DESIGN, DEVELOPMENT AND EXPERIMENTAL RESULTS OF A SOLAR DISTILLATION SYSTEM FOR THE PROCESSING OF MEDICINAL AND AROMATIC PLANTS

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1. Introduction

With the increasing population and industrialization, there is need to cut down the load of fossil fuels and to reduce environmental pollution. Solar energy investments in developing countries are imperative to avoid an energy crisis arising from over-dependence on fossil fuels. The situation is critical because fossil fuels are finite and fast depleting (Okoro, 2004). From a number of studies on industrial heat demand, several industrial sectors have been identified with favorable conditions for the application of solar energy. The most important applications of solar energy using heat are: sterilizing, extraction, pasteurizing, drying, solar cooling and air conditioning, hydrolyzing, distillation and evaporation, washing and cleaning, and polymerization. The ranges of all these processes lie between 60-280 °C (Kalogirou, 2003). Most of the agro-based industries can be operated in this medium temperature range. The use of solar energy in agriculture sector can be used to process many perishable agricultural products at farm level. At present, various kinds of solar collectors are in use in the sector of agriculture and post harvest technology, yet their applications are restricted only to drying and warming water etc. Beyond this low temperature applications there are several potential fields of application of solar thermal energy at a medium and medium-high temperature level. In particular, an important research effort has been directed towards power generation applications, chemical systems, and process heat (Estrada, 2007). Tremendous efforts have been made in areas of application of solar energy in the agricultural sector. This can be seen in areas of solar water heating for dairy and micro irrigation (Oparaku 1991; Jenkins 1995; Essandu-Yeddu 1993). The promotion of small scale agro-based industries by using innovative solar collectors can open new landmarks in rural development especially in tropical countries.

Essential oils extraction from medicinal and aromatic plants is one of the medium temperature agro-based industries. These oils are used in medicinal and pharmaceutical purposes, food and food ingredients, herbal tea, cosmetics, perfumery, aromatherapy, pest, and disease control, dying in textiles, gelling agents, plant growth regulators, and paper making (Öztekin & Martinov, 2007). A single ounce of most of the oils is worth thousands of Dollars. In the last decade, these oils remedies have gained enormous popularity in industrialized countries as well particularly in the multi-million-dollar aromatherapy business. Out of all extraction methods, the distillation methods have advantages of extracting pure and refine essential oils by evaporating the volatile essence of the plant material (Malle & Schmickl, 2005). At present, there are large and centralized distillation units mostly located in city areas. Due to their high operating costs, these are sometimes unmanageable by farmers or even groups of farmers in most of the developing countries. Further, some essential oils come from extremely delicate flowers and leaves that must be processed soon after harvesting. Thus, for functional, economic and environmental reasons, there is need of a decentralized distillation system. The on-farm solar distillation is a decentralized approach to reduce the post harvest losses and to prevent spoilage of essential oil components by processing the fresh herbs. Examples of the plants are Peppermint, Lemon Balm (Melissa), Lavender, Cumin, Cloves, Anise, Rosemarie, Patchouli, Caraway, Cassia, Oregano, European Silver Fir, and Fennel etc.

In order to run the distillation experiments, boiling, cooking and steam generation are the basic requirements.

Increasing awareness of the growing global need for alternative cooking fuels has resulted in an expansion of solar cooker research and development (Funk, 2000). A system for solar process heat for decentralized applications in developing countries was presented by Spate et al. (1999). The system is suitable for community kitchens, bakeries and post harvest treatment. The system employs a fix focused parabola collector, a high temperature flat plate collector and pebble-bed oil storage.

It is observed through comparison that the two axes tracking paraboloidal dish, which always faces the sun, is the most promising design for concentrating systems justifying the use of the Scheffler concentrator for industrial process heat applications (Bhirud & Tandale, 2006). These concentrators are capable of delivering temperatures in the range of 300 °C and are technically suitable for medium temperature applications (Delaney, 2003). Scheffler (2006) investigated that about half the power of sunlight which is collected by the reflector becomes finally available in the cooking vessel. The use of solar energy for the generation of steam is now an economically attractive possibility since the pay back period of such a system lies between 1.5 and 2 years. These cookers are economically viable if they are used regularly (Jayasimha, 2006). For small-scale applications in agriculture, post harvest technology and the food industry, this is a cheaper solution. A focal receiver absorbs the concentrated solar radiation and transforms it into thermal energy to be used in a subsequent process. The essential feature of a receiver is to absorb the maximum amount of reflected solar energy and transfer it to the working fluid as heat, with minimum losses (Kumar, 2007).

At present, solar energy is successfully utilized for cooking applications and steam generation. Processing of medicinal and aromatic plants by solar distillation system was a new research area of solar energy utilization in medium temperature range. By keeping all facts in view, the study has been initiated to develop a decentralized solar distillation system for essential oils extraction from medicinal and aromatic plants. The solar distillation system is installed at solar campus, University of Kassel, Witzenhausen, Germany. Beside the solar campus, a variety of fresh herbs and medicinal plants are available at the university farms and tropical greenhouse. The solar distillation system comprises of primary reflector equipped with daily and seasonal tracking devices, a secondary reflector, a distillation still with all mountings and fittings, a tubular condenser and Florentine vessels. The system was designed to conduct distillation experiments for on-farm processing of medicinal and aromatic plants.

2. Design of reflector parabola and reflector elliptical frame for solar distillation system

The paper is about the design and development of solar distillation system based on the Scheffler reflector technology. Out of all the components of solar distillation system, primary reflector is the most sophisticated and vital component. First of all, the paper presents the design and develops detail of the Scheffler reflector.

Scheffler reflector is a lateral part of a paraboloid and all calculations are made with respect to equinox with zero solar declination. In order to calculate the equation of the parabola curve, the calculations are made by considering the side view of the paraboloid. In this way, paraboloid and reflector frame are drawn in the form of a parabola curve and straight line respectively. The general equation of a parabola in *xy*-plane with its axis passing through y-axis can be written in the following form:

$$P(x) = m_p x^2 + C_p \qquad \text{(eq. 1)}$$

Where m_p is the slope of parabola and C_p is the y-intercept of the parabola

Taking first derivative of eq. 1 for the slope of parabola

$$P'(x) = 2m_p x \qquad \text{(eq. 2)}$$

Starting from a point P_n of the parabola curve in the positive coordinate axes where solar radiation is reflected at 90° as shown in Fig. 1.

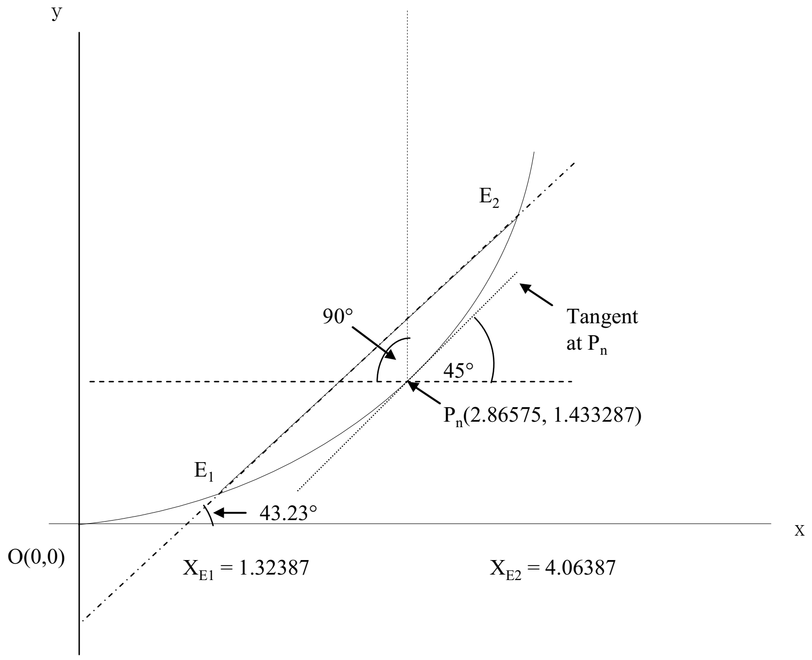

Fig. 1: Description of parabola of the Scheffler reflector

At this point of the parabola curve, the tangent is cut at 45° angle and the value of the y-coordinate is half that of the x coordinate. In order to design the reflector parabola, the study based on the following two aims:

1. To construct an 8 m^2 Scheffler reflector
2. The reflector frame should be balanced with respect to central pivot point

In order to meet these two aims, the following procedure is considered (Munir et al., 2010)

- Selection of x-coordinate of point P_n (x_P) in order to get a reasonable distance to the focal point; calculation of y-coordinate of point P_n (y_P) and slope m_P with the help of eq. 1 and eq. 2
- Selection of x_{E1} and x_{E2} in order to get a surface of approximately 8 m^2 and a balanced collector; calculation of y_{E1}, y_{E2} and angle of the line joining the points E_1 and E_2
- Check if the two aims are roughly reached (calculation of surface area right and left of P_m and check their difference for balancing and their sum for collector surface); otherwise adapt a new set of P_n, E_1 and E_2
- Calculation of semi-major and semi-minor axis of the reflector frame

The x-coordinate of point P_n (x_P) is selected as is taken as P (2.86575) for a surface area of 8 m^2. This point varies with different sizes of surface areas of Scheffler reflector. The first derivative of eq. 1 at this point is equal to slope at the point. The tangent cuts this point P_n at an angle of 45° with x-axis (directrix), so the first derivative at this point is found to be unity. According to definition of parabola, the y-coordinate at point P_n is 1.43287 i.e. half the x-coordinate.

Using eq. 1 and eq. 2, the values of m_p and C_p are calculated as 0.17447 and 0 respectively. The parabola equation for the equinox is given as:

$P(x) = 0.17447\,x^2$ (eq. 3)

For the construction of a balanced reflector (8 m^2 surface area), two points x_{E1} and x_{E2} are chosen on a graph paper as 1.32387 and 4.06387. The reason of selecting these points is to construct a balanced parabola in order to rotate the reflector with a very little force. In this way, the line joining these two points E_1 and E_2 of the parabola curve represents the cutting section of the elliptical frame of the Scheffler reflector. This line E_1E_2 is not parallel to the tangent at point P_n (which makes 45° angle with x-axis) but makes a 43.23° angle as shown in Fig. 1. The general equation of this straight line is given by:

$$G(x) = m_g x + C_g \qquad \text{(eq. 4)}$$

Differentiating eq. 4 with respect to x and taking the angle of straight line as 43.23°, the slope m_g is found to be 0.94 by simple calculation. The coordinate x of point E_1 (x_{E1}) is selected to be 1.32387 and the coordinate y is calculated to be 0.31. By substituting the values of x, y and m_g in eq. 4, the y-intercept (C_g) is calculated to be −0.94 and the equation of the straight line becomes:

$$G(x) = 0.94x - 0.93866 \qquad \text{(eq. 5)}$$

The coordinate x of point E_2 (x_{E2}) is calculated by comparing and solving eq. 1 and eq. 2, the general form of a quadratic equation formed is as follows:

$$x^2 - \left(\frac{m_g}{m_p}\right)x + \frac{C_p - C_g}{m_p} \qquad \text{(eq. 6)}$$

By solving eq. 6 with the help of a quadratic formula to get two points of intersection (x_{E1} and x_{E2}) of the parabola curve and straight line. The straight line cutting the curve represents a cutting plane of an ellipse with axes ratio $a/b = \cos \alpha$, where "a" and "b" are the semi-minor axis and semi-major axis respectively. For a given paraboloid, the cutting section of the lateral part will make an ellipse and its projection on the ground (horizontal plane) will make a circle. So, the semi-minor axis of the ellipse and radius of projection on the ground will become the same. The projection of this ellipse on the horizontal plane (xz-plane) is a circle with a diameter of $2a$. The general equation for the diameter of circle ($2a$) is calculated for a Scheffler reflector and is given in eq. 7:

$$2a = (2).\sqrt{\left(\frac{m_g}{2m_p}\right)^2 - \frac{C_p - C_g}{m_p}} \qquad \text{(eq. 7)}$$

The semi-minor axis of the ellipse is 1.37000 m and semi-major axis of the reflector is calculated to be 1.88029 m by dividing with axes ratio (cos 43.23).

A number of crossbars can be used but seven crossbars are sufficient to make the required section of the paraboloid for an 8 m^2 Scheffler reflector. Taking the centre of ellipse as origin and major axis along x-axis, the middle crossbar passes through the origin. The other crossbars are located at a distance of ±0.48 m, ±0.96 m, ±1.44 m from the origin along major axis and the corresponding points on minor axis are calculated as ±1.37000, ±1.3246, and ±1.17798 m respectively. After the construction work of reflector frame, intersections points of crossbars are marked on the elliptical reflector frame.

3. Calculation of equations for the crossbars ellipses

The cutting planes of the crossbars are perpendicular to the cutting plane of the reflector frame and are shown in the form of seven straight lines. The inclination angle of cutting plane of crossbars is found to be -46.77° by subtracting the angle of cutting plane of the reflector frame from 90°. These cutting lines are also ellipses with axes ratio (a_q/b_q) = cos 46.77°. Starting from the middle crossbar (q_4, passing through P_c), the basic equation of the line is given as:

$$q_4(x) = m_{q4}x + C_{q4} \qquad \text{(eq. 8)}$$

Slope of te middle crossbar is calculated by taking tan (- 46.77), x- coordinate of the point of intersection (C_f)

of the middle crossbar and the reflector frame is the central point of x_{E1} and x_{E2} and y-coordinate is calculated by substituting this value of x in eq. 8 and is found to be 1.59357.

Substituting the values of m_{q4}, $q_4(x)$ and x in eq. 8, the y-intercept (C_{q4}) for the middle crossbar is calculated and the equation of the middle crossbar (q_4) for 8 m^2 surface area of Scheffler reflector is given in eq. 9:

$$q_4(x) = -1.06377\, x + 4.45923 \qquad \text{(eq. 9)}$$

The slopes for all the cutting crossbars are the same as these are perpendicular on the same cutting plane of the Scheffler frame. As the crossbars are equally distributed (from center of the reflector frame), so the difference between two successive y-intercepts is calculated to be 0.70080 by dividing 0.48 with cos 46.77.

The equations for the 4th, 5th and 6th crossbars are calculated by adding 0.70080, 2(0.70080) and 3(0.70080) in the y-intercepts values of Eq. (4.13) respectively. Similarly, the equations for 3rd, 2nd and 1st crossbars are calculated by subtracting 0.70080, 2(0.70080) and 3(0.70080) from the y-intercepts values respectively.

The equations for all crossbars can be generalized as $q_n(x) = m_q x + C_{qn}$. Similarly, for semi-minor axis (a_{qn}) of any ellipse of a crossbar, eq. 7 can be modified for crossbars and reflector frame and is generalized as:

$$a_{qn} = \sqrt{\left(\frac{m_{qn}}{2m_p}\right)^2 - \frac{C_p - C_{qn}}{m_p}} \qquad \text{(eq. 10)}$$

where subscript "n" represents the number of crossbar

4. Calculation of depths and arc lengths for different crossbars

After the calculation of equations for different crossbars, depths and arc lengths for different crossbars are calculated for the construction of Scheffler reflector by using simple trigonometric equations (Munir et al. 2010). The detail is given in Table 1.

Table 1: Depths and lengths of different arcs of the crossbars for 8 m^2 Scheffler reflector

Crossbar "n"	Y_n (m)	Depth "Δ_n" (m)	Radius "R_n" (m)	Angle "β_n" (degree)	Half arc length "$b_n/2$"(m)	Arc length "b_n"(m)
1	0.88090	0.11965	3.30255	15.46997	0.89169	1.78338
2	1.17798	0.19820	3.59969	19.10163	1.20008	2.40016
3	1.32460	0.23403	3.86552	20.03966	1.35199	2.70398
4	1.37000	0.23529	4.10612	19.49036	1.39678	2.79356
5	1.32460	0.20781	4.32536	17.83280	1.34623	2.69246
6	1.17798	0.15595	4.52695	15.08281	1.19169	2.38338
7	0.88090	0.08305	4.71331	10.77170	0.88611	1.77222

After calculating the required parameters, the arcs of different radii are marked on the bending templates as given in Table 1. Mild steel round bars (10 mm thickness) are used for the crossbars and are cut according to the required arc lengths as detailed in Table 1. These lengths are then bent with respect to marked circular curves on the templates. After going through the straightness tests, these curves are then welded on the marked positions of the reflector frame. These welded curves are then thoroughly examined for precision and evenness with the help of a jig. Thereafter, aluminum profiles are fixed on the reflector frame to shape the base for the aluminum reflectors. These aluminum profiles are tied with crossbars with the help of steel wires. Aluminum reflecting sheets are pasted on these profiles with silicon glue to shape the required lateral part of the paraboloid. Aluminum profiles from Alcan Company, Germany are normally used with reflectivity at more than 87 %.

5. Installation and daily tracking of Scheffler reflector

While installing a Scheffler reflector at any site, the axis of rotation is fixed very precisely at an angle equal to “the latitude of the site” with horizontal in north-south direction. For daily tracking, these reflectors rotate along an axis parallel to polar axis with an angular velocity of one revolution per day to counterbalance the effect of daily earth rotation. The daily tracking is accomplished with the help of a small self-tracking PV system or clock-work operated by gravity which provide angular velocity at one revolution per day. Up until now, the paper has only discussed reflector design with respect to zero solar declination. The detail for the other days of the year is explained in the next article.

6. Calculation of seasonal parabola equations

In order to adjust the reflector with respect to the changing solar declination, the reflector is provided with a telescopic clamp mechanism to adjust the inclination of the reflector by half of the change of the solar declination angle and to attain the required shape of the parabola for any day of the year. In order to attain the required parabola equation, a fixed point B with x-coordinate 2.69338 on the parabola curve is chosen which the common point for all the seasonal parabolas. This point also acts as the central pivot point for the required shape change of the crossbars. As the point B lies on the same parabola, the y-coordinate is calculated to be 1.26469. The general form of a parabola equation for any day of the year is given below

$$D(x) = m_d x^2 + C_d \qquad \text{(eq. 11)}$$

Differentiating eq. 11 and equating to tan (43.224 + α/2) for the slope, we have

$$m_d x = \tan\left(43.224 + \frac{\alpha}{2}\right) \qquad \text{(eq. 12)}$$

where “α” is solar declination.

The general equation of seasonal parabola equations for standing Scheffler reflectors (8 m^2) in the northern hemisphere is calculated. The coordinates of new set of points at any day of the year are calculated by using the “Rotation Matrix” to rotate the point B(2.69338, 1.26569) about focus F(0,1.43287) and are given in eq. 13.

$$(x_d, y_d) = (x, y).\begin{bmatrix} +\cos\alpha & +\sin\alpha \\ -\sin\alpha & +\cos\alpha \end{bmatrix} \qquad \text{(eq. 13)}$$

This equation shows that the coordinates depend only on the solar declination and are calculated by expanding the rotation matrix given in eq. 13. By substituting the values of x_d, y_d and α in eq. 11 and eq. 12, the equation of parabola in terms of slopes and y-intercepts can be calculated for any day of the year.

In order to see the variation of parabola equations for two extreme seasonal positions on June 21 and December 21, the reflector has to rotate at half the solar declination angle. The angles at point B for summer (June 21) and winter (December 21) are +11.75 (+23.5/2) and -11.75 (-23.5/2) respectively with reference to equinox position. For summer, substitute the value of $\alpha = 23.5°$, $x = 2.69338$ and $y = 1.26569$ in eq. 13. The value of y-coordinate of focus i.e., 1.43287 is subtracted first from the y-coordinate of the point B i.e., 1.26569 before solving the matrix and is then added this value to the y-coordinate obtained from the specific day (in this case, y_s) after the solution as a rule of the rotation matrix.

Substituting the values of x, y in eq. 13, the equation for the summer parabola is found out and is given below:

$$y = 0.28123\,x^2 + 0.54394 \qquad \text{(eq. 14)}$$

For winter, substitute the value of $\alpha = -23.5°$, $x = 2.69338$ and $y = 1.26569$ in Eq. (4.23). The same procedure is repeated as done for the determination of the equation of the summer parabola; the equation for winter parabola is calculated and is given below:

$$y = 0.12736\, x^2 + 0.53004 \qquad \text{(eq. 15)}$$

The inclination of the fixed point B of parabolas on June 21 and December 21 are found to be 54.974° and 31.474° by adding and subtracting 11.75° to the inclination angle of fixed point B at equinox (43.224°). The detail of parabola equations for equinox, summer and winter for the northern hemisphere (standing reflectors) is shown in Fig. 2.

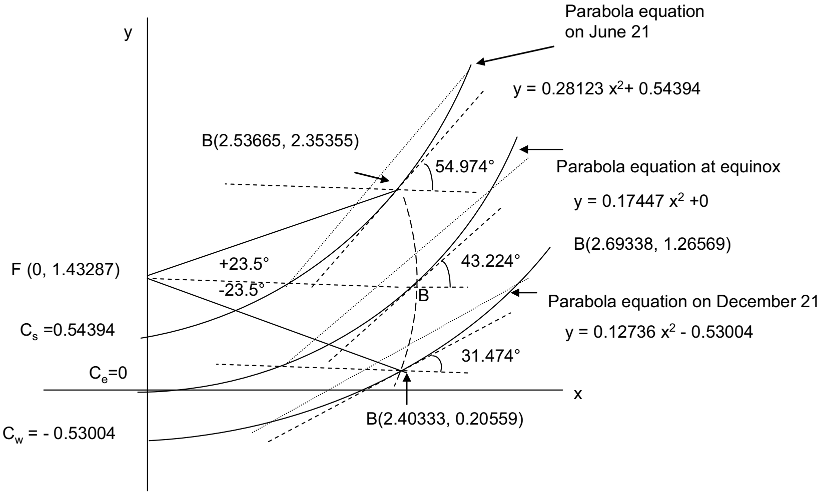

Fig. 2: Seasonal parabola equations for an 8 m^2 Scheffler reflector (valid for standing reflectors in the northern hemisphere) at equinox, summer (June 21) and winter (December 21)

It is evident from Fig. 2 that the shapes of parabolas are different in summer and winter. The slopes of parabola curves with respect to equinox (solar declination =0), summer (solar declination = +23.5) and winter (solar declination = -23.5) for the Scheffler reflector (8 m^2 surface area) are calculated to be 0.17447, 0.28123, and 0.12736 respectively. The y-intercepts of the parabola curves for equinox, summer and winter are found to be 0, 0.54394, and -0.53004 respectively. Through comparison with the equinox parabola curve, that of the summer parabola is found to be smaller in size and uses the top part of a parabola curve, while the winter parabola is bigger in size and using the lower part of a parabola curve to provide the fixed focus.

7. Development of solar distillation system

The solar system is designed as a fixed installation of Scheffler reflector (8 m^2 aperture area, standing reflector) and all parts of the reflector stand were fabricated and assembled with respect to the latitude of the site of installation (solar campus, university of Kassel, Witzenhausen, Germany Latitude: 51.3°). The Scheffler concentrator is a lateral part of a paraboloid and does not require any manual tracking during the whole day once it is set. Further, it provides a fixed focus for all the days of the year which can be best utilized during different distillation experiments. The solar distillation system includes development of primary reflector, secondary reflector, photovoltaic tracking system, distillation still, condenser, Florentine vessels etc. The Scheffler reflector is equipped with daily tracking and seasonal tracking systems.

The fixed secondary reflector further reflects the radiations onto the targeted distillation still bottom. Each morning, the primary reflector has to set back to a starting position in which the secondary reflector is illuminated to start the PV tracking system. The distillation unit is fabricated of a food grade stainless steel material (2 mm thickness) having 1210 mm column height and 400 mm diameter (400 mm diameter is the designed diameter of the receiver for 8 m^2 Scheffler reflector). Three I-bolts are used for quick opening and closing of the top dome of the distillation still. The still is also provided with safety mountings and fittings like safety valve, pressure gauge, water level indicator.

The distillation unit has provision to operate for water and steam distillation. A stainless steel pipe connects the top end of distillation still to the steel condenser. The condenser is provided with steel coil, a cold water inlet connection and warm water outlet connection and acts as a counter current flow heat exchanger. In order to record the power during distillation process, a barrel calorimeter is connected at the outlet steam connection of the distillation still to record dryness fraction during different intervals.

8. Performance of solar distillation system

Several experiments were carried out to evaluate the performance of the system under field conditions. Within the beam radiation range of 700-800 W m^{-2}, the temperature available at the focus was found to be between 300-400 °C. Scheffler (2006) showed that about half of the solar power collected by the reflector becomes finally available in the cooking vessel. Details of one performance evaluation of the solar distillation system with 20 liters of water on August 31 from 9:06 to 16:00 hour (test duration = 5.9 hour) are shown in Fig. 2.

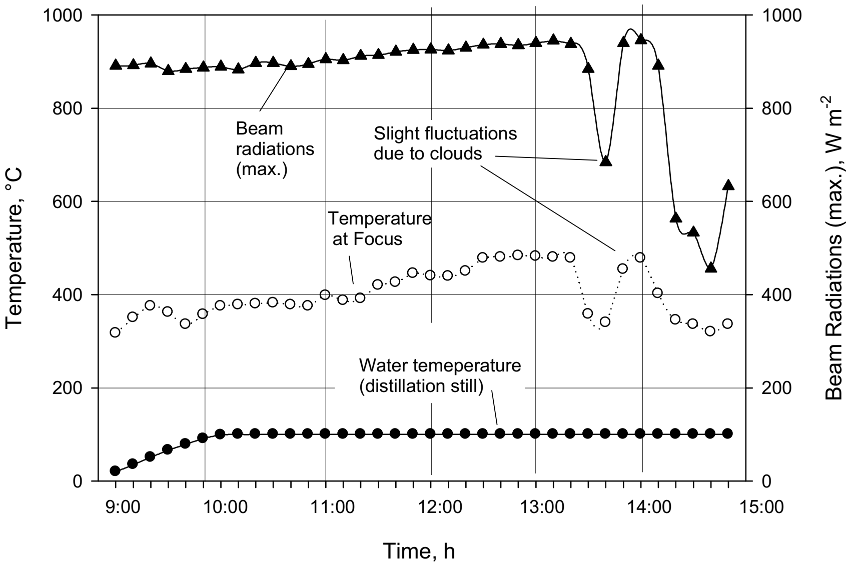

Fig. 3: Performance evaluation of solar distillation system with 20 liters of water

The graph shows the variation of beam radiation, focal point temperature and the process temperature versus time. It is evident from Fig. 3 that within the defined range of beam radiation, the temperature at the focus is effectively constant. This shows that beam radiations are converging at the targeted focus with the changing position of the sun during the test period. It is also clear from Fig. 3 that the temperature of the distillation process is well below the temperature at the focal point. This temperature gradient can be used successfully for all types of distillation processes. During this test, the total energy gained by the water (in sensible and latent heat phase) was calculated to be 9.136 kWh. The average power and system efficiency were found to be 1.548 kW and 33.21 % respectively at an average beam radiations of 863 W m^{-2}

9. Experimental results of solar distillation system for the processing of medicinal and aromatic plants

Distillation of medicinal and aromatic plants using solar energy provides an excellent opportunity to process fresh herbs for pure natural essence by using optimum harvesting time. For distillation experiments, the fresh herbs were harvested from the university farms located very near to the solar distillation system and dry herbs were purchased from the local market. Some of the medicinal plants like Melissa and Rosemary were used from the tropical green houses of the University of Kassel, Witzenhausen. In this way, the distillation system was evaluated with different kinds of medicinal and aromatic plants. Process heat energy consumption for different plant materials were calculated from the sensor system installed. In order to record data in steam generation phase, quantity of distillate (kg) and essential oils extracted (ml) were recorded with a regular interval of 10 minutes till end of the process. Beam radiations, water and steam temperatures, and temperature at focus were automatically recorded in the computer by data logger after 10 second pre-set interval. Different medicinal and aromatic plants (Melissa, Peppermint, Lavender, Fennel, Rosemary, Cumin, Basil and Cloves, Lavender etc) were processed successfully by solar distillation system (Munir & Hensel, 2008). The detail of some of the plant materials is gives in Table 2.

Table 2: Heat energy consumed and essential oil extracted during solar distillation of different plant material

Plant material	Part used	Weight, kg	Moistures contents (wb), %	Heat energy, kWh	Essential oil extracted, ml	Essential oil per unit plant d.m, ml kg^{-1}
Melissa	Leaves	11.6	78	3.868	1.425	0.558
Peppermint	leaves	9.1	74	3.180	28.2	11.918
Rosemary	leaves	3.0	72	4.626	4.6	5.476
Cumin	seeds	1.2	9	8.910	12.4	11.355
Cloves	buds	0.8	11	7.744	44	61.798

Table 2 shows the solar distillation experiments with different plant materials (Melissa, Peppermint, Rosemary, Cumin and Cloves) conducted by using different weights having different moisture contents. The heat energy consumed, essential oils extracted and essential oil obtained per unit weight of dry matter (d.m) were recorded for each experiment. The results show that different plant materials have different amounts of oils per unit dry matter. In these experiments, Melissa, Peppermint, and Rosemary plants were processed by using their leaves, Cumin plant by using seeds and Cloves plant by using buds. Under practical conditions, these specific parts of the plant materials are used for the extraction of essential oils. These results show that the solar distillation system can also be used for the processing of different parts of the medicinal and aromatic plants. The best fitted regression model for all plant materials was found to be the sigmoid/logistic curve (Munir & Hensel, 2010).

In summer seasons, the solar distillation system can be operated for 12 hours a day from 08:00 hours to 20:00 hours. About 18.58 kWh energy can be obtained for processing under similar conditions during 12 hours in one day. In several experiments, total energy consumptions for the processing of 10 kg batch of Melissa and Peppermint were recorded to be from 3 to 4 kWh. Therefore, 4-5 batches with 10 kg plant material were processed successfully using fresh herbs. These figures show the potential of solar distillation system during sunny days at the installed site. The results conclude that the processing of medicinal and aromatic plants can be successfully carried out by using solar energy.

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