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Prediction and experimental verification of performance of box type solar cooker. Part II: Cooking vessel with depressed lid

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Abstract

Our previous article (Part I) discussed the theoretical and experimental study of the performance boost obtained by a cooking vessel with central cylindrical cavity on lugs when compared to that of a conventional cylindrical vessel on floor/lugs. This article compares the performance of the cooking vessel with depressed lid on lugs with that of the conventional vessel on lugs. A mathematical model is presented to understand the heat flow process to the cooking vessel and, thereby, to the food material. It is found from the experiments that the cooking vessel with depressed lid results in higher temperature of the thermic fluid loaded in the cooking vessel compared to that of the thermic fluid kept in the conventional vessel when both are placed on lugs. Similar results were obtained by modeling the process mathematically. The average improvement of performance of the vessel with depressed lid is found to be 8.4% better than the conventional cylindrical vessel.

Keywords: Box type solar cooker; Conventional cylindrical vessel; Vessel with depressed lid; Thermic fluid; Intermittent azimuthal tracking

1. Introduction

Several researchers have performed work on different designs of solar cookers and their performance improvement since the late 19th century. The studies on solar cookers can be broadly classified into the following categories: (a) design, fabrication and testing of new types of solar cookers, (b) methods of boosting solar energy onto the cooker aperture using booster mirrors, (c) energy storage type of cookers for use indoors and also during off sun shine periods, (d) tests on different types of cooking vessels and (e) modeling and simulation techniques. The present study discusses the testing and modeling of a vessel with a depressed lid.

1.1. Different types of cooking vessels

Gaur et al. [1] studied the performance of a cooker with modified utensils with a concave shaped lid. Narasimha Rao and Subramanyam [2,3] demonstrated experimentally that a cooking vessel kept on supports (lugs) and also a cylindrical cooking vessel with central annular cavity performs much better when compared to a conventional cylindrical vessel on the floor of the cooker. Raji Reddy and Narasimha Rao [4] compared, both experimentally and theoretically, the performance of a cylindrical vessel with central annular cavity on lugs with that of the conventional cylindrical vessel on the floor of the cooker/on lugs.

1.2. Modeling and simulation

A few investigators have developed techniques for simulating the performance of a box type solar cooker. Garg et al. [5] developed mathematical model for studying the transient behaviour of a single glazed box type solar

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Nomenclature

A	area (m^2)
G	insolation (W/m^2)
M	heat capacity (J/ K)
Q	heat transfer (W)
T	temperature (K)
t	time (s)

Subscripts

1	conventional cylindrical vessel on lugs
2	cylindrical vessel with depressed lid on lugs
a	air inside cooker
amb	ambient air
av	air inside vessel
g_1	lower glass cover
g_2	upper glass cover
ins	insulation
p	absorber plate
sp	side plate
spr	side plate projected area
v	cooking vessel
vc	vessel cover
w	thermic fluid inside vessel
ws	wetted surface

cooker. Later, Aman Dang [6] presented an analytical model of a box type solar cooker assisted by single booster mirror using PCM (phase change material) as the storage system. Further, Thulasidas et al. [7,8] have modeled a box type solar cooker with a reflector and loaded with one, two or four vessels and studied the effect of base plate thickness, cooker size, etc. Binark and Turkmen [9] presented a mathematical model for the solar box cooker. They made a thermal analysis for a cooker with four pots, loaded with water, and compared with experimental results. El-Sebaii [10] presented a simple mathematical model for a box type solar cooker with outer-inner reflectors. Raji Reddy and Narasimha Rao [11,12] presented mathematical models in which a heat transfer analysis of a conventional vessel on lugs is compared with that of a conventional vessel on the floor of the cooker and also compared the performance of the vessel with a central cylindrical cavity on lugs with the conventional vessel on the floor of the cooker. In the above models, the estimated solar insolation values are supplied as input, whereas in the present model, observed values of insolation and ambient temperature are used.

Raji Reddy and Narasimha Rao [4] discussed the theoretical and experimental study of the performance boost obtained by a cooking vessel with a central cylindrical cavity on lugs when compared to that of a conventional cylindrical vessel on the floor/on lugs. In this article, the performance of the cooking vessel with depressed lid is presented. The lid of the cooking vessel intercepts the maximum amount of incident energy. Usually, the lid is separated from the food by an air gap. Therefore not much heat could be transferred directly to the food by conduction. A cooking vessel with depressed lid provides direct contact between the lid and the contents of the vessel. Because the lid is in direct contact with the contents of the cooking vessel, the heat transfer from the lid is more effective, thus resulting in a higher temperature of the thermic fluid/water present in the cooking vessel. This phenomenon was found to be correct during the tests conducted on the box type solar cooker loaded with a conventional cylindrical vessel on lugs and another vessel with a depressed lid on lugs. The experiments were conducted during November 2004 and January 2005 with a thermic fluid as working medium. The depressed lid is effective only in the case of a fully loaded vessel.

2. Description of the solar cooker and vessels

Fig. 1 shows the schematic of a box type solar cooker with cooking vessels. The cooker consists of a trapezoidal aluminum tray (35 cm × 35 cm at bottom, 49 cm × 49 cm at top and 10 cm height) made of 1 mm thick sheet. The conventional cylindrical vessel (∅ 20 cm) and another vessel (∅ 20 cm) with depressed lid (depth 2.5 cm) are kept on lugs. The details of the conventional cylindrical vessel and the vessel with depressed lid are depicted in Figs. 2 and 3, respectively. Each of the vessels was loaded with a fixed mass of thermic fluid (1 l). The sides and bottom of the tray are encased in a box made of sheet metal. The gap between the tray and the casing is filled with glass wool to provide thermal insulation. The tray is provided with a movable double glass cover, hinged to one side of the casing at the top. A plane glass mirror, encased in a sheet metal shell, is fitted to serve as a reflector. This serves as a cover for the double glass glazing when the cooker is not in use. The cooking vessels are cylindrical in shape and have a flat base. The vessels are provided with tight fitting covers. The tray and outer sides of the vessels are painted with dull black paint.

3. Mathematical model

A box type solar cooker with one conventional cylindrical vessel and another vessel with depressed lid, both kept on lugs, are considered. The various heat transfer processes are illustrated in Fig. 4. The absence of air inside the cooking vessel, i.e. between the contents of the vessel and the lid, for the vessel with depressed lid, facilitates direct contact between the vessel cover and the contents of the vessel.

A transient model is employed to evaluate the temperature of the elements of the cooker for every second, which

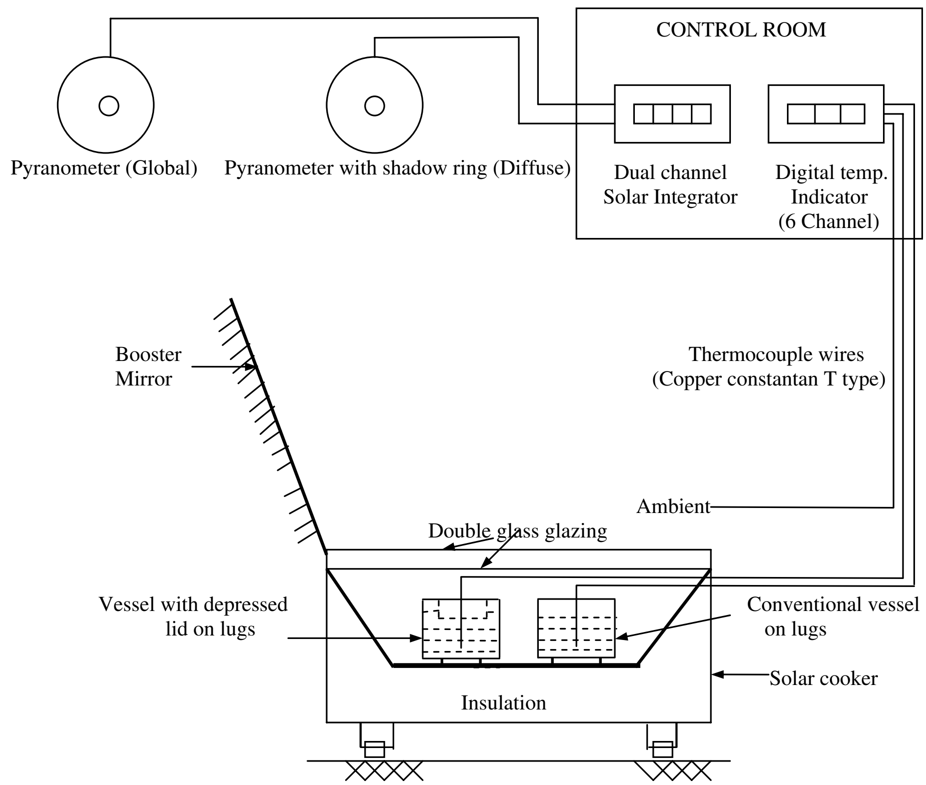

Fig. 1. Schematic of a box type solar cooker with conventional cylindrical vessel and another vessel with depressed lid, both on lugs.

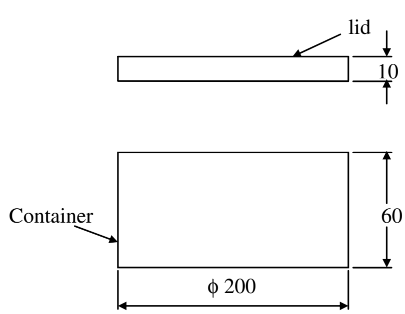

Fig. 2. Lid and container of a conventional cylindrical cooking vessel.

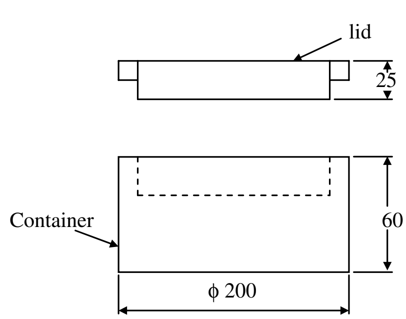

Fig. 3. Lid and container of a cylindrical cooking vessel with a depressed lid.

is fed as input to the next iteration. The various heat transfer processes are identified, and energy balance equations are obtained for the different elements of the cooker. The following assumptions are made:

1. Heat radiation between the sidewalls of the cooker and the vessel cover is negligible.
2. Solar radiation is incident only on the absorber plate, side plate and vessel cover.
3. The heat transfer coefficients are fixed and taken as constants.
4. Heat conduction between the horizontal absorber plate and the side plates and also between the vessel cover and the vessel side is negligible.
5. Air inside the vessel with depressed lid is negligible.
6. Heat loss due to air exchange between the cooker and the ambient is negligible.

3.1. Mechanism of heat flow in a cooking vessel

3.1.1. Conventional cylindrical vessel on lugs

The contents of the cooking vessel has three boundaries: (i) the bottom of the vessel, (ii) the sides of the vessel and (iii) the air layer above it. When the vessel is on the floor, heat transfer takes place by means of conduction from the absorber plate to the vessel bottom and vice versa. The heat flow from the sides of the vessel takes place by convection in both directions, i.e. inwards and outwards. When the net flow is inwards, the thermic fluid gains heat and its temperature rises, whereas the thermic fluid loses heat and cools if the net heat flow is outward. The lid of the vessel intercepts the maximum energy. However, this is not effectively transferred to the thermic fluid, as there

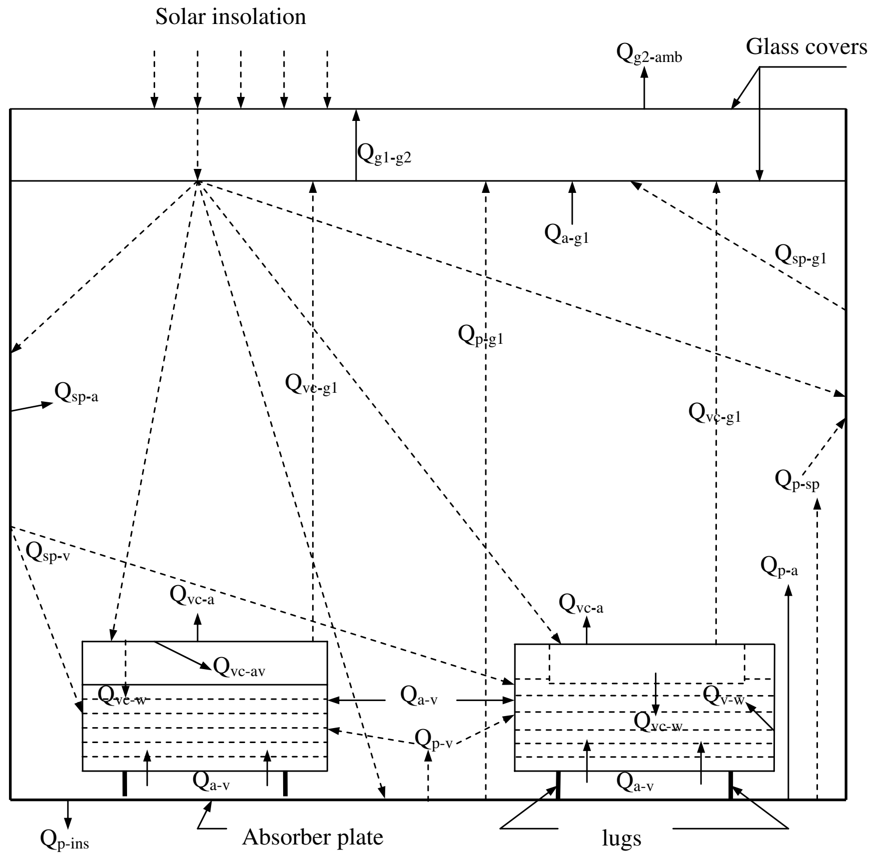

Fig. 4. A schematic indicating various modes of heat transfer in a box type solar cooker containing a conventional cylindrical vessel and another vessel with depressed lid, both on lugs.

is an air gap between the lid and the thermic fluid, which allows only convection between the lid and the working medium. By keeping the vessel on lugs, i.e. lifting the vessel above the floor of the cooker, it allows hot air in the cooker to circulate in the space between the bottom of the vessel and the plate, resulting in an increase in heat transfer to the contents of the vessel. Hence, the temperature of the contents of the vessel will be more than that when the vessel is on the floor.

3.1.2. Vessel with depressed lid

The lid of the cooking vessel intercepts the maximum amount of incident energy. Usually, the lid is separated from the food by an air gap. Therefore, not much heat could be transferred directly to the food by conduction. As the lid temperature rises, the surrounding air is heated and convection air currents are setup in the cooker interior. These hot air currents then transfer heat to the food material in the vessel through the side surface of the vessel, which is in contact with the food.

As mentioned earlier, the lids of the cooking vessels intercept the maximum portion of the solar energy that is received by the cooker aperture. Therefore, it is only appropriate that this energy should be conveyed to the food in as direct a manner as possible. The cooking vessel with a depressed lid (in the absence of air inside the vessel) provides direct contact between the lid and the food. Hence, the heat transfer from the lid is more effective, thus resulting in a higher temperature of the thermic fluid (oil). The depressed lid is effective only in the case of a fully loaded cooking vessel.

3.2. Heat balance equations

For the upper glass cover

$$M_{g2}\frac{dT_{g2}}{dt} = G_{g2} + Q_{g1-g2} - Q_{g2-amb} \tag{1}$$

For the lower glass cover

$$M_{g1}\frac{dT_{g1}}{dt} = G_{g1} + Q_{a-g1} - Q_{g1-g2} + Q_{p-g1} + Q_{vc1-g1} + Q_{vc2-g1} + Q_{sp-g1} \tag{2}$$

For air inside the cooker

$$M_{a}\frac{dT_{a}}{dt} = Q_{p-a} + Q_{vc1-a} + Q_{vc2-a} + Q_{sp-a} - Q_{a-g1} - Q_{a-v1} - Q_{a-v2} \tag{3}$$

For the absorber plate

$$M_{p}\frac{dT_{p}}{dt} = G_{p} - Q_{p-a} - Q_{p-v1} - Q_{p-v2} - Q_{p-g1} - Q_{p-sp} - Q_{p-ins} \tag{4}$$

For vessel cover 1

$$M_{vc1}\frac{dT_{vc1}}{dt} = G_{vc1} - Q_{vc1-g1} - Q_{vc1-a} - Q_{vc1-w1} - Q_{vc1-av1} \quad (5)$$

For vessel cover 2

$$M_{vc2}\frac{dT_{vc2}}{dt} = G_{vc2} - Q_{vc2-g1} - Q_{vc2-a} - Q_{vc2-w2} \quad (6)$$

For side plate

$$M_{sp}\frac{dT_{sp}}{dt} = G_{sp} + Q_{p-sp} - Q_{sp-a} - Q_{sp-g1} - Q_{sp-v1} - Q_{sp-v2} - Q_{sp-ins} \quad (7)$$

For vessel 1

$$M_{v1}\frac{dT_{v1}}{dt} = Q_{p-v1} + Q_{a-v1} + Q_{sp-v1} - Q_{v1-w1} - Q_{v1-av1} \quad (8)$$

For vessel 2

$$M_{v2}\frac{dT_{v2}}{dt} = Q_{p-v2} + Q_{a-v2} + Q_{sp-v2} - Q_{v2-w2} \quad (9)$$

For air inside vessel 1

$$M_{av1}\frac{dT_{av1}}{dt} = Q_{vc1-av1} + Q_{v1-av1} - Q_{av1-w1} \quad (10)$$

For the contents of vessel 1

$$M_{w1}\frac{dT_{w1}}{dt} = Q_{av1-w1} + Q_{v1-w1} + Q_{vc1-w1} \quad (11)$$

For the contents of vessel 2

$$M_{w2}\frac{dT_{w2}}{dt} = Q_{v2-w2} + Q_{vc2-w2} \quad (12)$$

4. Experiment

The temperature of the thermic fluid in each of the vessels and the ambient temperatures were recorded at preset intervals of time using a digital temperature indicator (range, 0–300 °C, accuracy, ±0.25%, resolution, 1 °C). Thermic fluid temperatures were measured by a copper-constant an thermocouple, whose hot junction is fixed inside the vessel through a small hole of the lid. The tip of the thermocouple is placed 10 mm above the base of the vessel. The solar cooker is not opened during the course of the tests. The cooker is tracked once every 30 min, in order to collect the maximum amount of insolation. The tracking is done by rotating the cooker azimuthally in such a way that the azimuth of the mirror normal and the sun are equal, and the reflected rays from the mirror illuminate the entire cooker aperture and aperture alone. The global and diffuse components of insolation were also recorded with the help of pyranometers (range, 0–1400 W/m^2, accuracy, ±0.5%, response time, 5 s) and a dual channel solar integrator (range, 0–2000 W/m^2, accuracy, ±0.2%, resolution, 1 W/m^2).

The experiments were conducted for several days at the Solar Energy Laboratory of the National Institute of Technology, Warangal (latitude 18°N, longitude 79.5°E and elevation 275 m above sea level) India.

5. Results and discussion

The energy balance Eqs. (1)–(12) are solved with a computer program written in MATLAB. This program is executed for every second as the time interval, whereas the temperatures are recorded for every half-an-hour. The variation of ambient temperature is considered in the modeling. The various parameters of the cooker used in modeling are tabulated in Table 1. This model takes care of the shape of the vessel and orientation, when both simultaneously exist in the cooker interior. Fig. 5 depicts the temperature time history of the thermic fluid in the conventional cylindrical vessel on lugs and that of the thermic fluid in the vessel with depressed lid on lugs. Second degree polynomial fits of the above data are also shown in the same figure. It is evident from the figure that the vessel with

Table 1
The heat capacity and the area of the various elements of the box type solar cooker

Heat capacity	J/K	Area	m^2
M_p	297.43	A_g	0.25
M_{sp}	443.72	A_{sp}	0.1826
M_a	23.09	A_{spr}	0.1276
M_{g1}	1638	A_p	0.1224
M_{g2}	1638	A_{vc1}	0.02836
M_{w1}	1699	A_{vc2}	0.04092
M_{w2}	1699	A_{v1}	0.0449
M_{vc1}	91.56	A_{v2}	0.0449
M_{vc2}	122.68	A_{ws1}	0.0273
M_{av1}	1.07	A_{ws2}	0.0273
M_{v1}	167.86	A_{av1}	0.0276
M_{v2}	167.86		

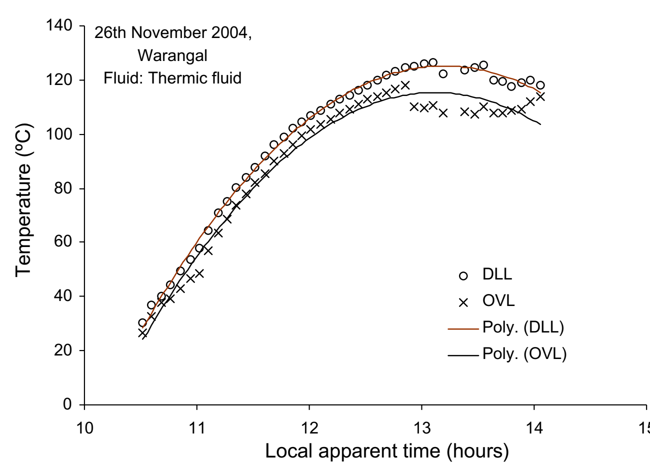

Fig. 5. Variation of temperature of thermic fluid in a cylindrical vessel kept on lugs (OVL) compared to that of the thermic fluid in a vessel with depressed lid on mild steel lugs (DLL). The experiments were conducted on 26th November 2004 at Warangal (latitude 18°N, longitude 79.5°E and elevation 275 m above mean sea level). Second degree polynomial fits of the experimental data are also illustrated.

depressed lid is performing better than the conventional vessel all through the day. It has also been observed that the maximum temperature of the thermic fluid in the conventional cylindrical vessel on lugs occurred at 13 h, and the same temperature could be attained in the case of the vessel with depressed lid nearly 45 min earlier. This is because the lid of the vessel, the heat recipient surface, provides direct contact between the lid and the food.

Fig. 6 shows the predicted and observed values of the temperature of the thermic fluid in the conventional cylindrical vessel on lugs. A second degree polynomial fit of the experimental data is also shown in the above figure. It has been found that the observed values of the temperature are less than the predicted values except for the period between 11.5 and 12.5 h. Fig. 7 illustrates the variation of the observed and predicted values of the temperature with time of the thermic fluid in the vessel with depressed lid on lugs. A second degree polynomial fit of the observed data is also shown in the same figure. The predicted values of temperature have been observed to be lower when compared to the observed values. However, the difference between the predicted and measured values of temperature is rather small at the beginning of the day and at the end of the day except for the period between 12 and 13 h.

It is observed from the experiments (see Fig. 5) that the vessel with depressed lid on lugs performed better than the conventional cylindrical vessel on lugs. The average improvement of performance of the vessel with depressed lid is found to be 8.4% more than that of the conventional cylindrical vessel. On the whole, the model is predicting lower values of temperature compared to observed values, but the temperature is higher only in the middle of the test. Otherwise, it is seen that the predicted and observed values are very close. The cooking vessel with depressed lid provides direct contact between the lid and contents of the vessel and, hence, makes the heat transfer more effective. It is a clear indication that the food is cooked faster in a vessel with depressed lid on lugs than in a conventional vessel on lugs.

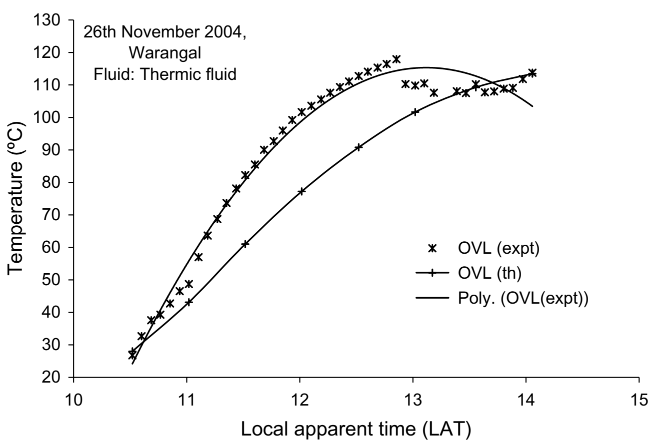

Fig. 6. The predicted and observed values of temperature of the thermic fluid contained in a conventional cylindrical vessel kept on mild steel lugs (OVL). The experiments were conducted on 26th November 2004 at Warangal (latitude 18°N, longitude 79.5°E and elevation 275 m above mean sea level). Second degree polynomial fit of the experimental data is also depicted.

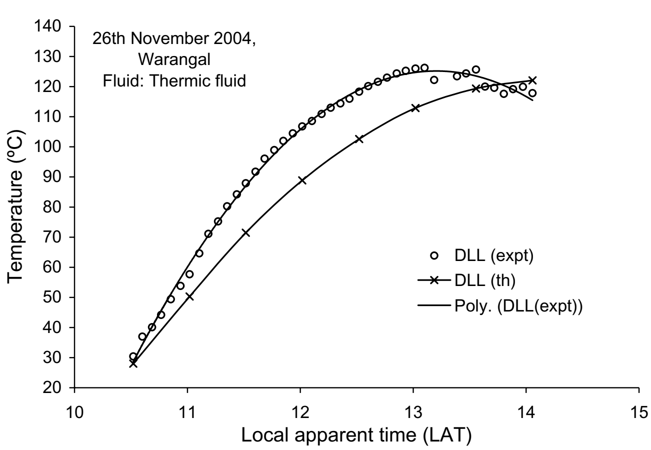

Fig. 7. The predicted and observed values of temperature of the thermic fluid contained in a vessel with depressed lid kept on mild steel lugs (DLL). The experiments were conducted on 26th November 2004 at Warangal (latitude 18°N, longitude 79.5°E and elevation 275 m above mean sea level). Second degree polynomial fit of the experimental data is also depicted.

6. Conclusions

The vessel with depressed lid performs better than the conventional cylindrical vessel. Hence, it is recommended for use in box type solar cookers.

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