Evaluation of heat transfer during the process of heating water in containers using a solar cooker box-type

H Terres¹, S Chávez, A Lizardi, E Alvarez

¹Universidad Autónoma Metropolitana, Unidad Azcapotzalco, Departamento de Energía, Area de Termofluidos, San Pablo 180, Col. Reynosa Tamaulipas, Azcapotzalco, 02200, México, D. F.

E-mail: tph@azc.uam.mx

Abstract. This work presents the experimental results and the evaluation of the heat transfer mechanisms by conduction, convection, and radiation that occur during the water heating process inside four containers with volumes of 250, 500, 750, and 1000 ml. using as for this process a box-type solar cooker. For the experimental measurements, a type k thermocouple arrangement was used, located in the water, the exterior surfaces of the containers, and the glass that forms part of the solar cooker cover. For the acquisition of the data perceived by the thermocouples, a Compact Field Point from National Instruments was implemented and for the measurement of global solar radiation, an Eppley 8-48 radiometer was used. The results obtained from the evaluation show that the most important heat transfer mechanism is by conduction located in the exterior glass of the solar cooker cover and the convection heat transfer in this same glass is the one with the lowest values. The evaluation of the results achieved contributes to the knowledge of the operation of solar cookers, which can contribute to the design and improvements of these solar energy devices.

1. Introduction
The solar devices should be operated in situations where the climatic variations as solar radiation or environment temperature and its consequent effects complicate the experimental work. These situations justify the work with numerical simulation such as the one presented in this work. Several types of solar cookers such as with concentrators, warmed by flat plate collectors, and box-type have been developed. The solar cooker box-type with inner reflectors has been studied by El–Sebaii and Domanski [1], their results have shown an adequate performance and the obtained temperature distribution agrees with the experimental results of constructed prototype.

Funk and Larson [2] presented a parametrical model of operation for a solar cooker to predict their cooking power based on three controlled parameters (area of solar interception, overall heat loss coefficient and thermal conductivity of the plateful base’s absorber) and three not controlled variables (insolation, temperature difference, and load distribution). Thulasi et al. [3] in Tanta, Egypt, obtained a mathematical model for a solar cooker box type that shows the problems posed by the great number of parameters involved in the operation of this cooker. Pohekar and Ramachandran [4], conducted a major study in India looking at nine solar cookers. They characterized their field of application in terms of the potential they offer. The criteria considered in his work take into account the socio-economic aspects to those related to the elements used in the cooking processes. Mirdha and Dhariwal [5], investigated various designs of solar cookers theoretically to optimize their performance.
Starting with a box-type solar cooker, they studied various combinations of the reflection mirrors to arrive at a final design, to provide a cooker that can be fixed to a window to the south (for the countries of the northern hemisphere, mainly, located near the Tropic of Cancer).

Her proposal provides a higher cooking temperature for a long day duration. Kumar et al. [6] designed, manufactured, and tested a truncated pyramid type solar stove. The geometry of the truncated pyramid concentrates the radiation of the incident light towards the bottom and the glass crystal surface at the top facilitates the capture of energy inside the kitchen. One of the main features of the proposed design is to eliminate the need for sun tracking during cooking. Saxena et al. [7] established that the detailed analysis of the elements that make up a solar cooker and the parameters involved in the development of the heating process are necessary to determine the efficiency of the solar cooker. They show that it is extremely important to take into account climatic conditions concerning construction parameters. They also considered the geometry and properties of the material of the container that contains the product to be cooked.

This work shows the experimental results of heat transfer by conduction, convection, and radiation during the process of heating water in containers using a box-type solar cooker. The evaluation of the results achieved contributes to the knowledge of the operation of solar cookers, which can contribute to the design and improvements of these solar energy devices.

2. Experimental procedure
The solar cooker box-type with internal reflectors is integrated by the following elements: A. A cover with two glasses with a clearance between them. B. Internal reflectors made in a commercial aluminium sheet placed to different tilt angles, C. Thermal insulator placed in the lateral part of the same one, and D. Four recipients containing water. The solar cooker is locked air tightly; this allows reaching considerable temperatures in the water. Figures 1 and 2 show the solar cooker and the containers and the experimental arrangement used in the experimental test respectively.

The containers contained different volumes of water. These were 250 ml, 500 ml, 750 ml, and 1000 ml. This was thus planned to evaluate the effect of the container on the water content. Figures 2 and 3 show the locations of the thermocouples in the glasses and the container respectively. Figure 4 shows the distribution of the containers with water.

Type k thermocouples were placed in different points of the solar cooker and in the containers, this allowed to record the temperatures during the thermal process of heating the water. The selected points were chosen as the most representative in the heating process, however, this fact does not avoid the affirmation that other points could also be important. Global solar radiation and outdoor ambient temperature were also measured during the test. An Eppley 8-48 radiometer was used for radiation, and a type k thermocouple was also used for temperature. The instrumentation used to obtain the temperatures was complemented with the use of a National Instruments Compact Field Point. The day of the test was March 16, in Mexico City (19.4 N, 99.1 W) and the duration of the test was one hour and 20 minutes.
3. Experimental results

Figures 5, 6, 7 and 8 show the values of the measured temperatures and correspond to the Global solar radiation and temperatures of the outdoor ambient, water, cover glasses, and the exterior surfaces of the containers, respectively.

4. Calculation of heat transfer in the solar cooker

With the temperature values for the points of interest, the heat transfer losses by conduction, convection, and radiation are calculated using the corresponding equations, Cengel and Boles [8]:

\[
\dot{Q} = k_1 A_j \frac{dT}{k_h}
\]  

(1)
Convection

\[ Q = h_i A_j \Delta T \]  

(2)

Radiation

\[ Q = A_j \varepsilon_i \sigma (T_2^4 - T_1^4) \]  

(3)

Where the terms \( i, j, \) and \( k \) correspond respectively to the material, the area of the part or component of the considered solar cooker, and the thickness of the referred element.

The values of the properties of the materials, areas and thicknesses considered are \( \varepsilon_g = 0.78 \text{W/mK}, \) \( h_{\text{between glasses}} = 7.0 \text{W/m}^2\text{K}, \) \( \varepsilon = 0.75, \) \( A = 0.64 \text{m}^2, \) \( L = 0.003 \text{m} \) and \( \sigma = 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4. \) The values of the convection coefficients used were estimated from the values used by Sebaii and R. Domanski [1]. The Hollands equation [9] was used to calculate the convection coefficients between glasses.

\[ N_{UL} = 1.0 + \left[ 1.44(1.0 - \frac{1708}{Ra_L}) \right]^0 + [(Ra_L/5830)^{1/3} - 1]^0 \]  

(4)

Where \( Nu \) and \( Ra \) are the Nusselt and Rayleigh numbers, respectively, and are defined as:

\[ Ra = \frac{(g \beta(T_1 - T_2) L^3)}{v^2 \rho_f} \]  

(5)

\[ Nu = \frac{h L}{v^2 \rho_f} \]  

(6)

The terms in the Hollands [9] correlation are both referred to with spacing between the glass covers, \( L; \) and \([\text{°}]\) indicates that if the quantity inside the parentheses is negative, it should be taken as zero.

Figures 8, 9, and 10 graphically show the values corresponding to the heat transfer by conduction and convection and radiation calculated.

Figure 8. Conduction heat transfer through glasses.

Figure 9. Convection heat transfer between glasses.

Figure 7. Radiation heat transfer glass 1 to outdoor ambient.
5. Discussion

The temperatures shown in Figures 5 to 7 indicate that the highest values correspond to the glass located inside the solar cooker. The glass that is located outside and exposed to the outside ambient temperature has the lowest values. This is consistent with the effects of convection and radiation on the glass surface and the differences in temperature between the glass and the exposure environment. This also happens because the glass cover is exposed to the effects of internal convection in the cooker.

The values of temperature corresponding to the surfaces of the containers indicate that for the volume of 250 ml of water the temperature value reached is the highest, while for the volume of 1000 ml the lowest values are obtained. This is congruent with the amounts of water to be heated.

It is observed that for the volumes of 750 and 1000 ml, the temperature values are close, this can be associated with the fact that the amount of water with respect to the maximum capacity of the container is close if it is taken into account that the containers have a maximum capacity of a 1000 ml. This situation does not happen for the volumes of 250 and 500 ml because the space occupied by free air of water inside these containers is greater than that of the volumes of 750 ml and 1000 ml.

According to the experimental results, the temperature differences tend to decrease with time, which is reflected in the different modes of heat transfer as a minor increase overtime.

Of all the heat transfer modes present during the water heating process, it is the conductive heat transfer in glass 1 that has the highest values. While the convective heat transfer for this same glass is where the lowest values are found.

6. Conclusions

The most relevant results of the evaluation of heat transfer in a solar cooker box-type were presented. The most important heat transfer mechanism is by conduction located in the exterior glass of the solar cooker cover and the convection heat transfer in this same glass is the one with the lowest values.

The evaluation of the results achieved contributes to the knowledge of the operation of solar cookers, which can contribute to the design and improvements of these solar energy devices.

Finally, the values of the temperatures achieved in these results can be useful where the heating water must be accompanied by UV solar radiation, for example, a mechanism to reduce the microbial load in the water, important application in the field of environmental engineering.

References

[1] El Sebaii A A and Domanski R, 1994, Experimental and Theoretical Investigation of a Box Type Solar Cooker with Multi-Step Inner Reflectors, Energy, 19 (10), 1011-1021.
[2] Funk P A and Larson D L, 1998, Parametric model of solar cooker performance, Solar Energy, 62 (1), 63-68.
[3] Thulasi Das T C, Karmakar S, and Rao D P, 1994, Solar Box Cooker: part I—modeling and part II—analysis and simulation, Solar Energy, 52 (3), 274–295.
[4] Pohekar, S D, Ramachandran M, Utility assessment of parabolic solar cooker as a domestic cooking device in India, Renewable Energy, 31, (11), September 2006, 1827–1838.
[5] Mirdha U S and Dhariwal S R, 2008, Design optimization of solar cooker, Renewable Energy, 33 (3), 530-544.
[6] Kumar, Naveen, Agravata, Sagar, Tilak Chavdaa, and Mistrya, H.N., 2008, Design and development of efficient multipurpose domestic solar cookers/dryers, Renewable Energy, 33 (10), 2207-2211.
[7] Saxena A., Varun P., Srivastav G, 2011, A thermodynamic review on solar box type cookers, Renewable and Sustainable Energy Reviews, 15 (6)3301-3318.
[8] Cengel Y A, Boles M A and Kanoglu M, 2019, Thermodynamics: An engineering approach, 9th edition, McGraw-Hill Global Education, 441-458.
[9] Hollands, K G T, Unny T E, Raithby G D, Konicek L, 1976, Free convective heat transfer across inclined air layers, J. Heat Transfer, 98, 189-193.