Asheville, NC
ASES 1996

CONF-960430--3

AN INVESTIGATION OF PHOTOVOLTAIC POWERED PUMPS IN DIRECT SOLAR DOMESTIC HOT WATER SYSTEMS

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ABSTRACT

The performance of photovoltaic powered pumps in direct solar domestic hot water (PV-SDHW) systems has been studied. The direct PV-SDHW system employs a photovoltaic array, a separately excited DC-motor, a centrifugal pump, a thermal collector, and a storage tank. A search methodology for an optimum PV-SDHW system configuration has been proposed. A comparison is made between the long-term performance of a PV-SDHW system and a conventional SDHW system operating under three control schemes. The three schemes are: an ON-OFF flow controlled SDHW system operating at the manufacturer-recommended constant flow rate, an ON-OFF flow controlled SDHW system operating at the optimum constant flow rate, and a linear proportional flow controlled SDHW system with the flow proportional to the solar radiation operating under an optimum proportionality.

1.0 INTRODUCTION

The increasing use of conventional fossil fuel-based energy systems has raised concern about the impact on the environment, and has motivated several efforts to establish less damaging alternatives. This concern, and others, has led to considerable interest in renewable and sustainable energy sources, such as solar energy. The most promising potential solar energy technologies are solar domestic hot water (SDHW) systems and photovoltaic (PV) systems.

Despite the promising potential of SDHW systems, several technical obstacles remain. Among these obstacles is that an SDHW system requires an auxiliary electric source to operate a pump to circulate the fluid through the thermal collector. The collector circulating fluid flows at a constant rate and is commonly controlled by an ON/OFF differential temperature sensing controller. This controller has long been recognized as the weakest mechanism in SDHW hardware (Cromer, 1983; Argonne National Laboratory, 1981 as reported in Winn, 1993), and the device that can produce operational instabilities which make the pump cycle between ON and OFF (Beckman et al., 1994). On the other hand, photovoltaic cells can be used to power the SDHW system's pump(s) providing a continual adjustment of fluid flow, and possibly improving the system performance. Parker (1975), Merchant (1977), and Czarnecki and Read (1978) experimentally demonstrated the practicability of using a photovoltaic power source to induce the flow in an SDHW system.

The use of photovoltaic arrays to power the pumps of SDHW systems is an attractive concept because it serves two purposes. The first is that a photovoltaic pumping system can act as a fast-response sensor to solar energy and therefore pumping will only occur at the times when the thermal collectors are also receiving solar radiation. Secondly, the use of photovoltaic power source eliminates the demand for an auxiliary power source to activate the pump. The pumps of conventional SDHW systems are always operating at the same time and their operating periods include the on-peak times. Therefore, a reduction in the on-peak electricity demand is expected if photovoltaic arrays are used to power the circulation pumps.

However, the promising idea is faced with various challenges. Among these challenges is the existence of numerous configurations of direct-coupled photovoltaic systems and SDHW systems. In each configuration, there exist a discrete set of components of various characteristics.

Therefore, it is essential to establish a search methodology for an optimum configuration of a PV-SDHW system. The objective of this investigation is to optimize the design and quantify the performance of PV-SDHW systems.

Several researchers have performed comparative analysis of PV-SDHW systems versus conventional SDHW systems. However, there is not a generalized procedure to size the system components. For example, Chandra and Litka (1979) numerically investigated the possibility of replacing the conventional AC pump and controller of a direct one-tank SDHW system with a photovoltaic panel directly coupled to a DC circulating pump. The flow rate was adjusted to achieve a maximum value equal to the value of the flow rate in a conventional SDHW system. Based on the simulation of one mutually sunny day with intermittent cloud cover, Chandra and Litka found the performance of the PV-SDHW system to be slightly better than the conventional SDHW system; the solar fractions of the PV-SDHW system and the conventional SDHW system were 84.3% and 82.3%, respectively. A preliminary economic analysis was included. Mertes and Carpenter (1985) numerically monitored the performance of a photovoltaic powered indirect two-tank SDHW system with an internal heat exchanger. The performance of the PV-SDHW system was compared to the performance of a thermosyphon and a conventional SDHW system. Mertes and Carpenter found that the PV-SDHW system produced 5% more energy than a conventional SDHW system and 5% less energy than a thermosyphon SDHW system under investigation. Comparisons were made by evaluating energy savings as a function of average flows. No detailed information was given on the method of computing the average flows of the thermosyphon and the PV-SDHW systems, nor did they furnish information about the configurations of the thermosyphon and the conventional SDHW systems. Miller and Hittle (1993) investigated the integration of a photovoltaic powered pump to drive the fluid through an SDHW system employing a wrap-around heat exchanger and an immersed auxiliary energy source. Results were compared to a base system composed of an identical collector configuration, storage tank and pump. However, a collector-tank heat exchanger was not considered. Instead, a fully-stratified variable-inlet water storage tank was assumed to replace the wrap-around heat exchanger and tank system. The base system was found to perform slightly better than the proposed system. However, Miller and Hittle stated that quantitative performance data on the operation of the SDHW system were not available to verify the accuracy of the wrap-around heat exchanger tank and photovoltaic powered pump models developed in the framework of the investigation.

Several techniques to simulate the performance of PV-pumping systems and PV-SDHW systems have been proposed. For example, Chandra and Litka (1979) simulated a PV-SDHW system by developing a correlation to monitor the performance of a direct-coupled photovoltaic pumping system integrated in the PV-SDHW system. The performance data were obtained experimentally and then used to develop a subroutine to model the performance of the photovoltaic pumping system. No information was provided on the performance indicator nor the experimental setup. Miller and Hittle (1993) simulated a direct-coupled photovoltaic pumping system by generating a correlation of flow rate profile versus the solar radiation. The correlation was generated from mathematical evaluations of the flow rate at five different solar radiation levels. A linear regression analysis was used to generate a linear correlation of the flow rate as a function of the solar radiation. The flow profile correlation was used to develop a pump subroutine to perform annual simulation of the PV-SDHW system.

In regards to SDHW systems, thermal performance is influenced by the rate at which the heat transfer fluid within the system is circulated. Different SDHW control schemes have been implemented to control the flow rates. Wuestling et al. (1985) performed simulations to monitor the thermal performance of direct SDHW systems operated under several control strategies. Among these strategies were reduced constant collector flow rates and variable collector flow rates. Wuestling concluded that an improvement in the thermal performance occurs at a reduced constant flow rate (on the order of 20% that of conventional flow rates). Also, if the collector flow rate was varied proportionately to the utilizable radiation, the system performance was found to be nearly equal to the optimum reduced fixed flow performance.

2.0 OPTIMUM SEARCH METHODOLOGY

Due to the complex nature of SDHW systems, a closed form mathematical expression for the efficiency of the system, the objective function to be optimized, cannot be obtained. Therefore, the methodology for the optimization will be based on a parametric analysis. The parameters having a significant effect on the efficiency of the system will be identified, and the efficiency of the PV-SDHW system will be considered as a function of these parameters. The annual solar fraction of the SDHW, $\mathcal{F}$, will be used as a measure of the performance of the SDHW system. The flow rate profile (the flow rate $\dot{Q}$ as a function of the solar radiation G) was found by most, if not all investigators, to be the most significant factor in the efficiency of the PV-SDHW system.

The search methodology for optimizing the PV-SDHW system's components has been performed in two phases. In phase one, the goal is to find the photovoltaic pumping system's flow rate profile that maximizes the annual solar fraction $\mathcal{F}$. Analyses of typical PV-SDHW systems showed that flow rate profiles can be represented by a second degree polynomial as:

$$G = a + b\,\dot{Q} + c\,\dot{Q}^2 \qquad 1$$

where G is the solar radiation, $\dot{Q}$ is the flow rate and a, b and c are parameters. Hence, each photovoltaic pumping system profile is completely determined by the values of the three parameters a, b and c. Figure 1 depicts a curve-fitting of equation 1 to a measured flow rate profile obtained from Cromer (1983).

Therefore, the problem in this phase is to maximize the solar fraction, $\mathcal{F}$, with respect to a, b and c, or:

$$\textbf{maximize} \quad \mathcal{F}(a,b,c) \qquad 2$$

Similar analyses are performed to obtain the optimum constant flow and the optimum proportionality of the ON-OFF constant-flow SDHW system and the linear proportional flow SDHW system, respectively.

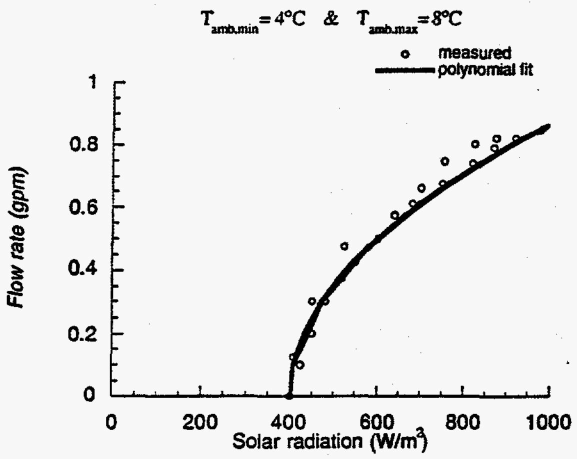

Fig. 1 Measured and fitted flow rate profile. Data obtained from Cromer (1983).

In phase two, the goal is to select the components of the pump-motor-PV array (hydraulic system). Each combination of pump, motor and PV array(s) exhibits a unique flow rate profile. Therefore, the problem is to identify the hydraulic system components that results in the best match to the optimum profile found in phase two. The objective function chosen to be minimized is the area ϕ between the profile induced by a given configuration and the optimum profile as shown in Figure 2. Hence, the problem is to minimize ϕ with respect to the hydraulic system components.

Selection of the hydraulic system components were performed given the following assumptions:

a) The photovoltaic array can be represented by N individual cells that can be grouped in different parallel P and serial S arrangements.

b) The centrifugal pump can be sized independently using the manufacturers' recommended method; the pump is chosen such that the operation of the hydraulic system occurs near the pump's maximum efficiency. Therefore the pump is eliminated from the optimization procedure.

Hence, the flow rate profile resulting from a given hydraulic system configuration can be looked at as a function of four parameters: two integer parameters P and S, and two real parameters corresponding to the values of the resistance and the coefficient of the separately excited DC-motor R_S and K_f, respectively. The problem in this phase is to minimize ϕ with respect to P, S, R_S and K_f, or:

$$\textbf{minimize} \ \phi(P, S, R_S, K_f) \qquad 3$$

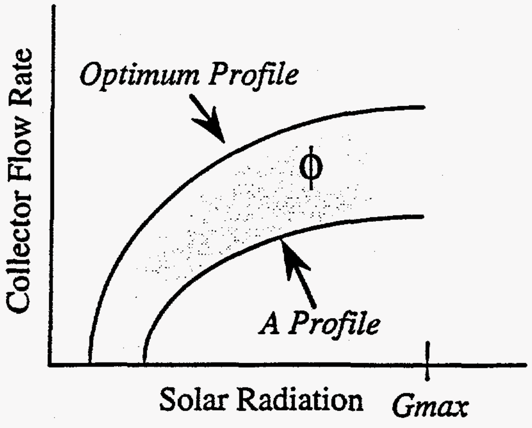

Fig. 2 Graphical representation of the function ϕ .

The mathematical model and the nomenclature for the SDHW system presented by Duffie and Beckman (1991) and the PV pumping system presented by Eckstein et al. (1990) were employed in this investigation.

3.0 RESULTS

3.1 Results of Phase # 1

Simulated Annealing (Flake, 1994) was used to search for the flow parameter set (a,b,c) that maximize the solar fraction of an SDHW system. The maximum solar fraction that can be achieved was found to be $\mathcal{F} = 0.69948$ at a=1.0302 kJ-hr/kg^2-m^2 b=0.0575 kJ/kg-m^2, and c=287.20 kJ/hr-m^2.

A closer examination of the optimum region reveals that the objective function is sensitive to the values of the parameters a and c, and is less sensitive to the value of the parameter b. Also, the objective function is almost flat, relative to the parameters a and c, at the maximum region. Figure 3 depicts a contour plot of the objective function as a function of a and c. For this plot, the value of b is set to zero.

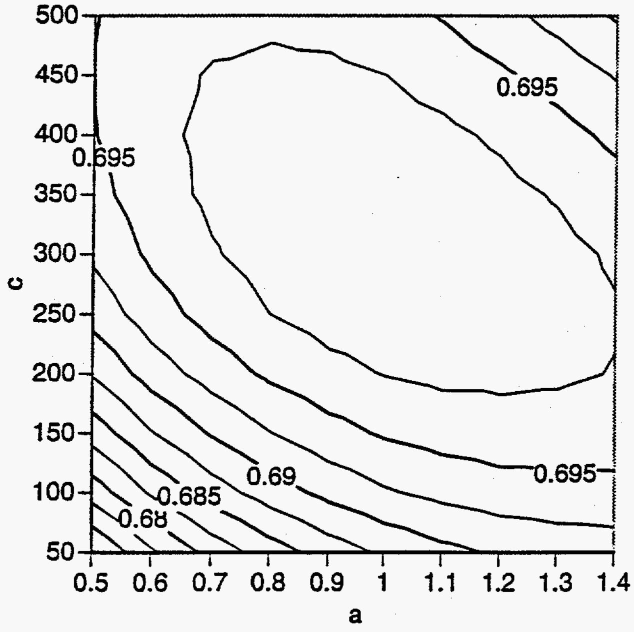

Fig. 3 Contour plot of the annual solar fraction of the SDHW system as a function of the parameter a and c. The value of the parameter b is zero.

Comparing the performance of the optimum PV-SDHW system found in this phase to the performance of the same SDHW system operating under three different control strategies reveals that the optimum PV-SDHW system is able to achieve the highest performance among all three systems. Figure 4 depicts the performance of a conventional SDHW system operating under optimum constant flow and the manufacturer-recommend flow. Figure 5 depicts the performance of a conventional SDHW system operating under a linear proportional flow controlled with the flow proportional to the solar radiation operating under an optimum proportionality.

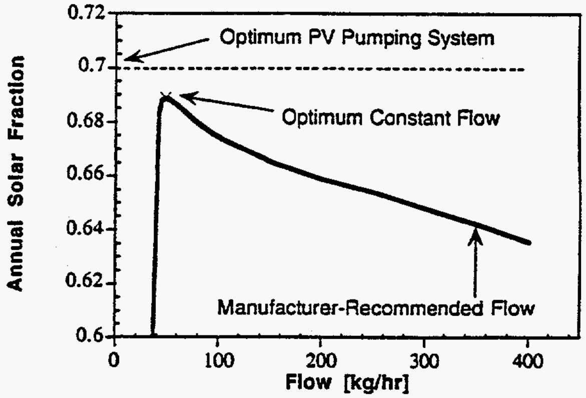

Fig. 4 Annual solar fraction of a conventional SDHW system operating under i) an optimum constant flow and ii) a manufacturer recommended ON-OFF flow controlled schemes. The value of the annual solar fraction of the optimum PV pumping system is plotted for comparison.

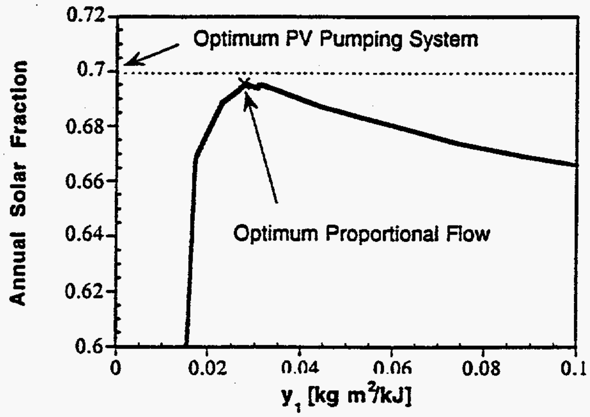

Fig. 5 Annual solar fraction of a conventional SDHW system operating under a linear proportional flow controlled SDHW system.

3.2 Results of Phase # 2

Given the optimum flow profile found from phase 1, the centrifugal pump and the hydraulic system specification, and the PV module specification, a second optimization analysis was performed. The two integer parameters P and S and the two real DC-motor parameters R_s and K_f were varied such that the optimum PV-SDHW system flow profile was matched. For the system under consideration, the optimum

PV-SDHW system profile could be reproduce by one PV module and a DC-motor that has an R_S of 40.22 and a K_f of 0.0021. Figure 6 depicts the optimum PV-SDHW system flow profile and the matched PV pumping profile.

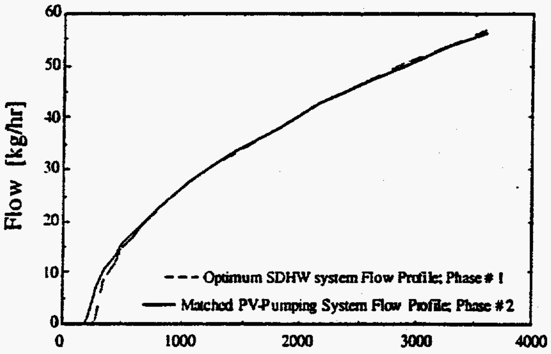

Fig. 6 The optimum SDHW and the matched PV pumping profiles.

4.0 CONCLUSION

A search methodology for the optimum configuration of a PV-SDHW system has been presented. The optimum PV-SDHW system proposed by this search methodology was found to achieve outstanding performance if compared to conventional SDHW systems.

APPENDIX A

PV and SDHW Systems Specification

Collector:
Consists of one glass cover with an area of 6.5 m2. The working fluid is water. The collector has a slope of 40° and faces due South.

Tank:
Volume of 0.39 m3 and was simulated with 5 isothermal layers.

Load:
300 kg of water per day evenly distributed over the day from 7:00 to 21:00 hours. Demand temperature is 60°C.

PV:
Short circuit current =0.385 Amp, current at the maximum power point =0.342, open circuit voltage=20.6, voltage at the maximum power point =16.63, short circuit and open circuit temperature coefficients =0.00251 & -0.0778, respectively, number of cell connected in series per module = 40. All data are measured under a solar radiation of 895 W/m^2 and a cell temperature of 323 K.

Pump:
Efficiency equation coefficients: 71428.571 & -2.55e9
Head equation coefficients: 0.45 & -5.1e8

Hydraulic System:
Static head = 0.05 m
Reference flow = 1.4 E -5 m3/s at a head of 0.35 m

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