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Experimental validation of a high-temperature solar box cooker with a solar-salt-based thermal storage unit

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ABSTRACT

Clear-sky conditions are an essential need to allow proper high-temperature solar cooking. Moreover, it is not an easy task to accomplish evening cooking, especially during wintertime when solar radiation is available only for a few hours. A solution to bypass these drawbacks lies in adopting a cooker provided with a thermal storage unit. The storage unit proposed in this work is a double-walled vessel composed by two stainless steel cylindrical pots assembled concentrically. The annular space between the pots was loaded with 4 kg of phase change material (PCM) based on a ternary mixture of nitrite and nitrate salts (solar salt: 53 wt% KNO_3, 40 wt% $NaNO_2$, 7 wt% $NaNO_3$). The thermal storage unit was characterized by means of a test rig including a high-concentration-ratio (10.78) solar box cooker. Four different sets of 14 experimental tests, divided into a heating and a cooling phase, were carried out to assess the performance of the solar cooker with the storage unit. It was found that the PCM thermal storage significantly improves the load thermal stabilization when solar radiation is not available: the load cooling time in the range 170–130 °C was determined to be from 65.12% to 107.98% higher than that without the solar-salt-based PCM thermal storage, proving the effectiveness of the proposed solution.

1. Introduction

Among thermal applications based on solar energy, solar cooking is one of the best and most promising options of utilization (Yettou et al., 2014). Unfortunately, solar energy is intermittent by its nature, being its availability seasonal and dependent on the meteorological conditions of the site. Intermittence and, thus, reliability of solar energy can be augmented by storing a fraction of it when there is excess of radiation; in this way, the stored energy can be used to cook food during partial clouds and/or in late evening hours. Energy storage allows to adjust temporal mismatches between the load and the variable energy source, improving the system utility (Sharma et al., 2009).

Different methods for storing solar energy are available: thermal, electrical, chemical, mechanical. Among thermal energy storages, phase change materials (PCMs) can be adopted to take advantage of their latent heat, which can be transferred to food over a narrow temperature range. PCMs absorb energy during the heating process as the phase change takes place, and release energy to the environment in the phase change period during the cooling process (Sharma et al., 2009).

Several works were proposed to assess the convenience in adopting PCM-based direct solar cookers (Table 1). In 1987, Ramadan et al. (1988) designed and realized a low-cost flat-plate solar cooker tested with both sensible (sand) and PCM (barium hydroxide octa hydrate) heat storage. The two materials were inserted as thin-layer jackets around the cooking pot. As stated by the authors, barium hydroxide has a melting point of 78 °C, which is suitable for meat cooking; however, the substance has also some drawbacks such as chemical decomposition and supercooling.

Domanski et al. (1995) investigated the possibility of cooking during evening hours using both stearic acid and magnesium nitrate hexahydrate as PCMs. They connected together two aluminum concentric cylindrical vessels (diameters 18 and 14 cm) to form a double-wall vessel with a gap between the outer and inner walls. The gap was filled with the two PCMs and the cooker performance was evaluated in terms of PCM charging and discharging times under different conditions. The cooker overall efficiency during discharging was 3–4 times greater than that for steam and heat-pipe solar cookers.

The feasibility of using a PCM in a solar cooker as storage to cook

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Nomenclature

Latin symbols

A	area (m^2)
AD	average deviation (%)
C	concentration ratio
c	specific heat (J/(kg·K))
DNI	direct normal irradiance (W/m^2)
F_1	first figure of merit (°C/(W/m^2))
F_2	second figure of merit
L	latent heat of fusion (kJ/kg)
m	mass (kg)
T	temperature (°C)
t	time (s)

Greek symbols

Δ	delta difference
η	thermal efficiency

Subscripts

a	absorber, aperture
amb	ambient
av	average
c	cooling
ch	characteristic
eq	equilibrium
f	fluid
g	glass
h	heating
i	inner
l	liquid
max	maximum
melt	melting
min	minimum
o	outer
ref	reference
s	specific, solid

Acronyms

DIISM	Department of Industrial Engineering and Mathematical Sciences
DSC	Differential Scanning Calorimeter
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
PCM	phase change material
TSU	thermal storage unit
UNIVPM	Marche Polytechnic University

Table 1
PCMs studied in literature for direct and indirect solar cookers.

Reference	Cooker type	PCM	T_{melt} (°C)	L (kJ/kg)	Cooking medium
Ramadan et al. (1988)	Box	Barium hydroxide octa hydrate	78	–	Water
Domanski et al. (1995)	Box	Stearic acid	67–69	–	Water
		Magnesium nitrate hexahydrate	89	–	
Buddhi and Sahoo (1997)	Box	Stearic acid	55.1	160	Rice and water
Sharma et al. (2000)	Box	Acetamide	82	263	Rice and water
Buddhi et al. (2003)	Box	Acetanilide	118.9	222	Rice and water
Sharma et al. (2005)	Indirect (ETC)	Erythritol	118.0	339.8	Water
Hussein et al. (2008)	Indirect (FPC)	Magnesium nitrate hexahydrate	89	134	Water
El-Sebaii et al. (2009)	–	Acetanilide	116	142	–
		Magnesium chloride hexahydrate	116.7	165–169	

and/or to keep food warm in the late evening was also studied by Buddhi and Sahoo (1997). The authors designed and tested a solar box cooker with a low temperature thermal storage. The cooker consisted of two aluminum trays. In the center of the inner tray, a cylindrical container was welded in order to accommodate the cooking pot. Aluminum fins were provided at the inner side of the tray and of the cylindrical container. The volume between the inner and the outer tray was filled with 3.5 kg of stearic acid. The experimental results were compared with those of a conventional solar cooker. It was found that, adjusting the loading time of the second batch and closing the solar cooker, it is possible to cook two batches with one pot. According to the authors, the results could have been better if the cooker had been well insulated from the top and bottom.

In the work by Sharma et al. (2000), a PCM storage unit using acetamide (2 kg) was designed and developed to cook food in the evening with a solar cooker. Similarly to the work by Domanski et al. (1995), the PCM container had two hollow concentric aluminum cylinders of diameter 18 cm and 25 cm. The space between the cylinders was filled with the PCM. Eight fins were welded at the inner wall of the container to enhance the heat transfer rate. Experiments were carried out with different loads and loading times during the summer and winter season. The thermal performance of the PCM-based solar cooker was compared with that of a standard solar cooker and it was determined that evening cooking is only possible with the former cooker. The authors concluded that the solar energy storage does not affect the cooker performance for noon cooking. Additionally, they stated that if a PCM having a melting temperature between 105 and 110 °C was used, cooking would be possible even in the nighttime. In a later work (Buddhi et al., 2003), the same authors found that evening cooking (up to 20:00) in the winter season is possible in a solar cooker having three reflectors to enhance the incident solar radiation with a PCM storage unit based on 4 kg of acetanilide.

An indirect solar cooker based on an evacuated tube solar collector (ETC) with a PCM storage unit was studied by Sharma et al. (2005). Erythritol was used as a latent heat storage material. Noon and evening cooking experiments were conducted with different loads (5, 7, 8, 10 kg), loading times, and operating/climatic conditions. It was found that noon cooking did not affect the evening cooking, and evening cooking using PCM heat storage was faster than noon cooking.

Hussein et al. (2008) designed, manufactured, and tested an indirect solar cooker with an outdoor elliptical cross section and an indoor PCM thermal storage based on magnesium nitrate hexahydrate. The experimental results show that the cooker is able to cook food at noon, afternoon, and evening times. It can be also used for heating or keeping meals hot at night and early morning.

In 2009, El-Sebaii et al. (2009) investigated the melting/