Data Acquisition and Control of a Thermal Energy Storage and Cooking System

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Abstract **— A thermal energy storage (TES) system has been developed using a packed pebble bed. An electrical hot plate heats up oil circulating in a copper absorber which charges the storage system. A Visual Basic program has been developed to acquire data for monitoring the storage system and to maintain a nearly constant outlet temperature from the charging point. The input power to the electrical hot plate has also been controlled to simulate an incident daily solar radiation on a clear day using another Visual Basic program. Results obtained can be used to characterise the system.**

Keywords **— Computer program, data acquisition and control, thermal energy storage, Visual Basic.**

I. Introduction

THERMAL energy storage (TES) in solar cookers has the advantages 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 [1]-[3] do not offer these advantages and as a result a TES and cooking system using pebble bed storage has been developed. Although other forms of thermal energy storage with varying advantages have been reported [4]-[6], a pebble bed system is particularly cheap to develop and to maintain [7]-[8]. This low cost is due to the fact that the pebbles that make up the storage are readily available and the pebbles replace a considerable fraction of the expensive heat transfer oil.

The storage and cooking system that has been developed utilizes two pumps; one to charge and the other to discharge the pebble bed storage using a heat transfer oil. Forty five thermocouples have been embedded in the pebble bed (five each at nine different levels) to monitor the temperature profile. The solar concentrator/ receiver is simulated by an ordinary electrical hot plate that heats up the oil. Values of the temperature in the whole TES and cooking system, the fluid flow rate in the charging and discharging loops and the power input to the hot plate need to be acquired. This necessitates the design of a computerized data acquisition system. To transfer thermal energy efficiently to a storage system, the charging temperature must be maintained at an almost constant value, a point that has been proposed by Camacho et al [9] in their design of a controller for a solar field. The input power to the hot plate should also simulate the daily solar radiation that is incident on a clear sky day and this is carried out during the charging process.

This paper gives a description of the TES and cooking system and describes the data acquisition and control techniques that have been developed. Further, the paper presents measurements carried out using the data acquisition and control system.

II. System Description

The designed TES and cooking system consists of an energy capture sub-system, an energy storage sub-system and a utilization sub-system as shown in Fig. 1.

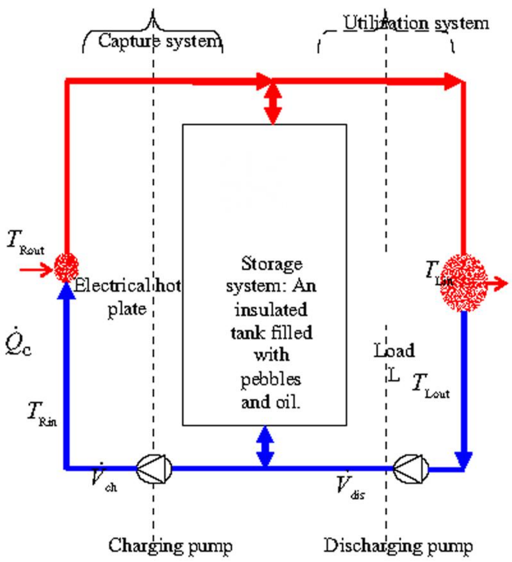

Fig.1. A conceptual diagram of the TES and cooking system showing energy capture, storage and utilization.

The energy capture system is simulated by an electrical hot plate that is in thermal contact with a copper absorber (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 small sandy stones surrounded by a heat transfer oil both contained in an insulated steel tank. The utilization system comprises a thermal energy discharging heat exchanger and a positive displacement

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pump.

Assuming no heat losses during the charging process, the heat transfer oil enters the capture system at a temperature T_{Rin} where it gets heated. It leaves at a higher temperature T_{Rout} after absorbing a portion of the power, $\dot{Q}_C$ 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 volumetric flow rate (or flux) given by $\dot{V}_{ch}$. During the discharging process, the hot oil from the top of the storage system is at a temperature T_{Lin} and is pumped to the utilization system out of where it emerges at a temperature T_{Lout}. The amount of heat lost by the storage system and gained by the utilization system is represented as a loss rate (or flux) given by $\dot{Q}_L$ at a volumetric flow rate of $\dot{V}_{dis}$.

III. Data Acquisition and Control Techniques

The overall setup of the data acquisition and control hardware is shown in Fig. 2 excluding the cooking part since it was not being controlled.

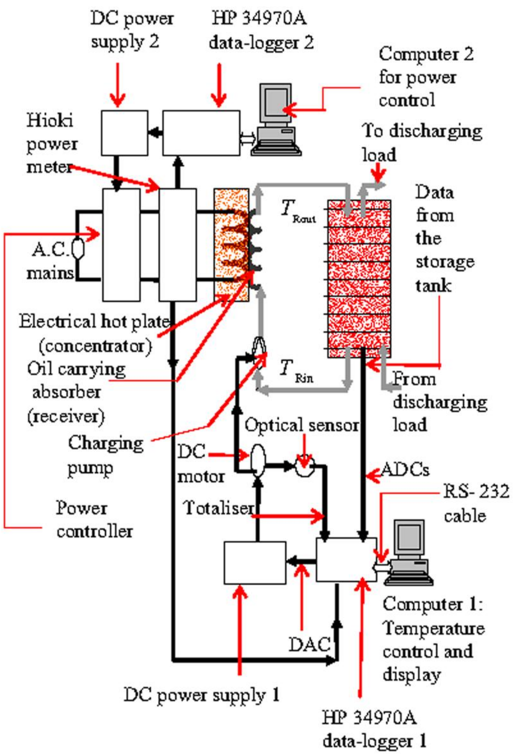

Fig.2. A block diagram of the data acquisition and control hardware showing two computers and two data-loggers used for temperature and power control.

The temperature in the whole TES and cooking system was measured with K-type thermocouples embedded in the system. The thermocouples were connected to the analogue to digital converter (ADC) channels of an HP 34970A data-logger 1 [10]. The data-logger was able to provide the necessary signal conditioning circuitry for measuring the individual temperatures. Communication between Computer 1 and data-logger 1 was done via the RS-232 interface. All the software was developed in the enterprise edition of Visual Basic 6 using the HP SCPI (standard commands for programmable instruments) commands.

A digital to analogue converter (DAC) in the multifunction module of data-logger 1 was used to supply a control voltage to a Goodwill Model GPS-3030 DC power supply. The output of the power supply was used to control the rotational speed of a DC motor and hence the rotational speed of the charging pump. The speed of the pump was thus able to give an inference of the flow rate. The inferred flow rate was measured with an optical incremental angular position sensor and a totaliser from the multifunction module of the data-logger. Values of the flow rate were displayed on Computer 1 in real-time together with the temperature values.

A voltage signal that is proportional to the input power that is supplied to the electrical hot plate was also measured with the ADC of data-logger 1. This voltage signal was provided by an output terminal of a Hioki Model 3181-01 power meter. The voltage signal was displayed on Computer 1 as well. The purpose of data-logger 2 was to measure and to control the input power to the electrical hot plate in order to simulate the variation of the incident solar radiation on a daily basis. The DC voltage signal that is proportional to the output power of the hot plate was also measured by the ADC of data-logger 2.

A. *Temperature control*

A combined parallel feedforward and feedback structure was used to attempt to maintain the temperature at a set point during the charging process. Major disturbances that were measured in the charging loop were the inlet temperature, T_{Rin} and the power input to the electrical hot plate, $\dot{Q}_C$. The feedforward flow rate that is required to maintain the set temperature was calculated from the classical relationship $Q = mc\Delta T$ which can be expressed as

$$\dot{Q} = \dot{m}c\left(T_{set} - T_{Rin}\right) \tag{1}$$

and so we get

$$\dot{V}_{chff} = \frac{\eta_{ch}\dot{Q}_C}{\rho(T)c(T)\left[T_{set} \quad T_{Rin}\right]} \tag{2}$$

which can also be represented as $\dot{m}_{chff}$ by transposing $\rho(T)$, where $\rho(T)$ is the oil density, $c(T)$ is the specific heat capacity of the oil, η_{ch} is the charging efficiency and T_{set} is the set temperature for the outlet charging loop.

If there exists a difference between T_{set} and T_{Rout} which cannot be completely compensated for by the feedforward flow rate an error signal is generated. The feedback loop attempts to remove this error and a simplified (PID) proportional, integral and derivative feedback system was used for this. An equation that describes the PID action as a function of time [11] is given as

$$M(t) = K_p E(t) + K_i \int_0^t E(t)dt + K_d \frac{d}{dt} E(t) \qquad (3)$$

where $M(t)$ is the manipulated variable while K_p, K_i and K_d are the proportional gain, the integral gain and the derivative gain, respectively. A block diagram depicting the combined structure is shown in Fig. 3.

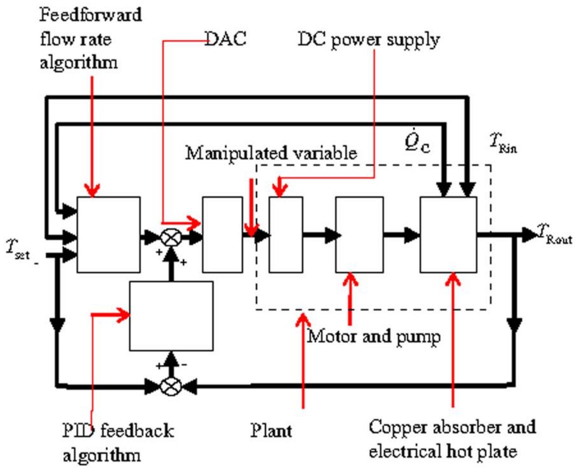

Fig.3. A block diagram of a combined parallel feedforward and PID feedback control structure.

The figure shows that the feedforward and the PID algorithms are used to calculate the manipulated variable which is the DC voltage of the DAC. This control voltage varies the output voltage of the DC power supply which acts as a voltage controlled source and controls the rotational speed of the motor and the pump. By controlling the rotational speed of the pump it was possible to control the flow rate of the oil through the copper absorber and thus to maintain the set temperature.

The combined structure was implemented as a software subroutine which was executed from Computer 1. The data values received for the control subroutine were obtained from a data-logging subroutine with a sampling period of 4 seconds. The subroutine was designed with the capabilities to save the acquired data into a spreadsheet for data analysis at a later time. The PID parameters were tuned manually through the graphical user interface of the temperature control software.

B. Power control

A combined feedforward and feedback structure was employed to control the input power to the hot plate in order to simulate the special case daily incident solar radiation on a clear day. The variation of the solar radiation can be approximated [12] by

$$I_{cd} = I_{on} \sin\left(\frac{\pi t}{\Delta T_{GMT}}\right) \qquad (4)$$

where I_{on} is the solar constant, where t is the time (0 for the sunrise hour) and ΔT_{GMT} is the day length which is given by

$$\Delta T_{GMT} = GMT_{sunset} \quad GMT_{sunrise} \qquad (5)$$

where GMT_{sunset} is the Greenwich meridian time at sunset and $GMT_{sunrise}$ is the Greenwich meridian time at sunrise. To use Equation (4) to give the received power a simulated optical efficiency η_{sop} and a simulated capture area A_C were incorporated to yield

$$\dot{Q}_R = \eta_{sop} A_C I_{on} \sin\left(\frac{\pi t}{\Delta T_{GMT}}\right) \qquad [6]$$

where $\dot{Q}_R$ is the received power. Any difference between the received power and the measured power was eliminated by the integral feedback action. A block diagram of the combined feedforward and feedback structure is shown in Fig. 4.

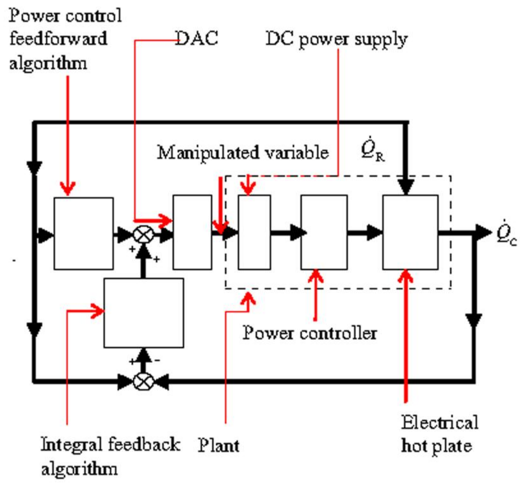

Fig.4. A block diagram of a combined feedforward and integral feedback power control structure.

In Fig.4, the voltage from the DAC was used to control the voltage of the DC power supply which was connected to the power controller. The DC power supply was used to supply the power controller with a control voltage in order to control the input power to the hot plate, thus enabling a sinusoidal variation of the radiation to be followed. This combined structure was implemented using a program which was executed on Computer 2.

IV. Results and Discussion

The temperature and power control test results obtained during charging of the storage at a temperature set to low values are shown in Fig. 5. Plot (a) of the figure shows a slow rate of rise of T_{Rout} to the set temperature from ~09:15 hrs to 09:45 hrs due to the small input power during this time interval. The temperature was set to 200 °C and this set value was followed closely from 09:45 hrs to 11:00 hrs. The inlet temperature T_{Rout} rises from ~25 °C to peak ~105 °C at ~10:45 hrs as the charging progresses after which it starts falling since the power is too small to overcome the heat losses.

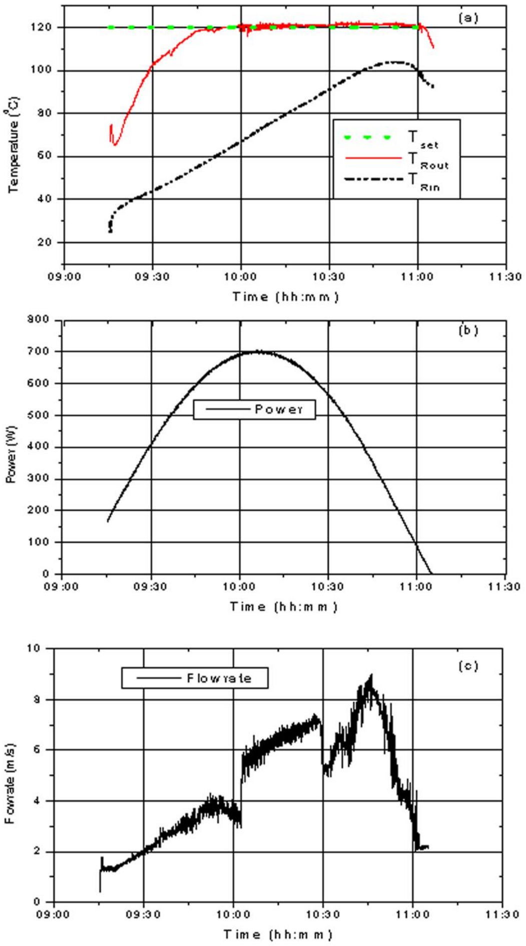

Fig.5. Power and temperature control test results obtained on 28 February 2005.

Plot (b) of Fig.5 shows that the input power to the hot plate varies sinusoidally from a power of ~150 W at 09:15 hrs to a maximum of ~700 W at 10:10 hrs after which it gradually drops to 0 W at ~ 11:05 hrs. The flow rate as shown in plot (c) varies nearly as the inlet charging temperature in its attempts to maintain the temperature at the set value. A maximum flow rate of ~9 ml/s is reached when the inlet charging temperature approached its maximum value. The sudden rise in the flow rate at ~10:00 hrs is due to the controller responding to the rise in the inlet charging temperature and the slow variation in the power when it approaches its peak value. The drop in the flow rate at ~10:30 hrs can be explained in terms of the compensation by the controller for the drop in the power as the maximum temperature is approached.

The profile of Fig. 6 illustrates the temperature distribution of the pebble bed storage during the charging process. Thermal stratification is evident as seen from the figure from 9:30 hrs to 10:00 hrs where the trace for Level I is the lowest while that for Level A is the highest. The storage is fully charged and this demonstrated by the fact that the temperature difference between layers is very small at the end of the charging process. At this point, the layer temperatures at the top of the tank have decreased and this is due to increased heat losses at the top of the storage.

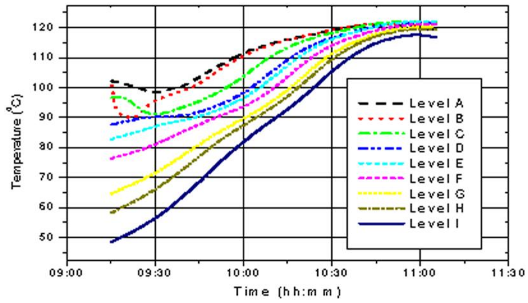

Fig.6. The corresponding temperature profile of the pebble bed storage measured at nine different levels during the charging process

V. Conclusion

Our results indicate that the temperature control program is able to maintain a nearly constant charging temperature of the TES system. The power control program enables the input power to the hot plate to follow the incident solar radiation on a clear day. The temperature profile of the pebble bed has also been measured during the charging period and this is found to indicate that the storage is fully charged.

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