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DEVELOPMENT AND THERMAL PERFORMANCE ANALYSIS EVALUATION OF A TRUNCATED PYRAMID SOLAR COOKER

[113]

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ABSTRACT

Study aimed to develop and evaluate the thermal performance of truncated pyramid solar cooker viz non-modified and modified. Tests have been carried out in Department of Agricultural Engineering, Faculty of Agriculture, Ain Shams University, Shubra El-Kheima, Egypt (Latitude 30^{o}11' N, Longitude 31^{o}24' E). The solar cookers were not loaded, and loaded with 0.5, 1.0 and 2.0 liter of water. The modified truncated pyramid was filled with different quantities of rice. The thermal performance was evaluated by using first figure of Merit, second figure of Merit and energy efficiency. textural properties of rice and biscuits and cost analysis were measured. The absorber plate temperature of the modified was 15. 8% higher than the absorber plate temperature of the non-modified cooker. The calculated values of first figure of Merit was 0.102 and 0.08 ^{o}C.m^2/W with modified and non-modified truncated pyramid cooker types, respectively. The value of second figure of Merit was 0.293 and 0.129 for modified and non-modified truncated pyramid cooker, respectively.

INTRODUCTION

A solar cooker is a device which utilizes solar energy to cook food. There are many types of solar cookers in the world and they are continually improved by researchers and manufacturers. **Cuce and Cuce (2013)** stated that the most of the solar cookers today fall within three main categories called solar panel cookers, solar parabolic cookers and solar box cookers. Egypt has a high potential for the utilization of solar energy that can be considered as a reliable energy source. The average solar energy has a magnitude of 5 to 8 kW.h/m^2 per day and sunshine duration per year extends to about 3500 hours **Sorensen (2004). Harmim et al (2012)** revealed that solar cooking is an important application in thermal conversion of solar energy however, By using sun's free energy, solar cookers offer an alternative solution for energy supply problems for the needs for cooking especially in rural, remote locations. **Yettou et al (2016)** showed that solar cooking is one of the important applications, solar cookers offer an alternative solution for ecological, economic and health problems. More ever, only box types have gained maximum popularity, in developing countries, among all other existing models because of its simple design operation and lowest cost. Extensive research has been conducted by many scientists, researchers and academicians regarding design development of experimentation with box solar cookers.

Kumar et al (2008) have designed a truncated pyramid type solar cooker. It was designed for multipurpose owing the geometry of design rays hitting inside the cooker (walls) and were reflected with high intensity to downwards a higher temperature was maintained at the absorber tray (bottom side). In continuation of work, **Kumar et al (2010)** have fabricated and tested a truncated pyramid geometry based multipurpose solar device which could be used for domestic cooking as well as water heating. The device was found to meet the requirement stipulated on two figures of merit. **Al-Soud et al (2010**) designed, operated and tested a parabolic cooker with automatic two axes sun tracking system. The test results showed that the water temperature inside the cooker's tube reached 90^{o}C when the maximum registered ambient temperature was 36^{o}C. In order to improve the perfor-

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mances of box-type solar cooker many works were carried out by several researchers. Some researchers brought solutions to enhance the heat capacity of box-type solar cookers by increasing the solar irradiation in the box with the help of reflectors. These various works have led to more effective box-type solar cookers; but always requiring movements and reflector adjustments for collecting solar radiation. There are cookers which require frequent adjustments **Amer (2003)**, those which need movements and reflector adjustments throughout the year or the season. **Hassan (2012)** investigated two designs of solar cooker (carton cooker in box shape and aluminum cooker in cylindrical shape) to apply some experimental measurements to evaluate its thermal performance. The temperature of the absorber plate reached to 110^{o}C and 95 ^{o}C with 0.5kg of water by using carton and aluminum box types respectively. **El-Shal (2016)** evaluated the thermal performance of the tire-solar cooker before and after adding the booster mirror under the local climatic conditions of Egypt. Hence, the proposed boosted tire-solar cooker can achieve a good thermal performance from small aperture area. A complete test method standard IS13429:2000 is available for testing of these systems **BIS. 2000**. According to this standard, two main tests are conducted (a stagnation test and a sensible heat test) for determination of two thermal performance parameters (figures of merits, F1 and F2) on the basis of relevant thermal profiles without considering the effect of reflector mirror. The Indian Standards IS13429 proposes the lower limit of F1 and F2 as 0.12 and 0.40 for a load of 8 kg/m^2. The specific objectives of this study are:

1- Develop and improve solar cooker system.

2 - Study the various factors that affect the performance of the system.

MATERIALS AND METHODS

Materials

A truncated pyramid was built and modified to improve its thermal performance. The developed cooker performance analysis and the required evaluation procedures had been carried out in the Department of Agricultural Engineering, Faculty of Agriculture, Ain Shams University, Shubra El-Khemia, Egypt (Latitude 30^{o} 11’ N, Longitude 31^{o} 24’ E).

Non-modified truncated pyramid solar cooker

The non-modified truncated pyramid solar cooker as shown in **Fig. (1)** is consists of:

Wooden truncated pyramid

The glazed surface of the cooker was made of glass with size 50 cm (length) × 50 cm (width) × 0.4 cm (thickness), double-glass cover and separated with 2 cm the distance between the glazed surface and the absorber plate was 49.2 cm according to **Kumer et al (2010)**. The internal sides of the cooker were covered by polished stainless steel with thickness 0.4 mm to reflect rays of the sun on the vessel placed at the absorber plate. This cooker was provided with mirror to reflect rays inside the cooker. It has dimensions 50 cm (length) × 50 cm (width). The angle between mirror and double-glass cover was 90^{o}.. The outsides and the bottom of the wooden box is insulated by 5 cm glass-wool.

Absorber plate

The absorber plate was made from plane aluminum sheet painted with a matt black, it has 37 cm (length) × 37 cm (width) × 0.8 mm (thickness).

Cooking pot

The cooking pot was made of aluminum painted matt black, cylindrical in shape and had flat base. It had a diameter of 21 cm, a height of 11.5 cm and thickness of 0.27 cm. It was placed in the center of the absorber plate inside the cooker box.

Modified truncated pyramid solar cooker

The modified truncated pyramid solar cooker, is similar to the non-modified truncated pyramid solar cooker in construction and the cooker was supplied with a solar concentrator with tracking system to improve the gained heat. The solar concentrator with tracking system has been designed by **Atia et al (2016)**.

A solar parabolic dish collector

A solar parabolic dish collector, has aperture diameter equal to 1.44 m with focal length of 0.69 m. Its interior surface was covered with polished stainless to reflect and concentrate sun rays to a point focus. The parabolic dish was equipped with dual-axis electromechanical tracking system.

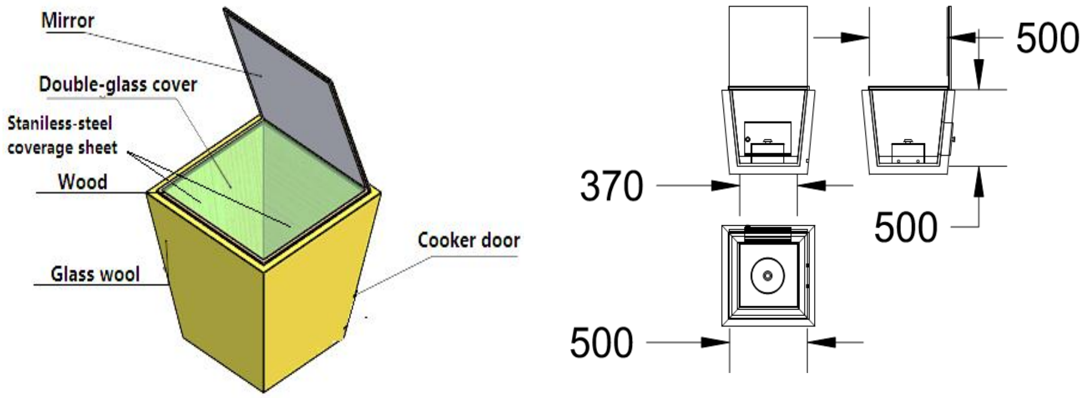

Fig. 1. Non-modified truncated pyramid solar cooker, the dimensions in mm.

Heat absorber plate

The heat absorber plate was placed in focal point of the parabolic dish faced the polished stainless to absorb the reflected sun rays. It was made of aluminum painted matt black with a square shape of 0.09 m^2. It was contacted with a copper tube painted matt black which was formed to serpentine shape with size 16 mm (outer diameter) × 0.1 mm (thickness) × 2.37 m (length). It was put in aluminum box and insulated by 25 mm glass wool from its sides.

The whole modified absorber plate system

As shown in **Fig. (2)** in the cooker box, the bottom of the absorber plate was contacted with a copper tube painted matt black which was formed to serpentine shape with size 10 mm (outer diameter) × 0.1 mm (thickness) × 2 m (length). The input and output of the tube were fitted with the output and input at respectively of the fluid tube from the solar concentrator from a closed-loop of working fluid.

Methods

Experiments and Measurements

As shown in **Fig. (3)**, two experimental set-up had been carried out of each prototype one of them was non-modified and the other was a modified solar cooker.

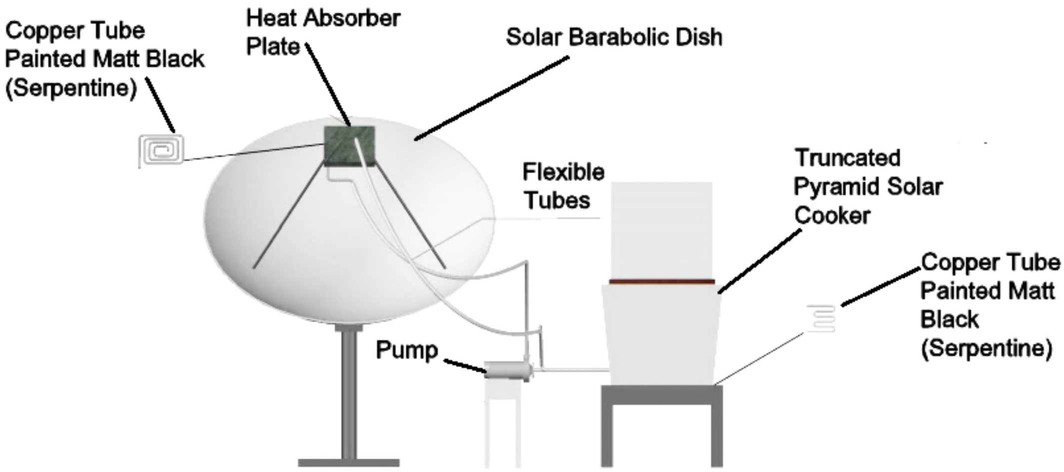

Fig. 2. Modified truncated pyramid solar cooker

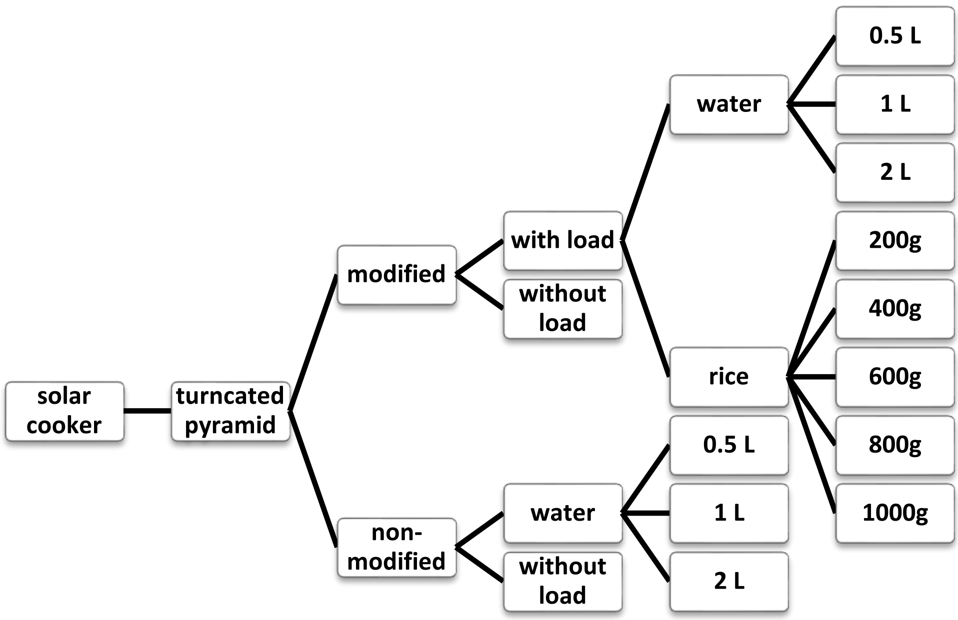

Fig. 3. Schematic diagram of experiments were carried out on the cookers

In the non-modified solar cooker, Sunrays hitting the inner sidewalls. The reflected sidewalls reflect and concentrate the sunrays on the absorber in the bottom.

In the modified solar cooker, there are two sources of the gain heat. One of them is similar to the non-modified solar cooker and the other one is from the parabolic dish.

In the modified prototype, the close loop was filled with soya bean oil. The sun rays falling on the reflective surface of the solar dish. The reflective surface reflects and concentrates the sunrays on the heat absorber plate that is in the focal point of the parabolic dish. The heat absorber transforms the concentrated sunrays into heat energy. The oil is heated up and flows out to the copper serpentine inside the cooker under the cooking pot then returned to the heat absorber again by centrifugal pump to more heating up and so on. The oil was circulated in the closed loop through insulated flexible rubber tubes as shown in **Fig. (4)**.

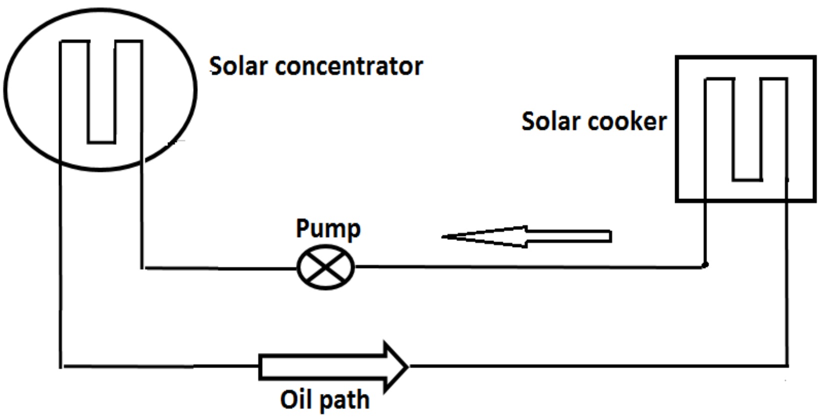

Fig. 4. The block diagram of the modified system of solar cooker

A series of tests were performed with one cooking pot filled with different quantity of water; 0.5, 1.0 and 2.0 liter to evaluate the thermal performance of the system.

For test the cooking, cooking pot of the solar cooker was filled with different volumes of rice with; 200, 400, 600, 800 and1000 g. Every quantity of rice to cook needs 1.5 times of water to cook **Syafutri et al (2016).** The rice needs a temperature of 78 ^oC to complete the cooking process for a specific period of time which varies according to the quantity of rice, **Yusufzai (1994)**.

Measurements are monitored at an interval of 10 min during the period range from 9.00 am to 4.00 pm on summer season 2017. The measured parameters were as follows:

Ambient air temperature (**T_{amb}**); Absorber plate temperature of the cooker box (**T_{ab}**); Water temperature in the cooking pot (**T_{wat}**); Temperature of oil at inlet of the solar absorber (**$T_{o,i}$**); Temperature of oil at outlet of the solar absorber (**$T_{o,o}$**); Air temperature inside the cooker box (**T_i**); Solar radiation **(I_s).**

The temperatures are measured by thermocouples (type K) which were coupled to digital thermometer. Also, the solar radiation was measured by pyranometer with sensitivity 14.11 $*10^{-6}$ v/W.m^{-2}.

System evaluation

Stagnation temperature test (first figure of merit F1)

This test was carried out under no-load and clear sky condition. The first figure of Merit (**F1**) presents the ratio of optical efficiency (η) to the heat loss factor (U_{LS}) and mathematically expressed by **Kumar (2005):**

$$F1 = \frac{\eta}{U_{LS}} = \frac{T_{ab} - T_{amb}}{I_s} \qquad (6)$$

Where

F1 : the first figure of merit ($^oC.m^2/W$); η : the optical efficiency (%); **U_{LS}** : the heat loss factor ($W/^oC.m^2$); **T_{ab}** : the absorber plate temperature (^oC); **T_{amb}** : the ambient temperature (^oC); **I_s** : the solar radiation (W/m^2).

The higher values of F1 would indicate better cooker performance, good optical efficiency, and low heat loss factor.

Determination of F2 (Second figure of merit F2)

The **F_2** is obtained by heating the containers (full of water) placed on the absorbing plate is mathematically expressed by **Kumar (2005):**

$$F_2 = \frac{F_1\ (MC)_w}{A(t_2 - t_1)} \ln\left[\frac{1 - (T_{w1} - T_{amb})/F_1 I}{1 - (T_{w2} - T_{amb})/F_1 I}\right] \quad , \qquad (7)$$

Where

t_1 : the time when water temperature reached **T_{W1}** in (^oC);

t_2 : the time when water temperature reached **T_{W2}** in (^oC);

(t_2-t_1) : the time taken for heating water from **T_{W1}** to **T_{W2}** in seconds;

T_{amb} : the average ambient temperature from the time period **t_1** to **t_2** in (^oC);

I_s : the average solar radiation from the time period **t_1** to **t_2** (W/m^2);

$(MC)_w$: the product of the mass of water and specific heat ($J/^oC$).

A high value of F2 indicates the effectiveness of the heat transfer from the absorber plate and the inside air to contents of the cooking pots.

Thermal performance of the system

Thermal performance of the system depends upon the input total incident energy and heat utilized for cooking. Following equations is used for data reduction.

Total input incident energy to absorber can be determined by **Ashok and Sudhir (2009)**.

$$Q_{incident} = I_s \times A_{SC} \qquad (8)$$

And energy output, i.e. energy utilized for the cooking is given by **Karande et al (2017)**,

$$Q_{system} = \frac{M_w \times C_w \times (T_{w2} - T_{w1})}{\Delta t} \qquad (9)$$

The energy efficiency of the solar cooker with inclined aperture area can be defined as the ratio of the energy gained by the solar cooker (energy utilized for the cooking) to incident energy **Karande et al (2017)**. Energy efficiency of the solar cooker was calculated by using the equation below:

$$\eta_{energy} = \frac{Q_{system}}{Q_{incident}} = \frac{\frac{M_w \times C_w \times (T_{w2} - T_{w1})}{\Delta t}}{I_s \times A_{SC}} \qquad (10)$$

Where M_w, C_w are the mass (kg) and specific heat (J/kg. ^oC) of water, respectively. $(T_{w2}-T_{w1})$ is the temperature difference between the maximum temperature and the initial temperature of water (^oC) during the interval Δt (s), I_s is the solar radiation (W/m^2) and A_{sc} is the aperture area of the cooker (m^2).

RESULTS AND DISCUSSION

Stagnation test

The average temperature of the absorber plate inside the modified cooker was always higher than the non-modified cooker as show in **Fig. (5)**. Initially the different of temperature was low then increased.

The average maximum temperature of absorber plate in the modified was reached to 121°C while the non-modified reached to 102°C on May 2017. The raise in both absorber plate temperature inside the both cookers are increasing significantly when the both cookers are operated near to the solar noon. The absorber plate temperature of the modified was 15. 8% more than the absorber plate temperature of the non-modified cooker when they reached to the maximum temperature.

The temperature of the modified cooker was higher than the temperature of the non-modified cooker, due to the added heat by heated oil. Furthermore afternoon the temperature of the non-modified was dropped, while the top of the modified was semi constant, it's due to the tracking of the sun by the solar dish.

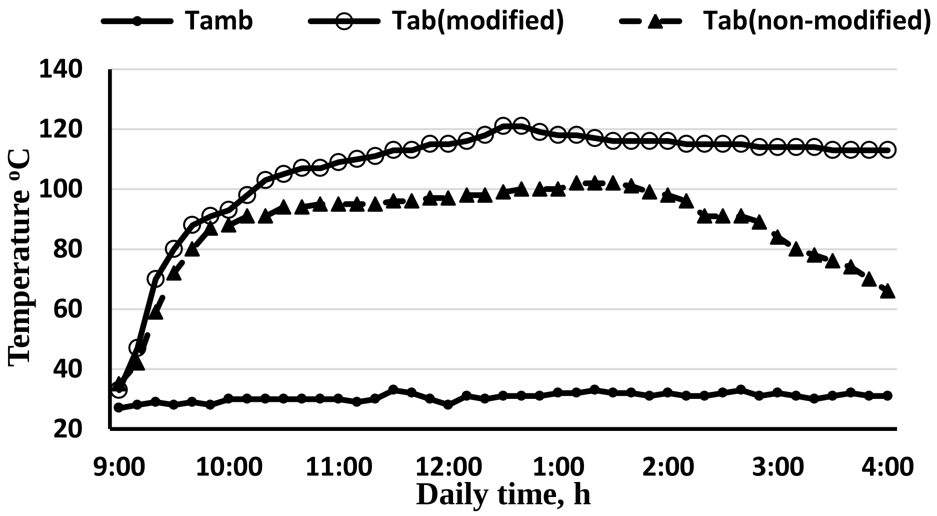

Fig. 5. Comparison between absorber plate temperature of modified and non-modified truncated solar cookers (2 May 2017)
Tamp: ambient temperature; Tab (modified): absorber plate temperature to modified cooker; Tab (non-modified): absorber plate temperature to non-modified cooker

Effect of the modified cooker on the water heating

The average maximum temperature of water heated by the modified cooker is 90, 86 and 80 ^oC was obtained with load 0.5, 1 and 2 liter From **Fig. (6, 7 and 8)**. While it reached to 79, 73 and 65 ^oC in the non-modified cooker with the same load.

This may be considered as good thermal performance for the modified cooker.

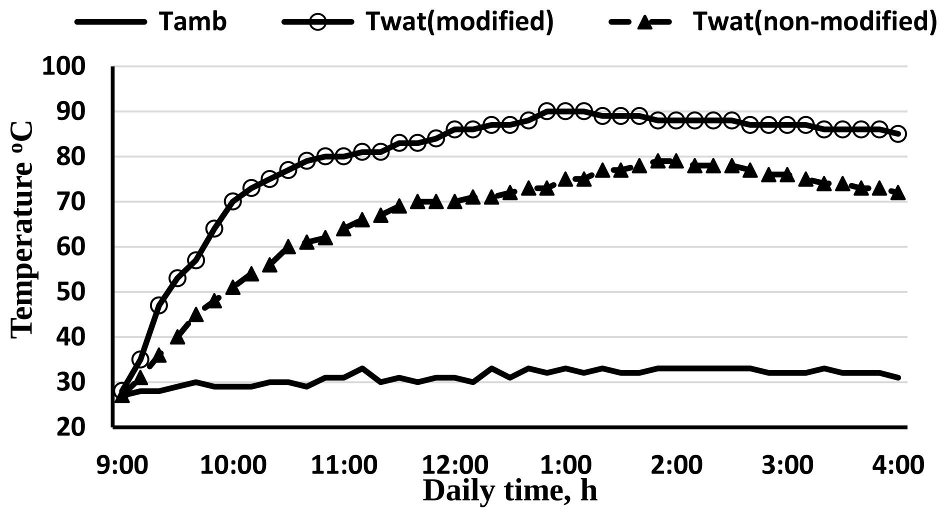

Fig. 6. Comparison between water temperature of modified and non-modified truncated solar cookers of 0.5 liter of water (7 May 2017)

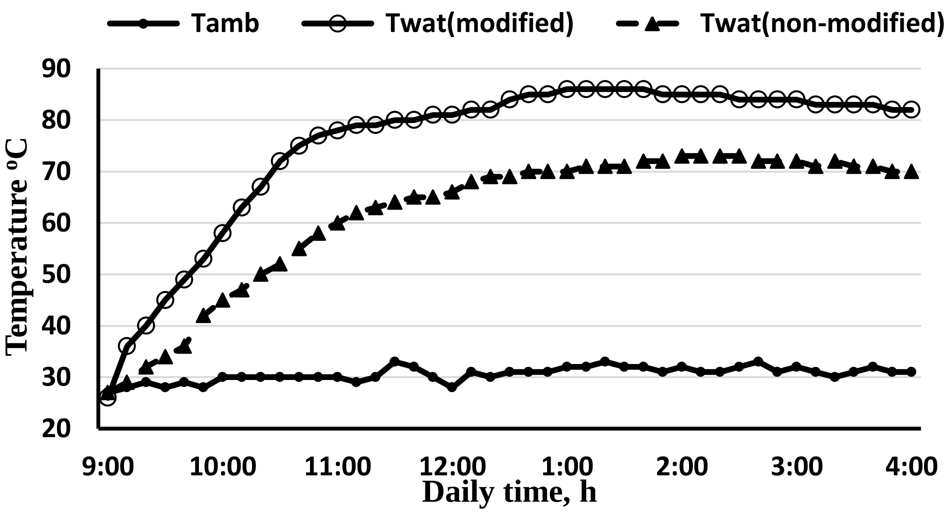

Fig. 7. Comparison between water temperature of modified and non-modified truncated solar cookers of 1.0 liter of water (4 May 2017)

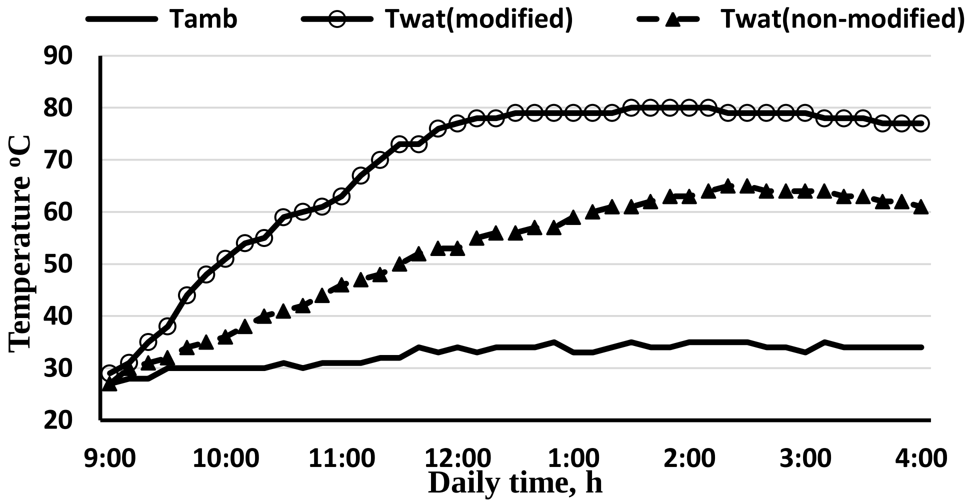

Fig. 8. Comparison between water temperature of modified and non-modified truncated solar cookers of 2.0 liter of water (6 May 2017).

First figure of merit (F1)

Under conditions T_{amb}=31, 33, T_{ab}=121, 1 02 and solar radiation=8 82W/m^2, the calculated values of F1 was 0.102 and 0.08 ^{o}C.m^2/W with modified and non-modified cooker types respectively.

Second figure of merit (F2)

The second figure of merit F2 gives an indication of the heat exchange efficiency factor of the cooker. Consequently, the value of F2 was 0.293 and 0.129 for modified and non-modified cooker, respectively. which also established the fact about the better cooking performance of the modified cooker.

Energetic efficiency of the truncated pyramid solar cooker

The mean energy gained of the modified truncated pyramid cooker for 0.5l, 1l and 2l of water was about 133.7, 246.6 and 451.4 kJ, respectively and the mean energy gained of the non-modified truncated pyramid cooker were about 98.2, 179.7 and 284.2 kJ, respectively. So, that the added energy by the oil is 35.5, 66.9 and 167.2kJ for 0.5, 1 and 2l, respectively. The mean energy efficiency of the modified truncated pyramid cooker for 0.5L, 1L and 2L of water is found to be 4.8, 8.5 and 13.2 %, respectively. and the mean energy efficiency of the non-modified truncated pyramid cooker for 0.5l, 1l and 2l of water is found to be 3.1, 5.2 and 8.5 %, respectively.

Generally, the modified cooker achieved a higher thermal efficiency than the non- modified cooker by about 36% at the maximum water mass of 2 l.

Quantities of cooked rice

The cooking was not achieved in the non-modified truncated pyramid solar cooker because the rice needs a temperature of 78 ^{o}C to complete the cooking process for a specific period of time which varies according to the quantity of rice, **Yusufzai (1994)**. **Fig. (9)** shows that the different quantities of cooked rice and the time required for cooking. It was about 130 min for cooking a 200 g of rice, while it was about 280 min for cooking a 1000 g of rice.

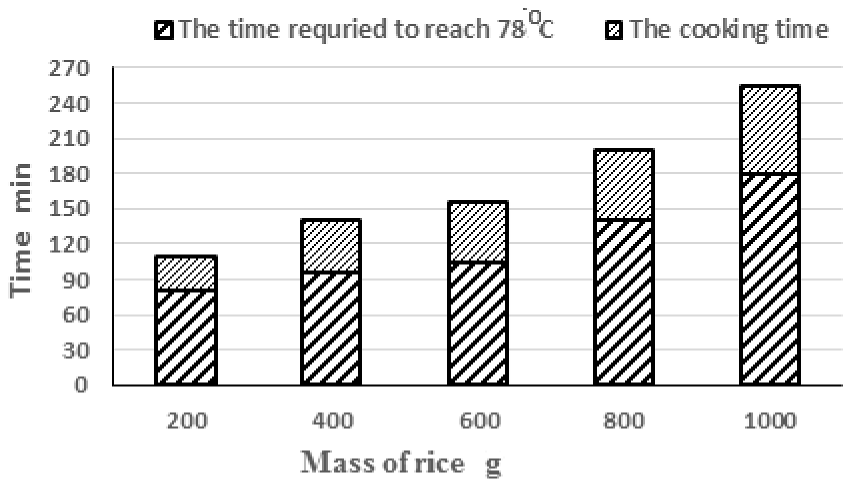

Fig. 9. The time required for cooking different quantities of rice

CONCLUSION

A truncated pyramid was built and was modified to improve its thermal performance. The thermal performance was evaluated by using first figure of Merit, second figure of Merit, energy efficiency. The concluded results from this study were:

1- The absorber plate temperature of the modified truncated pyramid cooker was 15. 8% more superior to absorber plate temperature of the non-modified cooker when they reached to the maximum temperature.
2- The calculated values of F1 and F2 were indicated that the modified cooker is efficient.
3- The added energy by the oil is 26.5, 27.1 and 37% for 0.5, 1 and 2l, respectively from the total gained energy.
4- The modified cooker achieved a higher thermal efficiency than the non- modified cooker by about 36% at the maximum water mass of 2 L.
5- The perfect time to cook by using the solar cookers was from 11:00 pm to 3:00 pm.
6- The cost analysis indicates that using modified truncated pyramid cooker is very economically.
7- The modified solar cooker operational cost represents 57.8% of gas cooker operation cost.

REFERENCES

Al-Soud, M.S., Abdallah, E., Akayleh, A., Abdallah, S. and Hrayshat, E.S. 2010. A Parabolic Solar Cooker with Automatic Two Axes Sun Tracking System. **Appl. Energy, 87, 463–70.**

Amer, E.H. 2003. Theoretical and Experimental Assessment of a Double Exposure Solar Cooker. **Energy Convers Manage. 44, 2651–63.**

Ashok, K. and Sudhir, C.V. 2009. Proposal for New World Standard for Testing Solar Cookers, **J. of Engineering Science and Technology, 4(3), 272 –281.**

Atia, M.F.M., Mostafa, M.M., El-Nono, M.A. and Abdel-Salam, M.F.M. 2016. Milk Pasteurization Using Solar Concentrator with Tracking Device. Misr **J. Ag. En. 33(3), 915-932.**

BIS, 2000. ‘Indian standards IS 13429: Solar Cooker - Box type’, first revision. Manak Bhawan, New Delhi: Bureau of Indian Standards (BIS). **[Cited from Yettou et al., 2016].**

Cuce, E. and Cuce M.P. 2013. A comprehensive review on solar cookers. **Appl. Energy. 102, 1399–1421.**

El-shal, H.M.S. 2016. Thermal Performance of an Experimental Car-tire Solar Cooker. **Misr J. Ag. Eng., 33(1), 63-74.**

Harmim, A., Merzouk M., Boukar M. and Amar M., 2012. Performance Study of a Box Type Solar Cooker Employing an Asymmetric Compound Parabolic Concentrator. **Exergy, 47, 471-480.**

Hassan, M. M. A., 2012. Thermal Performance and Evaluation of Two Types Low Cost Solar Cookers. **Misr J. Ag. Eng., 29(1), 395-408.**

Karande, P.D., Kumbhar, S.V. and Sonage, B.K. 2017. Experimental Study on Collection Efficiency of Solar Cooking System. **International**

Research J. of Engineering and Technology (IRJET), 4(2), 1564-1568.

Kumar, N., Agravat, S., Chavda, T. and Mistry, H.N. 2008. Design and Development of Efficient Multipurpose Domestic Solar Cookers/Dryers. **Renew. Energy., 33, 2207–2211.**

Kumar, N., Chavda, T., Mistry, H.N. 2010. A truncated Pyramid Non-tracking Type Multipurpose Domestic Solar Cooker/Hot Water System. **Appl. Energy, 87, 471–487.**

Kumar, S. 2005. Estimation of Design Parameters for Thermal Performance Evaluation of Box-type Solar Cooker. **Renew. Energy, 30, 1117–1126.**

Sorensen, B. 2004. Renewable Energy Its Physics, Engineering, Use, Environmental Impacts, Economy and Planning Aspects, 3rd El-sevier Academic press, Roskilde Univ., Energy & Environment Group, Ins. 2, Denmark, **pp. 35-51.**

Syafutri, M.I., Filli, P., Friska, S. and Achmad, F. 2016, Effects of Varieties and Cooking Methods on Physical and Chemical Characteristics of Cooked **Rice. Rice Science 23(5), 282−286.**

Yettou, F., Gama, A., Panwar, N.L., Malek, A. and Azoui, B. 2016. Experimental Investigation of Thermal Performance Evaluation and Thermodynamic Analysis of Domestic Box Type Solar Cooker with Inclined Aperture Area. **Revue des Energies Renewables, 19(2), 211-224.**

Yusufzai, Z.K. 1994. Design and Development of a Solar Collector. 2nd international seminar on Farm Machinery for developing countries, Tsukuba, Japan, Oct. 12-13**, pp. 101-121.**