Renewable and Sustainable Energy Reviews 75 (2017) 157–167

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage

Lameck Nkhonjera[a,b], Tunde Bello-Ochende[b,*], Geoffrey John[a], Cecil K. King'ondu[a]

[a] Nelson Mandela African Institution of Science and Technology, Department of Material and Energy Science and Engineering, PO Box 447, Arusha, Tanzania

[b] University of Cape Town, Department of Mechanical Engineering, Private Bag X3, Rondebosch 7701, South Africa

ARTICLE INFO

Keywords:
Thermal energy storage
Solar cookers
Cooking power
Phase change materials

ABSTRACT

This paper discusses the thermal energy storage units, heat storage materials and cooking performance of solar cookers with heat storage surveyed in literature. It is revealed that rectangular and cylindrical containers are widely used in the heat storage devices of the solar cookers. The geometry of the storage units, however, depended on the mode of heat transport into the storage medium and out to the cooking vessel from which, three categories of solar cookers (2-stage, 3-stage, and 4-stage solar cookers) are identified. Furthermore, oils and organic phase change materials dominated in the sensible and latent heat storage units respectively. Additionally, the inclusion of high thermal conductive material into the storage medium was the principal technique used in enhancing effective thermal conductivity. Besides, it is shown that there is no significant difference between the cooking power of cookers equipped with sensible and latent heat storage units. However, the design parameters of the cookers as well as thermal diffusivity of the storage medium greatly influenced the cooking power. The 3-stage cookers outperformed their 2-stage counterparts whereas cookers with cooking vessels integrated to the thermal storage unit outperformed the ones with non-integrated cooking vessels. On the other hand, lower thermal diffusivity of the storage medium increased cooking power in cookers with sensible heat storage but decreased the cooking power in cookers with latent heat storage. Finally, it is shown that the quest for the development of high temperature thermal storage units, and the optimization of the geometry as well as heat transfer characteristics of thermal energy storage units remain the potential areas of research in heat storage for cooking.

1. Introduction

Solar cooking is among the several methods available for domestic and institutional cooking. Like other cooking devices, it has merits and demerits. Meritoriously, it offers ecological benefits through savings on conventional fuels (firewood and fossil fuel) and reducing environmental pollution. It also provides social-economic benefits such as employment created through the production of the cookers as well monetary savings on cooking energy expenditures [1,2]. Nevertheless, the intermittent supply of energy from the sun is among the major drawbacks of solar cooking. In spite of this, Cuce and Cuce [3] and Panwar et al. [4] showed that numerous attempts to improve the performance of solar cookers were made over the past years. Part of these attempts involved inclusion of thermal energy storage (TES) in solar cookers to enable off-sun and indoor cooking. Several studies, for example Agyenim et al. [5], Chan and Russel [6], Kenisarin and Mahkamov [7] pointed out that TES designs and storage materials play an important role in the performance of TES units (TESu). Yet the previous reviews [3,8,9] on solar cookers with heat storage did not comprehensively compare performances of the cookers in relation to the TES designs and storage materials. Therefore, this study aimed at finding out the relationship of the cooking performance to TESu setups and heat storage materials. Specifically, the work searched for salient features that distinguished the configuration of one TESu from the other, surveyed classes and thermal physical properties of the storage materials utilized in the TESu as well as determining the influence of TES designs and thermal physical properties of storage material on the cooking power. This work, however, was limited to the solar cookers that were investigated over the past two decades.

2. The cooker categories

In the current work, 18 solar cookers were reviewed and categorized based on the mode of heat transport from the solar absorber to the

* Corresponding author.
E-mail addresses: nkhonjeral@nm-aist.ac.tz (L. Nkhonjera), tunde.bello-ochende@uct.ac.za (T. Bello-Ochende).

http://dx.doi.org/10.1016/j.rser.2016.10.059
Received 21 August 2015; Received in revised form 19 February 2016; Accepted 30 October 2016
Available online 06 November 2016
1364-0321/

Nomenclature

Notation	Concentrated solar collector
CSC	Concentrated solar collector
ETSC	Evacuated tube solar collector
FPSC	Flat plate solar collector
HTF	Heat transfer fluid
LHS	Latent heat storage
PCM	Phase change material
SHM	Sensible heat storage material
TES	Thermal energy storage
TESu	Thermal energy storage unit
LTESu	Latent thermal energy storage unit
STESu	Sensible thermal energy storage unit
TESicv	Thermal energy storage unit with integrated cooking vessel
TESncv	Thermal energy storage unit without integrated cooking vessel
c_p	Specific heat capacity at constant pressure (kJ/kg °C)
k	Thermal conductivity (W/m K)
m	Mass (kg)
r	Correlation coefficient
T	Temperature (°C)
T_{max}	Maximum Temperature (°C)
$\Delta_p h$	Specific phase change enthalpy (J/g)
$\Delta_p T$	Phase change temperature (°C)
ΔT_{l-a}	Temperature difference between cooking load and the ambient (°C)
Δt	Change in time (s)
ρ	Density (kg/m^3)

cooking load. Based on this criterion, three categories emerged as shown in Table 1. The 2-satage cookers [10–17] transported heat from the solar absorber to the heat storage medium in the first stage and from the storage medium to the cooking load in the second stage. In the 3-stage cookers [18–24], the first stage involved the heat transport from the solar absorber to heat transfer fluid (HTF) then from HTF to the storage medium in the second stage and then from storage medium to cooking load in the final stage. The 4-stage cookers [8,25–27] transferred heat from the absorber to HTF in first stage then from HTF to storage medium in second stage while the third and fourth stages involved heat flow from storage medium to HTF and then to cooking load.

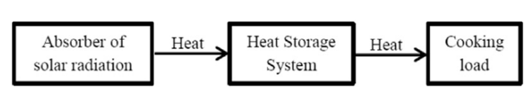
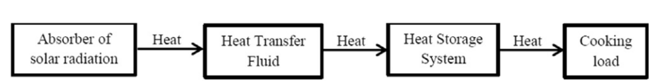
However, each category of the solar cookers employed a variety of solar collectors. Fig. 1 depicts the number of solar cookers arranged according to cooker category, the employed solar collector, and the year of study. The 2-stage cookers of box-type [10–12,14,16,17] were considered as the ones with flat plate solar collectors (FPSC) because their solar absorbers were enclosed in a glazed box, an arrangement similar to that of a typical FPSC, but there was no HTF involved. However, the typical FPSC that utilizes HTF for heat transfer were solely used in the 3-stage cookers [19,20,23]. All of the FPSC (both in 2-stage and 3-stage cookers) were fitted with reflectors to boost their optical performance and their reported operating temperatures were within 73–130 °C for the 2-stage cookers and 113–230 °C for 3-stage cookers. The latter had higher reflector to aperture ratios and hence higher operating temperatures.

On the other hand, the application of evacuated tube solar collectors (ETSC) involves HTF and thus applicable in 3 or 4-satage cookers. However, implementation of 4-stage cookers requires higher operating temperatures than what ETSC can afford. Therefore, ETSC were solely employed in 3-stage cookers [18,24]. However, the evacuated tubes used in Esen [18] were mounted on compound parabolic concentration reflectors and housed in a flat plate collector, thus the peak operating temperature (~210 °C) was higher than that (~135 °C) of typical ETSC found in Sharma et al. [24]. Unlike FPSC and ETSC, the concentrated solar collectors (CSC) were applicable to all cooker categories. They were employed in 2-stage cookers [13,15], 3-stage cookers [21,22], and suggested for application in 4-stage cookers [26–28]. The operating temperatures of the CSC in 2-stage and 3-stage cookers were within the range obtained by their FPSC and ETSC counterparts. Thus, CSC showed no advantage over other solar collector types. Further, data presented in Fig. 1 give an indication that box-type solar cookers were the most investigated over the last two decades. Lately, research focus has shifted from the box-type cookers to those with CSC. This can be attributed to the principle that CSC operate at higher temperatures than FPSC as well as ETSC [29] and thus they can potentially contribute to the heat storage at high temperatures thereby improving the cooking performance of the TESu.

3. The designs of thermal energy storage units (TESu)

The TESu designs varied from one cooker category to another due to different number of heat stages. However, design variation also existed within cookers under the same category. One notable distinction was that some TESu had integrated cooking vessel while others did not. The TESu with integrated cooking vessel are in this work termed TESicv while TESncv is an acronym for the TESu without integrated cooking vessel.

Table 1
Block diagrams of the setups of solar cookers with TESu.

Cooker category	Block diagram of the system setup
2-stage	
3-stage	
4-stage