OPTIMAL PERFORMANCE OF SOLAR HEATING SYSTEM

Bin-Juine Huang[1], Wei-Che Tung[2], Chen-Chun Wu[2], Hua-Wei Ko[2], Hsien-Shun Chang[2], Rue-Her Yen[2]

[1] New Energy Center, Department of Mechanical Engineering, Taipei, Taiwan

[2] National Taiwan University, Taipei, Taiwan

1. Introduction

Forced-circulation solar heating system has been widely used in process and domestic heating applications. Additional pumping power during the solar energy absorption is required to circulate the working fluid through the collector banks to absorb the solar heat. The solar heat absorbed increases with increasing flow rate as well as pumping power. A lot of solar heat systems were usually designed to operate at a flow rate given by the assigned flowrate of collector test standards, 0.02 kg m^{-2} s^{-1}, which may be over-estimated and causes large pumping power consumption.

Many researchers intended to develop an optimal control technique to reduce the pumping power at optimal solar heat collection [1-4] such as using exergy concept [2] or system optimization method [4]. The control algorithms however were very complicated and not easy to be implemented in field. In addition, no feedback control scheme was ever been applied to assure the optimal performance under variable solar radiation. In the present study, we intend to develop the technology maximum-power-point tracking control (MPPT) similar to MPPT of solar PV system and implement it in a solar heating system for field test.

2. Design of solar heating system

A solar heating system using flow-through vacuum-tube solar collector was designed and installed for experiment. The solar heating system consists of 24 sets of vacuum-tube solar collectors with 25.92 m^2 total absorber area, as shown in Fig.1. The piping is designed with 8 collectors in series and with 3 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 frequency control of the circulation pump was installed and a PC-based control system was developed to control the circulation pump. The system configuration is shown in Figure 2.

Most of solar heating systems design the flow rate according to the standard 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 0.02 L m^{-2} s^{-1} according to the test standard of collector, i.e. 31 L min^{-1} with 423 W pumping power. This may be too high and can be reduced without affecting the energy collection.

Fig. 1: Solar heating system used in present study

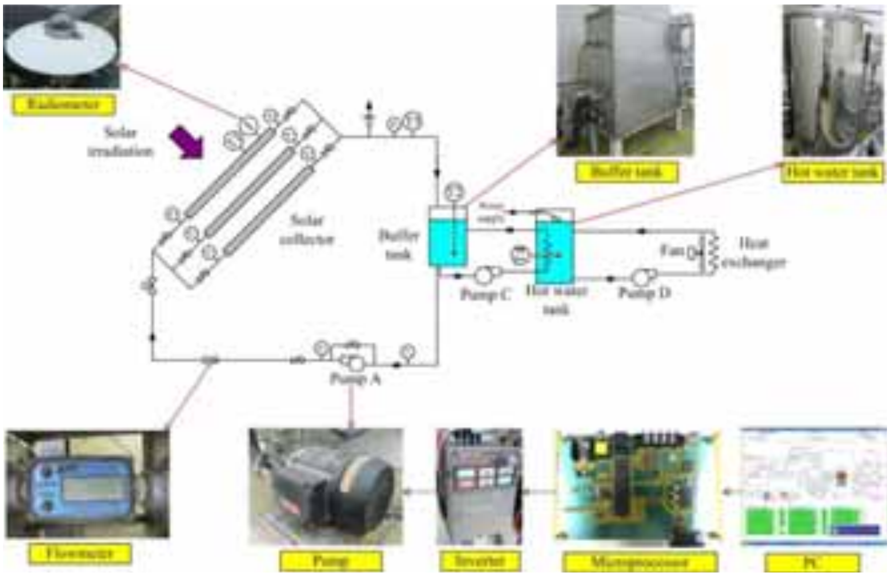

Fig. 2: Optimal control system

3. Cost function for MPPT control target of solar heating system

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

$$Q_{net} = Q_s - \frac{W_p}{\eta_e} \qquad (eq. 1)$$

where η_e is the primary energy efficiency of the electrical grid (0.365 in Taiwan). There seems exists an optimal flow rate at which the net heat collection is optimal and the pumping power is minimized. The definition of net energy gain Q_{net} is similar to the cost function of Kovarik and Lesse [4] or the exergy concept [2] and may have an optimal value as shown in Figure 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.

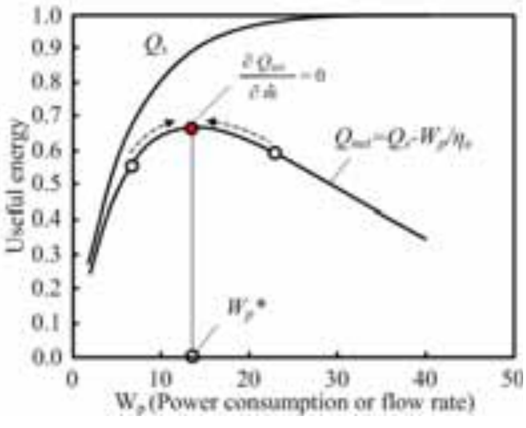

Fig. 3: Useful heat energy v.s pumping power

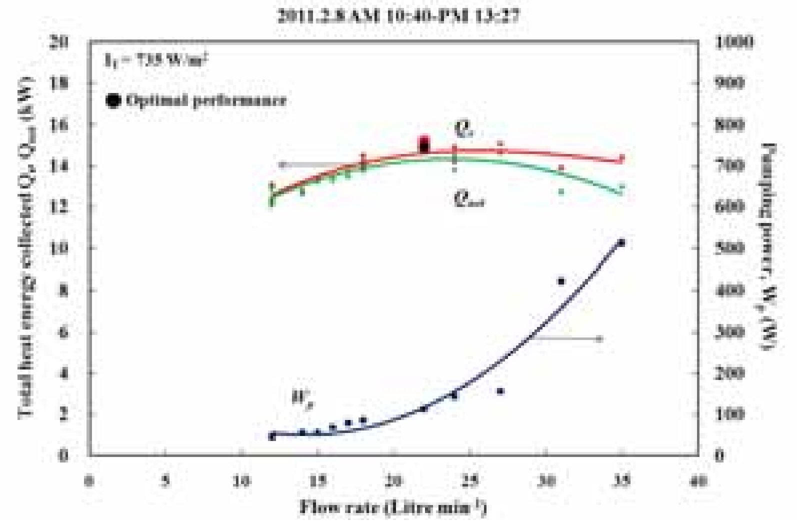

Fig. 4: Steady performance of solar heating system

A steady or quasi-steady state data were taken from field test at different mass flow rates to determine the instantaneous Q_s and Q_{net}. Figure 4 show that there exists an optimal flow rate at which the net heat gain Q_{net} is optimal. There exists an optimal Q_{net} (14.9 kW) at flow rate 22 L min^{-1}. The pumping power is 113 W with reduction of 73% pumping power and the total heat energy collected Q_s is 15.2 kW. A very high electrical COP of the solar heating system (Q_s/W_p=134.5) is obtained.

4. MPPT control system construction

4.1 System identification

The cost function existing optimal value (Q_{opt}) could be considered as MPP tracking target of solar heating system. The feedback control diagram can be designed as Figure 5 shown. The tracking filter includes the dynamic model of solar heating as eq. 2 and predicts the useful heat energy variation which would be substituted into cost function.

$$\tau \frac{dq_s}{dt} + q_s = F_R(\tau\alpha) \cdot I_T - F_R U_L \cdot (T_i - T_a) \qquad (eq.\ 2)$$

where $q_s = Q_s/A_c$, $Q_s = \dot{m} C_p (T_e - T_i)$, and τ is the time constant of the solar heating system which was determined from a step response test of the solar system (Figure 6) by shading the solar radiation at a steady state. The test result shows that τ = 237 s.

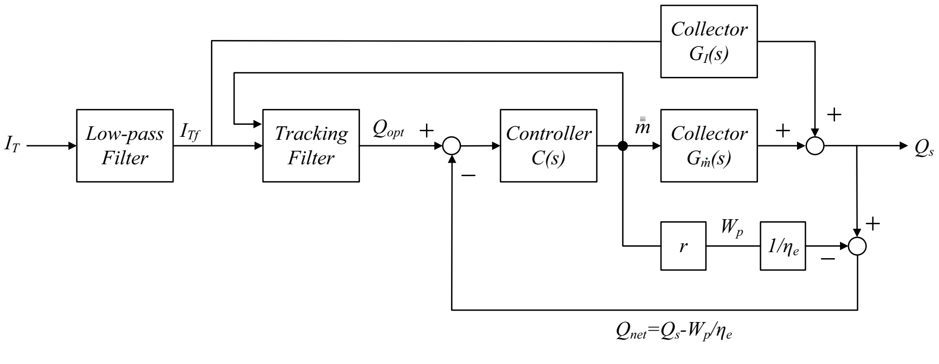

Fig. 5: Feedback control structure of MPPT

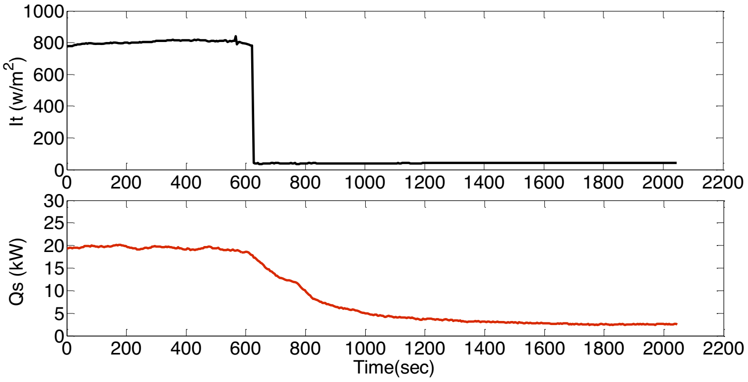

Fig. 6: Step response test of solar heating system

The two parameters $F_R(\tau\alpha)$ and F_RU_L are determined from the steady-state test data collected from field operation as shown in Figure 7. The following correlations were derived:

$$F_R(\tau\alpha) = -0.51\dot{m}^2 + 0.72\dot{m} + 0.62 \quad (eq.\ 3)$$

$$F_RU_L = -2.97\dot{m}^2 + 3.9\dot{m} - 0.14 \quad (eq.\ 4)$$

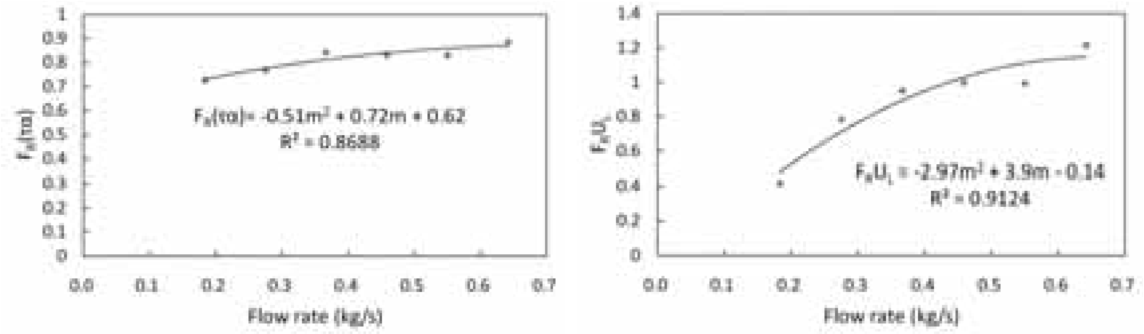

Fig. 7: Variation of $F_R(\tau\alpha)$ and F_RU_L with flowrate.

4.2 Low-pass filter design

The solar collector is a kind of low-pass system. The useful heat energy would almost not be affected by high-frequency variation of solar irradiation. A low-pass filter was designed with cut-frequency as 1/237 Hz and sampling time as 7 seconds. The transfer function of low-pass filter was derived:

$$H(z) = \frac{0.044 + 0.044z^{-1}}{1 - 0.911z^{-1}} \quad (eq.\ 5)$$

The frequency and time domain of first order low-pass filter were shown as Figure 8.

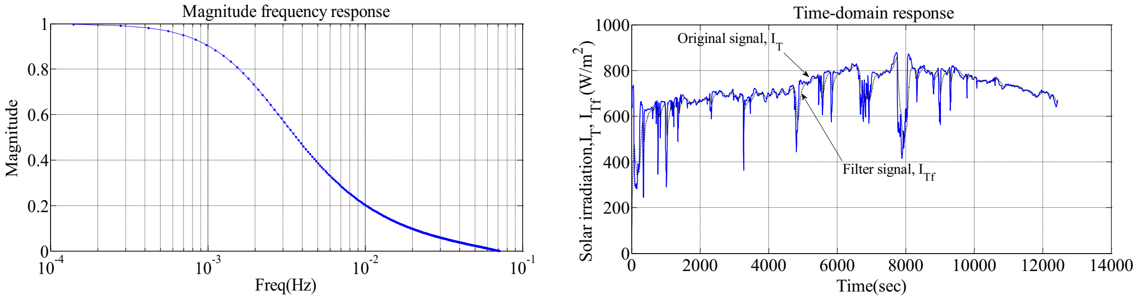

Fig. 8: 1storder filter response diagram

4.3 Tracking filter algorithm

Using the system dynamic model attained as section 4.2, the useful heat energy Q_s with different flow rates could be predicted. Substitute the Q_s into cost function and derivative by flow rate (eq. 6). The optimal cost function value, Q_{opt}, could be obtained.

$$\frac{\partial Q_{net}}{\partial \dot{m}} = \frac{\partial Q_s - W_p / \eta_e}{\partial \dot{m}} = 0 \qquad (eq.\ 6)$$

4.4 Optimal tracking controller design

The maximum cost function, Q_{opt}, calculated by tracking filter was considered as optimal control tracking target. In order to reducing the disturbance and steady state error, the PID controller was adopted in the present study. Use the program "Matlab Simulink" (Figure 9) to construct the solar heating system's dynamic model and the PID controller parameters was derived:

$$G_c(s) = 10 + \frac{0.2}{s} + 10s \qquad (eq.\ 7)$$

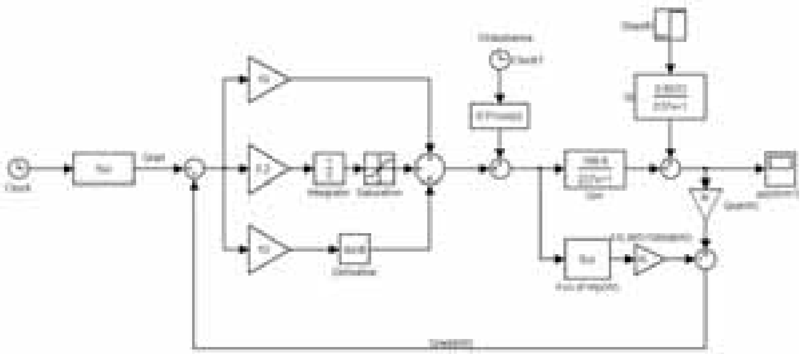

Fig. 9: Matlab simulink diagram

5. Test of solar heating system with MPPT

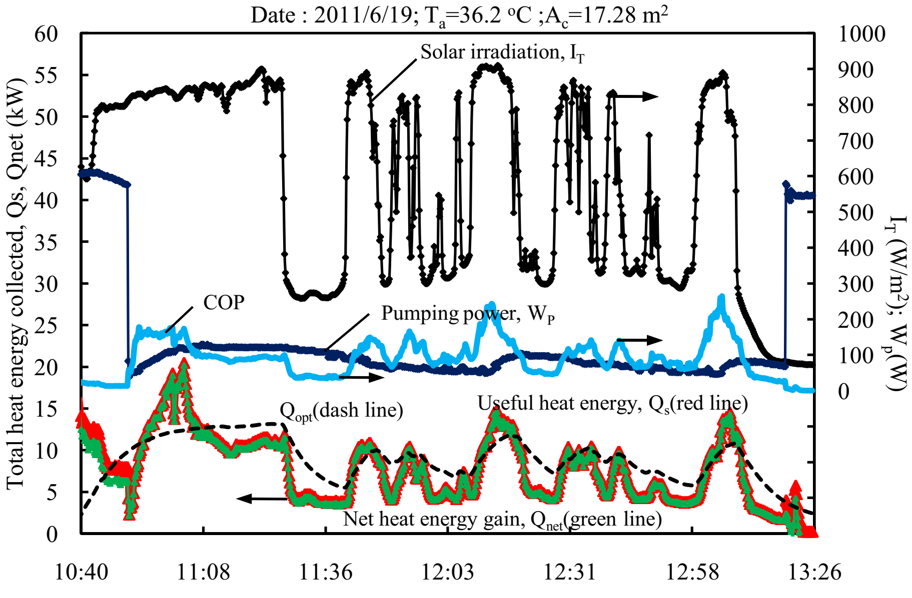

Fig. 10: Field test result at 2011/6/19

The solar heating system was tested with MPPT control. The test results from Fig. 10 show that the MPPT tracking control work well. The pumping power is between 50 W and 120 W with instantaneous energy collection Q_s is 4-20 kW. The maximum instantaneous COP is 260.5 at Q_s= 12.3 kW, pumping power 47 W and I_T= 872 W/m^2. The overall COP is 100.1 between test period AM 10:51 to AM 13:09 with average Q_s =8.43 kW and average pumping power 84.1 W.

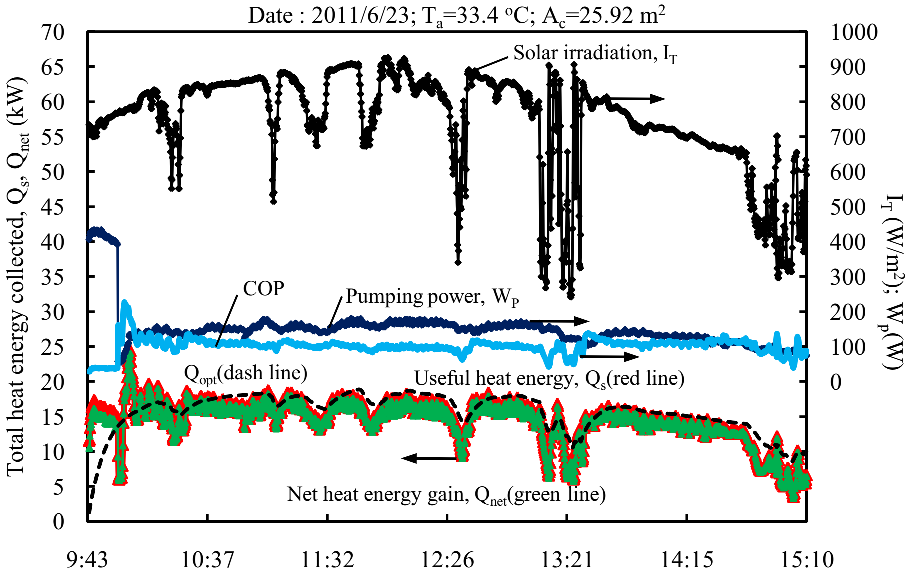

Fig. 11: Field test result at 2011/6/23

The test was also carried out for the larger collector area (25.92 m^2). The test result is shown as Fig. 11. The pumping power is between 80 W and 170 W with total energy collection Q_s is 15-18 kW during clear weather. The maximum instantaneous COP is 137.5 at Q_s = 14.7 kW, pumping power 107 W and I_T = 815 *W/m*^{2}. The overall COP is 103.9, for MPPT test period between AM 9:57 to PM 15:10, with average Q_s = 14.5 kW and average pumping power 139.8 W.

6. Conclusion

The present study developed a maximum-power point tracking control (MPPT) to obtain the minimum pumping power consumption at an optimal heat collection. The net heat energy gain Q_{net} ($=Q_s-W_p/\eta_e$) was found to be the cost function for MPPT. The optimal performance tracking controller was used in the feedback design of MPPT on Q_{opt}. The field test results show that the very high COP between field test period of solar heating system could be obtained (Q_s/W_p=103.9).

7. Acknowledgements

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8. References

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