APPLICATION OF SOLAR ENERGY IN TEA PROCESSING

by

M.W. Leelaratne

Abstract

In this paper the exploitation of solar energy for local tea manufacture has been studied in detail. This is only a theoretical one, carried out on a computer simulation programme, based on the actual data collected from the energy surveys conducted in tea industry by the Energy Management Centre of the NERD Centre.

The availability of solar energy was taken as 60% on the average for both up country and low country. Exploitation of solar energy was considered separately for Withering and Drying due to the different working temperatures of the two processes. Withering was very attractive for use of solar energy with respect to its very low working temperatures. Hence, more than 60% of the thermal energy requirement could be supplied by solar energy conveniently. In contrast to this, for Drying the solar energy could be considered only as a pre heating arrangement for working air which should be heated up to about 100°C. Therefore, the study revealed that for drying about 10% of the thermal energy requirement could be supplied by solar.

With regard to the savings possible one has to compare the results with the present energy crisis in the country. Savings may be as high as 39 million rupees per annum resulting from the reduction of more than 350,000 cu.yd of fire wood consumption. Moreover, the use of solar would invariably improve the environmental sanitation as it does not produce any pollution materials. The equipment needed to implement such a solar energy programme could be easily manufactured locally and the costs involved are very well paid back. The theoretical simple pay back periods ranges from 20 to 28 months. In the wake of the present energy crisis this should be a great relief to the country.

Introduction

This study is based on the actual data collected from field tests, carried out during energy surveys, in some of the selected tea factories in Sri Lanka. The prime objectives of this study is to ascertain the feasibility of exploiting solar energy to local tea manufacture where a large amount of fire wood and diesel oil are being used to produce hot air for withering and drying.

Since Sri Lanka being an equatorial country and therefore has been blessed with bounty of solar radiation, the time has come, in the wake of the present energy crisis, to exploit this abandon source of free energy for commercial use. Much work is being done towards this at a few research organisations in the country to find out its potential for local applications. Since Sri Lanka is a non oil producing country and having the problem of continuous forest depilation, the consumption of conventional sources of energy will have, in the long run, some adverse effects on her economy and future well being of the country. It is, therefore, worthwhile to divert our attention to see the possibility of harnessing the solar energy for tea processing, where possible.

1. Some Operating Aspects of Withering & Drying in Tea Processing

Basically there are two distinct moisture removal operations in tea processing namely,

a) Low temperature slow moisture removal, referred to as WITHERING, done at the very beginning of the process.

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b) High temperature fast moisture removal, referred to as DRYING, done at the very end of the process.

Green tea leaves contain, on the average, about 76% moisture by weight. Tea processing removes approximately 96% of this moisture by both withering and drying of which withering removes 46% and drying 53%. It follows that in a typical tea factory (10,000 kg of green leaves per day) in Sri Lanka, the amount of thermal energy needed for these two operations has been estimated to be about 6885 kWh per day for up country (both withering and drying) and to be about 4225 kWh per day for low country and mid country (drying only). As these two processes require very large amount of thermal energy (figures are given above) it is clear that consumption of conventional fuels are comparatively large. Presently, hot air needed for these two operations is being generated either by firing wood or diesel oil.

1.1 Withering and Drying Times

The operating schedule of Troughs and dryers of some of the up country and low country tea factories are given below. These are general operating times and may vary slightly around them depending on the other operations of the factory.

### Withering

<table>
<thead>
<tr>
<th>Factory</th>
<th>Location</th>
<th>Withering Times</th>
<th>Day % from Time</th>
<th>Total Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC 1</td>
<td>N'Eliya</td>
<td>11.00am to 8.00 am next day</td>
<td>6.5 120 %</td>
<td>4.5 hrs</td>
</tr>
<tr>
<td>UC 2</td>
<td>Watawela</td>
<td>11.00am to 7.30am next day</td>
<td>6.5 121 %</td>
<td>4.5 hrs</td>
</tr>
</tbody>
</table>

### Drying

<table>
<thead>
<tr>
<th>Factory</th>
<th>Location</th>
<th>Dryer Operating Hours</th>
<th>Day % from Time</th>
<th>Total Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC 1</td>
<td>Elpitiya</td>
<td>8.00am to 2.30am</td>
<td>9.5 154 %</td>
<td>6.5 hrs</td>
</tr>
<tr>
<td>LC 2</td>
<td>Galle</td>
<td>1.30pm to 10.30pm</td>
<td>4 150 %</td>
<td>6.5 hrs</td>
</tr>
<tr>
<td>LC 3</td>
<td>Elpitiya</td>
<td>10.00am to 11.00pm</td>
<td>7.5 62.5</td>
<td>6.5 hrs</td>
</tr>
<tr>
<td>UC 1</td>
<td>N'Eliya</td>
<td>1.30pm to 1.00 pm</td>
<td>5.5 148 %</td>
<td>6.5 hrs</td>
</tr>
<tr>
<td>UC 2</td>
<td>Watawela</td>
<td>4.00am to 12.30pm</td>
<td>5.0 159 %</td>
<td>6.5 hrs</td>
</tr>
</tbody>
</table>

According to the above operating times the use of solar energy can be considered for withering and drying in the case of up country and only for drying in the case of low country. Usually, for withering in low country hot air is not being used.
1.2 Working Temperatures

1.2.1 Withering

The optimum wet bulb depression for withering air has been established as 2.8°C to 5.5°C and the maximum dry bulb temperature set around 27°C. The minimum allowable wet bulb depression being 1.7°C.

1.2.2 Drying

Drying temperature ranges from 90°C to 100°C.

1.2.3 Thermal Energy Requirement

The amount of thermal energy required for tea processing is mainly dependent on the climatic condition of the area. Factors affecting are ambient temperature and the relative humidity. Given below are the approximate values of the thermal energy requirement of a typical tea factory where about 10,000 kg of green leaves are processed per day. Consider the trough capacity to be 1000 kg each and the dryer capacity to be 200-250 KgMT/hr.

<table>
<thead>
<tr>
<th>Location</th>
<th>Process</th>
<th>Rate kg/s</th>
<th>Thermal Energy Reqd. kWh/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up country</td>
<td>Withering</td>
<td>-5.7</td>
<td>2565</td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>5</td>
<td>4320</td>
</tr>
<tr>
<td>Low country</td>
<td>Drying</td>
<td>5</td>
<td>4225</td>
</tr>
</tbody>
</table>

2. Solar Energy as an Auxiliary Energy Supply for Withering and Drying

2.1 Withering

Operating schedules in Section 1.1 show that withering during day time amounts to about 20% of the total time period. Hence, a suitable thermal storage bed has to be considered, if energy to be supplied by solar during the other times of operation. Rock bed storage has been considered in this case. Here, unlike in drying, a higher air flow rate can be used in the air collectors. This would increase the collector efficiency considerably. Air collectors are to be connected individually to each of the troughs through a set of individual pebble beds.

2.2 Drying

According to the operating pattern about 50% to 60% of drying is done during the day time. Therefore, solar energy can be used to supply a substantial portion of the energy needed for drying. In order to reduce the frictional losses in the air collectors and to obtain elevated air temperatures it would be convenient to have low air flow rates. Operation at low air flow rate is possible by recirculating a portion of the exhaust air from the dryer back into the hot air generator. The amount of recirculation possible depend upon the relative humidity and the temperature of the exhaust air. Tests carried out on several dryers show that the exhaust air temperature and relative humidity are approximately 53°C and 35° respectively. Consequently, it has been found, that such conditions are favorable for up to about 40% recirculation, where relative humidity can be safely increased up to 50%. Recirculation of exhaust air in a dryer enables us not only to have low fresh air flow rates but also to recover some of the heat from hot exhaust air. The idea of the solar air heater is to pre-heat this quantity of fresh air prior to entering the hot air generator.

3. Air Heating System

3.1 Solar Radiation

Theoretical estimate of the solar insolation was carried out using a computer simulation for the day using established formulae and assuming various parameters as closely as possible to the actual situation. Following parameters were assumed.

\[ K_{	ext{mean}} \sim \text{Clarenness index as 0.6} \]

\[ R_{\phi} \sim \text{Ground reflectance as 0.2} \]

\[ I_{	ext{so}} \sim \text{Solar Constant as 1353 W/m}^2 \]

\[ \text{Latitude} \sim \text{as 6°97'} \]

The total solar radiation incident on a tilted surface is given by,

\[ Q_s = I_b \cos \theta + H_d \cos^2 \phi/2 + H_r \rho \sin^2 \beta/2 \]

Where 1st term represents the direct beam radiation, 2nd term the diffused component and the 3rd the contribution from ground reflection.

3.2 Useful Heat Collected

This is given by,

\[ Q_u = F \cdot A_r \cdot \rho_s \cdot (T_{\text{fin}} - T_0) \]
Where,

- Fr - Collector heat removal factor
- F' - Collector efficiency factor
- UL - Collector overall heat loss coefficient

And the ambient temperature Ta can be approximated by,

\[ Ta = \frac{(T_{\text{max}}+T_{\text{min}})}{2} + 0.5(T_{\text{max}}-T_{\text{min}})\cos \frac{2\pi}{24(H-15)} \]

3.3 Pebble Bed Storage Simulation

A pebble bed having an external insulation is to be considered. The system is schematically represented by Fig. 1.
Reference Fig. 2, let us consider that the bed is divided into n number of crosswise sections each of thickness δx. Following assumptions are made.

1. Uniform temperature prevails in the section δx of pebbles
2. The pebbles are spherical and made of uniform material
3. The heat conduction between pebbles are small and can be neglected for the analysis
4. The pebbles are small enough so that uniform temperature prevails within each pebble at all times.

Then for the ith section we can write the heat balance at time t. Thus,

\[
\begin{align*}
\frac{M \cdot \text{CPS}}{\delta t} &= \frac{hs \cdot A \cdot (T_f, i - 1 - Tb, i)}{1} - Q_i \\
&= \frac{hs \cdot A \cdot (T_f, i - 1 - Tb, i)}{1} - Q_i
\end{align*}
\]

and if \( M' \) is the mass flow rate of air through the pebble bed,

\[
M' \cdot \text{CPS} \cdot (T_f, i - 1 - Tb, i) = \frac{hs \cdot A \cdot (T_f, i - 1 - Tb, i)}{1} - Q_i
\]

and, \( Q_i = Kinsu_1 \cdot (HP+s) \cdot (WD+s) \cdot \delta x \cdot \delta t \cdot (Tb, i - Ta) \)

Therefore,

\[
T_{b, i} = T_{b, i} + \frac{hs \cdot A \cdot \delta t}{M \cdot \text{CPS}} \cdot \left( T_f, i-1 - T_{b, i} \right)
\]

\[
\delta t \cdot \text{CPS} \cdot (HP+s) \cdot (WD+s) \cdot \delta x \cdot \delta t \cdot (Tb, i - Ta) \]

\[
M \cdot \text{CPS, S}
\]

and,

\[
T_f, i = T_f, i-1 - \frac{hs \cdot A \cdot \delta t}{M \cdot \text{CPS}} \cdot \left( T_f, i-1 - T_{b, i} \right)
\]

Now, for convergence conditions of equation 4,

\[
1 - \frac{hs \cdot A \cdot \delta t}{M \cdot \text{CPS}} \cdot \frac{Kinsu_1 \cdot (HP+s) \cdot (WD+s) \cdot \delta x \cdot \delta t}{M \cdot \text{CPS, S}} \geq 0
\]

From this the maximum value of \( \delta t \) could be found, and for stability of equation 5,

\[
1 - \frac{hs \cdot A}{M \cdot \text{CPS}} \geq 0
\]

From which the value of \( x \) could be evaluated so that section area would satisfy the condition. \( A \leq \frac{M \cdot \text{CPS}}{hs} \)

3.4 Mathematical Model for Air re-circulation

Reference Fig. 3 we can write the following formulae for the air flow in the dryer system with a certain percentage of re-circulation.
Energy Balance at Point A

\[(1-X)Te.1 + x*Te.1 = T,T,1.1 \]

Moisture balance at Point A

\[(1-X)m' + x*m = M,1 \]
\[m = 0.017 + M \]

Average ambient temperature = 28°C.
Average relative humidity = 75%

Therefore,

Ambient moisture content \[m' = 0.018 \text{ kg/kg air}\]

Average temperature of dryer exhaust air = 53°C

Now, knowing the temperature of ambient air, temperature of air at the inlet to the hot air generator could be calculated from equation 1. Also, from equations 2 and 3 moisture content of inlet air to the hot air generator could be calculated. Having found the temperature and the moisture content, the heat content of inlet air could now be calculated or read directly from the psychrometric chart.

Let this be \[= H_1 \text{ kJ/kg}\]

Considering the heating of air in the hot air generator as a constant moisture process, the heat content of air at the furnace outlet (approx. 90°C) could be found similarly.

Let this be \[= H_2 \text{ kJ/kg}\]

Therefore,

Heat required to heat up air when a portion of exhaust air is re-circulated,

\[Q_2 = (H_2 - H_1) \text{ kJ/kg}\]

Likewise, heat required to heat up air when exhaust air is not re-circulated,

\[Q_1 = (H_2' - H_1') \text{ kJ/kg}\]

Also, heat required to heat up air when ambient air is pre-heated by solar energy and a portion of exhaust air is re-circulated,

\[Q_3 = (H_2^* - H_1^*) \text{ kJ/kg}\]

If fresh air requirement is \[MC \text{ kg/sec},\] power saved by using solar energy,

\[Q = MC(Q_3 - Q_2) \text{ kJ/sec}\]

Since the intensity of solar radiation varies with time, the pre-heated temperature of ambient air too varies with time. This must be taken into account when calculating the total energy transferred to air by the solar collector.

Power saved by re-circulating exhaust air

\[Q' = MC_Q1 - MC_Q2 \text{ kJ/sec}\]

4. Results

4.1 Hourly Solar Radiation

The hourly solar radiation as calculated by the computer simulation is graphically represented in Fig. 4. It follows that the solar radiation is available for about 10 hrs a day and the maximum is around 800 W/m². The pattern of solar radiation throughout the year, when available, would be more or less the same, due to the small attitude of the location. The availability of solar radiation is taken as 60%.

4.2 Withering

4.2.1 Outlet Air Temperature (Tfout) and Collector Efficiency

The Tout and the collector efficiency are graphically represented in Figs. 5 & 6 respectively. Air is heated up to a moderate value above ambient in order to obtain a higher collector efficiency. Satisfactory performances were obtained at the air flow rate of 2 kg/s, where air is heated maximum up to 18.7°C above ambient. Fig. 6 shows the variation of collector efficiency with time of the day at different air flow rates. Since this is an open loop system, the effect of loss coefficient on the efficiency term is negligible. Therefore, the expected efficiency is usually high.

4.2.2 Energy collected

For different collector areas the collected energy is represented graphically in Fig. 7. It shows that the energy collected by air is increasing gradually with the increase in flow rate. As seen from the Fig. 7, the
collector having the area 25m²3m is collecting 263.5 kWh per day at 2 kg/s flow. This is about the requirement for one trough for the whole day at 100% solar availability. Therefore, this collector was considered for further studies in the system.

4.2.3 Pebble Bed Storage

Storage of thermal energy, collected by air heaters, in the pebble bed was studied by a computer simulation. The amount of thermal energy that could be stored, in a pebble bed of a given volume, with respect to the time of the day was examined. The temperature stratification along the bed was also observed. The results thus obtained are represented graphically in Figs. 8 & 9. It was found that the amount of thermal energy stored in the pebble bed increases till about 1400 hrs and thereafter begins to decrease. This is due to the fact that, after certain time, the outlet air temperature from the collector becomes less than that of the upstream temperature of the bed, in which case some energy is extracted from this part of the bed. A closer examination of the results reveal that the collector outlet temperature falls below the upstream temperature of the bed around 1230 hrs. The effect is to lower the bed temperature at the beginning, while reducing the thermal energy storage in the upper part and at the same time continues to increase the temperature and the thermal storage in the down stream of the bed. Due to this reason the temperature profile of the bed becomes more and more towards the trailing hours of the sun. The temperature profile of the bed is shown in Fig. 9. It can be seen that the storage bed can be charged positively until about 1400 hrs and then the collectors must be connected directly to the trough, refer Fig. 8. It is clear that air after passing through the bed, has not enough temperature for withering before 1200 hrs. Therefore, a portion of air has to be diverted directly in to the troughs between 1000 hrs and 1200 hrs.

4.3 Drying

The operating condition of solar collector for drying has to be somewhat different from that for the withering. This is mainly due to the higher operating temperature required in drying. It is advantageous to operate the air collector at lower air flow rates than that for withering. However, the collector efficiency drops with the lowering of the flow rate due to the higher operating temperature. Parallel operation of several collectors would enable us to meet the situation comfortably.

4.3.1 Temperature Pattern and Collector Efficiency

Variation of collector outlet air temperature, furnace inlet air temperature and the collector efficiency for several parallel combinations, during the day, at various flow rates are graphically represented in Fig. 10, 11 & 12 respectively. For the assumed collector the air temperature increases from about 55°C at 3 kg/s to about 68°C at 0.5 kg/s at the maximum.

4.3.2 Energy collected

Based on the 60% availability, the energy collected by parallel combination of collectors of the size 20m²3m for different operating times have been represented graphically in Fig. 13. It can be seen that although the energy collected increases with the increase in the number of collectors, the marginal energy collected by adding an extra collector decreases.

5. Savings from solar

The estimated overall, annual savings possible by using solar energy is given in Table 1 and also represented graphically in Fig. 14, separately for high, medium and low country. The saving could be as much as 39 million rupees per annum which corresponds to a saving of about 361,450 cu.yd of firewood annually.

6. Conclusion

The average solar energy that could be collected easily is about 3 - 3.5 kWh per day per square meter of collector. Accordingly, given below is the requirement of collector areas in order to meet the total energy demand in tea processing.

<table>
<thead>
<tr>
<th>Location</th>
<th>Production (Mil kg/yr)</th>
<th>Energy Req'd (kWh/day)</th>
<th>Total Collector Area Needed (sq.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>77</td>
<td>6085</td>
<td>0.21</td>
</tr>
<tr>
<td>mid</td>
<td>53</td>
<td>4225</td>
<td>0.09</td>
</tr>
<tr>
<td>low</td>
<td>80</td>
<td>4225</td>
<td>0.13</td>
</tr>
</tbody>
</table>

100% avail 60% avail

(154)
In addition, a suitable thermal storage is also required to realise the above in both withering & drying.

The study has revealed that the solar energy can conveniently be harnessed by simple means and utilized to provide a portion of the total thermal energy demand for tea processing. It is possible to collect about 60% of the energy requirement of withering by collectors of area 25m*3m * 10 = 750 m² (per 10,000 kg green leaves) and about 10% of the energy requirement of drying by collectors of area 20m*3m * 6 = 360 m² (per 10,000 kg GL). The utilisation of solar energy will reduce the burning of wood and the dependence on imported diesel oil. Moreover, this will promote environmental health as the exploitation of solar energy does not produce any pollution materials. The supporting equipments, such as blowers etc., are reasonably sized so that they do not pose problems in the total cost of the system. The thermal storage system seems to have little difficulties in their arrangement at the moment, a further analysis of the model with respect to the individual cases would lead to more appropriate solutions. Also, it may be possible to reduce the thermal storage by re-scheduling the working phases so that withering could be commenced at an early stage.

Simple cost benefit analysis studied, reference Table 1, for the drying process indicates that the pay back period of the investment cost of a solar air heating system would be around 20 months and that for withering about 28 months which should be very attractive in the wake of the present energy crisis.

Nomenclature

θ = Incident angle of solar radiation on tilted surfaces - rad

H = Total terrestrial solar insolation on horizontal surface - W/m²
I_b = Solar beam radiation - W/m²
H_d = Diffused solar radiation - W/m²
Q_s = Total solar radiation incident on a tilted surface on earth - W/m²
β = Tilt angle of collector - °C
C_p = Specific heat of air - J/kg°C
A = Total collector area exposed to solar radiation - m²
γ = Transmissivity of the cover
T_{in} = Inlet air temperature to collector - °C
T_{max} = Maximum ambient air temperature - °C
T_{min} = Minimum ambient air temperature - °C
h_s = Convective heat transfer coeff. between air and pebbles - W/m²°C
M = Mass of pebbles in one section - kg
A = Total surface area of pebbles in the section - m²
H_p = Height of bed - m
W_d = Width of bed - m
s = Thickness of insulation - m
C_p_s = Specific heat of pebbles - J/kg°C
K_{ins} = Conductivity of insulating material - W/m°C
Q_{1} = Heat loss through the insulation - W
α = Absorptance of plate

List of References

1. Energy Audits Reports of the Tea Industry by Energy Management Centre, NERD Centre.
## Table I

| Line | Solar Collector | Energy | Firewood | Cost of | Saving | Operating | Annual | Overall | Overall | Overall | Overall | Overall | Overall | Overall | Overall | Overall |
|------|----------------|--------|----------|---------|--------|-----------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
|      | (kW)           | (kW)   | (kW)     | (kW)    | (kW)   | (kW)      | (kW)  | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   | (kW)   |
| 1    | 30 1 3          | 167.2  | 60        | 103.77  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 2    | 30 2 1.5        | 137.5  | 60        | 103.30  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 3    | 30 3 1          | 32 5737.63| 60        | 124.36  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 4    | 30 4 0.75       | 29 5710.44| 60        | 282.03  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 5    | 30 5 0.6       | 30 5531.06| 60        | 322.10  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 6    | 30 6 0.5       | 30 50037.1| 60        | 355.76  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |

### Collector Performance

**DEIING**

| Solar Collector | Energy | Firewood | Cost of | Saving | Operating | Annual | Overall | Overall | Overall | Overall | Overall | Overall | Overall | Overall | Overall | Overall |
|----------------|--------|----------|---------|--------|-----------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1 30 1 3       | 167.2  | 60       | 103.77  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 2 30 2 1.5     | 137.5  | 60       | 103.30  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 3 30 3 1       | 32 5737.63| 60       | 124.36  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 4 30 4 0.75    | 29 5710.44| 60       | 282.03  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 5 30 5 0.6     | 30 5531.06| 60       | 322.10  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
| 6 30 6 0.5     | 30 50037.1| 60       | 355.76  | 125.5  | 150       | 150    | 150    | 300    | 1430.75| 30      | 1.04  | 6907.25| 177   | 1.36 | 10425.04| 1210  |
**HOURLY SOLAR RADIATION**

<table>
<thead>
<tr>
<th>HOUR OF DAY - hrs</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADIATION - W/sqm</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>0</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIG. 4  NOTE - Day number is 125

**LOSS COEFFICIENT**

**OUTLET AIR TEMPERATURE**

**AMBIENT AIR TEMPERATURE**

<table>
<thead>
<tr>
<th>Airflow - kg/s</th>
<th>1</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>HOUR OF DAY - hrs</th>
<th>7</th>
<th>8</th>
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<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOSS COEFFICIENT, - W/sqm</td>
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<tr>
<td>OUTLET AMB. TEMP. - deg C</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
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</tbody>
</table>

FIG. 5  NOTE - Collector area = 25m*3m

(1:17)
COLLECTOR EFFICIENCY

Airflow - kg/s

--- 1
--- 2
----- 2.5
--- 3

HOUR OF DAY - hrs

FIG. 6 NOTE - Collector area = 25m² x 3m

ENERGY STORED IN PEBBLE BED WITH TIME

ENERGY STORED - kWh

150.0
147.5
145.0
142.5
140.0
137.5
135.0
132.5
130.0
127.5
125.0

TIME OF DAY - hrs

FIG. 7 NOTE - Collector area - 25m² x 3m, Airflow - 2 kg/s
ENERGY COLLECTED BY AIR COLLECTOR PER DAY

MASS FLOW RATE OF AIR – kg/s

ENERGY COLLECTED – kWh

FIG. 8  NOTE – Day number is 125

PEBBLE BED STORAGE
BED TEMPERATURE PROFILE – HEATING

BED TEMPERATURE – deg C

hour of day

1  2  3  4  5  6  7  8  9  10 11 12

NOTE – Length of bed – 3m, Airflow – 2 kg/s

(159)