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EXPERIMENTAL INVESTIGATION ON TWO NOVEL STANDARD PARAMETERS TO IMPROVE THE PERFORMANCE OF SOLAR BOX COOKERS

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Abstract

The size and shape of solar box cooker is determined by the volume of the vessel, which in turn depends on the number of family members. The primary objective of this study is to overcome the obstacles inhibiting researchers from crafting solar box cookers tailored to their specific research needs, as well as hindrances preventing manufacturers from effectively bringing them to market. This experimental study aims to identify two novel optimal volumetric efficiencies (VE_1 and VE_2) to minimize cooking time. To achieve this goal, we employed two identical solar box cookers made from the same materials and four vessels. The results obtained clearly show that the absorber temperature reached a maximum value of 124.9 °C and the boiling time was the shortest 02h50 when the first volumetric efficiency VE_1 had the least value of 6.2% and the second volumetric efficiency VE_2 had the greatest value of 100%. It is concluded that these two volumetric efficiencies could serve as benchmark parameters for future research, providing a standardized reference for developing solar box cookers of varied shapes and sizes under the same climatic conditions.

1. Introduction

In order to mitigate the adverse impacts stemming from the significant risks associated with various cooking fuels reliant on combustion for thermal energy production, it is imperative for the global community to prioritize the adoption of renewable energies that are

environmentally friendly and sustainable in nature. Employing solar energy in cooking food through the utilization of solar box cookers has become indispensable in mitigating both greenhouse gas emissions and the associated health hazards. Several studies have shown that solar box cookers are beneficial for people residing in remote areas without access to a natural gas distribution network, as they enable them to decrease their reliance on fossil fuels. This study suggests that solar box cookers can be utilized by any household with a part of their residence receiving daily solar radiation. As a result, there will be a rise in the number of users of solar box cookers, leading to a significant and effective decrease in greenhouse gas emissions and health risks. Researchers have developed and refined various types of solar box cookers to enhance their thermal efficiency and cooking effectiveness.

The main objective of the paper [1] is to examine the thermal capabilities of the single glazed solar box cooker that has been developed. Six experiments were carried out, consisting of three stagnation tests and three sensible heat tests. The solar box cooker equipped with a tracking reflector set at an optimal angle achieved a peak plate temperature of 148.7°C. Additionally, substituting the stainless steel vessel with an aluminum cooking vessel resulted in a 15.4% improvement in thermal efficiency. The researchers developed and tested a hybrid solar box cooker incorporating a trapezoidal duct to augment heat transfer rates and minimize cooking durations in [2]. Inside the duct, a 200 W halogen lamp was installed, while the solar box cooker itself contained 450 small hollow copper balls. A comparison between the conventional solar box cooker and the new design revealed that the latter can effectively cook various foods even under adverse ambient conditions. In the study [3], two solar box cookers of cylindrical design were built, sharing the same dimensions and material characteristics. However, one of the cookers was equipped with Bayburt stone as a sensible thermal energy storage medium, while the other served as a conventional cooker without any heat storage. The utilization of Bayburt stone in one cooker facilitated efficient, consistent, and sustained cooking operations extending into the late evening, thanks to its sensible thermal energy storage properties. The study [4] investigates the effectiveness of a double-glazed box-type solar oven equipped with three reflectors and a glazing wiper system. Findings indicate that employing the vapor wiper system enhances overall efficiency by 9.4% and decreases boiling time by 35.3 minutes. Techno-economic assessment reveals that the solar cooker with a vapor wiper system is dependable for outdoor food preparation and is economically viable. The article [5] presents an approach to designing a double glazed box solar cooker featuring an L-shaped absorber plate alongside one internal (bottom) and two external plane reflectors. Experiments were conducted on this solar cooker under three different configurations: using

only the top reflector (case-1), employing both top and front reflectors (case-2), and utilizing top, front, and bottom reflectors (case-3). The aim was to observe the maximum temperatures reached by the absorber plate on various days. Results indicate a significant 30% increase in absorber plate temperature for case-3 compared to case-1, where only the top reflector was utilized. However, the disparity between case-2 and case-3 is minimal. In the paper [6], three distinct configurations were investigated: an unmodified solar box cooker, one with hollow capsules, and another with a phase change material (PCM) encapsulation, to assess the thermal effectiveness of a low-cost solar box cooker. Experimenting with cooking across these configurations reveals that while all are suitable for cooking, the third option stands out as the most efficient, achieving superior thermal performance and significantly reducing cooking duration, even under similar ambient conditions to those of the other models tested. The efforts of the authors in [7] are directed towards creating a non-tracking solar cooker by substituting a flat reflector with a compound parabolic concentrator (CPC) mounted on the edge of a box-type solar cooker to enhance solar radiation collection efficiency. Results indicate that energy efficiency peaked at 34% when carrying a 3.5 kg water load with a specific boiling time of 22.58 minutes. However, the efficiency of solar cookers diminishes as the concentration ratio decreases from 1.8 to 1.4. Conversely, increasing the concentration ratio restricts the acceptance angle of the sun, rendering it less conducive for widespread adoption. The primary aim of the paper [8] is to conduct initial testing on a box-type solar cooker fitted with a finned absorber plate, which accelerates heat transfer to the air within the cooker. Through thorough analysis of experimental data, it was observed that the stagnation temperature of the box-type solar cooker with a finned absorber plate was approximately 7% higher than that of a cooker with a standard absorber plate. Moreover, employing a finned absorber plate led to a reduction in the time required to heat water to boiling temperature in both types of solar cookers, with an approximately 12% decrease noted. An experimental comparison in [9] was undertaken between two box-type solar cookers operating in different cooking environments. The first utilizes natural convection for heat transfer, while the second employs forced convection, aided by a fan for enhanced airflow. Results indicate a significant enhancement in thermal performance with the forced convection setup, enabling much faster cooking compared to the natural convection counterpart. The objective of study [10] is to create a solar cooker design that boosts the heat capacity of a box-type solar cooker by maximizing solar energy within the box for improved cooking efficiency, utilizing non-tracking concentrator optics. Experimental findings reveal that the concentrator solar cooker achieves a stagnation temperature 15–22 °C higher than that of a traditional box-type solar cooker with a booster mirror. Additionally, it is

noted that the concentrator cooker reaches the boiling point of water faster, by 50–55 minutes, compared to the conventional box-type cooker equipped with a booster mirror. The paper [11] assesses the effectiveness of box-type solar cookers through both theoretical analysis and practical experimentation, with adjustments made to the traditional design. Changes include removing bottom insulation and adding a glass cover at the bottom, along with implementing a set of reflectors to redirect radiation onto the backside of the absorber plate. Comparative results under identical operating conditions indicate that the absorber plates in the box-type cooker and the modified double exposure cooker reach temperatures of 140°C and 165°C, respectively. Overall, the double exposure cooker decreases cooking duration by approximately 30–60 minutes on average. The authors introduced an innovative non-tracking box-type solar cooker incorporating a stationary compound parabolic concentrator (CPC) in [12]. Numerous experiments were conducted under different conditions regarding water load and reflector presence (with/without load and with/without reflector). These tests, performed under the authentic climatic conditions of Adrar, demonstrate the cooker's capability to prepare two meals daily for a family of four, even during the colder seasons. Moreover, this system can be seamlessly integrated into a building's kitchen wall. The aim of the work [13] is to introduce a fresh design for a solar cooker featuring internal reflectors and a tracking-type bottom parabolic reflector, with the intention of contributing to the achievement of sustainable development goals. Real cooking trials were conducted for a family of four, illustrating the practical utility of the proposed solar cooker. The findings indicate that the cooker equipped with a tracking-type bottom parabolic reflector is capable of reaching intermediate temperatures of approximately 140–150°C.

The primary objective of this experimental investigation is to identify two optimal volumetric efficiencies (VE_1 and VE_2) with the aim of decreasing cooking duration. These efficiencies are intended to serve as benchmarks for researchers in the development of tailored solar box cookers (SBCs) for their studies, as well as for manufacturers in the commercialization of such cookers. To achieve this objective, the process involved using four vessels and two identical solar box cookers constructed with the same material properties.

The present study is described as follows: Section 2 identifies and clarifies the problem found in the literature. Section 3 proposes a solution for the problem defined in the previous section. Section 4 describes the SBC design methodology, measuring devices used and experimental tests. Section 5 reports the results of the study. Section 6 presents the conclusion of the work.

2. Description of the problem to be solved

Studies conducted on solar box cookers to enhance their energy efficiency and thermal performance have predominantly focused on two primary approaches. The first involves refining the fundamental components of the cooker, such as its cooking chamber [14], external structure [15], insulation [16], cover mirror [17], reflector [18,19,20] and thermal energy storage (TES) [21], aiming to optimize their functionality. The second approach explores modifications to the shape and material composition of the cooking vessel itself [22,23,24], recognizing its pivotal role in heat retention and distribution during the cooking process. Despite these efforts, there remains ample room for further exploration and innovation in the pursuit of maximizing the effectiveness of SBCs for sustainable cooking solutions.

Additionally, a common practice among researchers striving to assess and compare the thermal efficiencies of various SBC designs involves calculating figures of merit (F1 and F2) [25,26,27,28] from experimental data. These metrics serve as quantitative benchmarks for evaluating the thermal performance of different SBC configurations, facilitating meaningful comparisons and informed decision-making in the realm of solar cooking technologies.

The first figure of merit (F1) is defined as the ratio of optical efficiency (n_0) and the overall heat loss coefficient (U_L). F_1 is calculated during the stagnation test (without load) by equation (1).

The second figure of Merit ($F2$) is used to evaluate the cooker's optical efficiency and heat exchange efficiency under full load condition. F2 is calculated during the sensible heat test (with load) by equation (2)

$$F_1 = \frac{n_0}{U_L} = \frac{T_{p\,max} - T_a}{G} \tag{1}$$

$$F_2 = \frac{F_1 (mC_P)_w}{A_i \Delta t} \left[\ln\left(1 - \frac{T_i - T_a}{F_1 G}\right) - \ln\left(1 - \frac{T_f - T_a}{F_1 G}\right)\right] \tag{2}$$

Where we noted n_0 is the optical efficiency of the cooker (%), U_L is the overall heat loss coefficient (W/m K), T_p max is the absorber temperature max (°C), T_a is the ambient temperature (°C), G is the irradiance (W/m^2), m is the mass of the water (kg), C_p is the specific heat of water (J/kg K), A_i is the intercepted area of the cooker (m^2), Δt is the time interval (s), T_i is the initial temperature of water (°C), and T_f is the final temperature of water (°C).

In the referenced paper [29], procedures to calculate F1 and F2 have several limitations due to the complex of solar box cooker optical and thermal behavior. In response to these challenges, the authors of this paper advocate for a refined approach to these calculations,

which promises to yield more nuanced and practical figures of merit. By addressing the complexities of solar box cooker behavior comprehensively, this proposed revision aims to provide researchers and practitioners with enhanced tools for evaluating and comparing the performance of various solar box cooker designs, thereby advancing the field of solar cooking technologies.

While the proposed revision by [29] offers improvements in assessing solar box cookers' performance, it too encounters challenges when attempting to compare cookers with diverse characteristics, such as

- Inner sidewalls are made as an internal reflector or as absorbers
- Material used to construct the absorber
- Shape profile, number and thickness of the transparent cover
- Sides number of SBC exposed directly or indirectly to sun rays

These discrepancies in solar box cookers attributes can introduce complexities that may not be fully captured by the revised methodology. Consequently, achieving accurate and meaningful comparisons across a range of solar box cooker configurations requires a nuanced understanding of these inherent differences and their potential implications on performance metrics. Moreover, existing literature lacks comprehensive explanations regarding the rationale behind selecting specific dimensions for solar box cookers. In practice, it is commonly acknowledged that the inner chamber volume of the SBC should exceed that of the cooking vessel, ensuring adequate space for heat distribution and efficient cooking. However, the critical inquiry arises: what precisely should be the optimal disparity between these volumes? This unanswered question highlights the need for further exploration and empirical analysis to elucidate the ideal relationship between SBC dimensions and vessel capacities, contributing to the refinement of solar cooking technologies.

3. Proposed two new parameters to solving the problem

To remove the limitations that prevent researchers to manufacture SBCs adapted to their researches and manufacturers to market them, the present work is to demonstrate the relationship between three parameters (Water volume, vessel volume and inner chamber volume of the SBC) and their influence on the absorber plate temperature, the water temperature and the boiling time).

The primary objective of this study is to overcome the obstacles inhibiting researchers from crafting solar box cookers tailored to their specific research needs, as well as hindrances

preventing manufacturers from effectively bringing them to market. The present research endeavors to elucidate the intricate relationship among three critical parameters (water volume, vessel volume, and the inner chamber volume of the solar box cooker) and their profound impact on key variables such as absorber plate temperature, water temperature, and boiling duration. By shedding light on these connections, we aim to empower both researchers and manufacturers with valuable insights essential for enhancing the design, efficiency, and usability of solar box cookers in various contexts.

The incorporation of the two innovative parameters, namely volumetric efficiencies (VE_1 and VE_2), in the present investigation plays a pivotal role as a fundamental standard for enabling the evaluation of various geometric configurations of solar box cookers. These parameters are more appropriate than the two figures of merit because they can be used to serve as indispensable tools for comparing the effectiveness and performance of solar box cookers with different shapes and designs. By introducing these two volumetric efficiencies (VE_1 and VE_2), this study not only advances the understanding of solar box cookers but also provides a robust framework for researchers and practitioners to make informed decisions when selecting or designing solar box cookers tailored to specific needs and contexts.

The two novel parameters are defined by equations (3) and (4).
Additionally, these parameters offer practical guidelines for tailoring solar box cookers to accommodate varying household sizes. This advancement not only streamlines the evaluation process for different SBC designs but also provides a practical framework for manufacturers to create bespoke solutions that meet the specific culinary needs of households of varying sizes.

$$VE_1 = \frac{Vessel\ Volume}{\text{Inner Chamber Volume of SBC}} < 1 \tag{3}$$

$$VE_2 = \frac{Water\ Volume}{Vessel\ Volume} \leq 1 \tag{4}$$

4. SBC design methodology and experimental tests

In order to effectively address the objectives outlined in this study and ensure a comprehensive and equitable comparison, two solar box cookers of identical dimensions have been meticulously constructed, as illustrated in figures 1 and 2. Notably, these solar box cookers have been designed without the utilization of reflectors. Consequently, each sola box cooker possesses an inner chamber volume of precisely 24320 cm^3. This deliberate approach

is crucial for establishing a consistent baseline, thereby enabling a robust and logical evaluation of their respective performances and characteristics in subsequent analyses.

Table 1 comprehensively outlines the specific details of the two solar box cookers. In efforts to minimize heat dissipation, a sealing mechanism was implemented to prevent thermal losses between the upper sections of the outer boxes and the transparent cover. Furthermore, as illustrated in figure 3, the experimental configurations incorporated four vessels: two vessels measuring 24 cm in diameter, one vessel with a diameter of 20 cm, and another vessel with a diameter of 16 cm. This selection of vessels was meticulously chosen to explore and determine the optimal volume ratio between the vessels and the inner chamber of the two solar box cookers.

Table 2 showcases the dimensions of vessels readily available in Algerian markets, commonly utilized by Algerian households. Notably, these vessels feature glass lids, offering the advantage of visual monitoring of their thermal condition. This transparency enables users to assess and regulate heat levels with ease, enhancing the cooking experience and ensuring optimal results [30].



Figure 1. Two identical solar box cookers

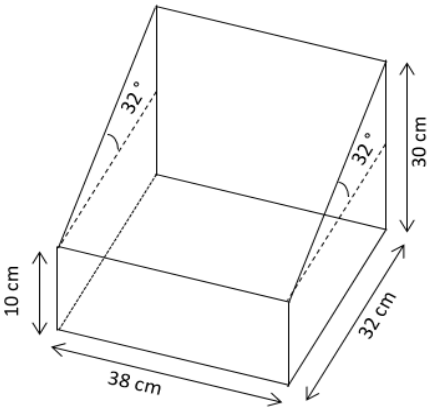


Figure 2. Inner chamber schematic of the two identical solar box cookers

Table 1. Detailed specifications of the two solar box cookers (SBCs).

Name	**Specifications (cm)**	**Material used**
Outer box	48×42×35	Plywood (Thickness : 1.5 mm)
Inner chamber of the solar box cooker	38×32×30	Stainless (Thickness : 1.1 mm)
Top transparent cover	47.5×46	Glass (Emissivity $\tau \approx 0.83$) (Thickness : 3 mm)
Bottom transparent cover	47.5×46	Glass (Emissivity $\tau \approx 0.83$) (Thickness : 5 mm)
Spacing between glass covers	1	
Insulation	Thickness : 5	Glasswool
Selective coating material		Black paint
Seal fixed on the top of the outer box	Thickness : 0.5 Large : 2	Extruded silicone rubber (-60 °C ~ + 260 °C)

Table 2. Vessels sizes according to the family members

Vessel	Diameter (cm)	Height (cm)	Volume (cm^3)	Number of family members
V1	24	12	5428.67	4 to 6
V2	20	9.5	2984.51	2 to 4
V3	16	7.5	1507.96	1 to 2

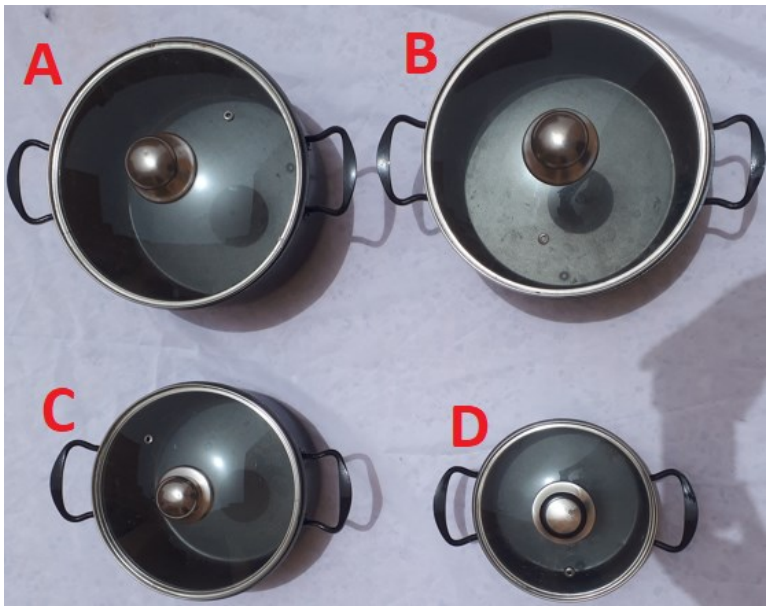


Figure 3. A and B: Vessels with a diameter of 24 cm. C: a vessel with a diameter of 20 cm. D: a vessel with a diameter of 16 cm

Five experiments were carried out in Ouargla city, situated at coordinates 31°56 N and 5°17 E, under clear climatic conditions. The internal temperature of the solar box cooker is influenced by several factors, including solar radiation, ambient temperature, and wind speed. Specifically, the solar radiation intensity should fall within the range of 450–1100 W/m^2, while the ambient temperature should be between 20 and 35°C. Additionally, wind velocity should remain below 1.0 m/s to ensure consistent experimental conditions. These parameters are crucial for maintaining standardized testing conditions and yielding reliable results [31].

From 10 AM to 4 PM, the different measurements were monitored and documented every 10 minutes using specific devices: a solar power meter to measure solar radiation, a temperature gauge equipped with K-type thermocouples to measure different temperatures, and an anemometer to measure wind speed. These devices were employed to ensure precise data collection, providing valuable insights into the fluctuations of environmental conditions throughout the experiments (figure 4). The orientation of the solar box cookers was manually fine-tuned to face the sun, requiring a 30-minute adjustment period. This meticulous adjustment ensured optimal positioning for harnessing solar energy efficiently, maximizing the

cooking performance of the solar box cookers. Throughout all the experiments, the solar box cooker (SBC1) with a vessel (V1) completely filled with water is being used as a reference for comparison and evaluation purposes. This selection was made to effectively assess results, accounting for the alterations in both water volume and vessel volume while maintaining consistent climatic conditions. By utilizing the solar box cooker SBC1 as a reference, a thorough analysis of the effects of varying volumes on performance was achieved, ensuring a comprehensive understanding of the experimental outcomes. Table 3 reports a comprehensive summary of the five outdoor experiments conducted, providing a detailed insight into the progression of the experimentation process. Notably, the initial test was conducted without load.



Figure 4. Devices used during testing

Table 3. Summary of 5 outdoor tests

Date	Test	Solar Box Cooker 1		Solar Box Cooker 2	
		Vessel	Water volume	Vessel	Water volume
27/05/2023	1	-	-	-	-
06/06/2023	2	V1	V_w1	V2	V_w2
07/06/2023	3	V1	V_w1	V3	V_w3
10/06/2023	4	V1	V_w1	V1	V_w3
13/06/2023	5	V1	V_w1	V1	V_w2

5. Experimental results and discussion

Test 1. Stagnation test

A stagnation test was performed to ascertain whether the two solar box cookers, operating without any load, produce identical readings under the same climatic conditions, including

factors such as solar radiation, ambient temperature, and wind speed. This experiment aimed to ensure the reliability and uniformity of measurements across the two solar box cookers under various environmental influences.

The outcomes depicted in figure 5, derived from the experimental assessment, reveal the following insights:

- Throughout the test duration, the variance between the absorber temperature of the SBC1 (T_{p1}) and the absorber temperature of the SBC2 (T_{p2}) fluctuated within the narrow range of 0 to 1 °C.
- The maximum temperatures attained by T_{p1} and T_{p2} at 14:00 were 144.3°C and 143.5°C, correspondingly. This data underscores the nuanced thermal dynamics exhibited by the system at the specified time, providing valuable insights into its temperature performance characteristics.

The consistent outcomes achieved by both solar box cookers enable us to explore a variety of loads and derive meaningful conclusions. These conclusions, grounded in reliable data, can serve as a valuable reference point for future research endeavors and practical applications within the field.

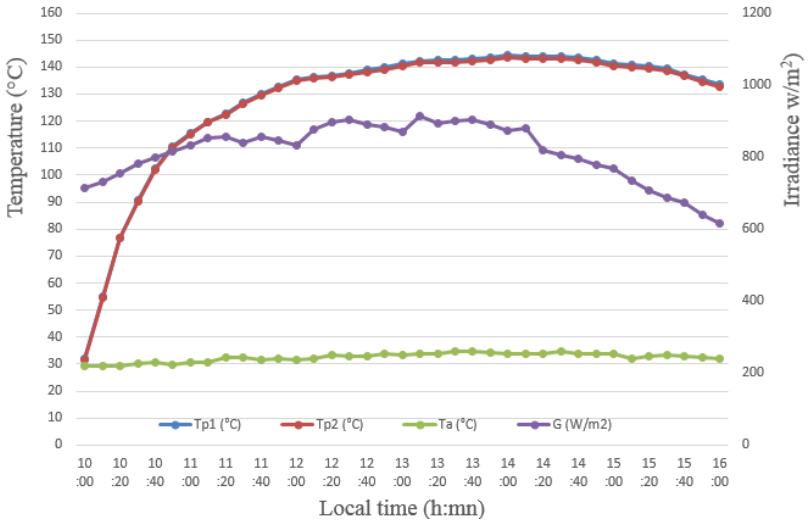


Figure 5. Comparison under stagnation test between T_{p1} and T_{p2}

Test 2

The experimental analysis revealed that the temperature disparity between the absorber temperature (T_{p1}) of the solar box cooker (SBC1) and the absorber temperature (T_{p2}) of the solar box cooker (SBC2) emerged shortly after the commencement of the experiment, peaking at 23.6 °C by 12:30, as depicted in figure 6. At 14:00, T_{p1} reached its maximum at 92.6 °C, while T_{p2} peaked slightly earlier, reaching 111.6 °C at 13:50. These findings highlight the

dynamic thermal behavior of the system over the course of the experiment, showcasing notable temperature variations between the two data points at specific time intervals.

In figure 7, it's evident that water volume (V_w2), placed within the vessel (V2), undergoes a more rapid heating process compared to water volume (V_w1) placed in the vessel (V1). This is demonstrated by V_w2 and V_w1 reaching temperatures of 100 °C at 13:40 and 86.8 °C at 16:00, respectively. Notably, water temperature (T_{w2}) of vessel (V2) attained 86.8 °C by 12:40 p.m, highlighting a time discrepancy of 3 hours and 20 minutes when compared to max water temperature (T_{w1} max) of vessel (V1). This observation underscores the significant disparity in heating rates between the two setups, suggesting potential differences in their thermal efficiency.

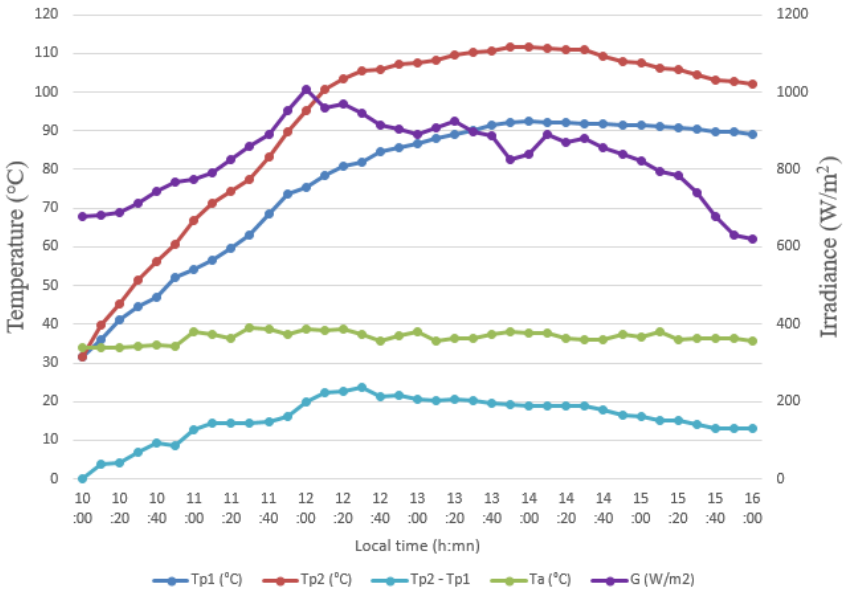


Figure 6. Comparison under test 2 conditions between T_{p1} and T_{p2}

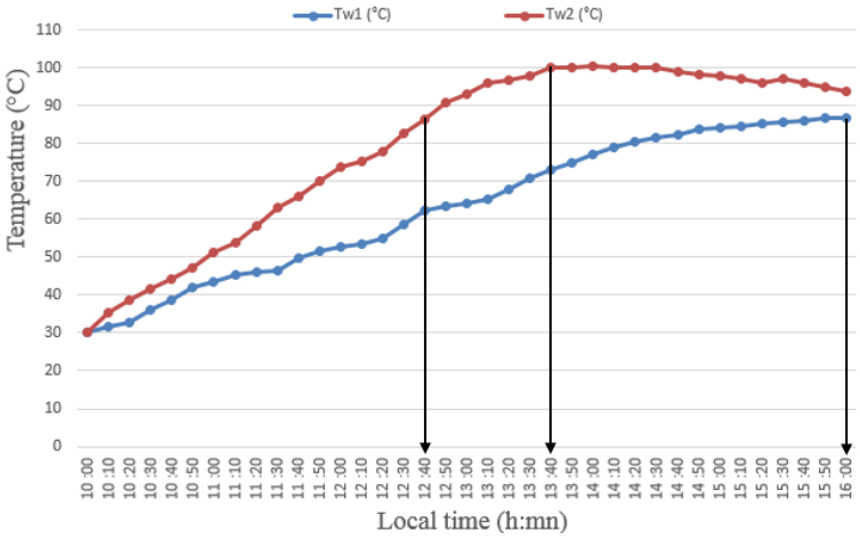


Figure 7. Comparison under test 2 conditions between T_{w1} and T_{w2}

Test 3

The experimental trial indicated that the temperature gap between the absorber temperature (T_{p2}) of the solar box cooker (SBC2) and the absorber temperature (T_{p1}) of the solar box cooker (SBC1) emerged shortly after the commencement of the experiment, peaking at a maximum deviation of 37.5 °C by 11:30 (as illustrated in figure 8). At 14:00, T_{p1} reached its peak temperature of 94.6 °C, while T_{p2} attained its maximum at 124.9 °C by 13:50. These findings underscore significant variations in thermal behavior between the two points of measurement, suggesting distinct heating dynamics within the system over the course of the experiment.

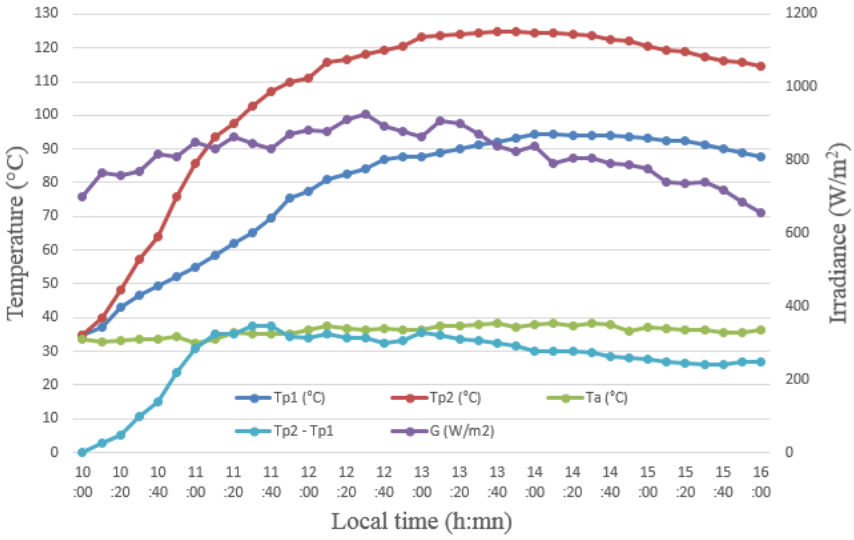


Figure 8. Comparison under test 3 conditions between T_{p1} and T_{p2}

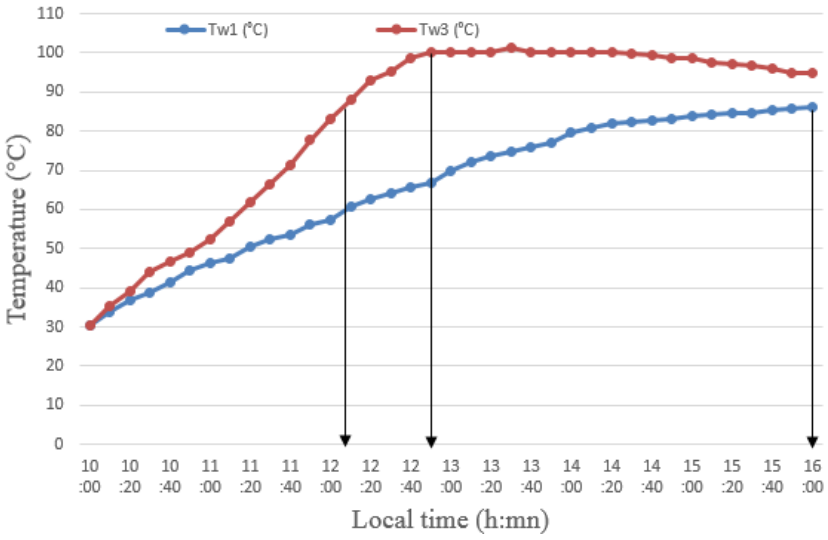


Figure 9. Comparison under test 3 conditions between T_{w1} and T_{w3}

Figure 9 illustrates that the water volume (V_w3), when placed in the vessel (V3), undergoes a more rapid heating process compared to the water volume (V_w1) placed in the vessel (V1). This is evidenced by the water temperature (T_{w3}) of vessel (V3) and water temperature ($T_{w1)}$ of vessel (V1) reaching 100 °C at 12:50 and 86.2 °C at 16:00, respectively. Notably, water temperature (T_{w3}) achieved a temperature of 86.2 °C by 12:08 p.m, indicating a time difference of 3 hours and 52 minutes compared to max water temperature (T_{w1} max) of vessel (V1). This observation underscores substantial disparities in heating rates between the two configurations.

Tests 2 and 3

As the experiments were conducted on two days with identical weather conditions, Table 4 displays the maximum absorber temperatures (T_p max), water temperatures (T_w), and boiling times for both volumetric efficiencies VE_1 and VE_2. Notably, it is observed that, as illustrated in figures 6 and 8, the absorber temperature of the solar box cooker (SBC2) with water volume (V_w3) placed in vessel (V3) reaches a higher temperature than the absorber temperature of the solar box cooker (SBC1) with water volume (V_w1) in vessel (V1) and the absorber temperature of the solar box cooker (SBC2) with water volume (V_w2) in vessel (V2). This observation underscores the influence of different configurations on the thermal performance of the solar box cookers.

Additionally, it's worth mentioning that the boiling time of water volume (V_w3) was notably quicker than that of both water volumes V_w2 and V_w1, as illustrated in figures 7 and 9. Upon comparing the obtained results, it can be inferred that in the case of a solar box cooker, when VE_1 decreases while VE_2 remains at 100%, the absorber temperature tends to increase, accompanied by a reduction in boiling time. This deduction emphasizes the proportional relationship between VE_1 and the boiling time within the solar box cooker (SBC) system.

Table 4. T_p max, T_w and boiling time in terms of VE_1 and VE_2 under tests 2 and 3 conditions

Test	SBC	Vessel	V_W (cm^3)	VE_1 (%)	VE_2 (%)	T_p max (°C)	T_w (°C)	Boiling time
2	1	V1	V_w1	22.32	100	92.6	86.8	
	2	V2	V_w2	12.27	100	111.6	100	10:00 to 13:40
3	1	V1	V_w1	22.32	100	94.6	86.2	

Table 5. T_p max, T_w and boiling time in terms of VE_1 and VE_2 under tests 4 and 5 conditions

Test	SBC	Vessel	V_w (cm^3)	VE_1 (%)	VE_2 (%)	T_p max (°C)	T_w (°C)	Boiling time
4	1	V1	V_w1	22.32	100	93.7	88.3	
	2	V1	V_w3	22.32	27.77	113.6	100	10:00 to 13:10
5	1	V1	V_w1	22.32	100	94	87.1	
	2	V1	V_w2	22.32	54.97	106	100	10 :00 to 14 :20

Test 4

The experimental investigation unveiled a conspicuous disparity between the absorber temperature (T_{p2}) of the solar box cooker (SBC2) and the absorber temperature (T_{p1})of the solar box cooker (SBC1), emerging shortly after the commencement of the experiment and culminating at a peak of 23°C by 12:20, as illustrated in figure 10. Noteworthy is the fact that while T_{p1} peaked at 93.7°C by 14:10, T_{p2} surged even higher, reaching its maximum at 113.6°C by 13:50. This divergence underscores the distinct thermal dynamics exhibited by each variable, emphasizing their unique behaviors under the experimental conditions.

As depicted in figure 11, the heating rate of water volume (V_w3) placed within vessel V1 surpasses that of water volume (V_w1) within the same vessel. Max water temperature (T_{w3} max) of vessel V1 and max water temperature (T_{w1} max) of vessel V1 reached 100 °C at 13:10 and 88.3 °C at 16:00 respectively, unveiling a noteworthy disparity in their heating progression. Notably, water temperature (T_{w3}) reached 88.3°C by 12:12, setting a time gap of 3 hours and 48 minutes when compared to T_{w1} max.

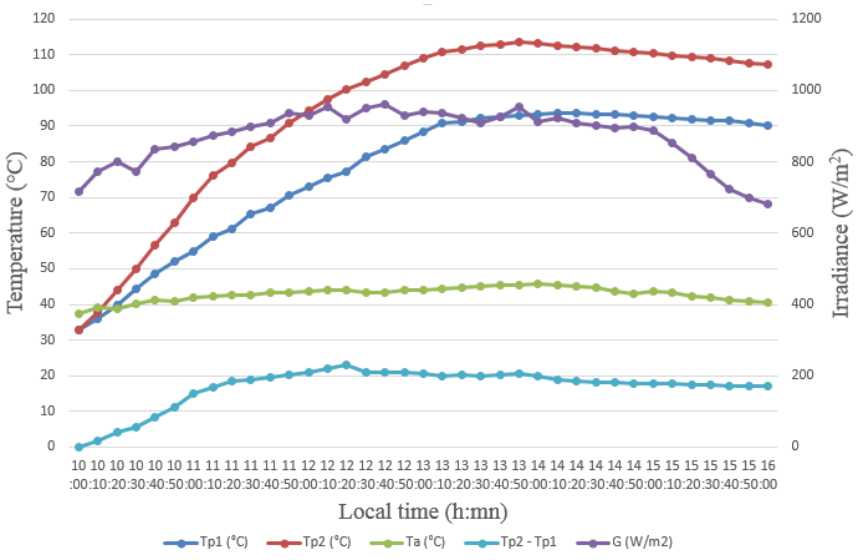


Figure 10. Comparison under test 4 conditions between T_{p1} and T_{p2}

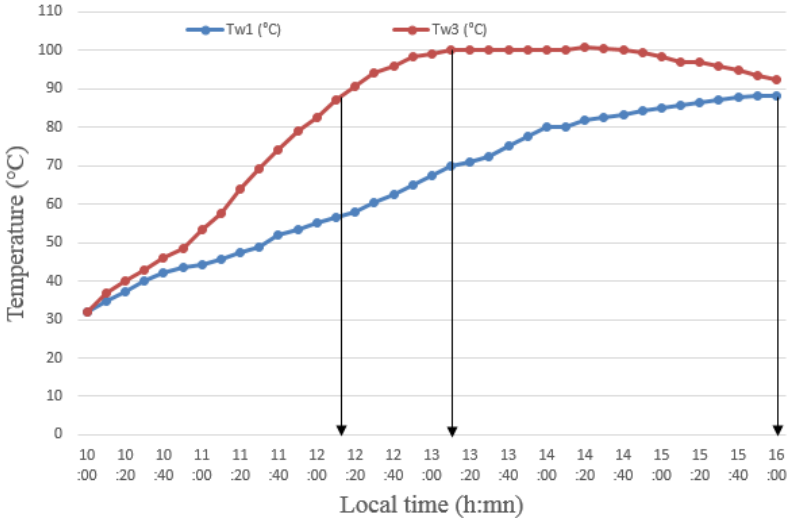


Figure 11. Comparison under test 4 conditions between T_{w1} and T_{w3}

Test 5

The experimental assessment revealed that the contrast between the absorber temperature (T_{p2}) of the solar box cooker (SBC2) and the absorber temperature (T_{p1}) of the solar box cooker (SBC1) emerged immediately following the commencement of the experiment, peaking at a maximum discrepancy of 12.9 °C by 12:50, as illustrated in figure 12. Notably, T_{p1} and T_{p2} attained temperatures of 94°C and 106°C, respectively, both by 14:00, showcasing distinctive thermal behaviors between the two solar box cookers.

Figure 13 illustrates that the heating rate of water volume (V_w2) placed in vessel (V1) surpasses that of water volume (V_w1) also situated within vessel (V1). Max water temperature (T_{w2} max) attained the boiling point of 100 °C by 14:20, whereas max water temperature (T_{w1} max) reached 87.1 °C by 16:00. Notably, T_{w2} reached 87.1 °C by 13:05, indicating a time disparity of 2 hours and 55 minutes compared to T_{w1} max.

Tests 4 and 5

Given that the experiments were conducted over two consecutive days with identical weather conditions, table 5 presents the max absorber temperatures (Tp max), water temperatures (T_w), and boiling times for both volumetric efficiencies VE_1 and VE_2. Notably, observations reveal that the absorber of solar box cooker (SBC2), featuring water volume (V_w3) place in vessel (V1), exhibits higher temperatures compared to both the absorber of solar box cooker (SBC1) with water volume (V_w1) in vessel (V1) and the absorber of solar box cooker (SBC2) with water volume (V_w2) placed in vessel (V1) as depicted in figures 10 and 12.

Furthermore, it's worth mentioning that the boiling time for water volume (V_w3) occurs more rapidly than for water volumes V_w2 and V_w1 as evidenced in figures 11 and 13.

Upon scrutinizing the obtained outcomes, it becomes apparent that when maintaining volumetric efficiency VE_1 constant while decreasing volumetric efficiency VE_2, the absorber temperature elevates, consequently leading to a shorter boiling duration.

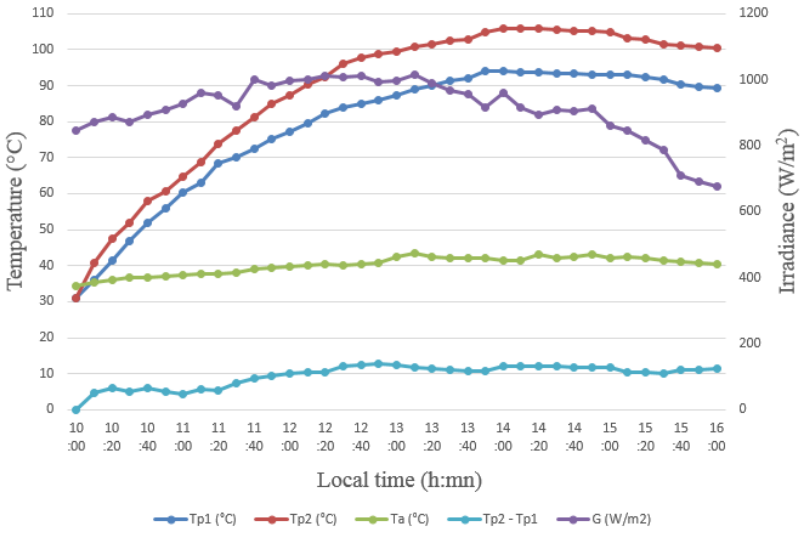


Figure 12. Comparison under test 5 conditions between T_{p1} and T_{p2}

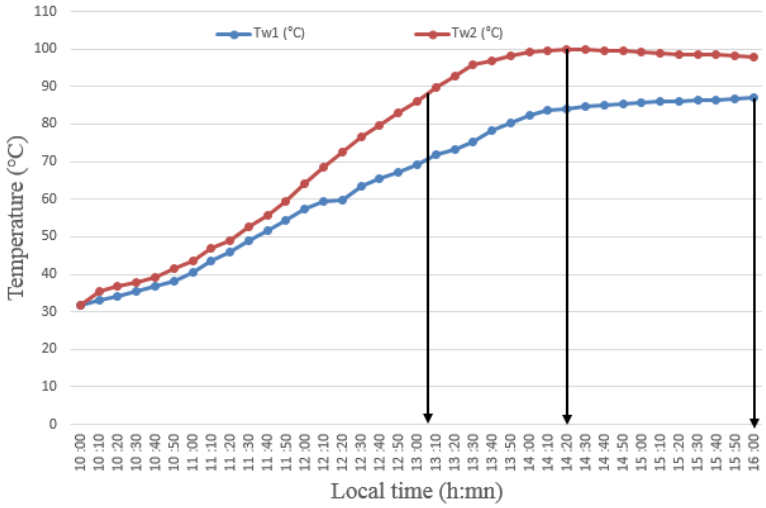


Figure 13. Comparison under test 5 conditions between T_{w1} and T_{w2}

Tests 2 and 5, and 3 and 4

Tables 6 and 7 present a detailed comparison between the outcomes derived from experiments 2 and 5, as well as experiments 3 and 4. Utilizing water volume (V_w1) placed in vessel (V1) as the reference across all four tests, an important deduction can be made regarding solar box cookers: when VE_1 decreases while VE_2 increases, there is a notable rise in the max absorber temperature (Tp max), accompanied by a reduction in the boiling time. This finding

underscores a significant relationship between the three critical parameters (water volume, vessel volume, and the inner chamber volume of the solar box cooker), indicating that adjustments in volumetric efficiency parameters directly influence the performance of solar box cookers.

The comparison between the results of these four tests also showed that the difference between absorber temperatures presents a maximum at a certain time, which can be attributed to :

- The solar box cookers SBC1 and SBC2 are identical.
- As shown in the table 8, the following can be concluded:
  - ❖ The VE_1 values of SBC2 and SBC1 in tests 4 and 5 are identical, this should result in similar heating of the absorbers in both solar box cookers over time. However, the difference in VE_2 values of SBC2 and SBC1 causes the maximum temperature difference between T_{p2} and T_{p1} in tests 4 and 5 to occur at close times.
  - ❖ In tests 2 and 3, as the difference between the VE_1 values of SBC1 and SBC2 increases and the VE_2 values of SBC2 and SBC1 are identical, the maximum temperature difference between T_{p1} and T_{p2} increases. However, when this discrepancy between the VE_1 values of SBC1 and SBC2 is not great, the maximum temperature difference between T_{p1} and T_{p2} in tests 2 and 3 also occurs at close times.

From the four conducted experiments, it can be inferred that the maximum difference between T_{p1} and T_{p2} presents a maximum at a certain instant when the VE_1 values of the two solar ovens are either identical or have a minimal discrepancy.

Table 6. T_p max, T_w and boiling time in terms of VE_1 and VE_2 under tests 2 and 5 conditions

Test	**Vessel**	**V_w (cm^3)**	**VE_1 (%)**	**VE_2 (%)**	**T_p max (°C)**	**T_w max (°C)**	**Boiling time**
2	V1	V_w1	22.32	100	92.6	86.8	
	V2	V_w2	12.27	100	111.6	100	10:00 to 13:40
5	V1	V_w1	22.32	100	94	87.1	
	V1	V_w2	22.32	54.97	106	100	10 :00 to 14 :20

Table 7. T_p max, T_w and boiling time in terms of VE_1 and VE_2 under tests 3 and 4 conditions

Test	**Vessel**	**V_W (cm^3)**	**VE_1 (%)**	**VE_2 (%)**	**T_p max (°C)**	**T_w (°C)**	**Boiling time**
3	V1	V_w1	22.32	100	94.6	86.2	
	V3	V_w3	6.2	100	124.9	100	10 :00 to 12:50
4	V1	V_w1	22.32	100	93.7	88.3	
	V1	V_w3	22.32	27.77	113.6	100	10 :00 to 13 :10

Table 8. Max difference between T_{p1} and T_{p2} vs VE_1 and VE_2

TEST	SBC1		SBC2		T_{p2} - T_{p1} Max °C	time
	VE_1 (%)	**VE_2 (%)**	**VE_1 (%)**	**VE_2 (%)**		
2	22.32	100	12.27	100	23.6	12:30
3	22.32	100	6.2	100	37.5	11:30
4	22.32	100	22.32	27.77	23	12:20
5	22.32	100	22.32	54.97	12.9	12:50

6. Conclusion

The configuration and size specifications of solar box cookers are intricately tied to the capacity of the cooking vessel, a factor directly influenced by the size of the household it caters to. So, the construction of solar box cookers is customized to meet the distinct demands and preferences of various household sizes, ensuring optimal functionality and efficiency. This study conducted a series of five experiments aimed at determining two novel volumetric efficiencies, denoted as VE_1 and VE_2, with the goal of minimizing cooking time. The objective was to identify the relationship between the three critical parameters (water volume, vessel volume, and the inner chamber volume of the solar box cooker) that determine the two volumetric efficiencies. The initial test was conducted to ensure that two solar box cookers operating without any load would yield consistent outcomes when exposed to identical environmental conditions, including factors such as solar radiation, ambient temperature, and wind speed. Subsequently, in the remaining four experiments, while maintaining a constant internal chamber volume for the solar box cookers, variations were introduced in both vessel volume and water volume. This systematic approach allowed for a comprehensive investigation into the influence of these variables on cooking performance. The findings unequivocally demonstrate that when VE_1 was minimized at 6.2% and VE2 maximized at 100%, the absorber temperature surged to its peak at 124.9°C, accompanied by the shortest boiling duration of 2 hours and 50 minutes. These results highlight the significant impact of these two novel volumetric efficiencies on the cooking performance of solar box cookers. This study concludes that VE_1 and VE_2 could serve as valuable benchmarks for future research endeavors, proposing them as novel standard parameters for manufacturing solar box cookers of varying shapes and sizes. By adopting VE_1 and VE_2 as standardized metrics, researchers can facilitate comparability across studies and enhance the reproducibility of findings in the field of solar cooking technology. This recommendation underscores the potential for advancing the design and optimization of solar box cookers to meet diverse environmental and household needs.

Abbreviation list:

A_i	Intercepted area of the cooker (m2)
C_p	Specific heat of water (J/kg K)
CPC	Compound parabolic concentrator
F1	First figure of merit
F2	Second Figure of Merit
G	Irradiance(W/m2)
m	Mass of the water (kg)
n_0	Optical efficiency of the cooker (%)
PCM	Phase change material
SBC1	Solar Box Cooker 1
SBC2	Solar Box Cooker 2
T_a	Ambient temperature (°C)
TES	Thermal energy storage
T_f	Final temperature of water (°C)
T_i	Initial temperature of water (°C)
T_p	Absorber temperature (°C)
T_p max	Max absorber temperature (°C)
T_p1	Absorber temperature of the SBC1 (°C)
T_p2	Absorber temperature of the SBC2 (°C)
T_w	Water temperature (°C)
T_w max	Max water temperature (°C)
T_{w1}	Water temperature of V1 (°C)
T_{w2}	Water temperature of V2 (°C)
T_{w3}	Water temperature of V3 (°C)
U_L	Overall heat loss coefficient (W/m K)
V1	Vessel with a diameter of 24 cm
V2	Vessel with a diameter of 20 cm
V3	Vessel with a diameter of 16 cm
VE_1	Ratio of the vessel volume to the inner chamber volume of SBC
VE_2	Ratio of the water volume placed in the vessel to the vessel volume
V_v	Vessel volume
V_w	Water volume
V_{w1}	Water volume of V1 (cm3)
V_w2	Water volume of V2 (cm3)
V_w3	Water volume of V3 (cm3)
Δt	Time interval (s)
τ	Emissivity

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