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Experimental Analysis of Solar Parabolic Trough Collector for Novel Solar Cooking System in Gujarat, India

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Abstract. Indian villages use wood, cow-buffalo dung cakes, and agricultural waste for cooking, while urban areas use piped natural gas and LPG. Desertification and rising fuel prices require renewable energy sources like solar energy. Three types of solar cookers are used for cooking like: box, concentrator, and indirect. The box solar cooker, popular for over two centuries, uses solar radiation to generate heat energy for cooking food. It can be powered by reflector sheets and energy-storing materials, with a 35.3-21.7 % energy efficiency compared to a standard cooker with 27.6-16.9%. Direct solar cookers with parabolic reflectors concentrate reflected energy, suitable for direct or indirect cooking. In winter, a parabolic dish solar cooker cooks at a faster pace and higher temperatures. Moreover, the Parabolic Trough Collector offers a more practical cooking solution. This research work evaluates the efficiency of the Parabolic Trough Collector (PTC) in various real-world climatic conditions using locally available materials for reflector having 97 % of reflectivity and absorber tube made-up of copper tube covered with black colour sheet. Cooking system efficiency was tested, and the results ranged from 5 to 40%. Further, this study aims to identify an applied performance evaluation in Gujarat, India.

1. Introduction

Indian villages, the main energy sources for cooking include wood, cow dung, buffalo dung cakes, and agricultural waste. Conversely, in metropolitan areas, the primary energy sources are piped natural gas (PNG) and liquid petroleum gas (LPG). Unfortunately, desertification is worsened by the deforestation caused by cutting down trees for firewood, and the use of animal dung cakes contributes to environmental pollution. Additionally, the continuous increase in fuel prices necessitates the adoption of various renewable energy sources for cooking [1]. India is fortunate to receive abundant solar energy, making solar cooking devices a promising prospect for the country's future. Box cookers, concentrator cookers, and indirect cookers are the three basic types of solar cookers used for solar cooking. These solar cookers offer a sustainable and eco-friendly alternative for preparing food [16].
The box-type solar cooker represents a fundamental and widely employed configuration designed to convert solar irradiance into thermal energy. This apparatus encompasses an insulated enclosure featuring a transparent upper surface or lid, serving to encapsulate solar radiation. Subsequent to its ingress, solar radiation undergoes conversion into thermal energy, subsequently harnessed for the culinary preparation of victuals ensconced within the confines of the apparatus. This approach

manifests as a straightforward and efficient methodology for harnessing solar irradiation to facilitate the cooking process. A subtype within this category, denoted as the Box-type Solar Cooker with Thermal Energy Storage, integrates a thermal energy storage medium, thereby conferring the capability to accumulate surplus thermal energy for subsequent utilization. This feature enhances its energy efficiency, and it can achieve energy efficiency levels of 35.3% to 21.7%, which is higher than standard box-type solar cookers [2]. Direct Solar Cookers employing Parabolic Reflectors employ precisely shaped parabolic reflectors to converge solar irradiance towards a singular focal point. The resultant concentrated solar energy finds application in both direct and indirect culinary methodologies. Through the incorporation of multifaceted optical elements such as Fresnel lenses and multifunctional mirrors, an extensive gamut of cooking alternatives catering to diverse food categories can be accommodated [3, 9]. Notably, the utilization of a dynamically tracked parabolic dish solar cooker, predominantly during winter conditions, purportedly imparts an accelerated cooking tempo (ranging from 2 to 6 times swifter) coupled with elevated temperatures in contrast to conventional box-type solar cookers [4]. The parabolic dish design enables the concentration of solar energy onto a focal point, providing high temperatures for cooking. The Parabolic Trough Collector is an advanced solar cooking solution that allows for rapid attainment of higher temperatures ranging from 60°C to 400°C. This collector design has shown to be a more practical and efficient solution for cooking food compared to the other types mentioned previously [5, 6].

This work focuses on a solar cooking device that utilizes a parabolic trough collector (PTC) along with a cooking vessel placed precisely at the PTC's focus point or line. Previous research on solar cookers and PTCs has been limited to local applications and specific cooker types. However, some studies have explored thermal storage units and cooker construction [7]. Economic implications of solar cooking systems have also been studied in particular regions, like Lebanon [5] and India [8].

However, existing research tends to focus on end uses rather than conducting comprehensive development and experimental analysis under specific local climatic conditions. To address this gap, this work conducts an extensive exploratory performance analysis of the PTC's efficiency under a wide variety of real-world climatic circumstances. Notably, the experimental system employs locally available materials for the PTC's reflector and absorber, representing a significant step towards an indigenous solution. The primary objective of this investigation is to assess the operational efficacy of the Parabolic Trough Collector (PTC) in the context of culinary applications, concentrating particularly on its applicability within the geographical confines of Gujarat, India. By assessing the applied performance of the PTC, this research contributes to enhancing solar cooking solutions in the region.

Nomenclatures and abbreviations

1. Solar Cooker Surface Area (A_{sc}) [m²]
2. Specific Heat of Water (C_{pw}) [J/kg·K]
3. Time Difference (dt)
4. Average Solar Insolation (I) [W/m²]
5. Mass of Water (m_w) [kg]
6. Thermal Efficiency (η)
7. Cooking Power (P) [W]
8. Standardized Cooking Power (P_s) [W]
9. Time (t)
10. Initial Water Temperature (T_1) [°C]
11. Final Water Temperature (T_2) [°C]

2. The development of proposed cooker

2.1. Methodology

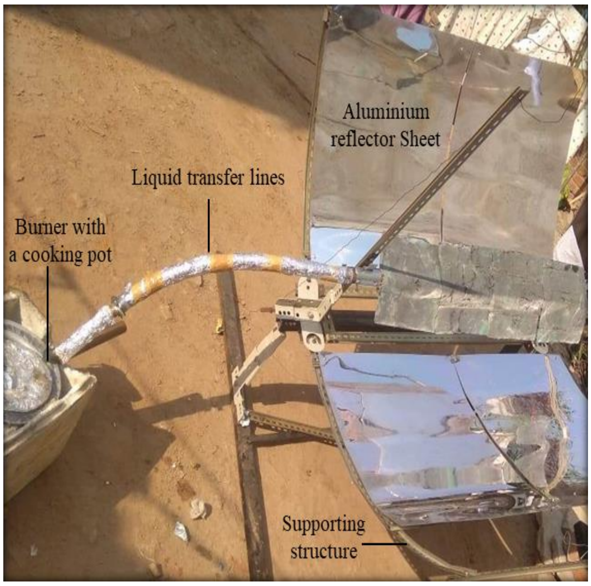


Figure 1. The actual pictorial view of Solar Cooker Using Parabolic Trough Collector

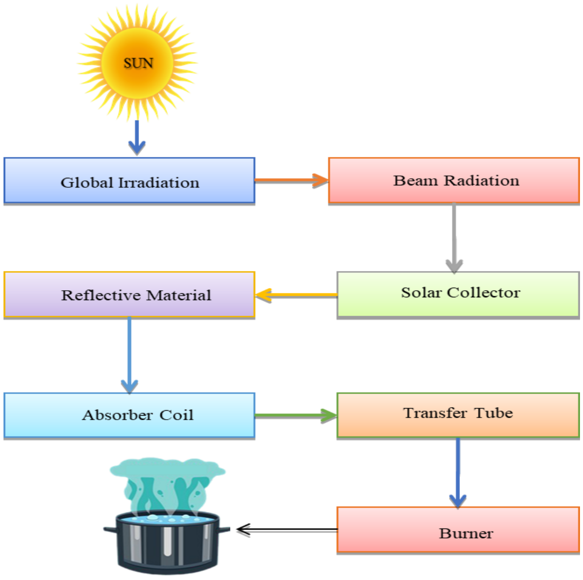
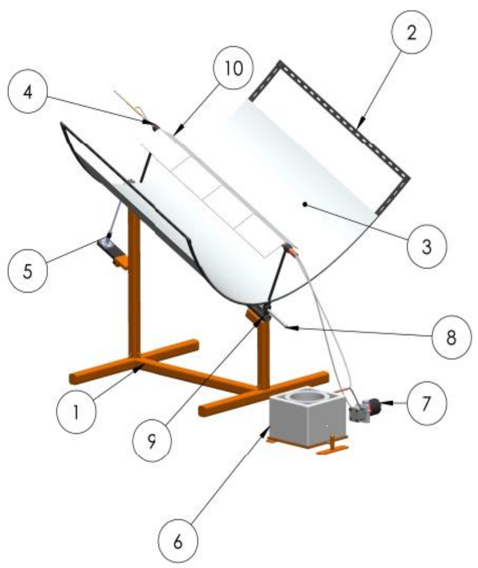


Figure 2. Flow diagram of proposed solar cooking system using parabolic trough collector

The parabolic trough collector consists of a reflector sheet, Absorber tube with cover, Liquid transfer lines, Burner with a cooking pot and supporting structure as shown in figure 1. The solar radiation receives on a reflector sheet which was transferred to the thermic fluid as heat energy. This heat then transfer to the cooking pot via liquid transfer lines as shown in figure 2.

2.2. Development details of the cooker

The solar cooker comprises of a parabolic trough collector. The collector reflective surface was built with polished aluminium sheet having 97% reflectivity. The absorber tube, constructed from copper tubes covered with a black reflective sheet, effectively absorbed solar rays. This tube was connected to both the cooking burner and cooking pot through copper tubes. The burner itself was designed with a brass double-walled structure. To retain the heat within the cooking kettle, glass wool insulation was employed, preventing heat loss into the atmosphere. A heat transfer (thermic) fluid circulated through the cooking pot using a mechanical hydraulic pump. The working fluid followed a path from the burner to the absorber tube and vice versa. Moreover, the system incorporated a lead screw mechanism, enabling adjustment of the parabolic trough collector's orientation, thus optimizing solar energy harvesting and thermal efficiency based on the sun's direction. The proposed cooker is shown in figure 3 and 4 The complete experimental setup was developed at Village Ichpura, Dist.: Mehsana, Gujarat, India.



NUMBER	PART NAME
1	Supportive Frame
2	Reflective Sheet Frame
3	Reflective Sheet
4	Copper Pipe
5	Lead Screw for Solar Tracking
6	Burner Assembly
7	Hydraulic Pump
8	Support for Anguler Displacement
9	Frame Channel
10	Reflectie Cover of Copper Pipe

Figure 3. 3D Model of proposed solar cooking system with parabolic trough collector

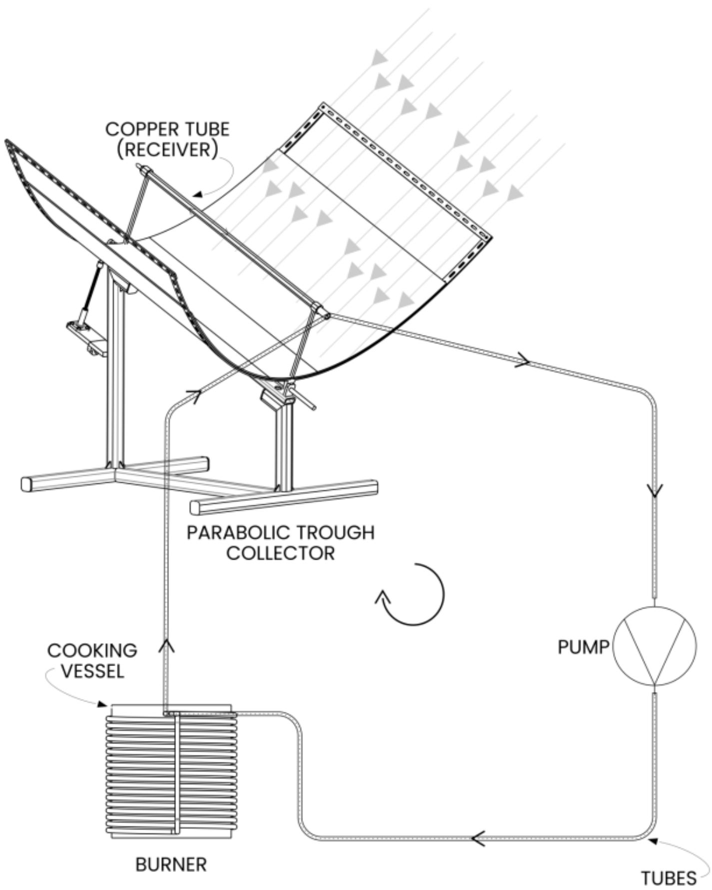


Figure 4. Solar Cooking System Using Parabolic Trough Collector

2.3. Testing and Evaluation

The experiments were conducted at Ichhpura village, located near Balol in Mehsana district, Gujarat, India (Longitude: 72.3881041, Latitude: 23.5275311). The solar cooking system was strategically positioned in an open area to receive unobstructed maximum solar radiation. To achieve this, the reflector sheet focused the sun's rays onto the absorber tube. It was covered with a black sheet, minimizing convective heat loss and maximizing heat absorption from the solar radiation. In this unique cooking method, a working fluid (thermic fluid) was employed to transfer the absorbed solar energy to the cooking burner and then gradually to the cooking vessel. The thermic fluid's capability to store and absorb heat made this cooking approach distinct. The testing of the solar cooker involved manual tracking of the collector to ensure optimal performance. To evaluate its efficiency, rice (Oryza sativa) and dal (Cajanus cajan), common Gujarati foods, were chosen as cooking loads. Initially, water was employed as the calorific load for the purpose of appraising the thermal efficacy of the solar cooker. The ensuing outcomes were subsequently juxtaposed against antecedent published datasets.

The experimental trials transpired over the time span encompassing the inaugural week of November through the commencement of December 2020. Within this temporal ambit, a spectrum of variables underwent continuous monitoring, comprising solar irradiation, ambient air temperature, wind speed, absorber surface temperature, and temperature within the cooking vessel. Subsequent to data acquisition, the evaluation of the solar cooker's operational prowess was conducted employing established formulations denoted as equations 1, 2, and 3. This analytical framework facilitated the computation of standardized solar cooking power, solar cooking power, and thermal efficiency. Standardized Solar Cooking Power [10, 11]: Employing the established reference value of standard solar irradiation at 700 W/m^2, the standardised cooking power is computed through the utilization of equation (1).

$$P_s = P\left(\frac{700}{I}\right) \tag{1}$$

Where, I represent the interval average solar irradiance in watts per square meter (W/m²), and P_s signifies the standardized cooking power in watts (W)

2.3.1. Solar Cooking Power [10, 11]: The effective solar energy intake during the heating process, quantified as the alteration in sensible heat content of water. The theoretical determination of solar cooking power is feasible through the utilization of equation (2).

$$P = \frac{T_2 - T_1}{t} m_w C_{pw} \tag{2}$$

Where, P represents the power demand for cooking, measured in watts (W), m_w denotes the mass of water being heated, expressed in kilograms (kg), C_{pw} signifies the specific heat capacity of water, measured in joules per kilogram per degree Celsius (J/kg·K), t stands for the duration of the heating process, represented in seconds (s), $T_1$and T_2 represents the initial and final temperatures of the water, respectively, in degrees Celsius (°C).

2.3.2. Thermal Efficiency [10, 11]: Thermal efficiency is determined by using the equations (3).

$$\eta = \frac{m_w * C_{pw} \, (T_2 - T_1)}{A_{sc} \int I dt} \tag{3}$$

Where, m_w denotes the mass of water being heated, expressed in kilograms (kg), C_{pw} signifies the specific heat capacity of water, measured in joules per kilogram per degree Celsius (J/kg·K), A_{sc} is the Solar Cooker Surface Area (m²), I represent the interval average solar irradiance in watts per square meter (W/m²), $T_1$and T_2 represents the initial and final temperatures of the water, respectively, in degrees Celsius (°C).

Based on the additional load testing, it was observed that with an average solar irradiation of 643.42 W/m2, the surface temperature of the absorber tube could be increased from 110°C to 120°C, highlighting the system's capabilities.

3. Result and discussion

The objective of this research was to develop a solar cooking system using a parabolic trough collector, enabling high-temperature cooking inside the kitchen. The parabolic trough collector consists of a polished aluminium sheet as its reflective surface, which harnesses solar radiation. The collected radiation energy was then converted into heat energy and absorbed by a heat transfer fluid (thermic fluid). This heat was then transferred through a pipe to the cooking burner. The cooking burner was constructed with a double-walled brass vessel, containing a copper coil. The coil receives the heat energy from the connected heat transfer fluid. To cook the food, it is placed in a cooking pot in proposed solar cooking system.

Many experiments on a proposed solar cooking system were conducted. Solar irradiation, wind speed, ambient temperature, receiver tube surface temperature, thermic fluid temperature, cooking burner water temperature, and so on were all measured. The data from the observations were also gathered and examined. K-type thermocouple, Work Zone make digital anemometer and tenmars make solar power meter was used to measure the temperature, wind speed, and solar irradiation respectively. Based on the available results various graphs have been plotted for the cooking performance prediction as shown in figure 5, 6, 7 and 8. During the entire measurement period, the weather was found clean. As a result, the average solar irradiation value varies from 611 to 685 W/m^2, leading to a maximum possible cooking burner water temperature. That is sufficient for cooking using solar energy.

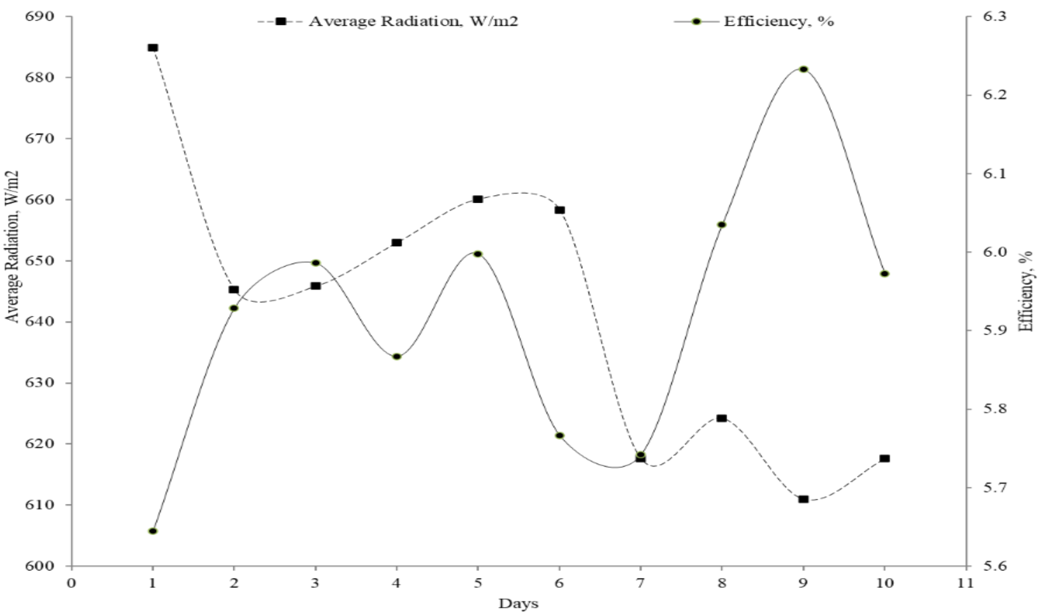


Figure 5. Variation of efficiency of the cooking device with solar radiation

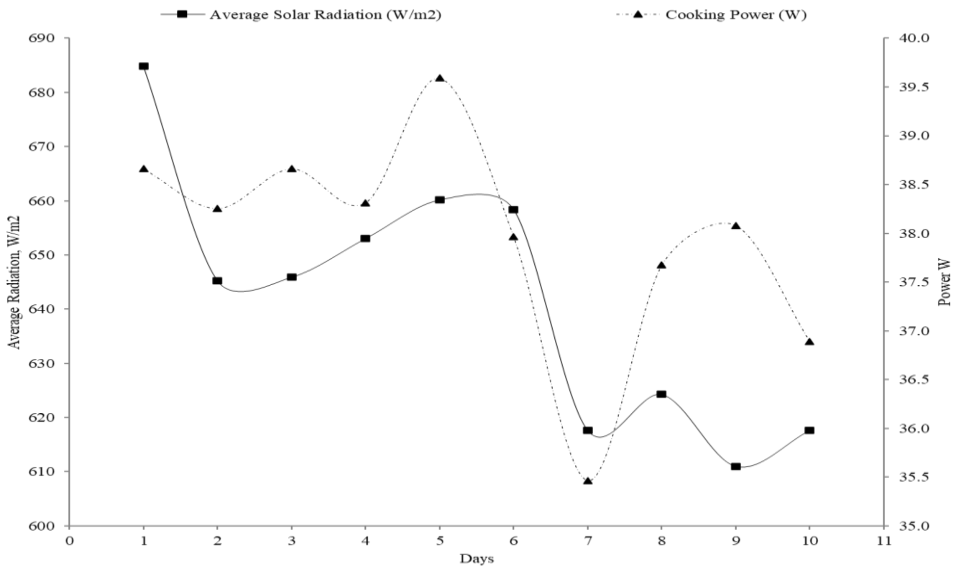


Figure 6. Variation of cooking power with solar radiation

The average cooking power of the cooking system was 38 W as per figure 6. The average standardized cooking power was calculated to be 41.4 W. The calculated value of cooking power and standardized power shows that the proposed final system can cook the different types of food. **Error! Reference source not found.**7 and **Error! Reference source not found.**8 shows the variation in efficiency and cooking power concerning water temperature.

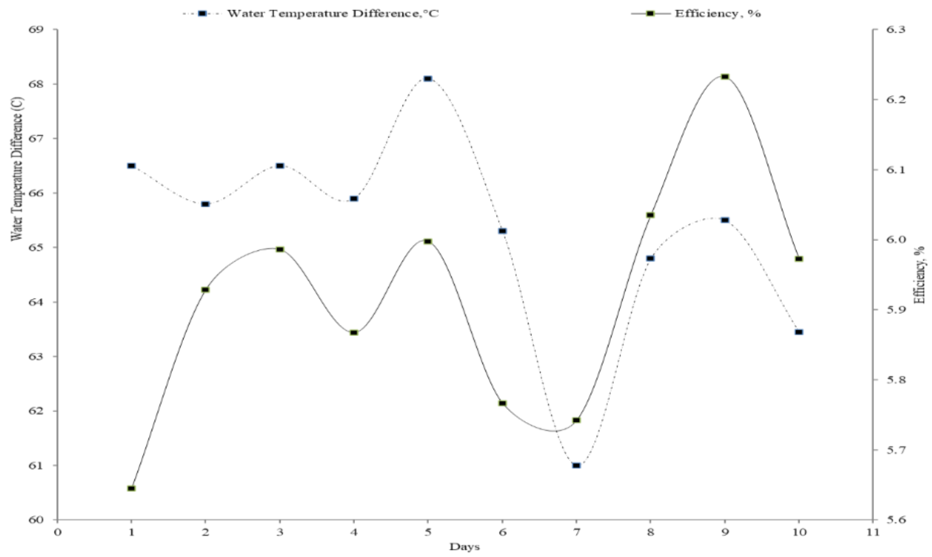


Figure 7. Efficiency and water temperature difference

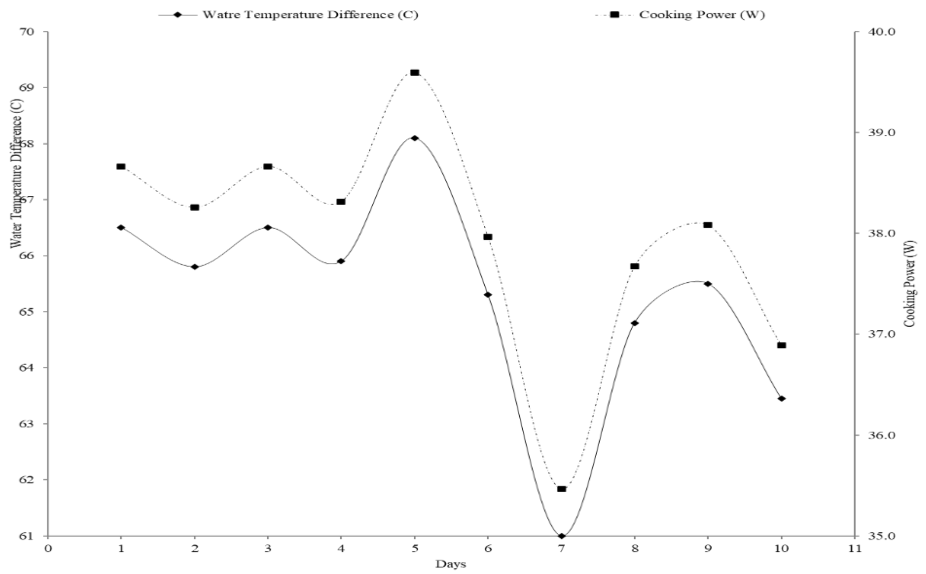


Figure 8. Cooking power and water temperature difference

4. Conclusion

In the village of Ichhpura, Balol, Mehsana, Gujarat, a functional solar cooking system was meticulously designed and successfully implemented. A comprehensive performance assessment was carried out through a meticulous load test. The ensuing test outcomes yielded significant insights into the inherent capabilities of the solar cooking arrangement. Throughout the testing phase, the prevailing ambient temperature was consistently registered at an average of 27.5°C. In tandem, the solar concentrator experienced an average incident solar irradiance of 642 W/m². The operational efficiency of the solar cooking mechanism was markedly pronounced, attaining a pinnacle water temperature of 91.9°C within the culinary receptacle. The empirical efficiency deduced from the experimental trials exhibited a notable variation, encompassing a spectrum ranging from 5% to 40%. This comprehensive range underscores the system's adaptability and potential for a diverse array of cooking endeavors, inclusive of tasks such as rice (Oryza sativa) preparation and water boiling. The practical findings substantiate the viability and applicability of the proposed solar cooking system, thereby establishing it as a promising and sustainable solution conducive to eco-friendly culinary practices.

References

[1] Avinash Chaudhary, Amit Kumar, and Avadhesh Yadav. 2013. "Experimental investigation of a solar cooker based on parabolic dish collector with phase change thermal storage unit in Indian climatic conditions", Journal of Renewable and Sustainable Energy 5, 023107.

[2] Pinar Marcuse. 2018. "Box-type solar cookers with sensible thermal energy storage medium: A comparative experimental investigation and thermodynamic analysis", Solar Energy 166, 432–440.

[3] F. Yettou, B. Azoui, A. Malek, A. Gama, N. L. Panwar. 2014. "Solar cooker realizations in actual use: An overview", Renewable and Sustainable Energy Reviews 37, 288–306.

[4] Hosny Z. Abou-Ziyan. 1998. "Experimental investigation of tracking paraboloid and box solar cookers under the Egyptian environment", Applied Thermal Engineering 18, 1375-1394.

[5] Herez, M. Ramadan and M. Khaled. 2018. "Review on solar cooker systems: economic and

environmental study for different Lebanese scenarios", Renew. Sustain. Energy Rev. 81, 421–432.

[6] E. Cuce and P.M. Cuce. 2013. "A comprehensive review on solar cookers", Appl. Energy 102, 1399–1421.

[7] Aramesh Mohamad, et al. 2019. "A review of recent advances in solar cooking technology", Renewable Energy 140, 419-435.

[8] Sunil Indora Tara C. Kandpal 2019 Solar energy for institutional cooking in India: prospectsand potential Environment, Development and Sustainability (Spinger) 22 7153 – 7175

[9] Piyushkumar M Mistri, Dr. Kedar Pathak 2020 A Scientific Pore over a Solar Cooking Systems *International Journal of Recent Technology and Engineering (IJRTE)***Volume-8, Issue-6** 148-153.

[10] Shawn Shaw 2002 Development of a Comparative Framework for Evaluating the Performance of Solar Cooking Devices Troy, NY 12180.

[11] Piyushkumar M Mistri, Kedar Pathak and Raj Kumar Satankar 2021 Building and Performance Evaluation of Novel Solar Cooking System in Gujarat, India IOP Conf. Series: Earth and Environmental Science 795/012015 doi:10.1088/1755-1315/795/1/012015

[12] N M Nahar 1991 Performance studies of a large size non-tracking solar cooker*Renewable Energy***Volume – 2** No. 4,5 pp. 421430.

[13] N. L. Panwar, S. C. Kaushik, Surendra Kothari 2012 State of the art of solar cooking: An overview *Renewable and Sustainable Energy Reviews***16** 3776– 3785.

[14] Shubhangi Ambade, Surbhi Tikhe, Pratik Sharma, and Vikrant Katekar 2017 Cram of Novel Designs of Solar Cooker *International Journal of Mechanical Engineering***Research Volume 7, Number 2** pp. 109-117.

[15] V. Pranesh, S. Christopher, V. Kumaresan 2019 A 50 year review of basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications *Solar Energy***187** 293–340.

[16] Luis Bernardo López Sos, Mauricio González Avilés, Dante González Pérez and Yuritzi Solís Gutiérrez 2014 Rural Solar Cookers, an alternative to reduce the timber resource extraction through the use of renewable energy sources: technology transfer and monitoring project Energy Procedia **57** 1593 – 1602.

[17] Muhammad Kamran 2021 Renewable Energy Conversion Systems, Pages **109-152.**