Maximum-power-point tracking control of solar heating system

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Abstract

The present study developed a maximum-power point tracking control (MPPT) technology for solar heating system to minimize the pumping power consumption at an optimal heat collection. The net solar energy gain Q_{net} ($=Q_s - W_p/\eta_e$) was experimentally found to be the cost function for MPPT with maximum point. The feedback tracking control system was developed to track the optimal Q_{net} (denoted Q_{max}). A tracking filter which was derived from the thermal analytical model of the solar heating system was used to determine the instantaneous tracking target $Q_{max}(t)$. The system transfer-function model of solar heating system was also derived experimentally using a step response test and used in the design of tracking feedback control system. The PI controller was designed for a tracking target $Q_{max}(t)$ with a quadratic time function. The MPPT control system was implemented using a microprocessor-based controller and the test results show good tracking performance with small tracking errors. It is seen that the average mass flow rate for the specific test periods in five different days is between 18.1 and 22.9 kg/min with average pumping power between 77 and 140 W, which is greatly reduced as compared to the standard flow rate at 31 kg/min and pumping power 450 W which is based on the flow rate 0.02 kg/s m^2 defined in the ANSI/ASHRAE 93-1986 Standard and the total collector area 25.9 m^2 . The average net solar heat collected Q_{net} is between 8.62 and 14.1 kW depending on weather condition. The MPPT control of solar heating system has been verified to be able to minimize the pumping energy consumption with optimal solar heat collection.

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1. Introduction

Forced-circulation solar heating system has been widely used in industrial and domestic heating process. The solar heating system consists of multiple banks of solar collectors and uses a pump to circulate the working fluid (water, glycol solution, or heating medium) through the collectors. The electric pumping energy is consumed. The solar heat absorbed increases with increasing flow rate as well as pumping power. Although a careful piping design to reduce the pressure loss in pipelines is important, the opti-

mal control of pumping flow rate can also effectively reduce the pumping power.

A lot of solar heating systems were usually designed to operate at a flow rate given by the standard flow rate used in the collector standard test, $0.02 \text{ kg m}^{-2} \text{ s}^{-1}$, which may be over-estimated and causes larger pumping power consumption. The purpose of the flow rate control is to reduce the pumping power but without changing the solar heat collection.

Many researchers intended to develop an optimal control technique to reduce the pumping power at optimal solar heat collection (Kovarík and Lesse, 1976; De Winter, 1992; Badescu, 2007; Bejan and Schultz, 1982) such as using exergy concept (Badescu, 2007) or system optimization method (Bejan and Schultz, 1982). The control

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Nomenclature

A_c	absorber area of solar heating system, m ²	T_e	outlet temperature of collector, °C
C_p	specific heat of working fluid, kJ/kg °C	T_i	inlet temperature of collector, °C
F_i	cost function at time instant i for tracking control	T_I	parameter of PI controller
$F_R(\tau\alpha)$	flow transmittance–absorptance coefficient of solar collector, dimensionless	W_p	pumping power consumption, W
$F_R U_L$	heat loss coefficient of solar collector, W/m ² K	η_e	efficiency of electric grid, dimensionless
I_T	solar radiation intensity on collector slope, W/m ²	τ_s	time constant of solar heating system, s
K_p	parameter of PI controller	η_s	energy conversion efficiency of solar collector, dimensionless
$\dot{m}$	mass flow rate through collector, kg s ⁻¹	$\tilde{I}_T(t)$	perturbed value of I_T
Q_{net}	net energy gain, kW	$\bar{I}_T$	steady state of I_T
Q_{max}	maximum Q_{net} , kW	$\tilde{q}_s(t)$	perturbed value of q_s
Q_s	total heat energy collected = $\dot{m}C_p(T_e - T_i)$, kW	$\bar{q}_s$	steady state of q_s
q_s	total heat energy collected per unit area of solar absorber = Q_s/A_c , kW/m ²	$\tilde{m}(t)$	perturbed value of $\dot{m}$
s	Laplace variable	$\bar{m}$	steady state of $\dot{m}$
T_a	ambient temperature, °C	$\tilde{T}_a(t)$	perturbed value of T_a
		$\bar{T}_i$	steady state of T_i
		$\tilde{T}_i(t)$	perturbed value of T_i

algorithms however were very complicated and not easy to be implemented. In addition, no tracking feedback control scheme has ever been applied to assure the optimal performance under variable solar radiation. In the present study, we intend to develop the technology of maximum-power-point tracking control (MPPT), similar to MPPT of solar PV system, but for solar heating system.

2. Design of solar heating system

A solar heating system using flow-through vacuum-tube solar collectors was designed and installed for experiment. The solar heating system, as shown in Fig. 1, consists of 24 sets of vacuum-tube solar collectors with 26 m² total absorber area. The piping is designed with eight collectors in series and three in parallel connections, for total 24 collectors. The reverse-return piping design is adopted to maintain a uniform flow through the collector banks. An inverter for

Fig. 1. Solar heating system used in the present study.

rotational speed control of the circulation pump was installed and a PC-based control system was developed for the control of the circulation pump. The system configuration is shown in Fig. 2, where T_e is the water temperature at solar collector outlet and T_i is the water temperature at the bottom of the buffer tank which is close to the inlet temperature.

Most of solar heating systems were designed at the flow rate 0.02 kg m⁻² s⁻¹ used in the standard test of solar collector. That is, the total flow rate for the present solar system will be rated at 31 kg/min with 450 W pumping power. This may be too high and can be reduced without affecting the energy collection.

3. Determination of cost function for optimal tracking control

In order to develop an optimal control for water pump, the cost function must be found first. The total solar heat absorbed by the solar collector Q_s increases with increasing flow rate. However, the associated pumping power may become unreasonably high. After certain range of high flow rate, the increase of flow rate no longer increases the total solar heat collection Q_s . The net energy gain Q_{net} can be defined as the total heat energy collected Q_s minus the electric pumping energy W_p which is converted into the primary heat energy:

$$Q_{net} = Q_s - \frac{W_p}{\eta_e} \quad (1)$$

where η_e is the primary energy efficiency of the electrical grid (0.365 in Taiwan), $Q_s = \dot{m}C_p(T_e - T_i)$, T_i and T_e are

Fig. 2. Schematic diagram of control system design of solar heating system.

Fig. 3. Concept of Q_s and Q_{net} vs. pumping power.

the collector inlet and outlet temperatures, respectively. There seems to exist an optimal flow rate at which the net heat collection is maximum and the pumping power is minimized. The definition of net energy gain Q_{net} is similar to the cost function of Kovarik and Lesse (1976) or the exergy concept (Bejan and Schultz, 1982) and may have a maximum value as shown in Fig. 3. Since Q_{net} varies with solar radiation and ambient conditions (wind and temperature), there may not be an optimal value of Q_{net} all the time. The feasibility of using Q_{net} as the cost function in the MPPT of solar heating system needs to be verified experimentally.

A steady or quasi-steady state data were screened out from field test data at different mass flow rates to determine the instantaneous Q_s and Q_{net} at fixed solar irradiation I_T . Fig. 4 shows that at a fixed solar radiation intensity

$I_T = 880 \text{ W/m}^2$, there exists an optimal flow rate at which the net heat gain Q_{net} is maximum and denoted as Q_{max} . Q_{max} (14.9 kW) is at flow rate 22 kg/min (0.37 kg/s). The measured pumping power is 113 W at a reduction of 73% pumping power and the total heat energy collected Q_s is 15.2 kW. The experiment was carried out from 11:00 AM to 13:00 PM on a clear day, thus, the solar radiation intensity is approximately constant.

To evaluate the performance of solar heating system, the coefficient of performance (COP) is defined as:

$$\text{COP} = \frac{Q_s}{W_p} \quad (2)$$

The power consumption of pump W_p (W) was determined experimentally at different mass flow rate $\dot{m}$ (kg/s) and an empirical relation was derived:

$$W_p = 2505.6\dot{m}^3 - 1124.6\dot{m}^2 + 393.5\dot{m} \quad (3)$$

It is seen that a very high electrical COP of the solar heating system ($Q_s/W_p = 134.5$) is obtained at the optimal point.

4. Design of MPPT control system

4.1. Feedback structure of MPPT

One of the feedback structures for MPPT in solar heating system can be the same as the popular step-up/step-down control used in the MPPT of solar PV systems (Salas et al., 2006), as shown in Fig. 5. The cost function at time instant i , denoted F_i , is fed back to the one-step delay filter to determine F_{i-1} . The comparator compares F_i and F_{i-1}

Fig. 4. Steady performance of a solar heating system at $I_T = 880 \text{ W/m}^2$.

Fig. 5. Step-up/step-down control in MPPT.

Fig. 6. Basic configuration of optimal tracking control system.

and outputs a signal $F_i - F_{i-1}$ to the controller. The step-up/down controller then outputs a control signal to regulate the flow rate up or down according to the sign of the change $F_i - F_{i-1}$. Since the electrical response to the variation of solar radiation is fast in PV system due to photovoltaic phenomenon, this kind of control algorithm may work very well with typical triggering such as perturbation and observation (P&O) (Salas et al., 2006; Enrique et al., 2010). However, for solar heating system, the thermal response of solar collector is relatively slow due to larger thermal mass in the solar-thermal process. The step-up/down controller cannot work very well when solar radiation is varying. A tracking control system is thus proposed in the present study.

Fig. 6 shows the basic configuration of the tracking control system for maximum Q_{net} (i.e. Q_{max}) in the solar heating system. The tracking filter Ft is used to determine the instantaneous maximum value of Q_{net} (i.e. Q_{max}) as the tracking target, from the calculation based on a known dynamic model. The tracking controller $C(s)$ can then be designed to track the time-variant Q_{max} .

4.2. Derivation of time-variant tracking target Q_{max}

Since the performance of solar heating system varies with solar radiation intensity I_T and the mass flow rate $\dot{m}$, Q_{max} is time-variant and can be determined at any time instant if the thermal analytical model of the solar heating system is known.

4.2.1. Derivation of system dynamic model of solar heating system

The tracking filter Ft is used to determine the instantaneous MPP of the solar heating system. The thermal performance of solar collector is a dynamic behavior due to the variation of environment including solar radiation, wind speed, etc. A first-order thermal model was first derived by Close (1967) using lumped concept, called “lumped model”, and then utilized and corrected by Klein et al. (1974) considering the fluid temperature variation with position, called “one-node capacitance model”. This model was further modified by Wang et al. (1987), called “first-order model”, and experimentally verified by Huang and Hsieh (1990) who showed that the first-order model can fit the experimental results reasonably well. Hence, we adopted the first-order model (Wang et al., 1987) in the present study:

$$\tau_s \frac{dq_s}{dt} + q_s = F_R(\tau\alpha)I_T - F_R U_L(T_i - T_a) \quad (4)$$

Fig. 7. Step response test of the solar heating system.

Fig. 8. Thermal efficiency test results of solar collector banks at $\dot{m} = 0.64$ kg/s.

where $q_s = Q_s/A_c$ and τ_s is the time constant of the solar heating system which represents the time to reach 63.2% of the step change due to a step input to the system. $F_R(\tau\alpha)$ and $F_R U_L$ are the collector parameters defined as the following steady-state thermal efficiency relation:

$$\eta_s = F_R(\tau\alpha) - \frac{F_R U_L (T_i - T_a)}{I_T} \quad (5)$$

The time constant τ_s was determined from a step response test of the solar system (Fig. 7) by quickly shading all the solar collectors when the solar heating system is

running at a steady state with approximately constant solar radiation, circulation flow rate, and inlet temperature. The experiment was carried out during the noon (11:00–13:00) with stable solar radiation. The test result shows that $\tau_s = 237$ s from fitting the test result to the first-order model, Eq. (4).

The two parameters $F_R(\tau\alpha)$ and $F_R U_L$ are determined by fitting the steady-state data collected from field tests to the relation, Eq. (5). Fig. 8 shows the result for $\dot{m} = 0.64$ kg/s. Repeating the experiments at different mass flow rate $\dot{m}$, we obtain Fig. 9.

The following correlations for steady-state performance were derived:

$$F_R(\tau\alpha) = -0.51\dot{m}^2 + 0.72\dot{m} + 0.62, \quad \text{dimensionless} \quad (6)$$

$$F_R U_L = -2.97\dot{m}^2 + 3.9\dot{m} - 0.14, \quad \text{Wm}^{-2}\text{K}^{-1} \quad (7)$$

The above Eq. (6) and (7) are derived for the solar system with total collector area 25.92 m². The unit of mass flowrate $\dot{m}$ is in kg/s.

Eqs. 4, 6, and 7 can be used to determine $Q_{\max}$ at $\dot{m} = \dot{m}_{\text{opt}}$ for solar radiation intensity I_T at any time instant.

4.2.2. Determination of $Q_{\max}$

The maximum Q_{net} (i.e. $Q_{\max}$) can be determined by taking derivative of Q_{net} with respect to mass flow rate $\dot{m}$, that is:

Fig. 9. Variation of $F_R(\tau\alpha)$ and $F_R U_L$ with mass flow rate $\dot{m}$.

$$Q_{max} = \left. \frac{\partial Q_{net}}{\partial \dot{m}} \right|_{\dot{m}=\dot{m}_{opt}} = \frac{\partial}{\partial \dot{m}} \left[Q_s - \frac{W_p}{\eta_s} \right]_{\dot{m}=\dot{m}_{opt}} = 0 \quad (8)$$

To determine the Q_{max} at any time instant, Eq. (4) is first written in discrete form at time interval Δt_s :

$$\tau_s \frac{q_{s,j+1} - q_{s,j}}{\Delta t_s} + q_{s,j} = [F_R(\tau\alpha)]_j I_{T,j} - [F_R U_L]_j (T_{i,j} - T_{a,j}) \quad (9)$$

The total net energy collection rate at time instant $j + 1$ is:

$$\begin{aligned} Q_{net,j+1} &= Q_{s,j+1} - \frac{W_p}{\eta_e} \\ &= \frac{\tau_s q_{s,j} + [F_R(\tau\alpha)]_j I_{T,j} - [F_R U_L]_j (T_{i,j} - T_{a,j})}{\frac{\tau_s}{\Delta t_s} + 1} A_c - \frac{W_p}{\eta_e} \\ &= \frac{A_c}{\frac{\tau_s}{\Delta t_s} + 1} \left[\frac{\tau_s}{\Delta t_s} q_{s,j} + (-0.51\dot{m}_j^2 + 0.72\dot{m}_j + 0.62)I_{T,j} \right. \\ &\quad \left. - (-2.97\dot{m}_j^2 + 3.9\dot{m}_j - 0.14)(T_{i,j} - T_{a,j}) \right] \\ &\quad - \frac{2505.6\dot{m}_j^3 - 1124.6\dot{m}_j^2 + 393.5\dot{m}_j}{\eta_e} \end{aligned} \quad (10)$$

It is seen from Eq. (10) that there exists a maximum value of $Q_{net,j+1}$ at which $\dot{m}_j = \dot{m}_{opt}$ for a given $I_{T,j}$, $T_{i,j}$ and $T_{a,j}$ at time instant j . Hence, we can determine the optimal mass flow rate by taking partial derivative with respect to mass flow rate $\dot{m}_j$ and setting it equal to zero at which $\dot{m}_j = \dot{m}_{opt}$. We then obtain:

$$\dot{m}_{opt} = \frac{-\beta + \sqrt{\beta^2 - 4\varepsilon\gamma}}{2\varepsilon} \quad (11)$$

where

$$\begin{aligned} \varepsilon &= \frac{7516.8}{\eta_e} \\ \beta &= [1.02I_{T,j} - 5.84(T_{i,j} - T_{a,j})] \frac{A_c}{\frac{\tau_s}{\Delta t_s} + 1} - \frac{2328.5}{\eta_e} \\ \gamma &= -[0.72I_{T,j} - 3.9(T_{i,j} - T_{a,j})] \frac{A_c}{\frac{\tau_s}{\Delta t_s} + 1} + \frac{393.5}{\eta_e} \end{aligned}$$

Q_{max} is then determined by the following equation.

$$\begin{aligned} Q_{max} &= Q_{s,j+1}(\dot{m}_{opt}) - \frac{W_p(\dot{m}_{opt})}{\eta_e} \\ &= \frac{A_c}{\frac{\tau_s}{\Delta t_s} + 1} \left[\frac{\tau_s}{\Delta t_s} q_{s,j} + (-0.51\dot{m}_{opt}^2 + 0.72\dot{m}_{opt} + 0.62)I_{T,j} \right. \\ &\quad \left. - (-2.97\dot{m}_{opt}^2 + 3.9\dot{m}_{opt} - 0.14)(T_{i,j} - T_{a,j}) \right] \\ &\quad - \frac{2505.6\dot{m}_{opt}^3 - 1124.6\dot{m}_{opt}^2 + 393.5\dot{m}_{opt}}{\eta_e} \end{aligned} \quad (12)$$

Eq. (12) associated with Eq. (11) will be used to calculate Q_{max} at time $j + 1$ as the tracking target in the MPPT control system. $I_{T,j}$, $T_{i,j}$ and $T_{a,j}$ are assumed constant during the time step Δt_s . $I_{T,j}$ can be taken as the filtered value using a low-pass filter F_i .

4.3. Design of MPPT

4.3.1. Identification of system dynamic model of solar heating system

For tracking control system design, the system dynamic model of solar heating system has to be known. The dynamic behavior of solar collector system is nonlinear. A linear perturbation model was then derived from Eqs. 4, 6, 7 using the following definitions:

$$\begin{aligned} \tilde{q}_s(t) &= q_s(t) - \bar{q}_s \\ \tilde{m}(t) &= \dot{m}(t) - \bar{m} \\ \tilde{I}_T(t) &= I_T(t) - \bar{I}_T \\ \tilde{T}_a(t) &= T_a(t) - \bar{T}_a \\ \tilde{T}_i(t) &= T_i(t) - \bar{T}_i \\ \Delta T_{ia}(t) &= T_i(t) - T_a \\ \Delta \tilde{T}_{ia}(t) &= [T_i(t) - \bar{T}_i] - [T_a(t) - \bar{T}_a] = \Delta T_{ia}(t) - \Delta \bar{T}_{ia} \end{aligned} \quad (13)$$

where $\bar{q}_s$ is the steady state of q_s , $\bar{m}$ is the steady state of $\dot{m}$; $\bar{T}_i$ is the steady state of T_i ; $\bar{I}_T$ is the steady state of I_T . The linearly-perturbed dynamic system is assumed to operate near the steady state with small variation.

Assuming that the variations of collector inlet temperature T_i and ambient temperature T_a are small during the tracking control period, we have $\Delta \tilde{T}_{ia}(t) = 0$. Substituting the linear perturbation relation into Eq. (4) and neglecting the second-order terms, we obtain the following linear perturbation equation:

$$\begin{aligned} 237\dot{\tilde{q}}_s + \tilde{q}_s &= [(-1.02\bar{m} + 0.72)\bar{I}_T]\tilde{m} \\ &\quad + (-0.51\bar{m}^2 + 0.72\bar{m} + 0.62)\tilde{I}_T \end{aligned} \quad (14)$$

Taking Laplace transform of Eq. (14), we obtain the following transfer-function model, whose block diagram is shown in Fig. 10:

$$G_m(s) = \frac{\tilde{q}_s(s)}{\tilde{m}(s)} = \frac{(-1.02\bar{m} + 0.72)\bar{I}_T}{237s + 1} \quad (15)$$

$$G_I(s) = \frac{\tilde{q}_s(s)}{\tilde{I}_T(s)} = \frac{-0.51\bar{m}^2 + 0.72\bar{m} + 0.62}{237s + 1} \quad (16)$$

Fig. 10. System dynamic model of solar heating system.

Fig. 11. MPPT feedback control system.

Fig. 12. Tracking system simulation P-control only.

Fig. 13. Tracking system simulation at different T_I ($K_p = 10$).

It is seen that the system dynamic behavior of solar thermal system is first-order.

4.3.2. Design of MPPT feedback tracking control system

The system dynamic model derived above can be used in the design of MPPT feedback control system as shown in Fig. 11. Since the system dynamic response of the solar collector has a low-pass property (with time constant $\tau_s = 237s$), a low-pass filter F_i can be used to filter out the fast variation of solar radiation pattern.

Given the variation of cost function $Q_{max}(t)$, the tracking performance of the control system can be simulated using Matlab/Simulink and the controller design $C(s)$ can be made. The PI control (Proportional–Integral) was chosen as the controller, the following equation:

$$C(s) = K_p + \frac{1}{T_I s} \quad (17)$$

In the system simulation, the control target $Q_{max}(t)$ was assumed a quadratic function from 0 to 10 kW in 420 s. Fig. 12 shows that the tracking error for P-control only is small and not sensitive for $K_p > 10$. Therefore, further simulation was carried out at $K_p = 10$ to find the suitable T_I for integral control. Fig. 13 shows that the tracking error for $T_I = 5$ performs satisfactory. The PI controller became:

$$C(s) = 10 + \frac{1}{5s} \quad (18)$$

5. Test of solar heating system with MPPT control

The solar heating system was tested using the above MPPT control system which was implemented on a PIC16F877A microprocessor-based controller. The whole control system is as shown in Fig. 2. The whole control system consists of a PC, a MPPT controller, some measuring devices for mass flow rate, power input of pump, temperatures, solar radiation intensity, and a RS232 interface for communication between them. A 8-bit DAC0800 was used to convert the digital control signal into analogue actuating signal to the inverter of the pump to change the rotational speed as well as the mass flow rate. The tracking target $Q_{max}(t)$ was calculated using Eq. (12) and the measurements at each time step Δt_s was set at 6 s.

The test results of 2011/8/10 (cloudy weather) as shown in Fig. 14 and Table 1 show that the MPPT control works well. During the MPPT control period 11:37–13:03, the solar radiation varies between 237 and 961 W/m² (average 487); the mass flow rate varies between 10 and 24 kg/min with pumping power 30–128 W (average 77 W); collector exit temperature between 85.2 and 96.5 °C (average 90.3); Q_{net} between 2.92 and 18.8 kW (average 8.62); Q_{net} tracking error between 0 and 4.02 kW (average 1.02); and the COP varies between 62 and 208 (average 120). It is seen that COP increases with increasing solar radiation I_T , with about one minute delay.

Fig. 14. Test result of MPPT (2011/8/10).

Table 1
Tracking performance of MPPT control.

	T_a (°C)	T_i (°C)	T_e (°C)	I_T (W/m ²)	Flow rate (kg/min)	W_p (W)	COP	Q_{net} (kW)	Target Q_{max} (kW)	Tracking error (kW)		
										$Q_{net} - Q_{max}$	$abs(Q_{net} - Q_{max})$	$abs\ error\ (%)$
2011/8/10 11:37–13:03												
Min	32.7	80.1	85.2	237	10.0	30	62	2.92	3.82	−2.64	0.00	0.1
Max	36.7	90.5	96.5	961	24.0	128	208	18.8	16.0	4.02	4.02	41.4
Average	33.9	83.2	90.3	487	17.6	77	120	8.62	8.62	−0.00	1.02	12.5
2011/8/11 10:38–12:09												
Min	32.0	78.0	82.6	242	11.0	39	57	4.2	4.1	−2.4	0.0	0.0
Max	39.7	100.5	102.7	1037	25.0	155	309	24.5	17.2	7.5	7.5	30.4
Average	34.4	87.8	92.4	517	20.0	91	112	10.1	9.8	0.3	0.7	5.8

The larger tracking error at the periods of sudden change of solar radiation as shown in Fig. 15 is due to the tracking system response problem and the prediction error of tracking target $Q_{max}(t)$ using the tracking filter, Eq. (12).

The MPPT controller was designed using a quadratic time function of tracking target $Q_{max}(t)$ from 0 to 10 kW in 420 s, at an average rate of change 1.43 kW/min. This is very close to the real test result: the rate of change of $Q_{max}(t)$ was about 1.83 kW/min at 12:35 and 1.65 kW/

Fig. 15. Tracking error of MPPT (2011/8/10).

Fig. 16. Test result of MPPT (2011/8/11).

min at 12:19, both are close to the assumed quadratic target function of $Q_{max}(t)$ in the MPPT controller design. The prediction error of tracking target $Q_{max}(t)$ using the tracking filter, Eq. (12), may come from the dynamic effect of fast variation of solar irradiation I_T .

The average tracking error is ± 1.02 kW, about 12% with respect to the average Q_{net} which is acceptable. The pumping power was reduced tremendous from 550 W to 30–128 W (average 77 W).

Another cloudy-day test (2011/8/11) shows similar phenomena as shown in Fig. 16. During the MPPT control period 10:38–12:09, the solar radiation varies between 242 and 1037 W/m² (average 517); the mass flowrate varies between 11 and 25 kg/min with pumping power 39–155 W

(average 91 W); collector exit temperature between 82.6 and 102.7 °C (average 92.4); Q_{net} between 4.2 and 24.5 kW (average 10.1); Q_{net} tracking error (abs) between 0 and 7.5 kW (average 0.7); and the COP varies between 57 and 309 (average 112). The error in tracking the target $Q_{max}(t)$ is greatly reduced in 2011/8/11, especially in the latter part of the test after 11:16, as shown in Fig. 17. This is due to the lower solar radiation fluctuation. The weather of 2011/8/11 was better than 2011/8/10.

We summarized the averaged results of some typical tests at the periods under MPPT control in summer, as shown in Table 2. It is seen that the highest average Q_{net} was 14.1 kW with COP = 104 in a clear day (2011/6/23) with average $I_T = 746$ W/m² and average collector inlet

Fig. 17. Tracking error of MPPT (2011/8/11).

Table 2

Averaged results at the periods under MPPT control.

Date	Test time h:min	T_a (°C)	T_i (°C)	I_T (W/m ²)	Flow rate (kg/min/m ²)	Q_{net} (kW)	W_p (W)	COP	A_c (m ²)
2011/6/22	2:40	35.9	89.8	570	0.70	10.5	101	111	25.9
2011/6/23	5:13	33.4	92.6	746	0.84	14.1	140	104	25.9
2011/8/08	1:14	35.2	86.7	684	0.88	12.4	130	99	25.9
2011/8/10	1:26	33.9	83.2	487	0.68	8.62	77	120	25.9
2011/8/11	1:31	34.4	87.8	517	0.77	10.1	91	112	25.9

temperature $T_i = 92.6$ °C. The test time is the longest, with 5 h and 13 min and the average pumping power is also the highest (140 W).

The measured lowest average Q_{net} was 8.62 kW with COP = 120 in a cloudy day (2011/8/10) with average $I_T = 487$ W/m² and average collector inlet temperature $T_i = 83.2$ °C. The average pumping power is also the lowest (77 W).

It is seen that the average mass flow rate of the specific test periods in five different days is between 18.1 and 22.9 kg/min with average pumping power between 77 and 140 W, which is greatly reduced as compared to the standard flow rate at 31 kg/min (0.02 kg/s m²) at 450 W pumping power.

6. Conclusion

The present study developed a maximum-power point tracking control (MPPT) technology for solar heating system to minimize the pumping power consumption at an optimal heat collection. The net solar energy gain Q_{net} ($=Q_s - W_p/\eta_e$) was found to be the cost function with maximum point from the analysis of steady-test results. The feedback tracking control system was developed to track the optimal Q_{net} (denoted Q_{max}). A tracking filter which was derived from the thermal analytical model of the solar heating system was used to determine the instantaneous tracking target $Q_{max}(t)$ to take into account the effect of time variation of solar radiation and temperatures. The system transfer-function model of solar heating system was also derived experimentally using a step response test. This model was then used in the design of tracking feedback control system for a given time-variant tracking target $Q_{max}(t)$. The PI controller was designed for a tracking target $Q_{max}(t)$ with a quadratic time function. The whole MPPT control system was implemented using a microprocessor-based controller, a PC, and measuring devices, etc. to control the mass flow rate of the solar heating system. The test results show a good tracking performance with small tracking errors.

It is seen that the average mass flow rate for the specific test periods in five different days is between 18.1 and 22.9 kg/min with average pumping power between 77 and 140 W, which is greatly reduced as compared to the standard flow rate at 31 kg/min (0.02 kg/s m²) at pumping power 450 W. The average net solar heat collected Q_{net} is between 8.62 and 14.1 kW depending on weather condition. The MPPT control of solar heating system has been verified to be able to minimize the pumping energy consumption with optimal solar heat collection.

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