

Design, Fabrication and Thermal Analysis of Trapezoidal Solar Cooker with Water Heating Facility

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ABSTRACT: Energy is an important source for all sectors of any country's economy. Due to rapid deterioration in the supply of fossil fuels, the solar energy can be the most appropriate option compared to other alternative energy resources. The solar cookers have a relevant place in the present fuel consumption pattern. But the position of the sun varies continuously throughout the daytime which affects the absorption rate of system and increases human effort.

In this project we are designing a trapezoidal solar cooker having internal mirror reflectors placed such that the solar radiation incident upon the surface gets concentrated towards the Centre of the cooker. This increases the concentration ratio of the system and enhances the thermal conductivity. Along with it water heating has been achieved by placing spiral copper coil at the bottom of solar cooker which utilizes the waste heat which was earlier absorbed by the sidewalls but now are reflected by the internal mirror reflectors.

Here we have fabricated 3 different models of solar cooker in order to check the effect of inclination of mirror reflectors on thermal performance of solar cooker. K-type thermocouples are used for temperature measurement purpose. In this proposed design notable increase in thermal efficiency of solar cooker is observed.

KEYWORDS: Fuel Consumption, Solar Cooker, Trapezoidal, Internal Mirror Reflectors, Concentrated, Spiral Copper Coil, Water Heating.

I. INTRODUCTION

Energy has become the utmost necessity of our life. Man has always desired to capture it and use it for mankind. Nowadays energy with lesser cost is helpful for economic development of any country. Increased use of fossil fuels and rapid depletion of natural resources have led to development of alternative source of energy which are renewable and environmental friendly. Solar Energy is the resultant outcome of thermonuclear reactions of fusion from "hydrogen" into "helium" taking place in the sun. These thermonuclear reactions release huge energy and radiate the energy to space continuously. This kind of energy which is continuous and perennial is available as solar energy. Solar energy is the easiest and simplest form of energy. Human consumes 1.11×10^{14} kWh of solar energy per year while the sun supplies 1.78×10^{14} kWh solar energy per hour. Also it is a safer and environmental friendly resource which is helpful for solving energy crisis and environmental problems.

SOLAR COOKER WORKING PRINCIPLE

Solar cooker concentrate sunlight onto a receiver such as cooking pan. The interaction between the light energy and receiver material convert light to heat. This conversion is maximised by using materials that conduct and retain heat.

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M. Balakrishnan et al. It cooks because the interior of the box is heated by the energy of the sun. Sunlight, both direct and reflected, enters the solar box through the glass top. It turns to heat energy when it is absorbed by the dark absorber plate and cooking pots. This heat input causes the temperature inside of the solar box cooker to rise until the heat loss of the cooker is equal to the solar heat gain. Temperatures sufficient for cooking food and pasteurizing water are easily achieved. Given two boxes that have the same heat retention capabilities, the one that has more gain, from stronger sunlight or additional sunlight via a reflector, will be hotter inside. Given two boxes that have equal heat gain, the one that has more heat retention capabilities - better insulated walls, bottom, and top - will reach a higher interior temperature. The following heating principles are considered:

- A. Heat gain
- B. Heat loss
- C. Heat storage.

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Using solar cooker preserves trees, the atmosphere and the soil. In order to progress with solar cooking technology, more resilient efforts must be made to educate the masses in rural areas and measures should be put into place to continue motivating individuals to use solar cookers on a regular basis. In India the villagers mostly depend on firewood for cooking purpose which has very ill effects on health and creates pollution.

Table 2.2.1 Cooking Energy Scenario in India

Urban Sector	Rural Sector
LPG (47.96%)	Firewood (64.10%)
Firewood (22.74%)	Other Sources of biomass – crop residue (13.10%)
Kerosene (19.16%)	Cow-dung (12.80%)
Other Fuels (10.14%)	LPG (5.67%) is now increasing in importance.

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Some guidelines are provided for thermal evaluation of box-type solar cookers. Box-type solar cookers are suitable mainly for the boiling type of cooking. A large fraction of the mass of most food products is due to water and more water may be added in the boiling type of cooking. As a result, sensible heating up to the cooking temperature requires almost 4.2 kJ/kg°C. The complete thermal analysis of the cooker is complex due to the 3-dimensional transient heat transfers involved. The procedures followed at present consist of determination of either cooking times of different food products, or of the time required for sensible heating of a known quantity of water up to the boiling point. However, the time for sensible heating depends on the climatic variables, solar radiation and ambient temperature.

Main Objectives of the project work are:

1. Design a trapezoidal type solar cooker.
2. Comparison with box type solar cooker in terms of material saving and compactness.
3. Effect of inclination in case of proposed solar cooker.
4. Utilization of incident solar energy for water heating in addition of cooking.
5. Perform comparative thermal analysis of solar cooker in order to calculate its efficiency.

II. DESCRIPTION OF SYSTEM

In the present project work trapezium type solar cooker is fabricated with spiral copper coil placed at the bottom such that solar radiation is not only incident upon the center of box but also heats up the coil. So same system can be used for cooking as well as water heating purpose by waste heat recovery which was earlier absorbed by sidewalls but now is reflected by the internal reflecting mirrors.

Following figure shows the conceptual design of trapezoidal solar cooker with different views such that the working of the trapezoidal design can be understood.

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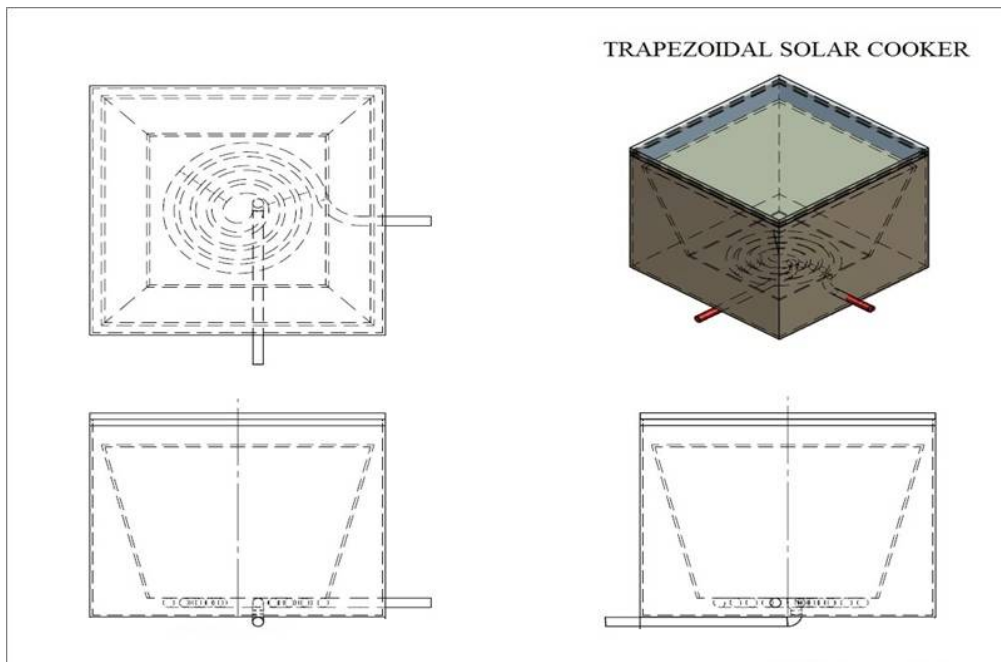
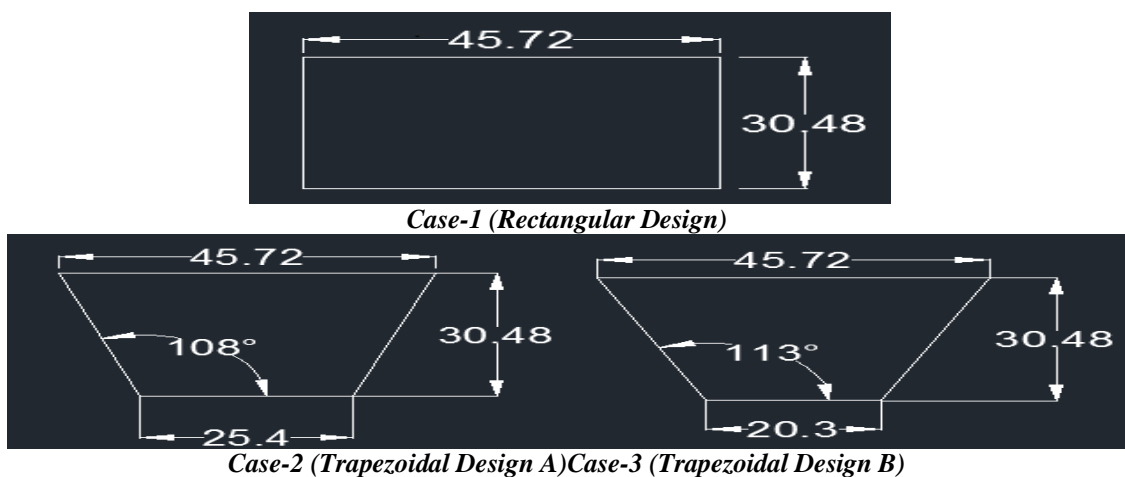


Fig: Schematic diagram of trapezoidal solar cooker

❖ Following are the 2D AUTOCAD drawings of all 3 models which we are going to fabricate for analysis purpose having different inclination angles and base length's in order to achieve higher concentration ratio.



All units are considered in centimeters.

GEOMETRIC CONCENTRATION RATIO(R):

❖ **R**, ratio between aperture area(collector) and absorber area(receiver):

$$R = \frac{\text{Aperture area}}{\text{Absorber area}}$$

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Case 1: **Rectangular** Design with square top:

$$R_1 = \frac{45.7^2}{45.7^2} = 1 = 100\%$$

Case 2: **Trapezoidal** Design-A with square top (Internal reflecting mirrors):

$$R_2 = \frac{45.7^2}{25.4^2} = 3.23 = 323\%$$

Case 3: **Trapezoidal** Design-B with square top (Internal reflecting mirrors):

$$R_3 = \frac{45.7^2}{20.32^2} = 5.05 = 505\%$$

Difference:

$$R_2 - R_1 = 323 - 100 = 223\%$$

$$R_3 - R_1 = 505 - 100 = 405\%$$

As $R_1 < R_2 < R_3$, hence Trapezoidal Design-B absorbs **maximum solar radiation** due to increasing R this is shown in below pie chart.

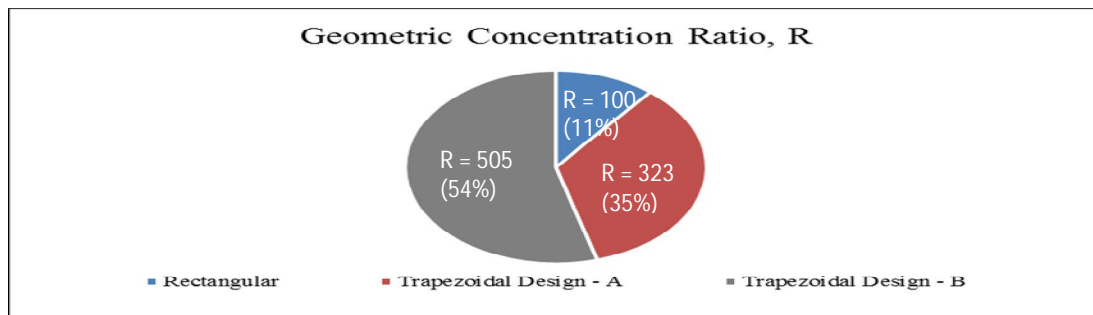


Fig: Pie chart showing the effects of geometric concentration ratio of all 3 designs of solar cooker.

MATERIAL DESCRIPTION:

The materials which we have selected for various components of solar cooker are plywood for structural and insulation purpose, mirrors for reflection, transparent glass top for heat retention, aluminum cooking pots, tin sheet as bottom base, copper coil for water heating purpose and water tank for water storage. Measuring instruments are K-type thermocouple set and measuring flask. The below figure describes the fabricated trapezoidal design of solar cooker.



Fig: Fabricated trapezoidal solar cooker

III. THERMAL ANALYSIS

Thermal analysis of the experimental setups is carried out. All the three models are painted black at the tin base and cooking containers are also painted black at top for more heat absorption. Firstly the water tank is connected with the setups and mass flowrate of all the three models is maintained same and its flow is noted down.

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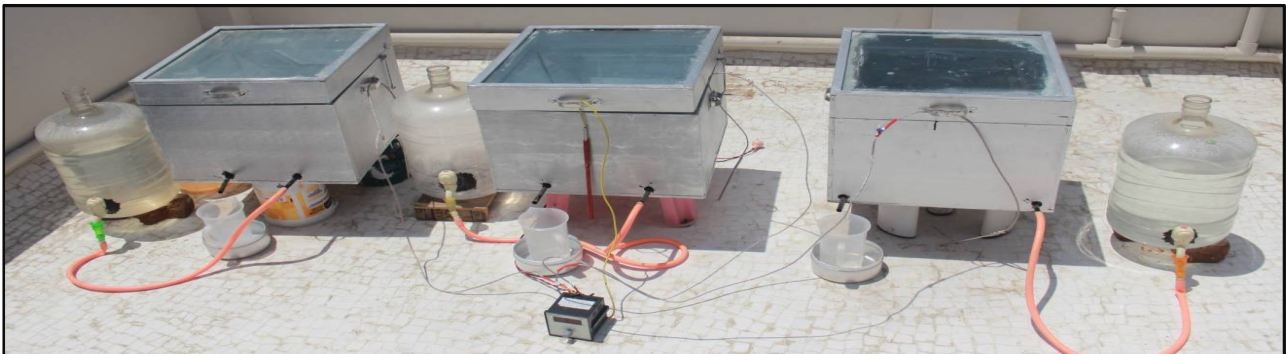


Fig: Experimental Setup for analysis

Now all three cooking containers are filled with water and its initial temperature is noted down. Then with the help of k-type thermocouple unit temperature of copper coil water outlet, cooking container and pot water is noted down at every 15 minutes intervals. The measured readings are tabulated for calculating thermal efficiency.

Initial temperature = 30°C

Time Interval	Temperature (°C)								
	Box (90°)			Trapezoidal-A (108°)			Trapezoidal-B (113°)		
	Water Outlet	Cooking Pot	Pot Water	Water Outlet	Cooking Pot	Pot Water	Water Outlet	Cooking Pot	Pot Water
12:00	33	46	35	35	47	36	36	50	38
12:15	35	50	37	36	49	38	38	54	42
12:30	37	54	40	38	53	41	39	57	45
12:45	38	57	42	41	58	44	41	61	49
13:00	39	60	45	42	63	47	43	65	51
13:15	42	63	47	43	68	49	45	71	53
13:30	44	68	49	45	74	52	46	75	56
13:45	45	71	51	46	78	55	47	79	58
14:00	46	73	54	48	81	57	49	85	61
14:15	47	75	56	49	84	60	52	93	64

From above table, it is quite clear that the solar cooker in which angle of inclination is more (trapezoidal solar cooker – B), the pot water, cooking pot and water outlet temperatures are higher compare to box and trapezoidal solar cooker – A. This may be because due to more inclination, higher amount of solar radiation is reflected upon the pot area and copper coil which leads to rise in temperature of water as well as pot inlet and outlet temperature. Due to black coloured coating on container and base, the heat absorption capacity of solar cooker increases and hence higher temperatures are obtained. This is shown in below graph.

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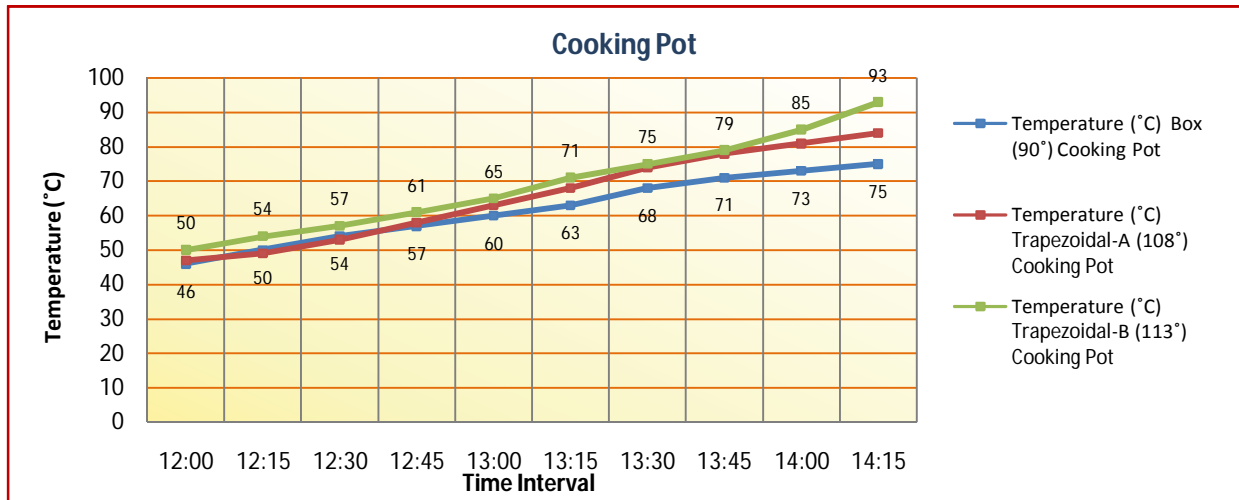


Fig: Graph showing temperature readings at certain time intervals of all 3 models of solar cooker

EFFICIENCY CALCULATIONS

Thermal efficiency can be calculated from below formula:

$$\text{Thermal Efficiency, } \eta = \frac{mC_p\Delta T}{I A_c \Delta t}$$

Where, m = Mass, kg

C_p = Specific Heat, Joule/kgK

$\Delta T = T_{\max} - T_{\min}$ = Temperature Difference, K

I = Solar constant, W/m^2

A_c = Aperture area of cooker, m^2

Δt = Time interval, seconds

$$\text{Aperture area} = 1.5\text{ft} \times 1.5\text{ft} = 2.25 \text{ft}^2 = 0.209 \text{m}^2$$

C_p for water = 4.2 J/kgK (assume)

I = 1.35 W/m^2 (constant value)

$$\eta_{\text{Total}} = \eta_{\text{Pot Water}} + \eta_{\text{Coil Water}}$$

$$\begin{aligned} &= \frac{mC_p\Delta T_p}{IA\Delta t} + \frac{mC_p\Delta T_w}{IA} \\ &= \frac{C_p}{IA} \left[\frac{m\Delta T_p}{\Delta t} + \dot{m}\Delta T_w \right] \end{aligned}$$

$$\text{Where, } \frac{C_p}{IA} = \frac{4.2}{1.35 \times 0.209} = 14.88$$

\dot{m} = Mass flow rate of water, kg/s

ΔT_p = Temperature difference of pot water = $T_{p_o} - T_{p_i}$

ΔT_w = Temperature difference of coil water = $T_{w_o} - T_{w_i}$

$$\eta_{\text{Total}} = 14.88 \left[\frac{m\Delta T_p}{\Delta t} + \dot{m}\Delta T_w \right]$$

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Now the temperature difference is calculated between initial temperature and measured values based on the readings obtained by the k type thermocouple unit .Hence the total efficiency of all three models of solar cooker can be calculated at various intervals of time from above formulae. The table of temperature difference is shown below for certain time intervals. As the temperature difference increases efficiency increases.

Initial temperature (Ti) = 30°C

Time Interval (sec)	Temperature Difference (°C)					
	Box (90°)		Trapezoidal Model - A (108°)		Trapezoidal Model - B (113°)	
	ΔT_w	ΔT_p	ΔT_w	ΔT_p	ΔT_w	ΔT_p
300	3	5	5	6	6	8
1200	5	7	6	8	8	12
2100	7	10	8	11	9	15
3000	8	12	11	14	11	19
3900	9	15	12	17	13	21
4800	12	17	13	19	15	23
5700	14	19	15	22	16	26
6600	15	21	16	25	17	28
7500	16	24	18	27	19	31
8400	17	26	19	30	22	34

Now,

$$\dot{m} = \frac{2}{60 \times 15} = 0.0022 \text{ kg/s}$$

m = Mass of pot water = 1.1 kg

$$\eta = 14.88 \left[\frac{1.1 \Delta T_p}{\Delta t} + 0.0022 \Delta T_w \right]$$

At 8400 seconds:

$$\eta_{\text{Box}} = 14.88 \left[\frac{1.1 \times 26}{8400} + 0.0022 \times 17 \right] = 60.7 \%$$

$$\eta_{\text{T-A}} = 14.88 \left[\frac{1.1 \times 30}{8400} + 0.0022 \times 19 \right] = 68.04 \%$$

$$\eta_{\text{T-B}} = 14.88 \left[\frac{1.1 \times 34}{8400} + 0.0022 \times 22 \right] = 78.64 \%$$

The below table shows the efficiency readings at certain time intervals .Higher comparative thermal efficiency is obtained in trapezoidal cooker-B due to more inclination angle.

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Time Interval	Efficiency (%)		
	Box (90°)	Trapezoidal-A (108°C)	Trapezoidal-B (113°C)
12:00	37.1	49.1	63.28
12:15	25.91	30.55	42.55
12:30	30.7	34.76	42.15
12:45	32.73	43.64	46.37
13:00	35.75	46.41	51.37
13:15	45.08	42.55	56.94
13:30	51.28	55.42	59.84
13:45	54.31	58.57	61.76
14:00	57.61	64.81	68.96
14:15	60.7	68.04	78.64

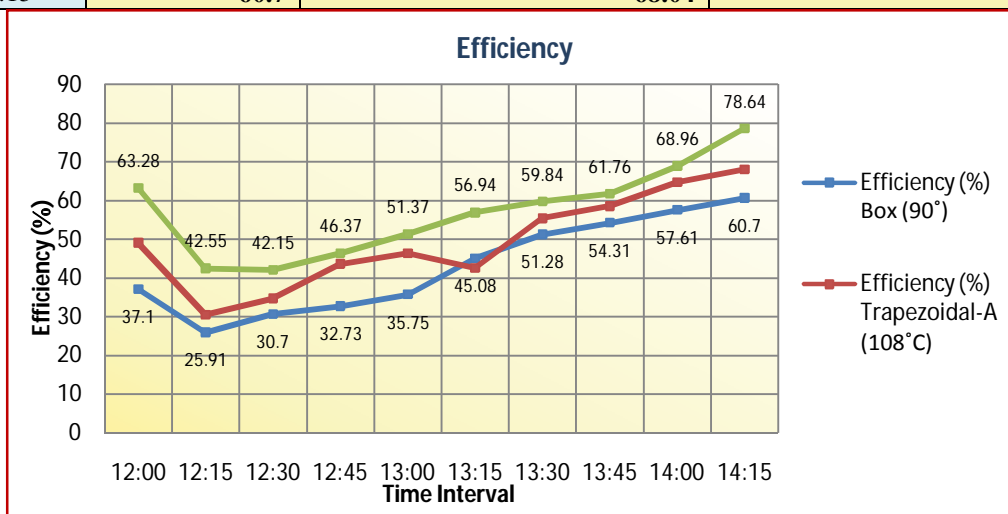


Fig: Graph showing Efficiency (%) readings at certain time intervals of all 3 models of solar cooker

IV. CONCLUSION

During the thermal analysis of solar cookers the results obtained shows that the trapezoidal model-B with 113°C is highly efficient as discussed above and the proposed trapezoidal model with internal reflecting mirrors is a successful design. The results obtained during cooking of 250grams of rice with 350ml water in it are shown in below table:

Atmospheric condition with outside temperature at 37°C

Solar Cooker Models	Time taken to cook rice
Trapezoidal cooker – B(113°)	2 hours and 35 minutes
Trapezoidal cooker – A(108°)	3 hours and 05 minutes
Rectangular Cooker(90°)	4 hours and 10 minutes

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Hence it can be concluded that trapezoidal cooker with black coloured coating on cooking pot and base having 113° inclination angle of mirrors reduces cooking time and reduces human effort.

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