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Thermal analysis of Cylindrical Honeycomb Encapsulated Double Exposure Box-type Solar Cooker

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Keywords:

Double Exosure;
Solar Cooker;
Thermal Performance;
Honeycomb;
Energy Balance.

Abstract

The Double Exposure Solar Cooker (DESC) has been developed with cylindrical type honeycomb structure improve the heat transfer from solar energy. The cooking experiments were conducted with the water loading time during the summer seasons. The thermal performance of DESC with cylindrical honeycomb structure unit was compared with standard solar cooker. Experiments have been conducted with the two cookers in the months of April and May 2013 in the Department of Physics, Karpagam University, Coimbatore, Tamilnadu, India. The F1 and F2 values of double exposure solar cooker is comparable with the BIS values and suitability of the cooker in the location has been discussed.

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1. Introduction

Honeycomb structure can suppress the natural convection and obstruct the infrared radiation heat loss. Francia (1964) first proposed the use of very high aspect ratio cylindrical honeycombs made of glass and carbonized paper to suppress radiative losses from a solar collector.

Hollands [1] has been found that the presence of selective transmitting honey comb in the collector helps to suppress and reduces the natural convection and radiation heat loss respective. The efficiency depends on the thickness of the honey comb wall. Arnold et al. [2] measured the heat transfer across liquid filled rectangular cell honeycombs with different aspect ratios and tilt angles.

Buchberg *et al.*, [3] has been proved that the efficiency of the solar collector is increased due to the presence of rectangular transparent honey comb. The use of honeycombs to reduce heat losses from solar collectors has been extensively studied.

Nahar [6] designed a double reflector hot box solar cooker with transparent insulation material.

Experiments are performed for solar cooker with the cylindrical type of honeycomb. The emphasis is to study the effects of diameter and aspect ratio of the honeycomb unit on the transmittance and efficiency of the solar cooker. In the present study, the proposed cooker with cylindrical honeycomb unit have been used to cook various food stuffs to predict the cooking time and it is found that the cooking time reduced when compared with ordinary box-type solar cooker.

2. Description of the DESC

The DESC consists of a 0.6 x 0.30 m rectangular copper tray constructed of 0.005 m thick sheet. The sides of the copper tray encased in rectangular type DESC box made of plywood. The clearance between the copper tray and the encasing is filled with glass wool to provide thermal insulation. A glass covers are provided at the top(g_1) and bottom(g_2) side of the DESC. The cylindrical honeycomb structure unit fixed on the top of the glass plate(g_1). A boost mirrors is used to direct the radiation on the backside of the absorber

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plate. The cooking vessels are cylindrical in shape and have flat bases(0.15 m diameter and 0.10 m in height). The cooking vessel are made of silver with copper bottom.

The use of honeycomb in solar cooker has the benefit of reducing the top heat loss and also the penalty of decreasing the optical efficiency. Thus unless proper design of honeycomb is accomplished, honeycomb may deteriorates the cooker performance. Apart from honeycomb material and aspect ratios, the proper design involves adequate length of honeycomb.

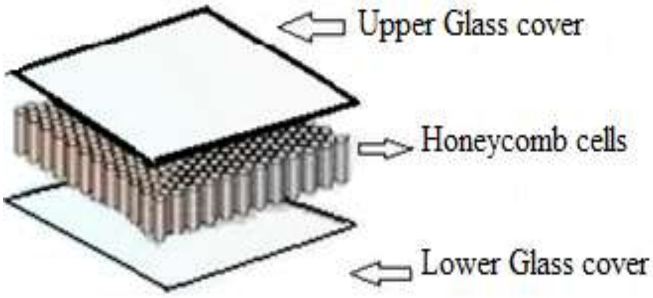

Figure 1. Figure 2.

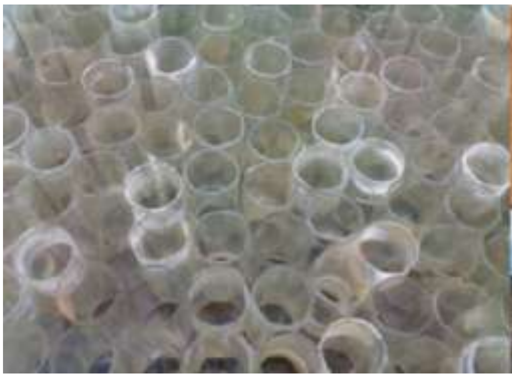

Figure 3. Figure 4.

Figure 1, 2,3 & 4 Arrangement in the Cylindrical-celled honeycomb solar collector

Figure 5.The photograph of the DESC with honeycomb cell

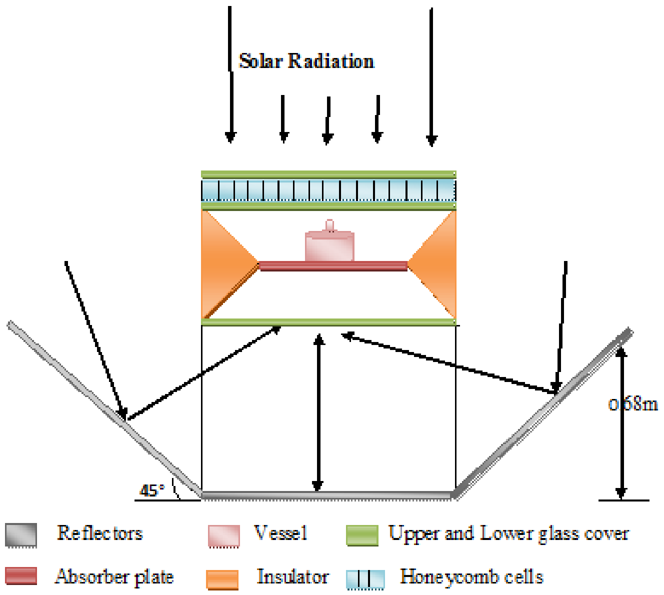

Figure 6.The schematic diagram of the DESC with honeycomb cell

3.Properties of Cylindrical honeycomb

The cylindrical honeycomb cells are design and made a transparent honeycomb of a small aspect ratio (L/D < 3) with thin walled glass. Honeycomb cells are ended cells whose axes are parallel to the normal vector of the plane of the glazing. They achieve high light transmittance because the cell walls are perpendicular to the plane of the glazing, and thus, any light that reflects from the cell wall continues in the forward direction.

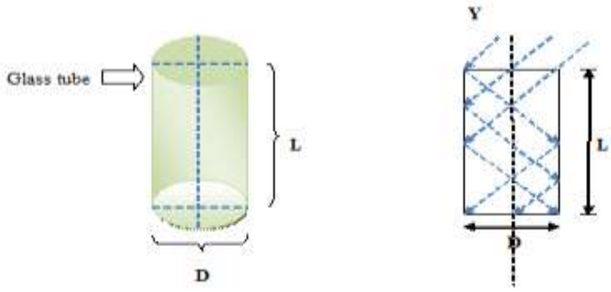

Figure 7.Schematic diagram of the honeycomb cell

Table 1.

Type of honeycomb	Diameter (D) cm	Height (L) cm	Thickness (d) mm	A_H cm	Transmittance (τ)	Reflectivity (ρ)
Cylindrical	3.5	7.5	2	2.148	0.90	0.04

4.Experimental Analysis

The solar radiation reaches the upper glass cover of the proposed cooker directly. The direct solar radiation is transmitted through the glass cover and due to honeycomb structure, the convection losses to the surrounding atmosphere will be suppressed.

The general energy balance of the cooker is derived and is used to predict the temperature variation in each part of the cooker, under both steady and transient conditions. In the present thermal analysis, the elements of the cooker to be considered while writing the energy balance equations are the base of the cooking vessel, the upper glass cover, lower glass cover, the stagnant air and the food to be cooked (or) the liquid (water or oil) to be heated. By applying the energy balance to the various components of the cooker, thermal equations have been derived to determine the behaviour of the cooker.

Following assumptions have been made to write the energy balance equations.

They are,

(i) The box is made of six basic elements

(ii) The lumped model has been applied by assuming that the temperature of each element is constant at a definite time.

Under these assumptions, energy balance equation of the upper glass cover requires

$$M_{g1}\frac{dT_{g1}}{dt}+h_{g1a}A_{g1}(T_{g1}-T_a)=A_{g1}h_{g1g2}(T_{g2}-T_{g1})+A_{g1}\alpha_{g1}I \quad (1)$$

Energy balance equation of the lower glass cover,

$$M_{g2}\frac{dT_{g2}}{dt}+h_{g1g2}(T_{g2}-T_{g1})A_{g2}=A_{g2}\left[h_{bsA}(T_{bs}-T_A)+\tau_{g1}\alpha_{g2}I\right] \quad (2)$$

Energy balance equation of the stagnant air inside the box,

$$M_A\frac{dT_A}{dt}+A_{g2}h_{Ag2}(T_A-T_{g2})=A_{bs}h_{bsA}(T_{bs}-T_A) \quad (3)$$

Energy balance equation of the base of the cooking vessel

$$M_{bs}\frac{dT_{bs}}{dt}+A_{bs}h_{bsA}(T_{bs}-T_A)+A_{bs}h_{bsi}(T_{bs}-T_i)+A_{g2}h_{bsg2}(T_{bs}-T_{g2})=A_{bs}\tau_{g1}\tau_{g2}\alpha_{g1}I \quad (4)$$

Energy balance equation of the insulation requires

$$M_i\frac{dT_i}{dt}+A_ih_{ia}(T_i-T_a)=A_ih_{bsi}(T_{bs}-T_i) \quad (5)$$

Energy balance equation of the food in the cooking vessel

$$M_f\frac{dT_f}{dt}=A_vh_{vf}(T_{bs}-T_f) \quad (6)$$

The differential equations for the six components can be solved numerically by the fourth order Range-Kutta method. A Computer program has been written for the solutions of the equations. Simulation studies with the solutions obtained can also be tried. The proposed model can be used for the determination of the performance at summer and winter conditions. Every theoretical observation has to be proved practically through experiments and tests in order to justify the results found from the theory. Keeping this in mind, various experiments have been conducted for a variety of ingredients which are commonly used in the Indian dishes.

5. Experimental Study

The amount of heat required to heat the material up to the boiling point of water is known as a “Sensible Heating”. After sensible heating, the cooking will be automatically completed by supplying the heat losses. This concept was taken to conduct the cooking test. Most of the Indian dishes are prepared by boiling the food materials. In view of this, water heating and cooling tests were conducted by the solar cooker and the time taken to boil a litre of water was noted.

First of all the cooker was used to boil one litre of water, and then, several food stuffs had been tried. The experiments were carried out at different times in many clear sky days, and the best of the observation was taken. During the course of any experiment, it is required to measure simultaneously the temperatures of the cookers, Ambient temperature (T_a), Water temperature(T_w), Base of the vessel temperature(T_b), Lid of the vessel (T_l), Solar irradiance (I_b), and the wind speed (V_s). These were noted in regular intervals of time. Copper-Constantan thermocouples have been used for the temperature measurements. Solar radiation monitor (EMCON, Cochin) is used to measure the solar radiation. A wind cup anemometer is used for wind speed measurements. A copper bottom cooking vessel with the capacity of 1.5 litre is used for these tests. The concentrators help to increase the solar intensity to the bottom glass cover of the solar cooker because of its reflection.

6. Results and Discussion

On 14th April 2017, the proposed solar cooker was exposed to solar radiation and loaded with one litre of water at 10.30 am. The ambient temperature and the beam radiation had been increasing simultaneously because it was a clear sky day. At that time, the average beam radiation was 990W/m^2 and the average ambient temperature was 34.31°C. The temperature of water inside the vessel, lid of the vessel, base of the vessel were recorded simultaneously and are shown in table 2. The water took 46 minutes to reach its boiling point.

Table 2. Water Heating and Cooling Test

Date : 14.04.17 Time:10.00am Amount of Water : 1lt

Time (min)	Beam Radiation ($W/m2^2$)	Ambient Temp. T_a (°C)	Water Temp. T_w (°C)	T_w - T_a (°C)	Base of the vessel Temp. T_b (°C)	Lid of the vessel Temp. T_l (°C)
0	920	31	32	1	32	34
5	931	32	37	5	36	40
10	938	32	45	13	44	52
15	939	32.5	53	20.5	54	58
20	981	32.5	63	30.5	64	65
25	982	32.5	71	38.5	72	72
30	999	33	77	44	78	79
35	1000	33	83	50	84	84
40	1151	33.5	91	57.5	92	93
42	1101	33.5	95	61.5	96	96
45	999	33.5	94	60.5	96	97
50	1001	34	93	59	94	96
55	999	34	91	57	90	91
60	1007	34	90	56	88	89
70	979	34.5	89	54.5	87	87
85	991	35.5	86	49.5	84	85
100	998	35.5	82	45.5	78	81
115	1001	35.5	80	43.5	75	77
130	1099	36	76	39	71	73
145	998	36	74	37	68	69
160	965	36	72	35	65	65
175	981	36	70	33	62	63
180	1000	36.5	68	31.5	60	60
195	971	36.5	63	26.5	57	56
210	921	35.5	61	25.5	53	53
225	927	35.5	59	23.5	47	48
240	929	36.5	57	20.5	44	45

The observations were stopped once the water attained the boiling point. The upper glass cover (lid of the cooker) was closed. The observations were made in the cooling process at regular intervals of time. After every 15minutes, the temperatures were recorded and it was continued upto 185 minutes. Even after 185 minutes, the water continued to retain its temperature as 22°C. During the cooling test, the wind velocity was notably high. The recorded observations are given in the table 2 and figure 8.

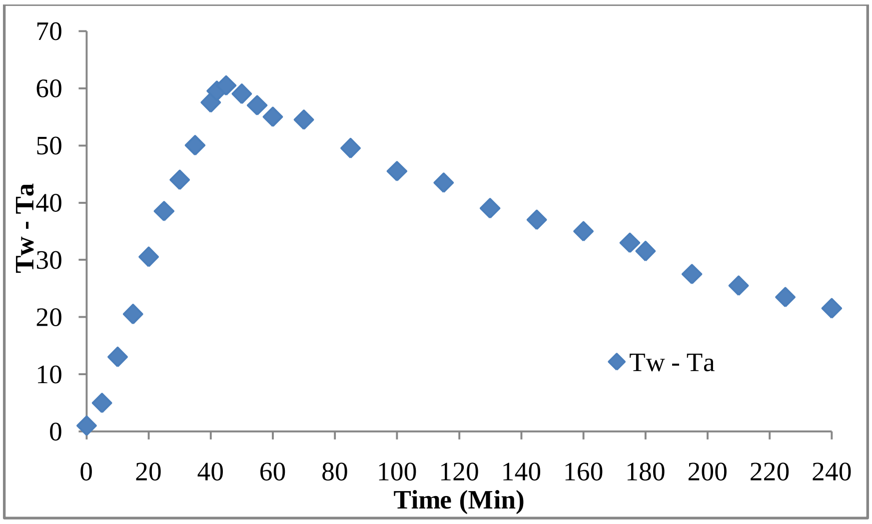

Figure 8. Water Heating and Cooling Test

Experimental observations have been done with different food stuffs like rice, dhal, egg, and wheat rava . On 15th April 2017, the cooker was loaded with 0.250 kg of rice and 0.5 litre of water at 11.30 am. The measurements of the different temperatures were shown in table 3.

Table 3. Cooking Test – Rice

Date: 15.04.17 Time: 11.30AM Weight:0.25 Kgs

Time (min)	Beam Radiation (W/m2)	Ambient Temp. T_a (°C)	Water Temp. T_w (°C)	Base of the vessel Temp. T_b (°C)	Lid of the vessel Temp. T_l (°C)
0	933	34	33	31	35
5	949	35	43	44	50
10	978	35	53	54	55
15	949	35	63	64	65
20	999	36	71	72	72
25	1000	36	77	78	78
30	1099	36	83	86	86
35	1099	36	87	90	90
40	1100	36	91	92	91
45	989	36	93	96	95
50	974	36.5	93	96	96
55	989	36.5	95	96	98
57	1000	37	96	94	97
60	1000	37	94	94	97
65	1100	37	92	92	95
70	1000	37.5	92	92	95

The rice was fully cooked in 57 minutes. The photograph [figure 11] shows the cooking test for rice. On the same day, 0.250 kg of dhal mixed with 0.5 litre of water was loaded at 12.45 pm. It was found that the dhal was cooked completely in 68 minutes. Table 4 , shows the temperature observations of dhal. The cooking tests for rice and dhal were illustrated in figures 9 and 10.

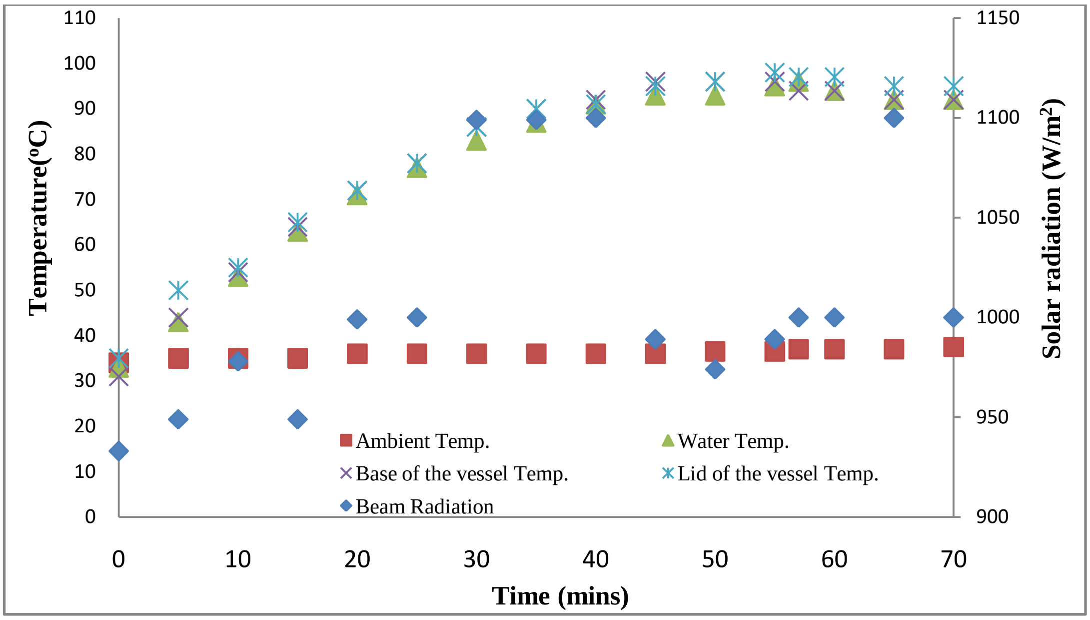

Figure 9. Cooking Test – Rice

Table 4.Cooking Test- Dhal

Date: 15.04.17 Time: 12.45PM weight: 0.250 Kgs

Time (min)	Solar Radiation (W/m2)	Ambient Temp. T_a (°C)	Water Temp. T_w (°C)	Base of the vessel Temp. T_b (°C)	Lid of the vessel Temp. T_l (°C)
0	974	37	34	34	38
5	989	37	44	42	46
10	969	37	53	53	56
15	984	37.5	60	60	62
20	984	37.5	66	54	66
25	989	38	72	72	72
30	980	38	76	76	78
35	1000	38	82	82	84
40	1000	38	86	87	87
45	1005	38.5	88	89	90
50	985	38.5	90	90	91
55	990	38.5	92	93	94
60	1000	38.5	94	94	95
65	1000	38.5	96	96	96
68	1000	38.5	96	96	96
70	990	38.5	93	93	95
75	980	38.5	90	91	95
80	995	38	91	91	95

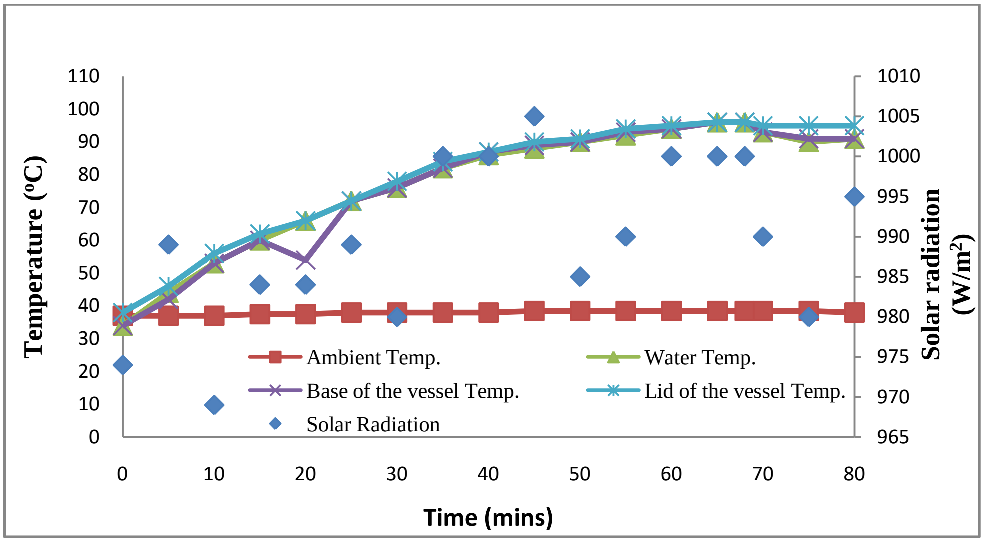

Figure 10. Cooking Test – Dhal

On 03rd June17, four eggs were kept inside the vessel with 0.300 litre of water at 10.10 am. The average beam radiation was 980 W/m^2. The eggs were boiled in 72 minutes. After some time 0.250 kg of wheat rava with 0.5 litre of water was put in the cooking vessel. The food stuff was cooked in 37 minutes. The observations for the above said items were tabulated in tables 5 and 6. The graphical representations of the cooking tests for egg and wheat rava were explained in figures 13 and 14.

Table 5. Cooking Test – Egg

Date:03.06.17 Time:10.10AM Weight:4 Eggs

Time (min)	Beam Radiation (W/m2)	Ambient Temp. T_a (°C)	Water Temp T_w (°C)	Base of the vessel Temp. T_b (°C)	Lid of the vessel Temp. T_l (°C)
0	889	32	32	32	32
5	899	32	40	40	48
10	899	32	51	50	56
15	940	32.5	58	58	64
20	946	32	65	60	70
25	960	32.5	70	66	74
30	965	32.5	74	72	76
35	985	32.5	78	74	80
40	987	32.5	83	79	84
45	990	32.5	86	82	89
50	981	32.5	88	87	92
55	980	32.5	90	92	94
60	960	33	92	93	96
65	1000	33	94	95	98
70	1000	33	96	96	98
72	1000	33	96	96	96
75	980	33.5	92	92	96
80	985	33.5	90	90	94

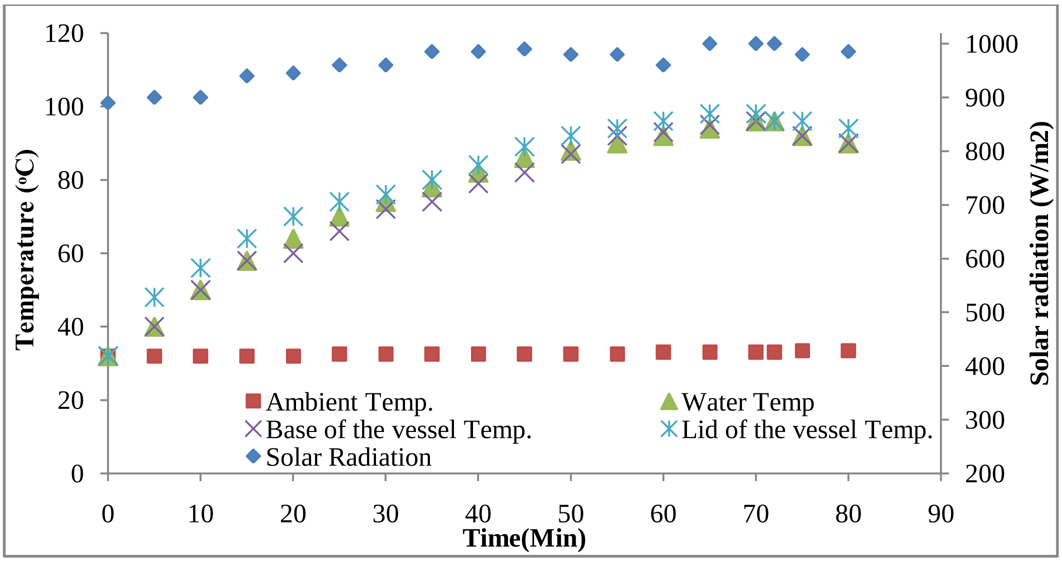

Figure 13. Cooking Test - Egg

Table 6. Cooking Test - Wheat Rava

Time (min)	Solar Radiation (W/m2)	Ambient Temp. T_a (°C)	Water Temp. T_w (°C)	Base of the vessel Temp. T_b (°C)	Lid of the vessel Temp. T_l (°C)
0	1005	33	34	34	36
5	1000	33	44	44	48
10	1100	33.5	54	54	56
15	1100	33.5	62	63	64
20	980	33.5	72	72	72
25	990	34	80	81	82
30	995	34	88	89	89
35	985	34	94	95	95
37	990	34	96	96	97
40	990	34	96	96	97
45	1000	34	92	92	95

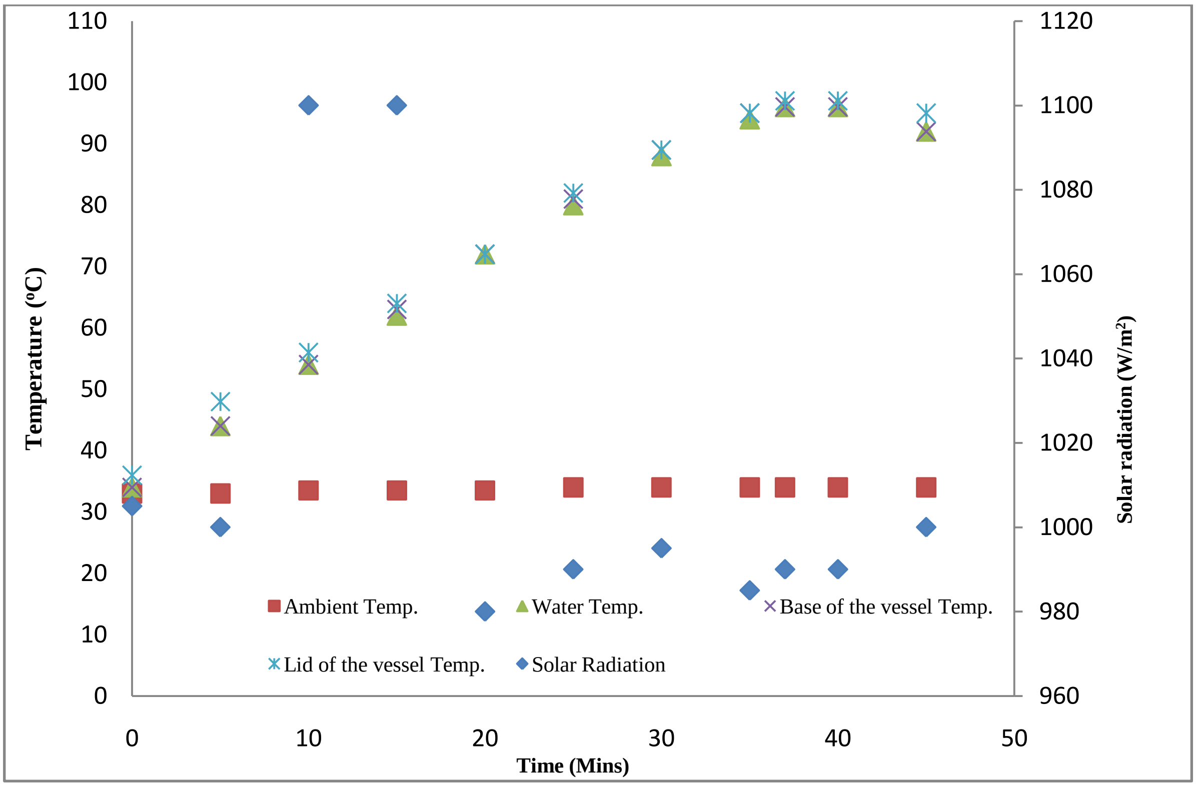

Figure 14. Cooking Test-Wheat Rava

7. Theoretical Analysis and Results

The Equations.1– 6 have been solved by using fourth order Runge-Kutta method and the solutions for the upper glass cover, lower glass cover, stagnant air, base of the cooking vessel, insulation and cooking fluid temperature has been derived. To appreciate the analytical solutions, the model has been validated with the experimental observations for 1 kg of water during boiling.

Figures. 15-20, shows the variation of the temperatures elements of the cooker. From all the graphs it is clear that the theoretical results based on the analysis are in close agreement with the experimental observations. Some deviations between the model and experiment is due to unaccountable factors such as the manual tracking of the cooker towards the motion of the sun throughout the day. Another factor for the overestimation of theoretical results is due to the opening and closing of the lid of the cooker during working hours of the cooker.

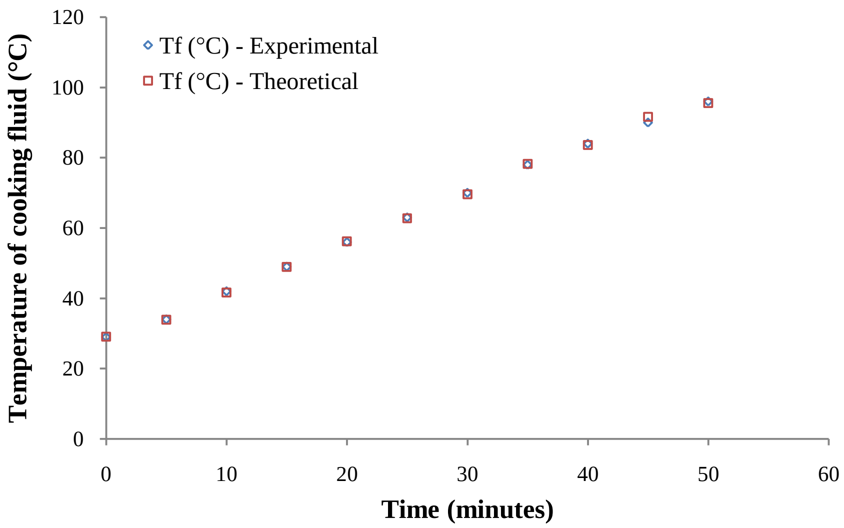

Figure 15. Variation of theoretical and experimental values of temperature of the cooking fluid during boiling of 1 kg of water

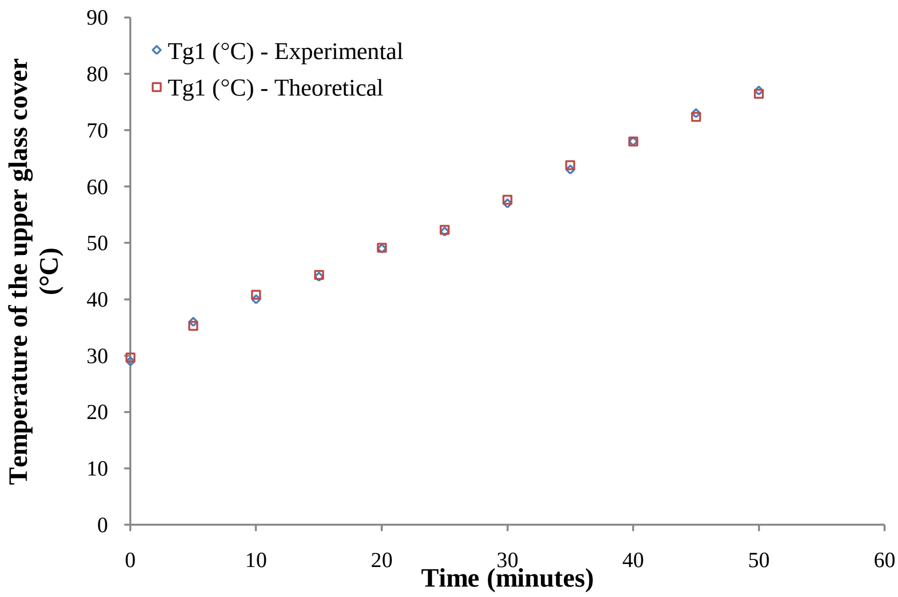

Figure 16. Variation of theoretical and experimental values of temperature of the upper glass cover during boiling of 1 kg of water

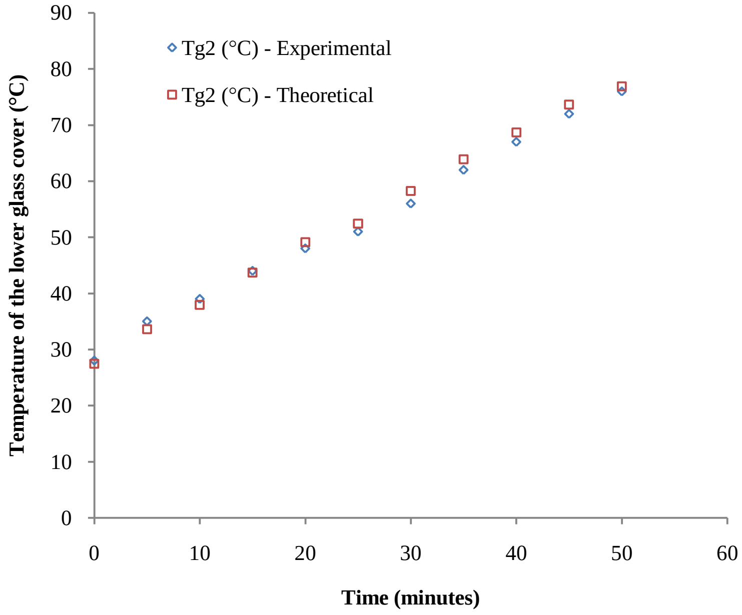

Figure 17. Variation of theoretical and experimental values of temperature of the lower glass cover during boiling of 1 kg of water

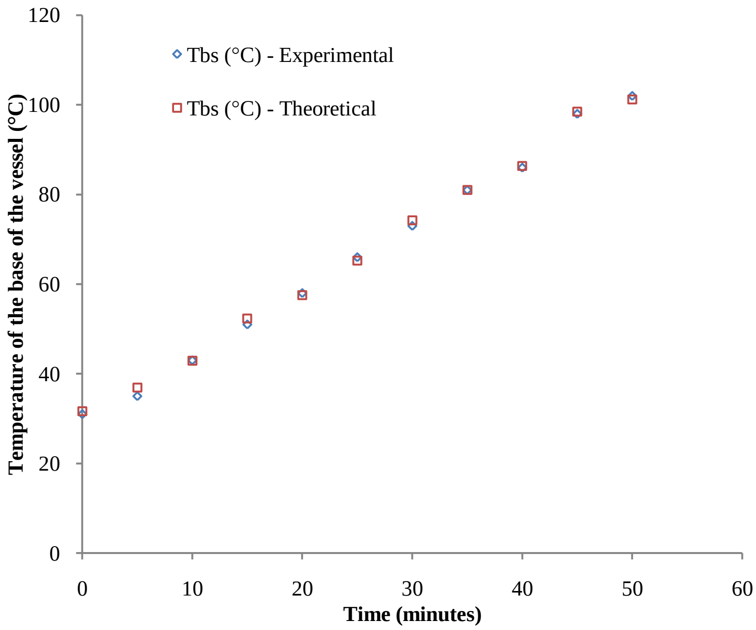

Figure 18. Variation of theoretical and experimental values of temperature of the base of the cooking vessel during boiling of 1 kg of water

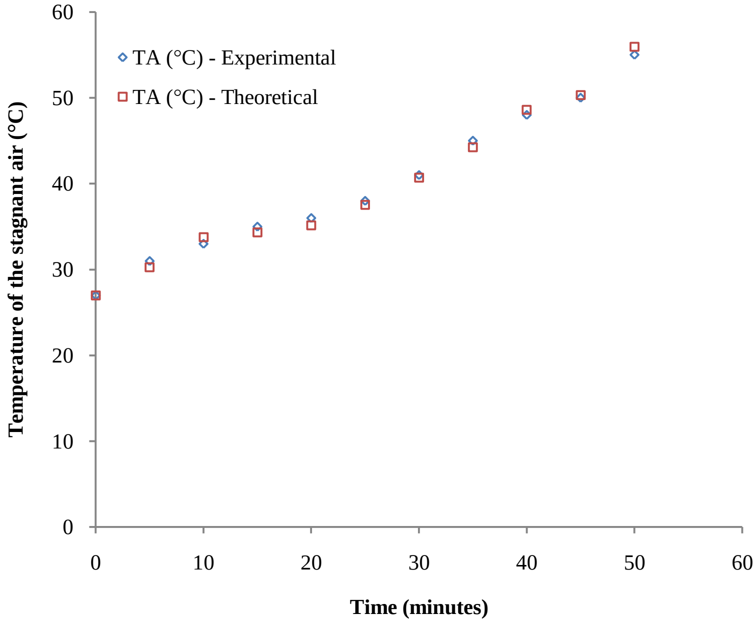

Figure 19. Variation of theoretical and experimental values of temperature of the stagnant air during boiling of 1 kg of water

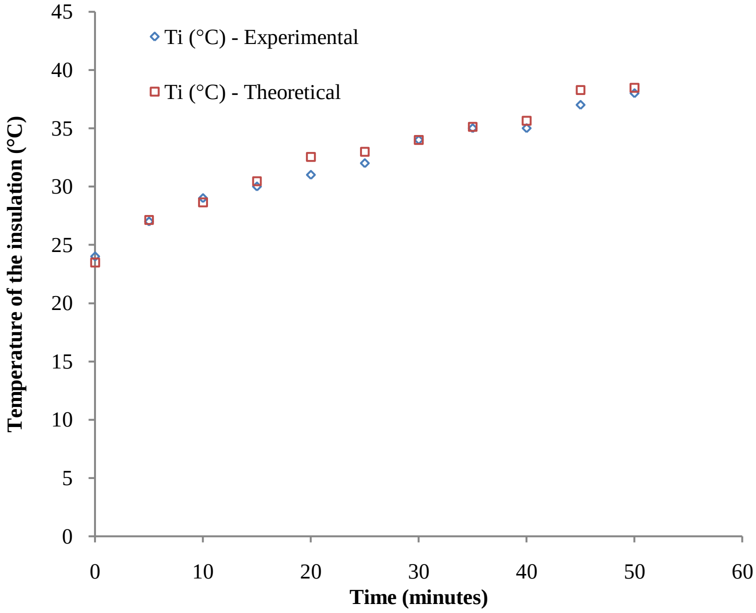

Figure 20. Variation of theoretical and experimental values of temperature of the insulation during boiling of 1 kg of water

The geometrical constants which are necessary for the solution of the equations have been taken from the cooker tested. Radiation and convection heat transfer coefficients have been calculated for each and every step and the other required constants have been taken from the literature. The numerical results obtained have same trend with the experimental results and the model proposed is found to be useful to study the parametric influence of the thermal performance of the cooker during peak sunny hours.

Conclusion

The data show consistency with various incoming solar radiations and different tilt angles. Therefore introducing honeycomb structures in to cooker spacing can be effective means to improve heat performances of cooker. Compared to the ordinary box type solar cooker models, the boiling of water consumes less time. Due to this fact, the cooking time for the ingredients will be minimized.

Nomenclature

A_H - Aspect ratio (A_H=L/D)
D - Diameter of the honeycomb cell
L - Length of the honeycomb cell

A_{bs}	-	Area of the base of the cooking vessel (m^2)
A_i	-	Area of the insulation (m^2)
A_{g1}	-	Area of the upper glass cover (m^2)
A_{g2}	-	Area of the lower glass cover (m^2)
A_v	-	Area of the cooking vessel (m^2)
h_{g1a}	-	Overall heat transfer coefficient from upper glass cover to ambient (W/m^2K)
h_{g1g2}	-	Overall heat transfer coefficient between upper and lower glass covers (W/m^2K)
h_{bsA}	-	Overall heat transfer coefficient from base of the vessel to stagnant air (W/m^2K)
h_{bsi}	-	Overall heat transfer coefficient from base of the vessel to insulation (W/m^2K)
h_{bsg2}	-	Overall heat transfer coefficient from base of the vessel to lower glass cover (W/m^2K)
h_{bsi}	-	Overall heat transfer coefficient from base of the vessel to insulation (W/m^2K)
h_{Ag2}	-	Overall heat transfer coefficient stagnant lower from air to glass cover (W/m^2K)
h_{vf}	-	Overall heat transfer coefficient from vessel to fluid (W/m^2K)
h_{ia}	-	Overall heat transfer coefficient from insulation to ambient (W/m^2K)
M_A	-	Heat capacity of stagnant air(cal)
M_{bs}	-	Heat capacity of base of the cooking vessel
M_f	-	Heat capacity of cooking fluid
M_i	-	Heat capacity of insulation(cal)
M_{g1}	-	Heat capacity of upper glass cover (M_{g1}= $\rho C_p V$)
M_{g2}	-	Heat capacity of lower glass cover
T_A	-	Stagnant air temperature (K)
T_a	-	Ambient temperature (K)
T_f	-	Temperature of the fluid (K)
T_i	-	Temperature of insulation (K)
T_{g1}	-	Temperature of upper glass cover (K)
T_{g2}	-	Temperature of lower glass cover (K)
T_{bs}	-	Temperature of the base of the cooking vessel (K)

Greek symbols

ρ	-	Density (kg/m^3)
α_{g1}	-	Absorptivity of upper glass cover
α_{g2}	-	Absorptivity of the lower glass cover
α_S	-	Altitude (sun)
τ_{g1}	-	Transmittance of the upper glass cover
τ_{g2}	-	Effective transmittance of honeycomb structure
β	-	Mirror angle (degree)

γ_m - Azimuth (mirror)
γ_s - Azimuth (sun)

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