창의융합연구
Journal of Creativity and Convergence
2021, Vol. 1, No. 1, pp.27-35
http://dx.doi.org/10.23021/JCC.2021.1.1.27

Design of Solar Concentrating and Redirecting Cooker "*Solcr Cook*":

An Innovative and Novel Thermal Hybrid Indoor Solar Cooking System

JEHANGIR AHMAD DAR[1)]
Innovator / Researcher, Entrepreneurship Development Cell/NIF Cell, University of Kashmir, India
MSc Student, Amity School of Applied Sciences, Amity University Haryana, India

Abstract

Innovative designs are sought in solar cooking systems to make the system more user friendly, highly efficient and cost effective. In seek of innovative designs this paper describes the conceptual design of novel and Innovative Thermally Hybrid Indoor Solar cooking system. In the system, by using a parabolic optical concentrator mounted on the top of structure/building the solar light is concentrated and focused to Focal reflecting element which re-directs it to the pair of Fresnel lens for converging the beam to transmit it for the larger distances. The Solar Redirector at the ground end of the system redirects the beam and transmits it to the core of the Innovative Thermal Hybrid Cooker (ITHC) using a novel approach of inbuilt ellipsoid shaped cavity adjusted with cone shaped reflective element inside the ITHC; where the solar energy gets scattered and reserved in the form of latent heat energy using Erythritol as a Phase Changing medium for late night cooking. The description of the different elements of the system is pointed out and an end-to-end optical energy efficiency analysis is performed. On estimation the system attains 83.2% of end-to-end optical efficiency, making the system novel in transmitting the solar energy directly to the core of building for cooking purposes. Using the solar radiant energy data collected by Indian Meteorological Department, Govt of India, the total transmitted diffused and global solar radiation for Jaipur city have been calculated paving the way for the exergy analysis, and further research and development of the system. The system possesses the potential to be adopted worldwide especially in Tropical regions of the globe.

Keywords

Solar Cooker, Phase Changing Medium (PCM), Solar Concentrator, Fresnel Lens

Manuscript received February 19, 2021 / Revision received April 20, 2021 / Accepted May 12, 2021
1) Jahangirahmad63@gmail.com

1. Introduction

Due to the lack and high cost of fossil fuels and other traditional energy sources, the search for effective and cheaper alternatives is a crucial issue within the humanitarian context (Rehfuess et al., 2006). Therefore, solar cookers have been introduced in an attempt to create the environment friendly, effective and cheap cooking system. They use solar rays to heat, cook or pasteurize foods and drinks (Saxena et al., 2011), and are widely spreading to several developing countries, villages and remote areas (Abu-Khader et al., 2011). Especially, in tropical countries, where the people suffer from shortages of cooking energy, but the solar energy is plentiful.

Harmim et al. (2014) classified the solar cookers under two groups: Direct ones with integrated solar reflector-collector and indirect ones with separate solar reflector-collector. First group consist of cookers where the solar collector and the cooking spotted area act as the same unit. While in second group cookers are made in two distinct parts, one part collects and converts solar energy into heat and other part consist of cooking chamber. Both separated parts are connected by duct through which the heat flows from one part to another part with the help of fluid flow. Out of the two groups, first group is globally used most commonly and is simpler and cheaper than the group two cookers. However, the indirect solar cookers are more user-friendly and have the advantage of installing the cooking chamber inside the kitchen and can be adapted with Sun Tracking system to avoid timely concentrator orientation problems and sun burn dangers.

Commercially successful direct type solar collectors are Box type and concentrating type cookers (Saxena et al., 2011). In the category of indirect solar cookers, flat-plate solar cooker (Schwarzer & Da Silva, 2003), evacuated tube solar cooker (Balzar et al., 1996) and concentrating type solar cooker (Hussein at al., 2008) are commonly available. The further details on Direct and Indirect solar cookers can be deliberated from the review study conducted by Mohammadreza Sedighi and Mostafa Zakairapour (Sedighi & Zakairapour, 2014).

In non-sunny days or prolonged non-sunny hours none of the Direct or Indirect solar cookers work, therefore an alternative cooking source is also required. To overcome the problem the concept of thermally hybrid Direct and Indirect solar cookers came into existence, where the solar energy is integrated with the conventional sources of energy like electricity, fire wood or LPG, etc.

In this objective, a thermally hybrid indoor solar cooker with parabolic solar concentrator and Phase Changing Medium (PCM) as latent thermal storage unit with inbuilt electric heating element as a conventional energy back-up and the possession of three cooking spots for the variable rates of cooking, is simulated here in the paper. Unlike, other solar cookers that use heat transportation medium to transmit the generated heat to the solar oven our system transmits solar radiation directly to the innovatively designed solar oven that is Innovative Thermally Hybrid Cooker (ITHC) and thus reduces the installation cost of the cooker, meanwhile making the system capable to be used in deep core of the buildings that is not possible in any other indoor and thermally hybrid solar cookers. Due to the parabolic design of concentrator for higher concentration ratios of solar energy, direct transmission of solar energy to the solar oven without usage of heat transportation medium, and highly sophisticated design of ITHC that uses black body radiation principle to harvest and store the energy and possess three cooking spots for different cooking purposes, our design '***Solcr Cook***' theoretically possess very efficient end-to-end energy efficiency, is more user-friendly and operationally more convenient than the available solar or conventional cookers.

2. Proposed Design of "Solcr Cook"

The schematic diagram of our proposed "*Solcr Cook*" is shown in Fig. 1. Its design comprises of three parts –

Solar concentration and Transmission system (SCATS), Transportation and Redirecting System (TR), and Innovative Thermally Hybrid Cooker (ITHC).

2.1 Solar Concentration and Transmission System 'SCATS'

The idea behind the solar concentration and the Transmission system 'SCATS' is to capture solar light with the help of a parabolic optical reflector and focus it to a small reflecting area to create a strong beam and then transmits it to solar cookers through the guidance of some optical processes and elements. The SCATS has been already introduced by the author in reference (Dar, 2019) and consist of three main optical parts – Solar concentrators, Focal Reflector 'FR' and Fresnel Lens Pair 'FLP'. The basic alignment of these parts is illustrated in Figure 1 and further details of components and their material considerations are given in the reference (Dar, 2019).

2.1.1. SCATS Design Summary

Using the value of Solar energy 'E_O' required to get transmitted to the core of ITHC and calculated value from the end-to-end optical efficiency 'η' analysis of the system shown later, the required value of total energy required to be concentrated 'E_i' can be calculated from the relation as below:

$$E_i = E_o/\eta \tag{1}$$

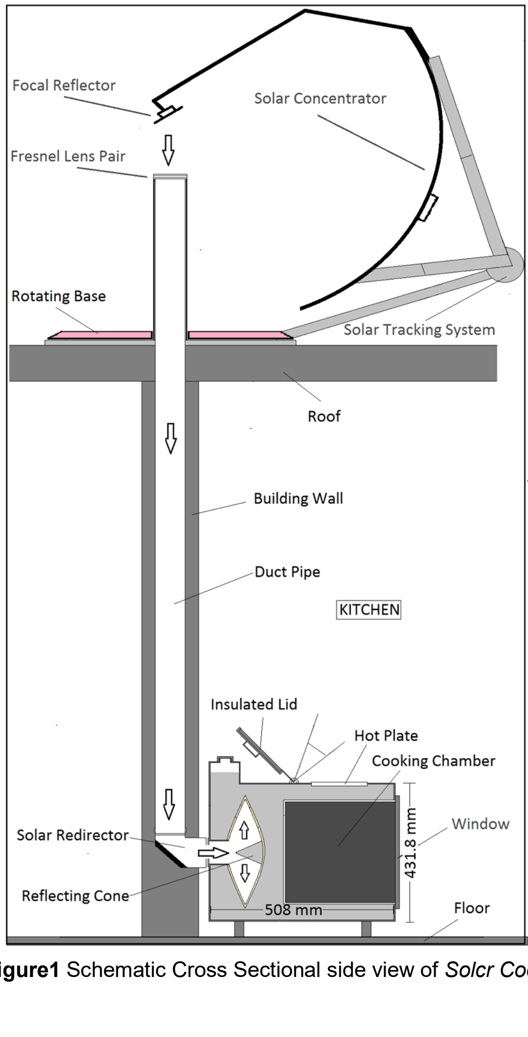

Figure1 Schematic Cross Sectional side view of *Solcr Cook*

The required area of solar concentrator 'A_{SC}' could be determined from the solar flux of 'I_o' falling on the face of concentrator as;

$$E_i = I_o . A_{SC} \tag{2}$$

A table summarizing different parameters of the solar concentrator to be used in *Solcr Cook* designs for the solar energy rich Jaipur (Rajasthan), India is shown in Table 1.

2.2. Transportation and Redirecting System (TR)

The converging beam from FLP is made diverging at some point while travelling through a highly internally reflective duct pipe. The diverging beam is made to travel through an innovatively designed Solar Redirector (SR) that consist a slab of Fresnel lens and a plane highly reflective element. Fresnel lens switches the diverging beam into parallel beam while the plane reflector deflects the parallel beam at right angles to the cavity of the cooker. For the safe passage of solar beam from FLP to SR a duct pipe is used that connects the FLP with the top opening of SR.

Table 1 Solar Concentrator Design Parameters

Parameter	Value	Units
Average Total (Global + Diffuse) Solar Intensity Falling on the Face of Concentrator	7.492	kWh/m^2
Average Solar Energy Transmitted to the Core of ITHC	43.63	kWh /day
Surface area of Parabolic Concentrator	7	m^2
Average Total Concentrated Solar Energy Per Day	52.44	kWh /day

2.3. Innovative Thermally Hybrid Cooker (ITHC)

For adoption of the solar cooker in energy rich societies the design of our Innovative Thermally Hybrid Cooker (ITHC) is made similar to the conventional cookers. ITHC consist of the PCM medium filled inside the hollow storage unit with outer wall made cuboidal in shape with outer dimensions of (508 mm, 431.8 mm, and 431.8 mm) and the inner ellipsoid shaped hollow structure with inner dimensions of (152.4 mm, 152.4 mm, and 76.2 mm). The hollow cylindrical cavity for inlet of solar beam with dimensions (101.6 mm in diameter and depth of 50.8 mm) is welded in between the walls with opening end fitted to outer back side of cuboidal case and other ends to the inner wall of ellipsoid shaped cavity wall. A cone shaped reflective element is fixed inside, so that the solar beam after entering the ellipsoid cavity get scattered in all directions for instant and efficient absorption of solar energy by PCM. The remaining surface of the inner part of the oval cavity and the exterior side of the cylindrical solar beam inlet is coated with black color for total absorption of the solar radiation using Black body radiation principle, while the outer cuboidal case of ITHC is made of thermally insulated material. The vacant space in between the outer cuboidal chamber and the inner ellipsoid chamber is filled with ~70 kg of Erythritol as a PCM for thermal energy storage.

To instantly warm and cook the food, ITHC consist an externally opened hollow cuboid shaped warm cooking chamber with the interior walls made of aluminum sheet and the external wall acting as lid is made of thermally insulated material. For the traditional cooking, two additional highly radiative circular oven plates of 152.4 mm in diameter are fixed and immersed in the top side of insulated ITHC box with the separation of 228.6 mm between their centres. Each plate is inbuilt with the electrical heating element for pertaining thermal backup in non-sunny days. The electrical energy for these heating elements is gained from the connectivity to the local electric grid and the graphite heating elements are preferred to be used in the design for better thermal radiation.

To stop the free flow of thermal energy losses from hot plates to the atmosphere, thermally insulated lids of the size of 203.2 mm in diameter are attached near the plates, to cover them when not in use. The lids are also attached with two highly thermally insulated very slim (0.5 -1 mm) circular rings with the inner and outer diameter values (25.4 mm and 50.8 mm) and (50.8 mm and 76.2 mm) attached with the common knot of lids as shown in Fig. 2. The lids help to control the rate of thermal flow to the cooking food from the oven plates as per our requirements. While the absorption of Thermal energy takes place, PCM melts and goes into the volumetric expansion; therefore, a long cuboidal hollow thermally insulated case of internal dimension (430 mm, 76.2 mm, 76.2 mm) is attached horizontally at the back side of the top of the ITHC while leaving the attachable side open for the free flow of volumetric expansion. At the opening of cylindrical solar beam inlet a glass with highly optical transmitting value is attached for entrapping the heat inside the core chamber of ITHC.

The schematic basic structure of the ITHC is illustrated in Fig. 2 & 3. For the better transmission of thermal energy from PCM, some Aluminum fins welded internally to the hot cooking plates and the walls of cuboidal warm chamber are made to run throughout the PCM.

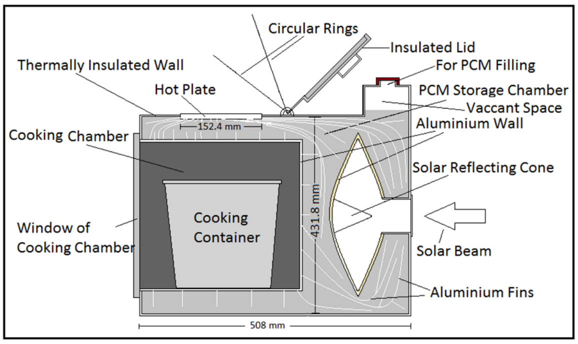

Figure 2 Schematic vertical cross-sectional side view of ITHC

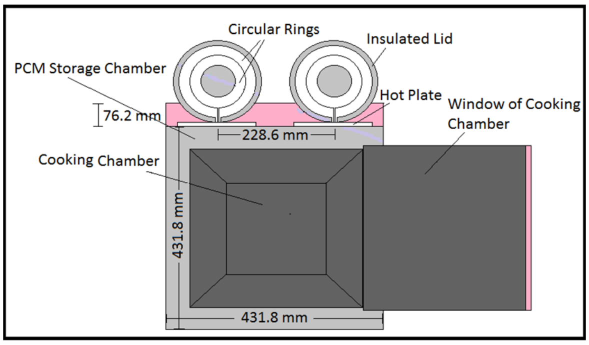

Figure 3 Schematic vertical front view of ITHC

2.3.1. Phase Changing Material (PCM)

Various PCMs with their properties, advantages and limitations have been comprehensively studied by Farid et al. (2004), Sharma et al. (2009), Zalba et al. (2003), and Agyenim et al (2010). A number of factors are to be considered when choosing an appropriate PCM like its latent heat of fusion, melting temperature, density, life of the PCM, etc. We considered Erythritol ($C_4H_{10}O_4$) to be used as the PCM in our design due to its melting point at 118°C, high latent heat of fusion (339 kJ/kg), its low cost (USD 5/kg), its non-toxic nature and its easy availability, and on the basis of recommendations made by Sharma et al. (Sharma et al., 2000) on choosing of PCM for evening cooking

3. End-to-End Energy Efficiency Analysis

End-to-end energy efficiency of solar cooker is defined as the total amount of solar energy 'I'that gets transmitted to the oval cavity of ITHC for heating and cooking purposes per the total amount of solar energy 'I_0' that fall on the solar collectors. The concentrated energy is calculated from the equation [2].

To calculate the total energy that gets transmitted to the core of ITHC for thermal storage and cooking, an optical end-to-end efficiency analysis needs to be calculated to account for various optical losses occurring while its optical conduction from concentrators to the oval cavity. By considering optical efficiencies of different elements used in the construction of the optical system from different references end-to-end optical efficiency of the system can be calculated. The highest possible optical efficiency values of these elements, as per the available data, are presented in the table 2.

Optical reflectors used in the construction of solar concentrator, FR, parabolic micro reflector of SR, and the reflector inside the core cavity of ITHC uses the commercially available heliostat reflector material produced by Practical Solar (Rohr, 2009) that can achieve 99.5 % of reflectivity. The maximum achievable refracting efficiency of Fresnel lens used in the development of FLP and SR for converging and diverging optical processes as per the study of W.A. Wong et al (Wong et al., 2000) is 96 %.

The 91.2 % efficiency of SCATS comes from the multiplication of efficiencies of its components which include two reflecting surfaces and a pair of Fresnel lens as illustrated in equation 3. Similarly 95.5% efficiency of SR is the product of efficiencies of its components which includes a reflecting surfaces and a Fresnel lens as given in equation 4. The total end-to-end efficiency 83.2 % of our *Solcr Cook* is calculated from the below relations.

$$\eta_{SCT} = \eta_{SC} \times \eta_{FR} \times \eta_F \times \eta_F \tag{3}$$

$$\eta_{SR} = \eta_F \times \eta_{PR} \tag{4}$$

$$\eta = \eta_{SCT} \times \eta_P \times \eta_{SR} \times \eta_I \times \eta_{OR} \tag{5}$$

Where, in the equations [3, 4, & 5] η_{SCT} ,η_{SR} and η are the end-to-end efficiencies of SCATS, SR and of our *Solcr Cook*. η_{SC} ,η_{FR}, η_{PR}, η_P and η_{OR} are the reflecting efficiencies of Solar concentrators, Focal reflector, plane reflector of SR, interior surface of duct pipe, reflecting cone of ITHC. While, η_F and η_I is the transmission efficiency of individual Fresnel lens, and transparent glass of solar inlet to cavity.

Table 2 End to end Efficiency Analysis

Parameter	Efficiency (%)	References
Reflecting Efficiency of Parabolic Concentrator	99.5	B. Rohr, 2009
Reflecting Efficiency of FR	99.5	B. Rohr, 2009
Solar Transmitting Efficiency of Each Fresnel Lens	96	W. A. Wong et al, 2000
End-to-end Efficiency of *SCATS*	91.2	B. Rohr, 2009 & W. A. Wong et al, 2000
Theoretical Transmission Efficiency Through Pipe	≈100	
End-to-end Efficiency of SR	95.5	B. Rohr, 2009 & W. A. Wong et al, 2000
Solar Transmitting Efficiency of Solar Inlet Glass	96	W. A. Wong et al, 2000
Efficiency of Beam Diffuser	99.5	B. Rohr, 2009
Solar Energy End-to-end Efficiency of *Solcr Cook*	~83.2	B. Rohr, 2009 & W. A. Wong et al, 2000

4. Estimated Results

Table (1) gives the percentage of total solar radiation that gets transported from the solar concentrators mounted at the top of the 'multi-storey' or 'single-storey building', to the core of ITHC. Accordingly, taking the area of the concentrators (A_{SC}) constant the total solar energy transmitted *(T_{SR})* to the core of ITHC, in the case of single storey building, at any instant is equal to 83.2 percentile of the solar energy that hits the concentrators in the same instant and can be mathematically represented as;

$$T_{SR} = \eta \text{ x } C_{SR} = \eta \text{ x } (I_{SR} \text{ x } A_{SC}) \tag{6}$$

Where, C_{SR} is the total concentrated solar radiation and I_{SR} is the solar radiation falling per meter on solar concentrator.

To estimate the amount of total Global and Diffuse solar energy that gets used for cooking and thermal storage in the unit of *Solcr Cook* used in Jaipur (India), the Solar radiant energy data collected by Indian Meteorological Department, Govt of India, under the editor-in-chief Dr. Ajit P. Tyagi (Tyagi, 2009), is used here.

Fig. (**4**) shows the monthly average daily global solar radiation 'Hg' and the monthly average extra-terrestrial diffuse radiation 'Hd' that get transmitted to the core of ITHC for the thermal storage and cooking purposes in the units of *Solcr Cook* installed in Jaipur city of Rajasthan in India.

Figure (**5**) shows the estimated hourly global solar energy (kWh) for the months of May and December, and figure (**6**) shows the estimated hourly diffuse solar energy (kWh) for the months of June and December that gets used for cooking and thermally storage purposes in ITHC of *Solcr Cook* using the measured hourly global and diffuse solar radiations for the months of May, June and December (Tyagi, 2009).

5. Conclusion and Further Research

The design of an Innovative Thermally Hybrid Indoor Solar Cooker for all cooking purposes at any instant of day and night was proposed. The system demonstrates the use of highly sophisticated materials and optical elements that can be cost-effective in volume manufacturing. An optically efficient Solar Concentration and

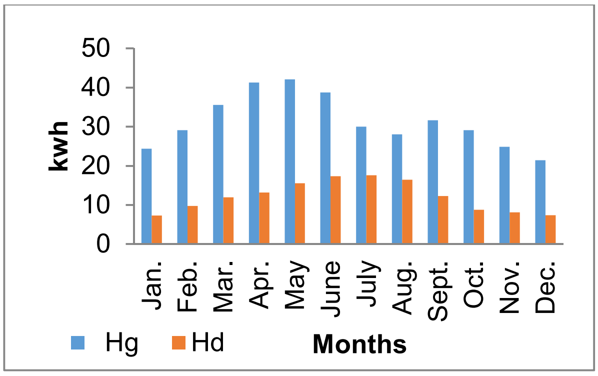

Figure 4 Monthly average daily global solar radiation (Hg) and averaged diffuse radiation (Hd) transmitted to core of ITHC

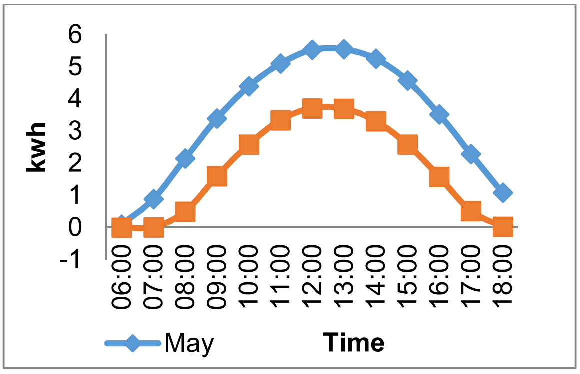

Figure 5 Hourly global solar energy transmitted to core of ITHC in the months of May and December

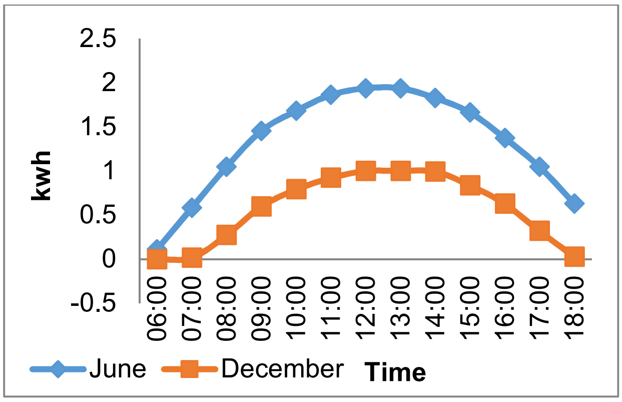

Figure 6 Hourly Diffuse solar energy transmitted to core of ITHC in the months of June and December

Transmission system can redirect and concentrate a strong beam of solar energy towards the core cavity of Innovative Thermally Hybrid Solar Cooker (ITHC) with the help of some optical processes. Using optical energy efficiency analysis, it is estimated that 83.2 % of concentrated solar energy gets transmitted, which increases the potential of the system to transmit solar energy to the deep core of buildings. Three cooking spots for different rates of cooking and for different cooking purposes is proposed. By using the Solar Tracking System, the shadow effect observed by the concentrators is neglected to increase the efficiency of the system. The potential of the proposed system to transmit solar energy to longer distances, using inbuilt cavity approach in ITHC for efficient energy absorption by the stored PCM and three inbuilt cooking spots for different cooking purposes makes it a novel approach to build highly energy efficient Hybrid

Indoor Solar Cooker. Collectively the proposed small community based ***Solcr Cook*** possesses much ease in use, is user-friendly and has operationally convenient features. Future research will focus on verifying this cost-effectiveness, demonstrating the additional energy-saving benefits and exergy analysis of the system.

Acknowledgements

The author is grateful for the support for this project that has been provided by the Amity University Haryana and National Innovation Foundation Cell, University of Kashmir, Srinagar, India. In addition, I would like to recognize Prof. Ranjeet Kumar Brajpuriya of Amity University Haryana and Prof. Sukhmander Singh of Central University of Rajasthan for their valuable discussions about the project.

References

Abu-Khader, M., Abu Hilal, M., Abdallah, S., & Badran, O. (2011). Evaluating thermal performance of Solar Cookers under jordanian climate. *Jordan Journal of Mechanical & Industrial Engineering*, *5*(1), 107-112.

Agyenim, F., Hewitt, N., Eames, P., & Smyth, M. (2010). A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). *Renewable and Sustainable Energy Reviews*, *14*(2), 615-628. DOI : 10.1016/j.rser.2009.10.015

Balzar, A., Stumpf, P., Eckhoff, S., Ackermann, H., & Grupp, M. (1996). A solar cooker using vacuum-tube collectors with integrated heat pipes. *Solar Energy*, *58*(1-3), 63-68. DOI : 10.1016/0038-092X(96)00024-2

Dar, J. A. (2019). Solar splitting day-lighting system 'SolsDays': The first beam splitting day-lighting system. *Smart and Sustainable Built Environment*, 9(2), 130-143.

Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management*, *45*(9-10), 1597-1615. DOI : 10.1016/j.enconman.2003.09.015

Harmim, A., Merzouk, M., Boukar, M., & Amar, M. (2014). Solar cooking development in Algerian Sahara: Towards a socially suitable solar cooker. *Renewable and Sustainable Energy Reviews*, *37*, 207-214. DOI : 10.1016/j.rser.2014.05.028

Hussein, H. M. S., El-Ghetany, H. H., & Nada, S. A. (2008). Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit. *Energy Conversion and Management*, *49*(8), 2237-2246. DOI : 10.1016/j.enconman.2008.01.026Get rights and content

Rehfuess, E., & World Health Organization. (2006). Fuel for life: household energy and health. Geneva, Switzerland.

Rohr, B. (2009). The promise of small heliostats. *Northeast Sun*, pp.7-12.

Saxena, A., Pandey, S. P., & Srivastav, G. (2011). A thermodynamic review on solar box type cookers. *Renewable* *and Sustainable Energy Reviews*, *15*(6), 3301-3318. DOI : 10.1016/j.rser.2011.04.017

Schwarzer, K., & Da Silva, M. E. V. (2003). Solar cooking system with or without heat storage for families and institutions. *Solar Energy*, *75*(1), 35-41. DOI : 10.1016/S0038-092X(03)00197-X

Sedighi, M., & Zakariapour, M. (2014). A review of direct and indirect solar cookers. *Sustainable Energy*, *2*(2), 44-51. DOI : 10.12691/rse-2-2-2

Sharma, A., Chen, C. R., Murty, V. V. S., & Shukla, A. (2009). Solar cooker with latent heat storage systems: A review. *Renewable and Sustainable Energy Reviews*, *13*(6-7), 1599-1605. _DOI : 10.1016/j.rser.2008.09.020

Sharma, S. D., Buddhi, D., Sawhney, R. L., & Sharma, A. (2000). Design, development and performance evaluation of a latent heat storage unit for evening cooking in a solar cooker. *Energy Conversion and Management*, *41*(14), 1497-1508. DOI : 10.1016/S0196-8904(99)00193-4

Tyagi, A. P. (2009). *Solar radiation energy over India*. Indian Meteorological Department, Ministry of Earth Sciences.

Wong, W. A., Geng, S. M., Castle, C. H., & Macosko, R. P. (2000). Design, fabrication and test of a high efficiency refractive secondary concentrator for solar applications. In Collection of Technical Papers. *35th Intersociety Energy Conversion Engineering Conference and Exhibit* (IECEC), IEEE, 2, 1117-1125.

Zalba, B., Marın, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering*, *23*(3), 251-283. DOI : 10.1016/S1359-4311(02)00192-8