCM, a charging time of 50 minutes was required to reach a temperature of 300°C. Similarly, a discharging time of 4.5 hours was observed for the PCM to cool from 300°C to 100°C. A commonly used thermal salt is the eutectic mixture of 60% sodium nitrate and 40% potassium nitrate, which can be used as liquid between 260 - 550 °C. It has a heat of fusion of 161 J/g, and a heat capacity of 1.53 J/ (gK). The sodium and potassium nitrate is observed one of the best PCM for this study. The latent heat storage material (PCM) utilized for effective heat storage, capable of retaining heat for approximately 24 hours, consists of a combination of KNO_3 and $NaNO_3$ in a 60: 40 percent ratio (mol %). It's worth noting that this specific salt mixture, which has demonstrated desirable thermal properties, is not only utilized for heat storage but also finds application in large - scale solar power plants that generate electricity (Chee Woh Foong 2010). Thermo physical properties of the mol. % - 60% $NaNO_3$ and 40% KNO_3 is illustrated in table 2.

Table 2: Thermo physical properties of the %mol. - 60% $NaNO_3$ and 40% KNO_3Eutectic (Chee Woh Foong 2010)

Parameter	Value
Thermal conductivity (W/m·K)	0.5
Density (kg/m^3)	2000
Enthalpy of fusion (kJ/kg)	108.67
Phase transition enthalpy (kJ/kg)	31.91
Temperature range	32°C to 496 °C
Melting Temperature	222°C

Heat Exchanger

In the heat exchanger there are tubes in hot fluid is flowing. The PCM salt which is the mixer of sodium and potassium nitrate in 60 - 40 manner is surrounded the tube to absorb heat. The space between thetubes is decided by Fourier laws of heat flow (Q) =K A dT/dx

Where k=thermal conductivity of pipe material, A=area of pipe, dT/dx=rate of change of temp w. r. t distance. The figure 4 illustrates the schematic of heat exchanger.

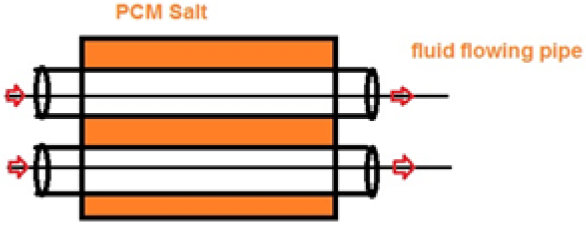

Figure 4: Schematic of heat exchanger

Thermal Analysis and Design

Heat Energy required for cooking the various types of food

Heat Energy required for cooking the food for four persons using SCU. It can differ depending on various factors such as the type of food being cooked, the cooking duration, and the desired cooking temperature. To estimate the heat energy requirement, it is necessary to consider the specific heat capacity of the food and the amount of heat required to raise the temperature of the ingredients. The type of food being cooked plays a significant role in determining the heat energy requirement.

Type of Food	Amount (gm)	Specific heat (KJ/Kg. K)	Cooking Temperature	Cooking Duration
Rice	500	2.22	218	30 min
Water	700	4.2	100	30 min
Pulses, vegetable	200+ 300	1.8	218	30 min

Let $(T_2 - T_1) = 218 - 30 = 188^oC$
Energy required in 30 min for cooking rice for 4 persons
Q_{rice}=500g of rice +700g of water
$=mc_{price} * (T_2 - T_1) + mc_{pwater} * (T_2 - T_1)$
=761400J
Therefore for cooking rice for two meals
=761400*2=1522800 J
Heat energy required for cooking two meals =1522800/3600=432 Whr. ~ 500 Whr.
Similarly for cooking pulses and vegetables for two meals in a day, heat energyrequired for cooking =800 Whr.
Therefore the total heat energy required for two times cooking is 1300 Whr. .
This heat energy is provided by salt and it can be analysed by calculating mass of PCM salt
Total Heat energy required = (Ms. Ls/ 3600) Whr. .
Mass of PCM salt required to absorb the 1500 Whr. (considering 15% losses for convenience)
Ms. Ls = 1300Whr.
Ms = 1500/ (108.67x1000/3600) = 50 Kg
Mass of salt required to store the 1500 Whr. heat is approximately 50 Kg.
Mass flow rate of heat transfer oil required to transfer the 1500 Whr. heat energy to the salt:
1500 Whr. = (Mox2.5x 188)
Mo=0.00195kg/sec=3.19 kg/hr.

Energy Exchange in Absorber Tank

The energy required for cooking purpose is 1500Whr., to heat 50 kg of PCM salt.
Then energy required to heat the heat transfer fluid in the storage tank= 5.4MJ.
The solar Irradiations in Jalgaon is $800W/m^2$, therefore useful energy received by the storage tank 240 W/m^2 (let 70% reflection losses).

Energy reflected by parabolic reflector of Area let $2m^2$ during 5hrs of direct sun and received by storage tank is $=240 W/m^2 x 5x3600 sec x 2 m^2= 8.64M J$.
This energy is transported by heat transfer oil from storage tank to kitchen box (30% losses of energy in piping).
Therefore total energy carried by heat transfer oil is 6MJ ie.1680Whr. > 1500 required.
Hence to provide of 2 m^2 of reflection area, around 3 parabolic reflectors are required.

Cost Analysis of solar cooking system with kitchen box is illustrated in table 3.

Table 3: Cost Analysis of solar cooking system with kitchen box

Sr. no	Material	Price (Rs)	Total Cost (Rs)
1	Parabolicreflector	4, 000	4, 000
2	Absorber Tank	3, 000	3, 000
3	Insulated Pipe	75/m	1, 500
4	Heat Exchanger	5, 000	5, 000
5	PCM	300	300
6	Kitchen Box	3000	3000
7	Miscllaneous		3, 200
	Total		20, 000

The approximate cost of solar cooking system with kitchen box Rs.20, 000.

Energy and Cost Saving

The design of solar cooking system with kitchen is for small family of 4 persons. The non conventional energy (mainly electrical energy) for cooking food for small family is 1500Whr., 1 unit of electricity =1000Whr. and cost/per unit is in the range of Rs.3 to Rs.13 (Rs.8 per unit). In one month energy saved by 45, 000Whr. So cost saved byRs.360 in cooking per month.

3. Conclusion

The solar cooking for household and commercial purposes offers several benefits. Firstly, it is environmentally friendly, as it relies on the sun's energy rather than fossil fuels. Although the initial cost of setting up solar cooking systems may be high, the operating costs are significantly lower compared to traditional cooking methods.

The use of phase change material (PCM) salt mixture, specifically $NaNO_3$ and KNO_3, proves advantageous for storing latent heat energy at temperature 222°C. In solar thermal power generation, temperatures of PCM may even rise up to 350°C, enabling efficient energy utilization. The thermal design includes the determination of mass of PCM salt 50Kg, required 3 parabolic collectors to harness 5.4MJ of heat energy. The Thermia b is suggested as heat transfer fluid. The cost for cooking the food of four persons per month is Rs.360 and the approximate cost of SCU is Rs.20, 000.

Additionally, the incorporation of a kitchen box in SCU ensures continuous cooking in the kitchen, making it convenient for users throughout the day and night. With its numerous advantages, solar cooking systems have the potential to increase in popularity, contributing to a sustainable and energy - efficient future.

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