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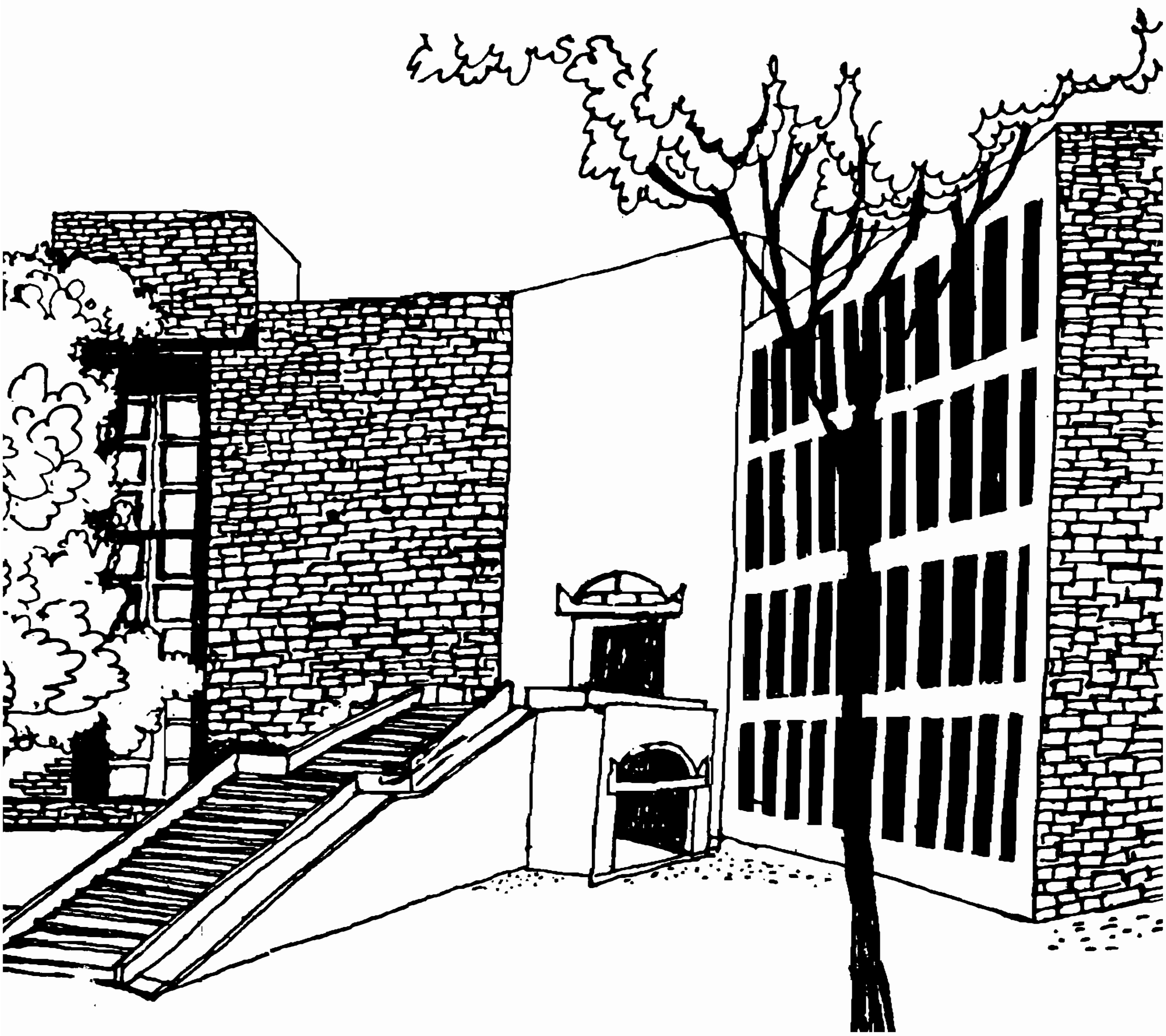

An Investigation Into Utility of Electrical Back-up in Box Solar Cooker

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Abstract

Systematic efforts to promote the use of box solar cookers began in 1979 in Gujarat, along with similar efforts in other parts of the country. During this 15 year period only about 34,000 units have been sold in Gujarat. This is much better than other states. But on absolute basis this number is very small compared to the vast number of households, who live in rural areas, use wood as fuel and experience great difficulty in getting it.

Thus solar cooker is yet a long way from becoming a substitute for conventional devices. It is argued that if the cooker can be made less vulnerable to climatic factors, its acceptability will increase. With this in view, the utility of a built-in backup source is explored in this paper.

Introduction

Many special programs have been launched in the country to alleviate the problem of cooking fuel shortage in rural areas. Promotion of box solar cooker (cooker for short) is one such program, which was launched in the late seventies. Gujarat could be rated as a region of high potential for cookers characterised as it is by high insolation, high ambient temperatures, low cloud cover on one hand and low fuel wood supply on the other. Gujarat has indeed done better than other areas in the adoption of cookers.

While comparatively, Gujarat ranks high the total number of cookers sold between the year 1979 when these were introduced and the year 1993, is very small, 34,000. Recent data on annual sales (**Table 1**) suggests that a certain stagnation has set-in.

It is often observed that innovations (new products, devices, even ideas) tend to diffuse slowly in the beginning, pick-up pace and eventually reach a saturation. The cumulative number of adopters of the innovation, when plotted against time since introduction displays a stretched 'S' shape, such as a typical cumulative probability distribution function or a logistic curve. Let us hypothesise that cooker, which is an innovation, will also follow such a pattern. Accordingly, the cumulative sale data shown in **Table 1** was used to fit a logistic curve. The resulting expression is shown in **Equation 1. Figure 1** shows the actual data and the curve resulting from **Equation 1.**

$$N(t) = \frac{46100}{1 + e^{-(-3.017+0.271t)}} \qquad (1)$$

where N(t) cumulative sales (no.)
t time (years), t(0)=1979

Table 1
Growth of Solar Cookers
(Gujarat)

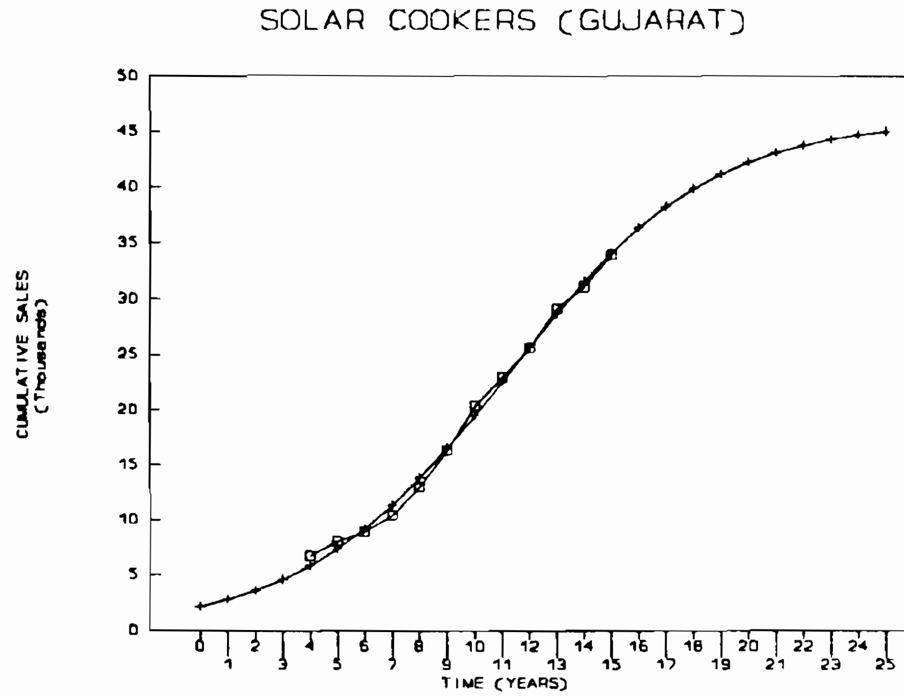
Year	Sale (no.)	Cumulative (no.)
1979-83	--	6725
1983-84	1294	8019
1984-85	856	8875
1985-86	1510	10385
1986-87	2566	12951
1987-88	3334	16285
1988-89	4101	20386
1989-90	2559	22945
1990-91	2666	25611
1991-92	3544	29155
1992-93	1898	31053
1993-94	2827	33880

The curve shows some interesting features, though we must bear in mind that it is only a hypothesis that adoption of cooker will follow a logistic curve. **Figure 1** shows that the number of cookers adopted in Gujarat will rise from approximately 34,000 presently (1994) to about 46,000 in next 5 years, reaching a saturation. It is too small a number to make a significant impact on cooking fuel problem.

Efforts to increase cooker's acceptability have been on. Improvements have been made in marketing infrastructure and mix. Based on user's feedback modifications have also been made in the design (1). Cooker now marketed is much lighter, more easily portable and has fewer maintenance problems. Yet, clearly there are still aspects that need improvement.

In our view, long time required for cooking, performance not sufficiently independent of climatic factors, restricted range of items that can be cooked are still critical impediments to wider adoption. Vaishya *et al* (2) for instance reported that the cooker fails to achieve cooking temperature (120 C) in Delhi in winter months (December, January) due to the fact that both the solar intensity and ambient temperatures are low. Stagnation temperature remains less than 100 C in these months. More northerly locations will also experience such difficulty.

Figure 1



In order to make the cooker less vulnerable to climatic conditions the idea of multi-energy cookers has been suggested by some of those working on solar cooking devices, see for instance Grupp and Klingshirn (3). Some work on adding an electrical back-up in the box cooker has been reported by Nandwani cited in (3). A recent experimental work by Patel and Patel (4) suggests that only a small amount of power would be sufficient to assist the cooker by electrical source. Their work was carried out at Vallabh Vidyanagar (Gujarat) in the month of April. However, altogether the studies on assisted cookers are yet extremely small in number.

The aim of this paper is to explore the utility of an electrical back-up in the cooker. This exploration will be done by using a transient thermal model to simulate the cooker performance in computer. We shall briefly review the transient thermal models of cooker available in the literature. We shall select one of the existing models and modify it to provide for a feedback controlled electrical source. Simulations will be carried out with climatic data of Ahmedabad.

Review of Literature

Chandra and Pandey (5) treated the cooker as one (lumped) unit and did heat balance on it. The overall heat loss coefficient was obtained by adding the heat loss coefficient of glass cover and side walls weighted suitably in accordance with areas of the exposed surfaces. Polynomial expressions for insolation and ambient temperature for Bhopal were developed. Using these, the model equation was numerically integrated to get the temperature inside the box, as the day advanced. The comparisons were satisfactory for empty cooker. Accordingly, they suggested that an overall lumped parameter model was a satisfactory representation of the cooker.

Mannan and Singh (6) were concerned with the problem of the cooker with usual, one reflector, not achieving sufficiently high temperatures in northern areas in winter. To boost performance they designed one with a folding, two step asymmetric reflector. They also formulated a lumped parameter model of this device similar to that of Chandra and Pandey (5). Simulations were carried out to predict the inside temperature achieved at Ludhiana and the results compared with the measurements. The predicted temperatures were close to that measured in the unloaded condition. The comparison does not appear as satisfactory when the cooker was observed under load (water). The reason could be that mode of heat exchange between vessel, food and cooker were not really built into the model equation. The load was accounted for merely by adding to the heat capacity of the cooker.

Mullick *et al* (7) worked on developing figures of merit that could be used to compare various makes of cookers sold in the market. They suggested two figures of merit, one being the stagnation temperature and the second, time taken to bring a quantity of water to near boiling temperature. Expression for the second figure of merit was obtained by doing heat balance on the vessel containing water placed inside the cooker.

Yadav and Tiwari (8) developed an analytic model of cooker with reflector mirror set normal to the glass cover. This model is more comprehensive as it does heat balance of components--glass cover, inside air, vessel, water and absorber plate. Heat capacities of glass, vessels and plate and air are assumed negligible. Radiative transfers inside the cooker are ignored. Under these simplifications, closed form solution for water temperature with time is obtained, which gives insight into the transient behaviour.

Dang (9) developed analytic model of solar cooker augmented with a booster mirror and using PCM as storage. PCM storage was intended to store energy which could be used beyond sunshine hours. Heat balance on glass cover, absorber plate and PCM was done. They also developed Fourier representation of insolation and ambient temperature at Delhi. Using these and empirically determined heat transfer coefficients they simulated the working of an unloaded cooker, to show plate temperature during and after sunshine hours.

Pejak (10) developed transient thermal model of box cooker made of cardboard lined with reflecting material and loaded with an idealised mass of food. Heat balance was done on cover, walls and food. Pejak's cooker is lined with reflecting material (such as aluminium foil) and not with an absorber as is the case in all others reviewed here.

As of now, the most comprehensive model of box-type cooker has been reported by Thulasi Das *et al* (11). Their model includes heat balance on glass cover, inside air, vessel cover, vessel, contents of the vessel, and plate. Unlike models reported earlier, they consider all modes of heat transfer inside the box including radiative. Also the model considers one, two and four vessel cases. Using experimentally determined heat transfer coefficients, they simulated the working to get time and temperature graphs of all components. Simulated results give insights into the importance of various modes of heat transfer which can be used by designers for optimisation of various design aspects. They reported that conductive heat transfer from plate to vessel is very important. This finding conflicts somewhat with that of Philip *et al* who found that conduction was not that important and hence plate can be grooved to prevent peeling of paint.

Table 2 summarises some aspects of the transient thermal models reviewed here. Review suggests that beginning with overall heat balance on the cooker, models have generally evolved towards detailed multi-component treatment. Complex heat transfer processes inside the cooker have begun to be modelled explicitly. This will help improve the design procedures.

Transient Analysis

As stated, first we shall pick one of the existing models to carry out transient analysis. Based on the insight thus gained, we shall modify or make a new model with a view to increase its utility to a designer. Ease of obtaining solutions and carrying out computations will also be a criteria while developing a new model. To start with we shall pick the Chandra-Pandey model of a hot box. **Equation 2** gives their representation of the hot box.

Table 2
Some Transient Thermal Models of Box-type Solar Cooker

By	Modelled	Heat balance on	Modes of transfer considered	Other aspects
Chandra and Pandey (1985)	Empty cooker without reflector	Lumped cooker	Conductive convective	Polynomial expression for diurnal variation in insolation and ambient temperature
Mannan and Singh (1989)	Cooker with folding two stage reflector	Lumped cooker	Conductive convective	Expression for flux from reflector
Mullick et al (1987)	Cooker loaded with vessel containing water	Vessel	Conductive convective	Expression for time to cook
Yadav and Tiwari (1987)	Cooker with reflector loaded	Cover, inside air, vessel water and plate	Conductive convective	
Dang (1985)	Empty cooker with reflector and PCM storage	Cover, plate, PCM	Conductive convective	Fourier expressions of insolation, ambient temperature
Thulasi Das et al (1994)	Cooker with reflector loaded with one, two, four vessels, containing water and food	All components- cover, inside air, vessel cover, vessel, food, plate	Conductive convective and radiative inside box	Expression for view factors etc. inside box
Pejak (1991)	Cardboard cooker, lined with reflecting material, loaded with idealised food mass	Cover, walls and food	conductive convective and radiative	

$$m\, C_p \frac{dT}{dt} = \tau\alpha A_g\, H - U\, A(T - T_a) \tag{2}$$

Where

A	total exposed surface area of cooker (1.15 m^2)
A_g	glass area (0.325 m^2)
H	solar energy incident on glass cover (W/m^2)
mc_p	thermal capacity (7500 J/ C)
T_a	ambient temperature (C)
T	cooking zone temperature (C)
t	time (sec)
U	overall heat loss coefficient (2.65 W/m^2 C)
$\tau\alpha$	optical efficiency (0.80)

Based on the data given in the 'Handbook of Solar Radiation Data For India' (by Mani), we have built Fourier series representation for ambient temperatures and global insolation for an average day of each month, for Ahmedabad, Bhavnagar, Bombay and Jodhpur. We shall use Ahmedabad as a case study. The Fourier coefficients for the ambient temperature series and the global insolation at Ahmedabad are shown in **Table A1 and A2** of appendix.

Simulated Results

Consider an empty cooker, with all its components at uniform temperature equal to that of the ambient air. The cooker is placed outdoors at 7 am. As it gains heat from the sun the inside temperature will begin to rise. **Figure 2** shows the temperature and the hour-of-day curve for Ahmedabad, on an average day in January month. Note the maximum temperature achieved is 92 C. Similar simulations were carried out for all the twelve months. **Table 3** gives the maximum temperature achieved. It is generally accepted that temperatures of 120 C are needed to carry out cooking process satisfactorily. Thus in this cooker at Ahmedabad, cooking will not be satisfactory in seven out of twelve months. The situation can be improved if a mirror reflector is provided. Simulations indicated that it would then be only 5 months when the maximum achieved would be less than 120 C.

Table 3
Stagnation Temperature
(Simulated)

On A Day in	Max. Temp. Inside Cooker (C)
Jan	92
Feb	103
Mar	116
Apr	122
May	124
Jun	106
Jul	85
Aug	81
Sep	90
Oct	98
Nov	97
Dec	90

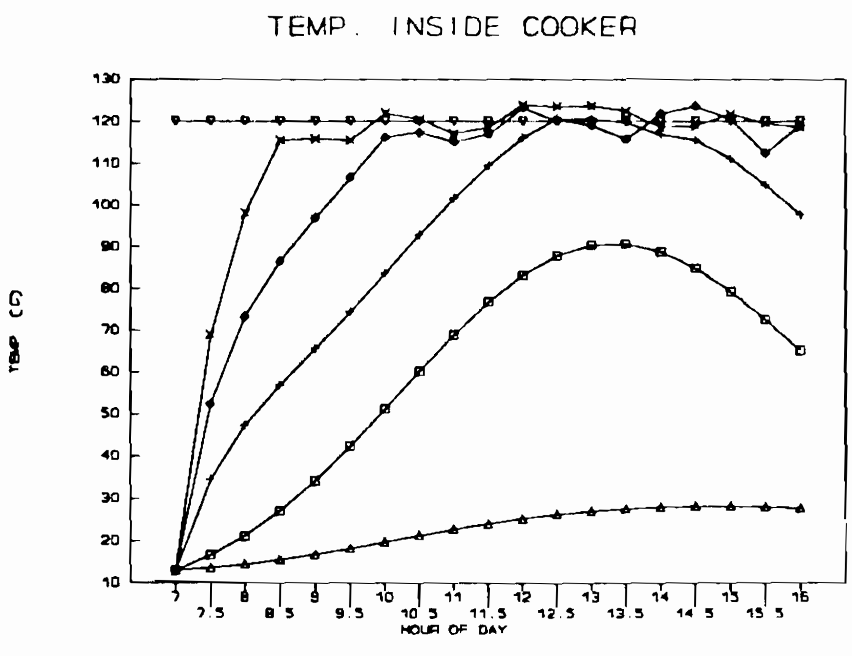
Feedback controlled On-off Backup source of Constant strength

Now consider the same cooker has been provided with a backup source of a given strength say, S, watts. The source is automatically turned-on when the temperature in the cooking chamber falls below a given level, say, T_r. It is off otherwise.

Thus now,

$$m\, C_p \frac{dT}{dt} = \tau\alpha A_g\, H - U\, A(T - T_a) + S(t) \tag{3}$$

Figure 2



$$S(t) = \frac{W}{2} + \frac{W}{2}\,\mathrm{Sign}(T_s - T) \quad (4)$$

where W — power of back up source (W)

T_s — desired minimum temperature of cooking chamber, here 120 C.

Sign — signum function

Sign(T_s-T) — 1 when $T_s - T > 0$; -1 when $T_s - T \leq 0$

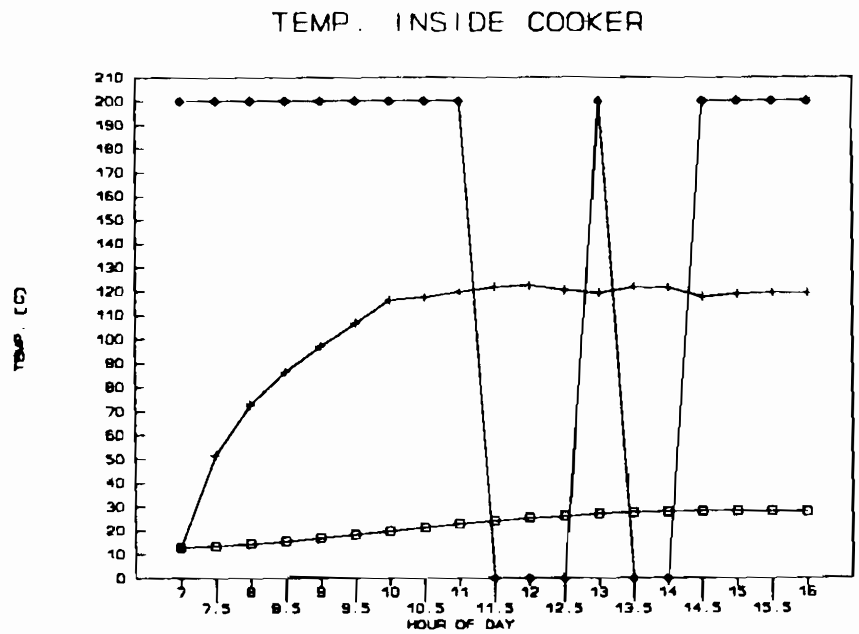
The temperature and hour-of-day graphs for source strengths of 100, 200 and 300 watts are also shown in **Figure 2.**

Note that a back-up of 100 watts is helpful in raising the temperature but not sufficient to take it to 120 C except for a short while after 12 noon. Increasing the strength of the back-up to 200 watts, enables the cooker to reach 120 C earlier, 10 a.m. Increasing the back-up strength further to 300 watts, will enable the cooking to be done 7.30 a.m. onwards, if desired.

Recall that the back-up source is triggered by a feedback channel. This is illustrated in **Figure 3.** The figure shows that the back-up source (here 200 watts) comes on at 7 a.m. It remains on until cooker temperature reaches 120 C. It then turns itself off. The figure shows the duration for which the back-up source remained on or off.

It may be mentioned here that Patel and Patel (4) have reported that about 225 watts back-up was adequate for the cooker tested by them. It may be of interest also to note that the rice cooker marketed by National Company has the rating of 440 watts.

Figure 3



Performance when Sky Obscured or Cooking Indoors

One of the impediments to acceptability of box cooker is that it can not be used when it is raining, or sky is obscured. It would, therefore, be of interest to see what the performance will be of a cooker with electrical back-up when used indoors.

A set of simulations were done with insolation reduced to zero (H = 0) and ambient temperature set to a constant 25 C to mimic the indoor conditions.

Table 4 shows the maximum temperature achieved, time taken to reach 300 C when source strength was varied from 300 watts to 1200 watts. We chose time taken to reach 300 C because this is the highest temperature setting available in electrical ovens available in the market. Also one of the popular brands (**Bajaj**) has 1200 watt heating element made up of 4 elements of 300 watts connected in series. The Bajaj cooker can thus be used with source strength of 300, 600, 900 or 1200 watts.

Table 4
Solar Cooker Indoors or Sun Obscured
No Insolation, Ta = 25 C

Backup source strength (watts)	Max. Temp. Reached (C)	Time To Reach 300 C
300	123	
600	222	
900	320	120 mts
1200	418	45 mts

Note the cooker without modification accept the addition of back-up source, will achieve temperatures of 300 C only with strength of 900 watts and above.

Also note the sluggish response of this cooker. It takes as much as 2 hrs to reach 300 C with the strength of 900 C. Even with 1200 watt strength it takes 45 minutes to reach 300 C. The electrical oven available in the market respond faster. This is due to the fact that electrical ovens are provided with better radiation shielding.

The solar cooker, if it is desired that it performs well indoors, will not only need a back-up source of sufficient strength, but also better shielding against losses.

Need for better model

The overall heat loss coefficient (U) used here has been treated as constant as was done by Chandra and Pandey. In reality it is not a constant but depends on temperature gradient between cooker and the ambient. It will be necessary to improve upon this model.

Summary and Conclusion

Gujarat can be expected to have high potential for use of solar cooker. This is in view of the fact that on one hand it is short of fuel wood resources and on the other it has high insolation, high ambient temperature and low cloud cover most of the time. Gujarat also has good entrepreneurial base.

Yet during the 15 year period since introduction only about 34,000 units have been sold which is very small compared to the potential. Annual sales have also begun to show stagnation.

There is need to increase the acceptability of the cooker. For this, among other things, it is necessary to make the cooker more independent of the climatic and weather condition. One way of doing so is to provide an electrical back-up.

A simulation study was, therefore, carried out to examine the utility of a back-up in the cooker. Climatic data of Ahmedabad was used as a case study. The following conclusion emerged.

1. The existing cooker will fail to achieve cooking temperature (120 C) in Ahmedabad in five out of twelve months, mostly during winter.

2. If an electrical source is provided, appropriate strength appears to be between 200 watts to 300 watts. This will enable the users to start early and use the cooker practically any time during the day, if needed.

3. If it is also desired that the cooker be made capable of cooking indoors or when sun is obscured not only the strength of back-up source will need to be increased, but cooker will need to be redesigned to provide better radiation shielding.

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Table A1
Fourier Coefficients for Air Temperature Series
AHMEDABAD

	n	0	1	2	3	4	5	6
Jan	A	20.01	-3.92	0.89	-0.44	0.23	0.07	-0.18
	B		-6.07	1.63	0.35	-0.48	0.20	0.08
Feb	A	23.13	-3.97	0.98	-0.36	0.35	0.14	-0.27
	B		-6.70	1.67	0.60	-0.48	0.17	0.15
Mar	A	27.37	-3.54	0.79	-0.40	0.20	0.17	-0.18
	B		-6.42	1.36	0.59	-0.44	-0.05	0.09
Apr	A	31.55	-2.94	0.69	-0.30	0.16	0.13	-0.08
	B		-6.12	1.15	0.55	-0.31	-0.05	0.06
May	A	33.77	-2.53	0.31	-0.08	0.11	0.13	-0.04
	B		-5.90	1.20	0.39	-0.14	-0.09	0.03
Jun	A	31.83	-2.08	0.06	0.11	0.04	0.00	-0.08
	B		-3.74	1.07	0.20	-0.12	-0.08	0.06
Jul	A	28.74	-1.24	0.08	0.04	0.00	0.01	-0.04
	B		-2.07	0.54	0.10	-0.12	-0.03	0.06
Aug	A	28.03	-1.12	0.12	0.02	0.03	0.01	-0.03
	B		-2.07	0.50	0.06	-0.10	-0.03	0.04
Sep	A	28.00	-1.76	0.34	0.00	0.04	0.01	-0.08
	B		-2.60	0.71	0.13	-0.17	-0.03	0.08
Oct	A	27.69	-4.02	1.02	-0.13	0.03	0.07	-0.18
	B		-4.65	1.33	0.55	-0.51	0.01	0.19
Nov	A	24.27	-4.73	1.27	-0.26	0.03	0.07	-0.17
	B		-5.31	1.48	0.48	-0.65	0.11	0.23
Dec	A	21.03	-4.20	0.99	-0.26	0.20	0.00	-0.23
	B		-5.47	1.70	0.31	-0.58	0.08	0.16

Table A2
Fourier Coefficients for Global Solar Radiation Series
AHMEDABAD

	n	0	1	2	3	4	5	6
Jan	A	204.00	-338.23	181.47	-42.61	-17.21	14.71	1.42
	B		-41.58	44.65	-14.90	-10.61	10.81	1.58
Feb	A	240.63	-392.23	197.26	-35.04	-23.92	13.02	4.58
	B		-48.16	48.42	-11.77	-14.29	9.54	4.67
Mar	A	280.71	-448.12	207.89	-23.61	-28.71	8.56	7.25
	B		-54.54	50.50	-7.34	-16.09	5.54	7.17
Apr	A	305.33	-476.38	201.47	-9.08	-29.33	2.20	8.17
	B		-57.02	47.79	-1.48	-15.88	0.53	8.00
May	A	316.54	-485.23	191.02	-0.06	-26.46	-2.29	7.08
	B		-62.47	50.45	-0.85	-14.36	-1.55	6.50
Jun	A	265.71	-405.17	156.52	0.90	-20.75	-1.65	3.75
	B		-55.21	45.48	-3.41	-9.81	-1.78	4.50
Jul	A	201.42	-307.80	119.41	1.85	-18.13	-0.55	4.58
	B		-44.68	37.99	-4.22	-8.01	-0.59	3.75
Aug	A	185.88	-287.54	117.54	-2.73	-17.17	0.91	3.58
	B		-45.99	40.92	-5.92	-9.38	0.55	5.17
Sep	A	230.83	-364.81	162.70	-13.87	-23.04	5.32	4.42
	B		-49.01	44.06	-4.69	-14.94	4.43	6.08
Oct	A	240.25	-388.49	189.58	-29.41	-23.54	9.85	5.83
	B		-47.73	46.29	-8.95	-15.08	8.26	5.33
Nov	A	207.21	-342.21	181.09	-40.68	-17.42	13.32	2.25
	B		-39.12	40.72	-11.58	-11.55	9.81	2.33
Dec	A	190.88	-318.26	174.50	-44.73	-13.92	14.03	0.58
	B		-38.45	42.04	-15.03	-9.38	10.78	0.67