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Experimental characterisation of a thermal energy storage system using temperature and power controlled charging

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Abstract

The experimental set-up and technical aspects for charging a thermal energy storage (TES) of a proposed solar cooker at constant temperature and variable electrical power are presented. The TES is developed using a packed pebble bed. An electrical hot plate simulates the concentrator which heats up oil circulating through a copper coil absorber charging the TES system. A computer program to acquire data for monitoring the storage system and to maintain a nearly constant outlet charging temperature is developed using Visual Basic. The input power to the hot plate is also controlled to simulate the variation of the daily solar radiation by using another Visual Basic program. A combined internal model control (IMC) and proportional, integral and derivative (PID) temperature control structure is tested on the TES system under varying conditions and its performance is reasonable within a few degrees of the set temperature points. Results of the charging experiments are used to characterise the storage system. The different experiments indicate various degrees of stratification in the storage tank.

Keywords: Data acquisition and control; IMC; PID; Thermal energy storage (TES); Pebble bed; Visual basic

1. Introduction

Solar cookers using thermal energy storage (TES) have been developed and reported in recent years [1–3] to cater for the drawbacks of non-storage cooking systems [4–6]. The primary advantages of solar cookers with thermal storage are that the cooking can be carried out at any time of the day, that the cooking speed is fast and that the cooking capacity can be maximized. Conventional solar cooking non-storage systems do not offer these advantages and as a result, a TES and cooking system using pebble bed storage has been developed. A pebble bed system is particularly cheap to develop and to maintain [7,8]. This low cost is because the pebbles that make up the storage are readily available and that the pebbles replace a considerable fraction of the expensive heat transfer oil. The TES system also enables a solar cooker to be developed with an appeal similar to a conventional electrical cooker [1]. Using a TES unit can also limit the demand on electrical energy for cooking.

A major control problem in solar plants using TES is that the charging outlet temperature must be maintained at an almost constant value to transfer thermal energy efficiently regardless of the variation of the solar radiation and the inlet charging temperature by manipulating the flow rate. This control objective has been used by Camacho et al. [9] in the design of controllers for the solar collector field at Plataforma Solar de Alemeria in Spain. Various control strategies [10–14] have been proposed and tested on the same plant. It is thus necessary to attempt to maintain a constant outlet charging temperature of the TES system. Although the amount of solar radiation cannot be controlled, it is possible to control the variation of the input power to the hot plate to follow the approximate variation of the solar radiation on a daily basis. To characterise a TES system in the laboratory where there exists no solar radiation our power and temperature control techniques can be used.

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This paper is organised as follows. Section 2 gives a description of the TES and cooking system and presents theoretical considerations related to TES. In Section 3, the control techniques for the control problems are developed and discussed. An analysis of the measurements performed during the charging experiments is given in Section 4. Conclusions drawn up from the work carried out are given in the last section.

2. TES and cooking system description and theoretical considerations

The designed TES and cooking system consists of an energy capture subsystem, an energy storage subsystem and an energy utilisation subsystem as shown in Fig. 1.

The energy capture system is simulated by an electrical hot plate that is in thermal contact with a copper absorber/receiver (hollow spiral coil) through which a heat transfer oil is circulated by use of a positive displacement pump. The storage system is a two-phase system that consists of a packed pebble bed made of sandy stones surrounded by a heat transfer oil both contained in an insulated 20 L steel tank. The utilisation system comprises a thermal energy discharging heat exchanger and a positive displacement pump.

Assuming no heat losses through the pipes, during the charging process, the heat transfer oil enters the capture system at a temperature $T_{\mathrm{R\,in}}$ where it gets heated. It leaves at a higher temperature $T_{\mathrm{R\,out}}$ after absorbing power from the electrical hot plate. The heated oil then enters the top part of the storage system where it charges the pebble bed at a mass flow rate (or flux) given by $\dot{m}_{\mathrm{ch}}$. During the discharging process the hot oil from the top of the storage system is at a temperature $T_{\mathrm{L\,in}}$ and it is pumped to the utilisation system out of where it emerges at a temperature $T_{\mathrm{L\,out}}$. The amount of heat lost by the storage system and gained by the utilisation system is represented as a loss rate (or flux) given by $\dot{Q}_{\mathrm{L}}$ at a mass flow rate of $\dot{m}_{\mathrm{dis}}$. The charging and discharging processes represent the basic operating principles of the energy capture and storage system which are described in more detail in the subsections that follow.

2.1. The solar energy capture (SEC) system

The major components of the SEC system are illustrated in the schematic diagram of Fig. 2. An electrical hot plate simulates a solar collector that supplies an energy flux $\dot{Q}_{\mathrm{C}}$ to a copper spiral coil absorber. The copper spiral coil is in thermal contact with the hot plate and it is assumed to absorb an energy flux equal to $\dot{Q}_{\mathrm{R\,in}}$. The total energy flux or power supplied by the electrical hot plate can be expressed as

$$\dot{Q}_{\mathrm{C}} = \dot{Q}_{\mathrm{R\,in}} + \dot{Q}_{\mathrm{R\,loss}}, \tag{1}$$

where $\dot{Q}_{\mathrm{R\,loss}}$ is the energy flux that is lost from the hot plate to the environment.

In order to control the energy flux from the hot plate, a power controller is used and this is monitored by a power meter. The charging pump circulates a heat transfer oil through the copper spiral coil absorber at a mass flow rate of $\dot{m}_{\mathrm{ch}}$. In this way the energy flux of the electrical hot plate is transferred through to the oil. The energy flux gained by the oil in a circulating sequence can be expressed in terms of the inlet and outlet temperatures of the copper spiral coil absorber as

$$\dot{Q}_{\mathrm{R\,in}} = \dot{m}_{\mathrm{ch}} \int_{T_{\mathrm{R\,in}}}^{T_{\mathrm{R\,out}}} c(T)\, dT, \tag{2}$$

where $T_{\mathrm{R\,in}}$ is the inlet temperature, $T_{\mathrm{R\,out}}$ the outlet temperature and $c(T)$ the specific heat capacity of the oil. This equation is very important in describing the charging process since it represents the total energy gained by the oil.

The power controller should be able to simulate the amount of power in terms of the variation of incident solar

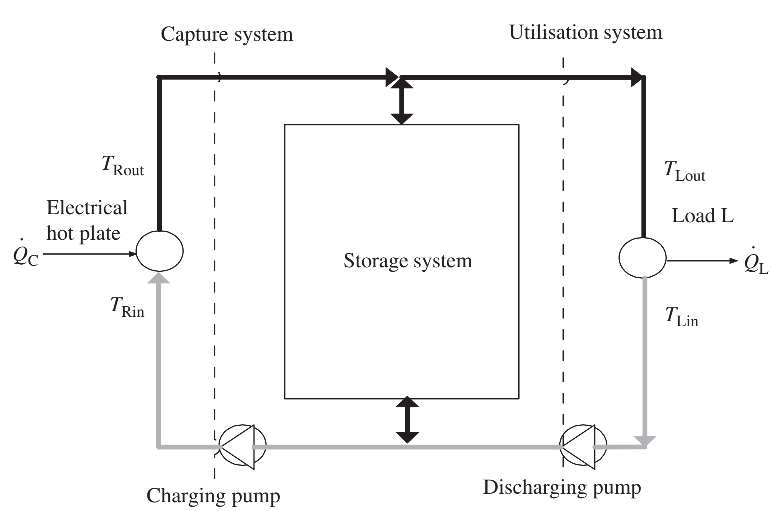

Fig. 1. A conceptual diagram of the TES and cooking system showing energy capture, storage and utilisation.