SOME ASPECTS OF A PV/T COLLECTOR/FORCED CIRCULATION FLAT PLATE SOLAR WATER HEATER WITH SOLAR CELLS

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Abstract—Solar energy is mainly utilized via two routes—thermal and electrical. Two forms of energy are generated by two separate systems. The present work is about the study of a system which combines thermal and photovoltaic systems in one unit. The system is basically a conventional forced circulation type water heater. It is converted into a combined system by pasting solar cells directly over the absorber plate. The system equations are solved by a finite difference method. The simulations are done for different solar cell areas, mass flow rates and different water masses. The differential temperature controller, i.e. pump-off and pump-on, are used.

It is shown that the pump-on time is more or less independent of the total stagnant water mass in the collector unit. The pump-off time is a sensitive function of the water flow rate. At higher flow rates, the pump is switched off early in the afternoon. Since the total working time decreases, the efficiency also decreases. There is an optimum flow rate for which the collector efficiency is a maximum. The cell efficiency, which is a function of temperature, is calculated using an iterative method. The average cell efficiency turns out to be more or less independent of the solar cell area on the absorber plate. This result helps in saving calculation time because the total electrical energy available for any solar cell area can be calculated simply. A normal domestic solar water heater of about 2 m² generates sufficient electrical energy (after taking into account the various losses in storage, etc. and the energy required by the pump) to run 2 tube lights of 20 W each for 5 h and 1 television of 30 W for 4 h.

Photovoltaics PV/T collector Theoretical model Finite difference method

NOMENCLATURE

$A_c$ = Aperture area of collector (m²)
$A_s$ = Surface area of storage tank (m²)
$A_{so}$ = Solar cell area (m²)
$b$ = Flow tube spacing (m)
$C_w$ = Heat capacity of water (J/kg)
$d$ = Internal diameter of tube (m)
$D_h$ = Internal diameter of header (m)
$D_o$ = Internal diameter of connecting piping (m)
$D_t$ = Internal diameter of storage tank (m)
$F_r$ = Heat removal factor
$F_c$ = Collector efficiency factor
$F_f$ = Friction factor
$g$ = Acceleration due to gravity (m/s²)
$h$ = Height between collector and storage tank (m)
$K_h$ = Head loss coefficient
$L$ = Length of each tube on absorber plate (m)
$M_w$ = Mass of water in tank (kg)
$n$ = Water mass flow rate (kg/s)
$N$ = Total number of tubes on absorber plate in collector array
$P$ = Ratio of solar cell area to collector area
$\Delta P$ = Pressure drop (N/m²)
$Re$ = Reynolds number
$S$ = Solar insolation (W/m²)
$T_a$ = Ambient temperature (°C)
$T_m$ = Storage temperature (°C)
$T_{oc}$ = Outlet collector water temperature (°C)
$\Delta t$ = Time interval (s)
$U_h$ = Heat loss coefficient for collector (W/m²°C)
$u$ = Flow mean velocity (m/s)
$\rho$ = Density of water (kg/m³)
\( \delta h_{\text{total}} = \) Total head loss due to connecting pipes, tubes, bends, tees, etc.
\( \alpha = \) Absorptance of absorber plate
\( \tau = \) Transmittance of glass cover
\( \eta_c = \) Efficiency of solar cell
\( \eta_{\text{col}} = \) Collector efficiency
\( \eta_{\text{PV/T}} = \) Daily efficiency of (PV/T) system

**INTRODUCTION**

During the last two decades, utilization of solar energy has increased considerably. As a result of concentrated efforts by a community of scientists all over the globe, several systems have reached near perfection. Two of the systems which have been discussed most are flat plate collectors and photovoltaic systems. These two systems are used in different applications and also separately. Recently, in order to decrease the overall cost of the solar systems, a new kind of system, photovoltaic–thermal (PV/T) or hybrid system, has been proposed [1–3]. It is basically a flat plate collector with the solar cells pasted directly over the absorber plate. Such a system would generate both kinds of energy, i.e. thermal and electrical, simultaneously from the same panel. It would certainly be less expensive than the two separate units, one each for thermal and photovoltaic.

So far, hybrid systems have received very scant attention. Only a few authors have discussed these systems. In this work, we present a study of a forced flow solar water heater which is converted into a hybrid system. The hybrid system is studied theoretically. The first order differential equations are solved by a finite difference method. Since the efficiency of a solar cell depends on the absorber plate temperature, which is unknown in the beginning, an iterative method is used to solve the system equations.

When a pump is used between the collector and the storage unit, a system is used to switch on the pump and switch it off in the evening. The pump-on time is calculated from the rise in stagnant water temperature. When it reaches a predetermined temperature, the pump is switched on. It is found that the pump-on time is not a sensitive function of the stagnant water mass in the collector. In contrast, the pump-off time is a sensitive function of the water flow rate. Since, as the water flow rate increases, the total operating time of the pump decreases, the efficiency of the collector would also decrease. There would exist a flow rate for which the efficiency would be maximized. The system efficiency is maximized when the flow rate is \( \approx 0.03 \text{ kg/s} \).

The cell efficiency is found to be more or less independent of the cell area over the absorber plate. This is an interesting result in the sense that calculations can be done for only one cell area. The total available electrical power from the panel is then obtained simply by multiplying the average cell power/m² by the cell area under consideration.

A hybrid system should be self-sufficient in the sense that the power required by the pump should be provided by the solar cells. The solar cell area necessary to supply energy to the water pump is calculated. It is seen that the pumping power is very little, hence the required solar cell area is very small. If more solar cell area is used, then one could have sufficient electrical energy to run some domestic utilities.

It is shown that, if a 2 m² collector is completely covered by solar cells, it could provide sufficient energy to run 2 tube lights of 20 W each for 5 h and 1 television of 30 W for 4 h. The available electrical energy is obtained after taking into account the energy losses in the storage and the energy consumed by the pump.

**MODEL FORMULATION**

The single domestic system analysed in this work is shown in Fig. 1. The hot water storage tank is located at its usual position near ground level, and the solar panel is mounted on the roof.

The system has two separate units; a storage tank and a flat plate collector, which are connected to each other through pipes. The water is circulated by a pump. In order to simplify the formulation, it is assumed that the pipes connecting the storage unit to the collector unit are well insulated so that there is no heat loss through them. The energy is absorbed only by the collector unit. Part of the energy falling on the collector is used in heating water and the rest is lost. The tank only loses energy. The inlet water temperature to the collector would be the same as the mean storage tank water temperature. The temperature of the water entering the tank would be the same as the outlet water temperature of the collector.
If \( q_u \) is the quantity of heat collected by the water, then the heat balance equation for the collector gives

\[
q_u = A_c F_R [S\tau - U_L (T_m - T_a)]
\]  
(1)

where \( F_R \) is the heat removal factor and is given by

\[
F_R = \frac{\dot{m}c_w}{A_c U_L} \left[ 1 - \exp\left( -\frac{A_c U_L F'}{\dot{m}c_w} \right) \right]
\]  
(2)

where \( F' \) is the collector efficiency factor (0.841).

The useful energy \( q_u \) collected by the water in terms of its temperature rise is also written as

\[
q_u = \dot{m}c_w (T_{out} - T_{in}).
\]  
(3)

It gives

\[
T_{out} = T_m + \frac{q_u}{\dot{m}c_w}
\]  
(4)

as, by assumption, \( T_m = T_{in} \).

The energy collected by the collector is transferred to the storage tank. If the tank is assumed to be at mean temperature, \( T_m \), then the heat balance equation for the tank would be

\[
q_u = M_w C_w \frac{dT_m}{dt} + U_S A_S (T_m - T_s).
\]  
(5)

The energy balance equation for the whole system, thus, becomes

\[
A_c F_R [S\tau - U_L (T_m - T_a)] = M_w C_w \frac{dT_m}{dt} + U_S A_S (T_m - T_s).
\]  
(6)

**Photovoltaic/thermal system (PV/T)**

The main aim of the present study is to study a hybrid system in which the photovoltaic and thermal systems are integrated. The conventional thermal system described before is converted into a hybrid system by pasting solar cells directly over the absorber plate. In the hybrid system, the absorption of solar radiation is no longer simple because the solar cells have different absorption characteristics than that of the black metallic absorber plate. In order to simplify the analysis, the following assumptions are made:

(i) The part of insolation which is not converted into electrical energy is transmitted to the absorber plate and is absorbed there,
(ii) The radiative properties of the absorber plate and the front part of the cells are the same, and
(iii) The cells are at the mean temperature of the absorber plate.

In the presence of the solar cells, equation (6) should be modified. It now becomes

$$F_R \alpha S \left( A_C - A_{cell} \eta_c \right) - F_R U_L A_C (T_m - T_a) = M_w C_w \frac{dT_m}{dt} + U_S A_S (T_m - T_a)$$

(7)

where $\eta_c$ is the solar cell efficiency at the mean absorber temperature, $T_p$, and $A_{cell}$ is the solar cell area.

The cell efficiency is a function of the cell temperature. The variation of cell efficiency with temperature is calculated from the following linear relation (4).

$$\eta_c = \eta_r \left( 1 - \frac{T_p - T_r}{T_c^* - T_r} \right)$$

(8)

when $\eta_r = 10\%$, the cell efficiency is evaluated at the reference temperature, $T_r = 25^\circ C$. Since the cell efficiency decreases as its temperature increases, at some temperature, it would become zero. $T_c^*$ is the cell temperature at which the efficiency drops to zero. It is taken as $270^\circ C$. The temperature of the absorber plate in terms of the collector parameters is given by

$$T_p = \frac{S (\alpha S (A_C - \eta_c A_{cell}) - A_C \eta_{cell})}{U_L A_C} + T_a.$$ 

(9)

**Pumping power**

The system considered is a forced flow type. A pump is required to circulate water through the system. The pump would need electrical energy. Part of the electrical output of the solar cells would be utilized in running the pump. Thus, in order to determine the net electrical energy available from the hybrid system, it is necessary to know the total energy required by the pump to maintain a constant flow through the collector. The pumping power is calculated as follows [5, 6]. The frictional pressure drop is given by

$$\Delta P = \rho g \delta h_{total}$$

(10)

where

$$\delta h_{total} = \delta h + \delta h_f + \delta h_{buoy}.$$ 

(11)

$\delta h$ is the head loss due to the frictional resistance encountered by the flowing water and is given by

$$\delta h = 4 f \frac{1}{D} \frac{u^2}{2g}$$

(12)

where $u$ is the mean flow velocity of water in the system and is given by

$$u = \frac{m}{\rho \pi D^2 / 4}$$

(13)

The frictional factor, $f$, for laminar and turbulent flow, respectively, is as follows

$$f = \frac{16}{Re} \quad \text{for laminar flow}$$

$$= \frac{0.079}{(Re)^{1/4}} \quad \text{for turbulent flow}.$$ 

The Reynolds number is written as

$$Re = \frac{\rho u D_p}{\mu}.$$ 

(14)

The head loss due to fittings, bends, etc. is defined as

$$\delta h_f = K \frac{u^2}{2g}.$$ 

(15)
Table 1. The value of $K_t$ for some kinds of fittings

<table>
<thead>
<tr>
<th>Type of fitting or value</th>
<th>$K_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45° elbow</td>
<td>0.35</td>
</tr>
<tr>
<td>90° elbow</td>
<td>0.75</td>
</tr>
<tr>
<td>Globe valve</td>
<td>9.5</td>
</tr>
<tr>
<td>Gate valve</td>
<td>4.5</td>
</tr>
<tr>
<td>Tee</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$K_t$ is a constant which is different for different kinds of fittings. The values used in the calculations for the different fittings are shown in Table 1.

The third term $\delta h_{\text{buoy}}$ in equation (11) is due to the buoyancy of the hot water. It depends on the water temperature. In order to simplify the calculations, this term is evaluated at a mean temperature of 45°C. At this reference temperature, the buoyancy head is given by the following expression.

$$\delta h_{\text{buoy}} = \frac{\rho \text{ at } (45 - \Delta T/2) - \rho \text{ at } (45 + \Delta T/2)}{\rho \text{ at } 45°C} \cdot h$$

where $h$ is the height between the collector and the storage tank and is 3.35 m. $\Delta T$ is the temperature rise in the water. The power required to circulate water through the system at a mass flow rate $\dot{m}$ is

$$\text{Power} = \frac{\dot{m} \Delta P}{\rho}.$$  

**STORAGE OF ELECTRICAL ENERGY**

The electrical energy generated by the hybrid panel is stored in batteries for use during the night for running the television, fans or for lighting. The instantaneous photovoltaic energy generated by the panel is given by [7].

$$P_E = S \eta_c A_{\text{cell}}.$$  

The total daily photovoltaic energy is obtained by integrating the above equation. About 90% of this energy is stored in a battery. When an appliance uses energy from the battery, about 80% of the stored energy is available. Thus, only about 72% of the energy generated by the photovoltaic panel is converted into useful energy.

For the PV/T system, three kinds of efficiencies are defined:

For the collector alone, it is defined as

$$\eta_{\text{col}} = \frac{\dot{m} c_w (T_{out} - T_m)}{SA_c}.$$  

The average daily solar cell efficiency is defined as

$$\eta_{\text{cell}} = \frac{\text{Total electrical energy output}}{\text{Total solar insolation}} = \frac{\int P_E \, dt}{A_{\text{cell}} \int S \, dt}.$$  

The daily efficiency of the PV/T system is defined as

$$\eta_{\text{PV/T}} = \frac{\text{Total thermal energy + total electrical energy}}{\text{Total insolation over the collector}}$$

$$\eta_{\text{PV/T}} = \frac{M_w c_w (T_{final} - T_{initial}) + \int P_E \, dt}{A_c \int S \, dt}.$$  

**CONTROLS**

When a pump is used, controls are provided to switch it on in the morning when sufficient solar radiation is available. It is switched off in the evening when the collector outlet water temperature
is slightly above or equal to the inlet water temperature. Two types of control schemes [8] are commonly used on solar collectors: on-off and proportional. With an on-off controller, a decision is made to turn the circulating pump on or off depending on whether or not useful output is available from the collector. With a proportional controller, the pump speed is varied such that a specified temperature level at the collector outlet is maintained. The differential controller is more common. A typical differential thermostat controller consists of two sensors; one sensor which measures the collector temperature and a second which measures the storage temperature. When fluid is not flowing, the mean plate temperature, $T_p$, is taken equal to the stagnant water mass temperature, $T_{wt}$, in the collector. When the plate temperature at no flow conditions exceeds a predetermined temperature compared to the tank temperature, $T_{in} + \Delta T_{on}$, the pump is turned on. In order to avoid oscillations of the pump, $\Delta T_{on}$ is taken between 8 and 11°C. In this work, we have taken $\Delta T_{on} = 8°C$. At the no flow condition, the heat balance equation for the collector would be

$$S = PM_w C_w \frac{dT_{wt}}{dt} + U_L (T_{wt} - T_s)$$

(22)

where $PM_w$ is the water mass per m² collector area.

During the evening hours, when sufficient solar energy is not available, the pump must be switched off. The control senses the collector outlet water temperature and compares it with the collector inlet water temperature. As soon as $T_{out} - T_{in} \leq 2°C$, the pump is switched off.

![Fig. 2(a, b). The hourly solar radiation and ambient temperature.](image)
Table 2. Numerical values of the design parameters of the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>2 m$^2$</td>
</tr>
<tr>
<td>$A_s$</td>
<td>1.9 m$^2$</td>
</tr>
<tr>
<td>$b$</td>
<td>0.10 m</td>
</tr>
<tr>
<td>$C_w$</td>
<td>4190.0 J/kg °C</td>
</tr>
<tr>
<td>$d$</td>
<td>$1.9 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>$D_h$</td>
<td>$2.54 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>$D_p$</td>
<td>$2.54 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>$D_{st}$</td>
<td>$0.36 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>$g$</td>
<td>9.80 m/s$^2$</td>
</tr>
<tr>
<td>$N$</td>
<td>16</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1000 kg/m$^3$</td>
</tr>
<tr>
<td>$U_t$</td>
<td>6.0 W/m$^2$ °C</td>
</tr>
<tr>
<td>$U_s$</td>
<td>3.0 W/m$^2$ °C</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>10 s</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The meteorological data used in this work are for 11 May 1988 and for 22 January 1989. The hourly solar radiation and ambient temperature are shown in Figs 2(a) and (b).

In an earlier work, experimental and theoretical results were reported for a thermosyphon system. In the present work, the same system is studied, but it is a forced flow system. The physical characteristics and some of the parameters used in the present work are shown in Table 2.

Equation (22) which governs the pump-on time and equation (6) which governs the behaviour of the system are first order differential equations. They are solved by a finite difference approach. An interval of 10 s was found to be satisfactory. The solar radiation and ambient temperature are known only at hourly intervals. In order to evaluate these at 10 s intervals, two methods could be used. In one method, a linear fit is made for the data between 2 h. From the linear fit, data at the required interval are obtained. In another method, used in this work, it is assumed that the data can be represented by a time series (Fourier series). Six harmonics represent the data quite well. The Fourier coefficients are determined from the data. These are then used to determine the data at the required times.

The solution of the system equations for only the water heater is straight forward. The problem arises for the hybrid system because equation (7) contains a term $\eta_c$, which is the solar cell efficiency at a mean plate temperature, $T_p$. In the beginning, $T_p$ is unknown and so is $\eta_c$. An iterative method is used. To start, the cell efficiency is assumed to be 10%. The system equations are solved, and the mean absorber temperature is calculated. At this absorber temperature, the cell efficiency is obtained from equation (8). With the new cell efficiency, the calculations are repeated. The process is continued until the difference between two successive values of cell efficiency is less than 1%. It is found that only two or three iterations are sufficient. In the hybrid system, a new parameter, that is cell area, appears. The system performance will depend on the cell area. A dimensionless parameter $P$ is defined as follows.

$$P = \frac{A_{\text{cell}}}{A_c}$$  \hspace{1cm} (23)

For $P = 0$, the system is a simple water heater, while for $P = 1$, the whole collector area is covered by solar cells.

Two kinds of solar cells are available, square and circular. If square shaped cells are used, then the whole absorber area could be covered by solar cells, or $P$ can be made as 1. Square cells are expensive and normally not available on the Indian market. For circular cells of 10 cm dia, the maximum absorber area covered by solar cells will be 0.75 m$^2$.

In the morning, until the pump is on, water does not circulate through the collector. When the sun rises, the water and absorber temperatures start rising. The pump-on time is calculated from equation (22). As soon as $T_{wt} > T_{in} + 8$ °C, the pump starts. The pump-on time for a given collector will depend mainly on two factors; solar isolation and the amount of water in the collector. In Table 3, the dependence of $t_{on}$ on the stagnant water mass for two sets of weather data is shown. For
Table 3. Pump-on time as a function of total water mass in the collector unit

<table>
<thead>
<tr>
<th>Collector stagnant water mass (kg/m²)</th>
<th>Pump-on time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
</tr>
<tr>
<td>8.0</td>
<td>7:21:20</td>
</tr>
<tr>
<td>12.0</td>
<td>7:29:10</td>
</tr>
<tr>
<td>16.0</td>
<td>7:36:20</td>
</tr>
<tr>
<td>20.0</td>
<td>7:42:40</td>
</tr>
</tbody>
</table>

a given area, the collector water mass in the collector can be increased by increasing the number of tubes, i.e. by decreasing the tube spacing. It is seen that the pump-on time is not a sensitive function of the stagnant mass. It does depend on the level of solar insolation and ambient temperature because, in the winter months, the pump starts late.

The pump-off time, $t_{off}$, as a function of the mass flow rate is shown in Fig. 3 for three values of total water in the tank. It is seen that, as the mass flow rate increases, $t_{off}$ drops sharply. At higher flow rates, the system efficiency would be higher because the average working temperature of the absorber would be lower. However, since the total operating time is less, the overall efficiency would be less, thus there should exist an optimum flow rate for which the collector efficiency would be a maximum. This is clear from Fig. 4 where the average daily thermal efficiency as a function of the mass flow rate is shown. The maximum efficiency occurs for a mass flow rate around 0.03 kg/s or 108 kg/h. This is an interesting result.

In Fig. 5, the temperature of the tank water as a function of time is shown for two different cell areas, for four mass flow rates and for two total water masses. It is seen that the maximum water temperature decreases as the cell area increases and also as the total water mass increases. However, the difference in temperature for the two cases, $P = 0$ and $P = 1$, is very little. At $m = 0.03$ kg/s and $M_w = 100$ kg, the maximum temperature for $P = 0$ is about 76.6°C, while for $P = 1$, it is about 73.3°C. If, for the same flow, the total water mass becomes twice as big, i.e. $M_w = 200$ kg, the maximum temperature for $P = 0$ is about 59.2°C, while for $P = 1$, it is about 57.3°C. Thus, the total water mass has the more pronounced effect on the storage temperature.

It is also seen from the same figure that, at $M_w = 100$ kg, for a mass flow rate, $m = 0.03$ kg/s, the maximum temperature, $T_{max}$, is reached at 4.15 p.m. while for $m = 0.09$ kg/s, $T_{max}$ is reached at 1.00 p.m. In Fig. 6, the instantaneous collector efficiency as a function of time is shown for two different cell areas and for two total water masses. The collector efficiency decreases as time increases and increases as the mass flow rate increases. The collector efficiency is more at $P = 0$ than at $P = 1$.

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![Fig. 3. The variation of pump-off time for three water masses with different mass flow rates.](image-url)
In Fig. 4, the effect of mass flow rate and fraction of collector area, $P$, covered by solar cells, on average daily thermal efficiency for three water masses.

In Fig. 7, the cell efficiency as a function of time is shown for some design parameters. At a mass flow rate, $\dot{m} = 0.03$ kg/s, it is seen that the cell efficiency decreases with time and is minimized when the solar insolation is a maximum. This is expected because, at this time, the absorber temperature is a maximum. After this hour, the cell efficiency increases until the water temperature is a maximum. The cell efficiency decreases suddenly afterwards, but after a little time, it starts increasing. When the collector outlet water temperature becomes less than the storage water tank temperature, the flow rate through the collector becomes zero. Solar insolation is still falling on the collector. Since no heat is removed by the water from the collector the absorber temperature, instead of decreasing, increases. A sudden increase in plate temperature decreases the cell efficiency.

At a mass flow rate, $\dot{m} = 0.09$ kg/s, the cell efficiency drops up to 9:00 a.m. and then suddenly increases because, at this time, the pump is switched on. The water starts circulating and decreasing the absorber temperature. The water circulates up to 1:00 p.m. and then the pump is switched off. The absorber plate temperature increases, and the solar cell efficiency decreases suddenly afterwards, but after a little time, it starts increasing.

In Fig. 8, the average cell efficiency, average daily PV/T efficiency and storage temperature as a function of mass flow rate is shown for three different cell areas, i.e. $P = 0$, $0.5$ and $1.0$, for three total water masses, $M_w = 100$, $150$ and $200$ kg. The average cell efficiency and the average daily PV/T efficiency increase as the total water mass increases, but the maximum storage temperature decreases as the total water mass in the system increases.

**UTILIZATION OF ELECTRICAL ENERGY**

The electrical energy generated by the cells could be utilized directly or first stored in a battery and then used later. The second alternative should be preferred because the panels do not generate power at a constant rate. Furthermore, electrical energy is often required during the night time.
The energy generated by the panels is stored in a battery. Some energy is lost in the charger. The d.c. output of the battery is first converted into a.c. Some energy is also lost here. The efficiency of the appliances, like tube lights or fans, is not 100%. Some energy would also be lost here. If all the various intermediate energy losses are taken into account, then only about 70% of the photovoltaic output is converted into useful energy. In Table 4, the useful available energy for some combinations is shown. The average cell efficiency is more or less independent of $P$. For $P = 1$, the photovoltaic output is about twice that for $P = 0.5$. This is an interesting result. One can calculate the available energy for any value of $P$.

It is seen that, for $A_c = 2.0 \text{ m}^2$, $P = 1.0$, $M_w = 100 \text{ kg}$ and $\dot{m} = 0.03 \text{ kg/s}$, about 340.9 Wh/day of useful electrical energy would be available. This is sufficient to run two tube lights of 20 W for 5 h and 1 black and white television of 30 W for 4 h. In India, television transmission for rural areas is about 4 h. If bigger collectors are used, then one could use more appliances.

**CALCULATION OF POWER FOR PUMP**

The collector unit consists of a single glazed, optimized aluminium flat plate absorber. It consists of 16, 1.46 m long, 1.9 cm o.d. galvanized iron tubes brazed longitudinally at 8 cm pitch across an aluminium sheet. The total harnessing area of the collector is 2.0 m$^2$. The tubes are joined at the ends by 2.54 cm o.d. GI headers. It is assumed that the collector unit is connected to an insulated galvanised iron (GI) sheet storage tank via 2.54 cm o.d. insulated GI pipes. The storage tank is 1.5 m long and 36 cm dia. The surface area of the tank is 1.91 m$^2$ and to all of this surface is affixed an 8.0 cm uniformly thick layer of glass wool insulation.

![Fig. 5. The effect of mass flow rate and fraction of collector area, $P$, covered by solar cells, on the storage tank temperature with time for two water masses.](image-url)
With the help of equations (11)–(16), the total head loss has been calculated. For the system described above, it comes to $\delta h_{\text{total}} = 222.0$ mm. Putting the value of $\delta h_{\text{total}}$ in equation (10), the pressure drop can be calculated.

$$\Delta P = 1000 \times 9.8 \times 222.0 \times 10^{-3} = 2175.6 \text{ N/m}^2.$$ 

Hence,

$$\text{Power} = \frac{0.03 \times 2175.6}{1000} = 0.065 \text{ W}.$$ 

The pump operates for 8 h. The total energy needed for the whole duration of the pump is 0.52 Wh.

For the mass flow rate, $m = 0.07$ kg/s, the pump power is 0.176 W. If the pump operates only for 5 h, then the total energy needed for the whole duration of the pump is 0.88 Wh.

The energy generated by one silicon solar cell of 10 cm dia (area of the cell $A_{sc} = 7.85 \times 10^{-3}$ m$^2$) is determined as follows:

The energy available from one cell for 1 day is

$$E_{sc} = n_{e} A_{sc} \int s \, dt.$$ 

Here,

$$n_{e} = 8\%, \quad A_{sc} = 7.85 \times 10^{-3} \text{ m}^2, \quad \int s \, dt = 6.2 \text{ kWh/m}^2.$$
Hence,

\[ E_{\text{sc}} = 3.89 \text{ Wh}. \]

However, because the starting current of the pump unit was somewhat higher than its running value, it would not self-start on one solar cell until the insolation had reached a suitable value. Once started, it would only stall when the insolation decreased to 0.20 kW/m\(^2\).

Table 4. Useful electrical energy with different fractional areas of collector covered by solar cells

<table>
<thead>
<tr>
<th>Mass flow rate (kg/s)</th>
<th>( M_w = 100 \text{ kg} )</th>
<th>( M_w = 150 \text{ kg} )</th>
<th>( M_w = 200 \text{ kg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>( P = 0.5 )</td>
<td>7.65 238.2 166.7</td>
<td>238.2 7.83 244.9 171.4</td>
<td>244.9 7.94 248.5 173.9</td>
</tr>
<tr>
<td>( P = 1.0 )</td>
<td>7.69 482.0 337.4</td>
<td>241.0 7.87 492.3 344.6</td>
<td>246.2 7.98 499.3 349.5</td>
</tr>
<tr>
<td>( P = 0.5 )</td>
<td>7.71 241.4 168.9</td>
<td>241.4 7.90 247.0 172.9</td>
<td>247.0 8.07 252.6 176.8</td>
</tr>
<tr>
<td>( P = 1.0 )</td>
<td>7.76 485.4 339.8</td>
<td>242.7 7.93 496.5 347.6</td>
<td>248.3 8.11 507.5 353.2</td>
</tr>
<tr>
<td>( P = 0.5 )</td>
<td>7.29 227.9 159.6</td>
<td>227.9 7.73 241.8 169.3</td>
<td>241.8 7.83 244.9 171.4</td>
</tr>
<tr>
<td>( P = 1.0 )</td>
<td>7.35 459.6 321.7</td>
<td>229.8 7.77 486.4 340.5</td>
<td>243.2 7.87 492.5 344.7</td>
</tr>
<tr>
<td>( P = 0.5 )</td>
<td>7.07 221.2 154.8</td>
<td>221.2 7.43 232.4 162.6</td>
<td>232.4 7.50 234.6 164.2</td>
</tr>
<tr>
<td>( P = 1.0 )</td>
<td>7.15 447.5 313.2</td>
<td>223.7 7.48 468.0 327.6</td>
<td>234.0 7.55 472.5 330.7</td>
</tr>
</tbody>
</table>

(1) Average cell efficiency (%); (2) total available energy (Wh/day); (3) useful or actual energy (Wh/day); (4) available energy (Wh/day m\(^2\)).
Fig. 8. The effect of mass flow rate and fraction of collector area, \( P \), covered by solar cells, on the average daily solar cell efficiency, average daily PV/T efficiency and maximum storage temperature for three water masses.

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