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A solar distillery of essential oils with compound parabolic collectors (CPCs)

Yunus Kültürel[a], Sefa Tarhan[b*]

[a]*Gaziosmanpasa University, Tokat Technical Sciences Vocational School, Machine Program, 60250, Tokat, Turkey*
[b]*Gaziosmanpasa University, Faculty of Engineering and Natural Sciences, Mechatronics Engineering Department, 60250, Tokat, Turkey*
[*]Sorumlu yazar/corresponding author: sefa.tarhan@gop.edu.tr

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ABSTRACT

A new essential oil distillation system was developed to produce the essential oils of medicinal and aromatic plants by water-steam distillation. This distillation system was composed of solar CPCs and distillation units. The solar CPCs unit comprised of seven solar compound parabolic collectors (CPCs), having 3.4 m² aperture area 1.9 concentration ratio. The distillation unit had a distillation tank, a condenser and an oil separator. The distillation unit was sized to distill 5 kg plant material each batch. 5 kg water steam was passed through 5 kg plant pile. The heat gained by solar CPCs was transferred to the distillation unit to boil distillation water. An electrical heater was placed at the bottom of distillation tank to complete distillation processes in case of insufficient solar energy supply. Three distillation trials were conducted in August. One of trials was conducted by covering the CPC reflectors with a black fabric sheet to determine the contribution of concentrating solar irradiance. Experimental data such as solar radiation intensity, temperatures of water, heat transfer oil and steam, etc. were collected and stored in a computer. In case of no clouding, the distillation process was successfully completed since the temperature of heat transfer oil easily increased to 123 °C without needing auxiliary electrical heating. In case of clouding, the electrical heater was switched on in the later period of distillation process. When solar radiation was not concentrated, the temperature of heat transfer oil increased only to 95 °C and the distillation water had to be boiled by electrical heating. The overall thermal efficiency of solar CPCs ranged from 27.9% to 34.3%.

Anahtar Sözcükler:
Compound parabolic collector
Essential oils
Solar Energy
Water-steam distillation

Birleşik parabolik toplaçlı (BPT) güneş enerjili uçucu yağ damıtma sistemi

ÖZET

Tıbbi ve aromatik bitkilerden su-buhar damıtma yöntemiyle uçucu yağ çıkarmak amacıyla yeni bir uçucu yağ damıtma sistemi geliştirilmiştir. Damıtma sistemi birleşik parabolik toplaçlar ve damıtma ünitelerinden oluşturulmuştur. Birleşik parabolik toplaç ünitesi (BPT), yoğunlaştırma oranı 1.9 ve toplam 3.4 m^2 açıklık alanına sahip yedi adet birleşik parabolik toplaçtan imal edilmiştir. Damıtma ünitesi damıtma tankı, yoğuşturucu ve yağ ayırıcıdan ibarettir. Damıtma ünitesi, 5 kg taze bitkiyi damıtmak için boyutlandırılmış ve 5 kg su buharı bitkiden geçirilmiştir. Birleşik parabolik toplaçlar tarafından kazanılan ısı enerjisi damıtma ünitesine transfer edilerek suyun kaynatılması sağlanmıştır. Güneş enerjisinin yetersiz olduğu durumlarda damıtmayı tamamlamak için damıtma tankının altına bir elektrikli ısıtıcı yerleştirilmiştir. Ağustos ayında üç damıtma denemesi gerçekleştirilmiştir. Denemelerin birinde yoğunlaştırılmış güneş ışınımının etkisini belirlemek için birleşik parabolik toplaçların yansıtıcı yüzeyleri siyah bir örtüyle örtülmüştür. Güneş ışınım şiddeti, su, ısı transfer yağı, buhar sıcaklıkları vb. deneysel veriler elektronik olarak toplanmış ve bilgisayarda depolanmıştır. Bulutlanma olmadığında, elektrikli ısıtıcıya ihtiyaç duyulmaksızın ısı transfer yağı sıcaklığı 123 ^{o}C'ye yükseldiğinden damıtma başarılı bir şekilde tamamlanmıştır. Bulutlanma olduğunda, damıtma sonuna doğru elektrikli ısıtıcı kullanılmıştır. Güneş ışınımı yoğunlaştırılmadığında ısı transfer yağı sıcaklığı 95 ^{o}C'ye yükselmiş ve damıtma suyu elektrikli ısıtıcı kullanarak kaynatılmıştır. Birleşik parabolik toplaçların termal verimliliği %27.9-34.3 arasında değişmiştir.

Keywords:
Birleşik parabolik toplaç
Uçucu yağ
Güneş enerjisi
Su-buhar damıtması

1. Introduction

Averagely half of worldwide energy consumption belongs to industry sector. Solar energy has a high potential to be used in many different branches of industry. While high-temperature applications (greater than 300°C) are used mostly in steel, glass and ceramics industries, moderate temperature applications (between 100-300°C) are used in many other branches of industry. Moderate temperature applications are commonly used in food, textile, paper, chemical and wood industries. Low-temperature applications (less than 100°C) are mostly used for the supply of domestic and industrial hot water and for drying newly harvested agricultural products (Mekhilef et al., 2011). While flat plate collectors are used in low-temperature applications, concentrating collectors are used in moderate and high temperature applications in order to reach higher temperatures by concentrating the solar radiation. The necessary concentration ratio and concentrating collector type are selected depending on the required temperature range (Kalogirou, 2004). Parabolic trough collectors with solar tracking system and compound parabolic collectors (CPCs) are sufficient to provide heat to the moderate temperature applications. The advantage of compound parabolic collectors is their ability to concentrate the diffuse solar radiation in addition to direct solar radiation (Yong et al., 2008). The solar CPCs with acceptance half angle up to 30^{o} and concentration ratio up to 2 are called as the solar CPCs with low-concentration ratio and they do not need solar tracking. The long axis of solar CPC can be oriented toward east-west or north-south direction and its aperture is tilted to the equator. If the long axis of solar CPC is oriented through the north-south direction, solar tracking is used to see sun continuously (Kalogirou, 2003). The solar CPCs are used together with different receiver types (flat one-sided receiver, fin receiver, wedge receiver and tubular receiver) (Rabl, 1985). A steam generator consisting of 60 compound parabolic collectors having all-glass evacuated tubes with the total aperture area of 32 m^2 generated steam exceeding 200°C with pressure ranging from 0.10 to 0.55 MPa. A metal concentric annular tube was inserted into the all-glass tubes and a mixture of heating oil and graphite powder was filled between them to accelerate heat transfer from the selective absorber to working fluid flowing in the concentric tube. This steam generator had an average efficiency of 30% on sunny and cloudy days in summer. It gave 8 to 11 kW output power for 3 h at noon (Liu et al., 2014). These research results show that solar CPCs can be used to generate water steam efficiently at moderate temperatures. In another study, 12 mini CPC reflectors (C<1) and the evacuated tubes with U-pipe absorbers were used to heat 200 kg water at different initial temperatures (18.0 to 62.6°C) to different final temperatures (43.3 to 95.1°C) under winter conditions (average ambient temperature: 15.2±0.8°C and average solar irradiation density: 667±38 W·m^{-2}) in China. The overall thermal efficiencies of this system ranged from 44.8% to 60.7%. This results shows that the solar water heating systems having mini CPC reflectors and evacuated tubes have much higher overall thermal energy efficiencies than the solar water heating systems having flat-plate solar collectors (Gang et al., 2012). CPC reflectors having higher concentration ratios (3× and 6×) were also used with the evacuated tubes with U-pipe absorbers to obtain moderate temperatures up to 250°C (Li et al., 2013). The overall thermal efficiencies of the 3× and 6× CPCs were 40% and 46%, respectively at the collecting temperature of 200°C. Buttinger et al. (2010) covered CPC reflectors having 1.8 concentration ratio and pipe absorbers with a flat-plate antireflection glass instead of using evacuated tubes. The space under the flat-plate antireflection glass was vacuumed or filled with krypton gas at 0.01 bar to suppress heat losses due to inside convection between absorber and reflector respectively glass cover. The overall thermal efficiency reached more than 50% with krypton gas at 0.01 bar and more than 40% with air at 0.01 bar to obtain process heat at 150°C with a solar irradiation of 1000 W·m^{-2} and 20°C ambient temperature.

Medicinal and aromatic plants have special secondary metabolites and are used as the raw materials of drugs and cosmetics products for the protection and healing of human health in addition to food materials such spices and herbal teas (Öztekin and Martinov, 2007). The world's essential oil exports in 2006 amounted to about $ 2 billion with increase of 11% compared to 2005. The main essential oils traded worldwide are orange, peppermint, lemon, eucalyptus, clove, citronella and lime oils (Bektaşoğlu, 2008). The most commonly used method to extract essential oils from plants is distillation. The distillation process is performed by using three different methods: water distillation, water-steam distillation and steam distillation. In water distillation, the plant material is boiled together with water after putting them into the distillation tank. The resulting water vapor and essential oil mixture is cooled while passing through the condenser and are collected in the separation container as liquids separated from each other. In water-steam distillation, the plant materials are placed on the top of boiling water, and the essential oil is extracted only by water vapor in the distillation tank. In the steam distillation, the steam produced in an external steam generator is sent to the plant materials in the distillation tank. Water-steam distillation is the most commonly used distillation method because of its relatively low cost compared to steam distillation and its higher efficiency and higher quality of essential oil extraction compared to water distillation since the water and plant materials are not directly in contact with each other (Handa et al., 2008).

Various energy sources are used to generate steam. While biomass energy (wood and other plant residues) is used more commonly for the distillation of essential oil in rural areas, commercial energy sources (electricity, LPG, etc.) are used in large scale industrial productions (Schmidt, 2010). Solar energy can be used for the distillation of essential oils since the water-steam distillation of essential oils is in the temperature range of the moderate (medium) temperature applications of solar energy. In a doctorate study completed about the essential oil distillation by utilizing solar energy, a distillation system with two separate solar reflectors was designed to extract the essential oils of various medicinal and aromatic plants. The first reflector was a 8 m² Scheffler reflector and it tracked the sun and sent the solar radiation coming from the sun to the second stable reflector located under the distillation tank. The second reflector focused the solar radiation to the bottom of distillation tank. The first phase of the study consisted of laboratory tests performed to determine the amount of thermal energy to be used in the distillation for the unit weight of different plants. The obtained experimental data were used to size the first reflector. The power and efficiency of the system were found as 1.548 kW and 33.21%, respectively in the field trials at a solar radiation intensity of 863 $W \cdot m^{-2}$. The efficiency of the system was 49.8% and 40% for only the first reflector used and both reflectors used, respectively. The amount of steam and thermal energy required for the distillation of 1 kg fresh plant varied according to the plant species. In the distillation experiments performed with 100 g plant samples at the laboratory, the amounts of electric energy consumption ranged from 1.63 to 7.18 kWh. According to the field trials, 28.2 mℓ essential oils was obtained by consuming 3.18 kWh thermal energy for 9.1 kg peppermint leaves. 3.868 kWh thermal energy was used for 11.6 kg melissa leaves and 1.425 mℓ essential oil was obtained (Munir, 2010; Munir et al., 2014).

The solar compound parabolic collectors have two main advantages to be used for essential oil distillation compared to other concentrating collectors. Those advantages are their ability to collect diffuse radiation, their ability to generate heat efficiently at moderate temperatures without needing solar tracking. Therefore, the aims of this study were to develop a unique essential oil distillation system with solar CPCs gaining its thermal energy from solar energy and determine its experimental performance.

2. Materials and Methods

The essential oil distillation system developed in this study consisted of two main units. These units were the compound parabolic collectors which transformed solar energy into thermal energy and the distillation unit in which essential oil was extracted from plant materials by water-steam distillation. Design and construction of these sections were described thoroughly in the following sections.

2.1. Dimensions and manufacturing of the distillation unit

The distillation unit is the unit where the essential oil of the peppermint is extracted from plant materials by water-steam distillation. The distillation unit consists of a distillation tank, a distillation basket, a condenser and an oil separator. The distillation tank consists of an upper and a lower section fastened to each other with flange. The upper section is a 300 mm diameter, 530 mm long vertical cylindrical container made of 2 mm thick stainless steel sheet having 304 steel quality. The lower section is a 300 mm diameter, 530 mm deep vertical cylindrical container made of 2 mm thick stainless steel sheet having 304 steel quality. It has a ½ inch drain valve, the connector of circular involute heating coil and the connector of electrical heater at its bottom. The whole distillation tank was insulated with 100 mm thick glass wool. There is a circular involute heating coil by which heat was transferred to the distillation water from the hot heat transfer oil coming from solar CPCs. The heating coil tube has a 16 mm outer diameter. There is also an auxiliary 1.25 kW electrical resistant heater used to complete the distillation process when solar energy is insufficient. The upper cover of distillation tank was made of a ready-made stainless lid having a diameter of 300 mm and a built-in water-tight sealing. The lid was welded to the distillation tank. The 298 mm diameter, 500 mm long distillation basket in which 5 kg chopped fresh peppermint is placed for distillation was made of 1 mm thick stainless sheet having 304 steel quality. The bottom of basket was covered by 1 mm thick perforated steel sheet having 10 mm holes made with a plasma cutting machine.

The condenser, which is used to condense the mixture of steam and essential oil having passed through the plant pile in the distillation basket, consists of a water tank, a spiral cooling coil, circulation pump and an aluminum radiator (210×205 mm) with an electrical fan. The 225 mm diameter, 410 mm long cylindrical water tank was made of 1 mm thick black steel sheet. The spiral cooling coil made of a 8 mm diameter 1500 mm long copper tube was placed in the water tank to cool steam and essential oil mixture by water. The steam passing through the copper serpentine pipe condensates by transferring its heat to the cooling water is in the cooling water tank. The cooling water is sucked at the bottom of tank by a circulation pump and is sent back to the upper level of tank after losing its heat to air flowing through the radiator. The pipe of condenser is a ½ inch plastic pipe. The circulation pump (Alarko NPVO-26-P type) was run at the second operating level during the experiments.

The oil separator consists of a glass bottle and a glass jar. The condensed water and essential oil drip into the 70 mm diameter, 340 mm long glass bottle, which was placed into the 180 mm diameter glass jar having the volume of 8 ℓ. A 6 mm diameter hole was drilled at the bottom of glass bottle to let water flow into the glass jar. At the beginning of each trial, 1.5 kg soft water was poured into the glass jar to block the leakage of essential oil into the glass jar and to collect condensed essential oil only in the glass bottle. The condensed essential oil accumulates over the condensed water because of their density differences in the glass bottle. The distillation tank was connected to the condenser with 2 inches stainless pipe.

2.2. Dimensioning and manufacturing of solar CPCs with evacuated tubes

The monthly average daily horizontal radiation intensity of Tokat (Turkey) city was considered to size solar CPCs. The heat energy needed to increase the temperature of 7 kg water poured into the distillation tank for each trial from 20^{o}C to 100^{o}C was calculated as follows:

$$Q_w = m_w \times c_w \times \Delta T_w \quad (1)$$

Where m_w is the mass of water (kg); c_w is the specific heat of water (kcal·kg^{-1}·^{o}C^{-1}); ΔT_w is the increase (100-20= 80^{o}C) of water temperature.

The heat energy needed to evaporate 5 kg of 7 kg water at 100^{o}C was calculated as follows:

$$Q_s = m_w \times L_w \quad (2)$$

Where L_w is the specific heat of vaporization of the water (kcal·kg^{-1}) at the standard atmosphere pressure. 2 kg water was not evaporated to keep the heat exchanger and the electrical heater in water in the distillation tank.

The mass of steel parts (pipes, fittings, distillation tank, etc.) of the distillation unit and solar CPCs was accepted to be 100 kg and the heat energy was stored by these metal parts was calculated as follows:

$$Q_{st} = m_{st} \times c_{st} \times \Delta T_{st} \quad (3)$$

Where m_{st} is the mass of steel parts (kg); c_{st} is the specific heat of the steel (kcal/kg·^{o}C) and ΔT_{st} is the temperature increase (100-20= 80^{o}C) of the steel parts. The energy to increase the temperature of 18 kg heat transfer oil filled in the distillation unit from 20^{o}C to 100^{o}C was calculated as follows:

$$Q_o = m_o \times c_o \times \Delta T_o \quad (4)$$

Where m_o is the mass of heat transfer oil (kg); c_o is the specific heat of heat transfer oil (kcal·kg^{-1}·^{o}C^{-1}); ΔT_o is the temperature increase (100-20=80^{o}C) of heat transfer oil.

The total amount of heat energy needed for distillation was calculated as follows:

$$Q_n = Q_w + Q_s + Q_{st} + Q_o \quad (5)$$

During a day, the efficiency of solar CPCs varies with the difference between the temperature of the working liquid and ambient temperature, and solar radiation. While the increase of incident radiation intensity increases the efficiency of solar CPCs, the increase of the temperature difference decreases it. The average daily efficiency of solar CPCs was chosen to be ~46% by considering the average solar radiation intensity of 750 W·m^{-2} and the temperature difference of 100^{o}C (Kalogirou, 2004). The size of distillation unit, ambient conditions and the amount of the water that is used for distillation affect the efficiency of the distillation unit. The efficiency of distillation unit is the percentage of the heat used to heat and evaporate 5 kg water to the heat gained by solar CPCs from the solar energy. It was chosen to be 50% because of heat losses from the parts of distillation unit and heat stored by the parts of distillation unit.

The overall efficiency of the distillation system with solar CPCs was found to be 23% by multiplying the efficiencies of the distillation unit and solar CPCs. The total aperture area of the CPCs was calculated as follows:

$$A_t = {}^{Q_n}\!/_{Q_{sol} \times \eta_s} \quad (6)$$

Where Q_n is the total amount of heat energy (kcal) needed for distillation; Q_{sol} is the daily total solar energy (kcal·m^{-2}·day^{-1}) falling on the inclined surface of solar CPCs based on the data obtained from the literature; η_s is the overall efficiency of the distillation system.

The maximum concentration ratio of a solar CPC can be calculated as follows (Rabl, 1976):

$$YO = {A_a}/{A_r} = {1}/{\sin\theta_A} \qquad (7)$$

Where A_a is the aperture area of a solar CPC (m^2); A_r is the area of a receiver tube (m^2) and θ_A is the half acceptance angle.

The aperture area of a solar CPC was calculated as follows:

$$A_a = W \times L \qquad (8)$$

Where W and L stand for the width and length of a solar CPC, respectively.

The parabolic curves making up the two parts of a solar CPC reflector were drawn based on the half acceptance angle (θ_A) and the radius of the tubular absorber that has a vacuumed gap surrounded by a concentric glass envelope (Figure 1). The reflector curve (DCF) consisting of the DC and CF curves were plotted in the Cartesian coordinate system by calculating x-y pairs as follows:

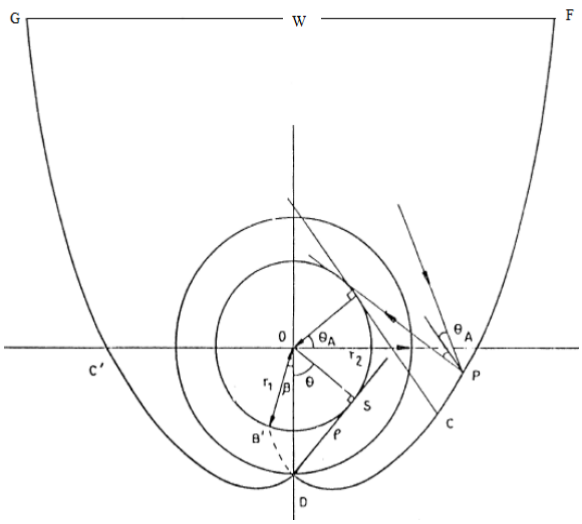


Figure 1. Reflector dimensions of solar CPCs with vacuum tubes (Oommen and Jayaraman, 2001)

$$x = r_1 \sin\theta - \rho\cos\theta \qquad (9)$$

$$y = -r_1\cos\theta - \rho\sin\theta \qquad (10)$$

Where r_1 radius of tubular absorber and θ is the angle at the origin measured from the negative axis (line OD) in the anti-clockwise direction to the line joining the origin and the point of tangency of the incident or reflected ray on the absorber as shown in Figure 1 (Oommen and Jayaraman, 2001).

The length of the tangent to the absorber from a given point on the reflector for the θ angle changing from D to C was calculated as follows:

$$\arccos\left({r_1}/{r_2}\right) \leq \theta \leq \left(\theta_A + {\pi}/{2}\right) \qquad (11)$$

$$(\rho = r_1\theta_1' = r_1(\theta+\beta)) \qquad (12)$$

The length (ρ) of the tangent to the absorber from a given point on the reflector for the θ angle changing from C to F was calculated as follows:

$$\left(\theta_A + {\pi}/{2}\right) \leq \theta \leq \left({3\pi}/{2} - \theta_A\right) \qquad (13)$$

$$\rho = r_1\left[\theta + \theta_A + {\pi}/{2} + 2\beta - \cos(\theta - \theta_A)\right] / \left[1 + \sin(\theta - \theta_A)\right] \qquad (14)$$

Where β is the angle of B'OD. Its value was calculated as follows:

$$\beta = [(r_2/r_1)^2 - 1]^{1/2} - \arccos\left({r_1}/{r_2}\right) \qquad (15)$$

The x-y pair values of solar CPC reflector were calculated in Excel for 32° half acceptance angle 48 mm diameter tubular absorber having a selective surface. These values of x-y pairs were transferred to AutoCAD to draw the CPC reflector. The concentration ratio of 1.9 was obtained by truncating solar CPC reflector. The aperture area of the CPC reflector was 3.4 m^2. The width, length and height of solar CPC reflector were 285 mm, 172 mm and 237 mm, respectively.

The plywood sheets of 1250×2500×18 mm were cut based on the drawings of solar CPC reflector transferred to a CNC machine to make the four frames of CPC reflectors. Each frame had 7 solar CPCs reflector profiles on it. These four frames were assembled axially using woodscrews.

The reflectors of solar CPCs were made of anodized aluminum sheets that had a thickness of 0.4 mm and 89% reflectivity. The aluminum sheet was curved by using a plate rolling machine and then was embedded and fixed inside to the assembled solar CPC frames by a pneumatic stapler as seen in Figure 2.

Figure 2. Assembling the reflectors of CPCs

The solar evacuated tubes having 58 mm external glass tube outer diameter, 47 mm internal glass tube outer diameter, 1800 mm length and selective absorber surface were centered with the optical axis of solar CPC reflectors were centered and then fixed to the solar CPC frames. The inner diameter of the internal glass tube was 44 mm. A ½ inch steel pipe were concentrically were inserted into a 1 inch steel pipe and then they were welded each other from their ends by using flat washers. The air gap between these two pipes provided insulation between the incoming and exiting heat transfer oil and the amount of the heat transfer oil to be used was reduced by decreasing the internal volume of the evacuated tube. Nine 30 mm long, 2 mm thick metal thin flat bars were welded around the outer surface of the 1 inch steel pipe at 0.5 m longitudinal intervals in order to insert and place these concentric steel pipes centrically into the solar evacuated tube. The cold heat transfer oil coming from the distillation unit enters into the inner steel pipe and exits from the other end of the inner steel pipe. After exiting the inner pipe, the heat transfer oil flow through the gap between the inner surface of the internal glass tube and the outer surface of 1 inch steel pipe and gains heat from the absorber. The hot heat transfer returns back to the collector head and goes to the distillation unit. The evacuated tube was mounted to the collector head with leak proof sealing. The circulation of the heat transfer oil in the evacuated tube is shown schematically in Figure 3.

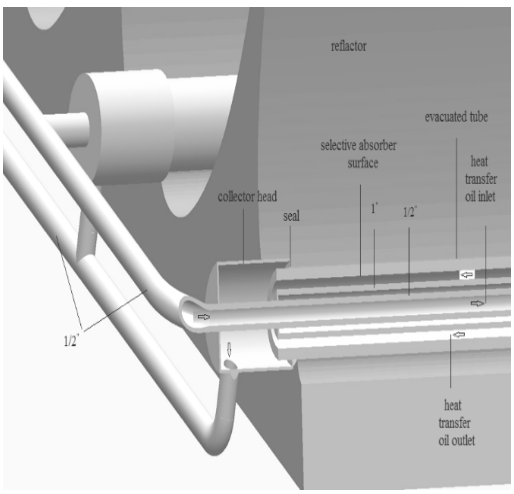


Figure 3. The flow of heat transfer oil in an evacuated tube

The solar CPCs were tilted at the angle 15^o less than the degree of latitude (40.2^o) in Tokat to maximize solar insolation over solar CPCs in summer time (Kılıç and Öztürk, 1983).

2.3. Assembly of solar CPCs and distillation unit

The solar CPCs and the distillation were connected to each other via ½ inch welded steel pipes. The collectors were connected in parallel. ½ inch stainless ball valve was located to the inlet pipe in order to adjust the amounts of oils entering the collector. The heat transfer oil was circulated by a circulation pump (Dab VSA 65/130 m) resistant to 140^{o}C operating temperature and placed in the collector return line and that had 50 ℓ·min^{-1} flow rate and 5.8 mSS head. The heat transfer oil circulated in the system boiled the water by transferring its heat energy to the distillation water while passing through the circular involute heating coil in the distillation tank. An open expansion tank with a 2.5 m height from the ground was placed and connected to the suction line with ½ inch pipe in order to prevent the heat transfer oil from damaging the instalments. Two valves were placed at the upper ends of distribution and collection manifolds of the collectors to throw out the air trapped within the installation. The heat transfer oil was filled to the system from the expansion tank. Two valves were placed at the lower points of the distribution and collection manifolds of the collectors to discharge the heat transfer oil from the system. The heat transfer oil used in the system is Mobiltherm 605 and can be used up to 200^{o}C in open systems and 300^{o}C in close systems. The general view of solar CPCs assembled with the distillation unit is shown in Figure 4.

Figure 4. Assembled solar distillery with solar CPCs

2.4. Data collection

The incident solar radiation intensity on the inclined surface was momentarily measured with pyranometer (Kipp&Zonen CM11). The pyranometer was placed at the collector inclination angle on the top of solar CPCs. A stainless turbine flow-meter (Bass Instruments TDSS.015) was attached to the pump pressure line to measure the volumetric flow rate of heat transfer oil. Its maximum operating temperature was 150 °C. Six Pt100 temperature sensors (Tetcis TR03B1M306-5Ü.TK) were used to momentarily measure the temperatures of the heat transfer oil entering to CPCs and exiting from them during trials, the temperature of water in the distillation tank, the temperature of steam in the steam chamber, the temperature of steam leaving the distillation tank and the temperature of cooling water. The ambient temperature was measured in the shade every half an hour with a digital thermometer (TES1361). Wind speed was measured every half an hour at the mid-height of the collectors with an anemometer (Kestrel 1000). The temperatures of the evacuated tubes were measured every half an hour with an infrared thermometer (Fluke 65) to determine extremely hot points on the tubes.

2.5. Analysis of experimental data

The amount of energy (θ_o) transferred to heat transfer oil was calculated as follows (Duffie and Beckman, 2006)

$$\theta_o = \int \dot{m} \times c_o \times \Delta T_o \quad (16)$$

Where $\dot{m}$ is mass flow rate of heat transfer oil (kg·min^{-1}); c_o is the specific heat of the heat transfer oil (kcal·kg^{-1}·°C^{-1}); ΔT_o is the difference of the temperatures (°C) of heat transfer oil entering and exiting the solar CPCs.

The mass flow rate of heat transfer oil was calculated as follows:

$$\dot{m} = v \times d \quad (17)$$

Where v is the volumetric flow rate of heat transfer oil (m·min^{-1}) and d is the density of heat transfer oil (kg·m^{-3}). The density of heat transfer oil was calculated as follows (Anonymous, 2014):

$$d = 5.99 \times 10^{-6} \times T_i^2 - 0.607 \times T_i + 892.47 \quad (18)$$

Where T_i is the entering temperature of heat transfer oil to the collectors (°C).

The specific heat of the heat transfer oil was calculated as follows (Anonymous, 2014):

$$c_o = 8.6 \times 10^{-8} \times T_i^2 + 0.0014 \times T_i + 0.37 \quad (19)$$

The total measured amount of the incident solar radiation on the surface of the collectors was calculated as follows (Duffie and Beckman, 2006):

$$\theta_T = \int I \times A_a \quad (20)$$

Where I is the total amount of incident solar radiation per unit area (kcal·min^{-1}·m^{-2}) coming on the collector and A_a is the total collector aperture area (m²).

When the incident solar radiation was not concentrated by covering the reflectors with a black cover, the total measured amount of the incident solar radiation on the surface of evacuated tubes was calculated as follows:

$$\theta_T = \int I \times A_p \quad (21)$$

Where A_p is the diffuse reflection area of evacuated tubes (m^2). It was calculated as follows (Liandon et al., 2010);

$$A_p = 2 \times D_a \times L \times n \quad (22)$$

Where D_a is the diameter of absorber surface; L is the length of evacuated tubes and n is the number of evacuated tubes. Equations 16, 20 and 21 were numerically integrated by using experimental data.

3. Results and Discussion

Three trials were performed with the new distillation unit in August. During the trials, the solar radiation intensity, the collector entering and exiting temperatures of heat transfer oil, the volumetric flow rate of heat transfer oil and the temperature of distillation water, the temperature of the steam chamber over the water, the temperature of the steam leaving the distillation tank, the temperature of cooling water were measured over time. The data were recorded every minute. All of the trials started at 08:00 am. and the peppermint plants used in the experiments were harvested early in the morning and filled into the distillation basket after chopping. Two (A and B trials) of three trials were performed while the incident solar radiation was concentrated by solar CPC reflectors. Trial A was conducted on August 13, 2013 and sky was covered partially by clouds in time. Trial B was conducted on August 28, 2013 and sky was clear. During the third trial (Trial C) conducted on August 22, 2013, the solar CPC reflectors were covered by a black cloth sheet and only the solar radiation falling on the evacuated tubes were absorbed.

3.1. Solar radiation intensity

The trial (Trial A) in which clouding was observed during the day lasted for 8.33 hours. Clouding began

8.25 hours later after the start of Trial A. Rapid decreases in solar radiation intensity (down to 166 W·m^{-2}) occurred due to cloudiness. The temperature of heat transfer oil dropped to 105^{o}C as a result of increased clouding at the end of the day and the distillation process slowed down. Since the distillation was very slow and all of the 5 kg water could not been evaporated, the electric heater was turned on at 16:43 and the trial was completed at 16:50. As the electric heater was turned on, the heat transfer oil circulation pump was turned off. The solar radiation intensity increased from 354 W·m^{-2} at the beginning of the trial to its highest value of 1134 W·m^{-2} at 12:48 pm. The average solar radiation intensity during the experiment was 876 W·m^{-2}, average ambient temperature was 29.05°C and average wind speed was 0.53 m·s^{-1}. The measured values of solar radiation intensity on the inclined surface values over time during the trial were given in Figure 5a.

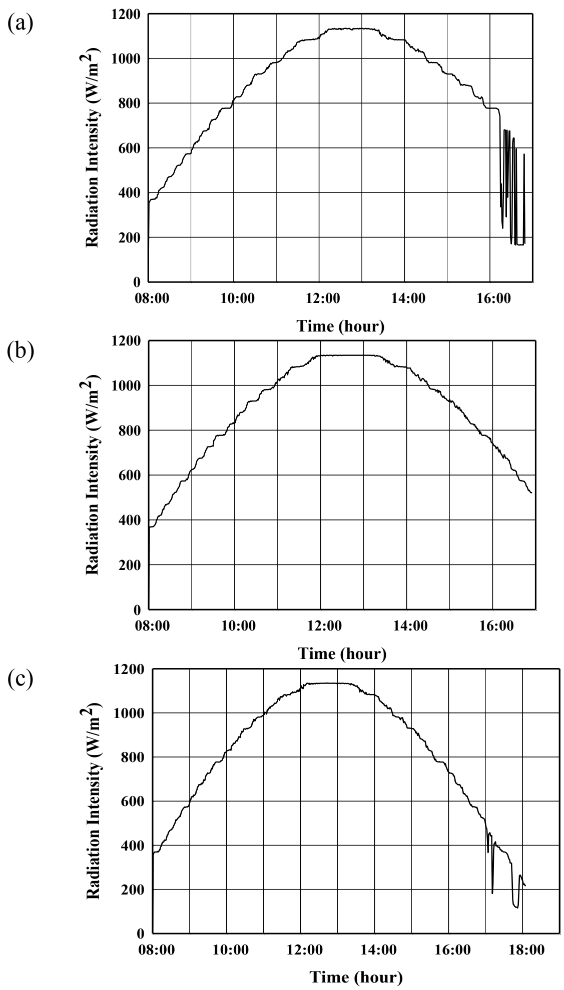


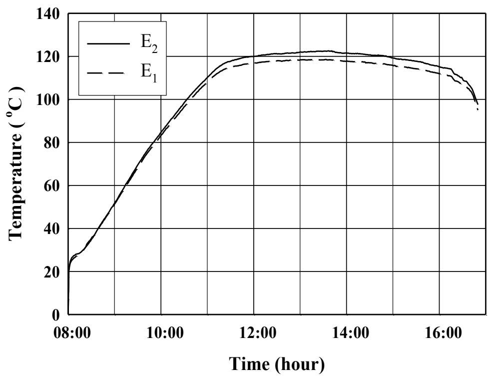
Figure 5. The measured values of solar radiation intensity on the inclined surface values over time during the trials (a: Trial A, b: Trial B, c: Trial C)

The trial (Trial B) in which there was no clouding during the day lasted for 8.9 hours. 5 kg water was evaporated in this trial without the use of electric heater. The solar radiation intensity increased from 368 W·m^{-2} at the beginning of the trial to its highest value of 1134 W·m^{-2} at 12:40 pm. There were no instant decreases in the solar radiation intensity because of no clouding and the average solar radiation intensity was found to be 887 W·m^{-2}. The average ambient temperature was 28.07°C and the average wind speed was 0.6 m·s^{-1}. The measured values of solar radiation intensity on the inclined surface values over time during Trial B were given in Figure 5b. The distillation water could not reach the boiling temperature until 15:00 during Trial C in which the solar CPC reflectors were covered with the black fabric sheet to demonstrate the effect of solar concentration. Therefore, the electrical heater was turned on at 15:00 to complete the distillation process. Trial C was completed after evaporating 5 kg distillation water at 18:05. The solar radiation intensity increased from 356 W·m-² at the beginning of the trial to its highest value of 1134 W·m-² at 12:15 pm. The average solar radiation intensity during the trial was 916 W·m-². The average ambient temperature was 26.54°C and the average wind speed was 0.6 m·s-1. The measured values of solar radiation intensity on the inclined surface values over time during Trial C were given in Figure 5c. The time interval of each plot was selected by considering the total duration of the considered trial.

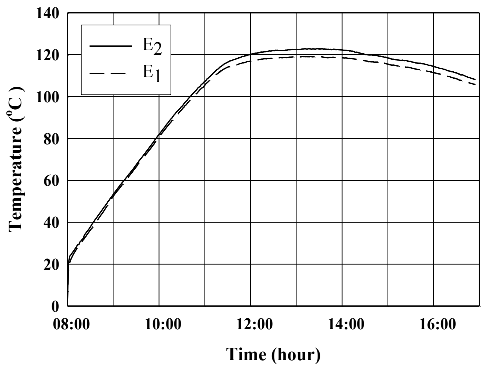
3.2. The collector entering and exiting temperatures of heat transfer oil

The collector entering (E_1) and exiting (E_2) temperatures of heat transfer oil were 20.10°C and 20.87°C respectively at the beginning of Trial A in which partial clouding was observed. They gradually increased up to 118.35°C and 122.53°C, respectively and stayed almost constant for a while. The start of distillation water boiling stabilized the collector entering and exiting temperatures of heat transfer oil until the values of solar radiation intensity were not enough to boil water. The average difference between them was 2.59°C during the trial time. The occurrence of clouding caused a rapid decline in them after 16:15 (Figure 6a). The collector entering and exiting temperatures of heat transfer oil were 16.44 and 18.91°C respectively at the beginning of Trial B in which no clouding occurred. They gradually increased up to their maximum values of 118.98°C and 122.84°C, respectively (Figure 6b). They decreased slowly similar to the decrease of solar radiation intensity in the afternoon. The average difference between them was 2.55°C during the trial time. The collector entering and exiting temperatures of heat transfer oil were 15.68°C and 16.66°C respectively at the beginning of Trial C in which the solar CPC reflectors were covered the black fabric sheet and no solar concentration occurred. They were able to increase only up to 93.55°C and 94.97°C, respectively (Figure 6c). Therefore, the distillation water could not been boiled with the solar energy gained by the solar evacuated tubes. Therefore, the electrical heater was turned on. The average difference between them was 0.95°C before the electrical heater was turned on.

(a)



(b)



(c)

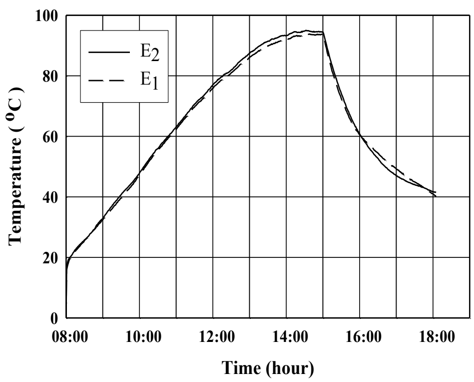
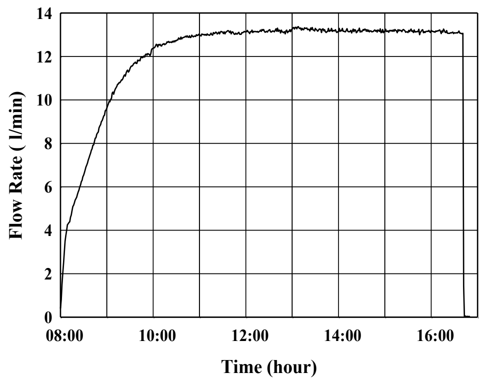


Figure 6. The collector entering and exiting temperatures of heat transfer oil over time (a: Trial A, b: Trial B, c: Trial C)

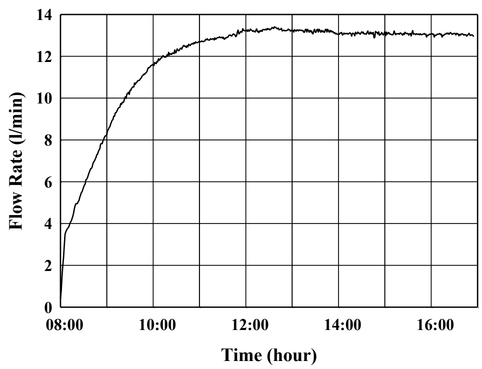
3.3. The volumetric flow rates of heat transfer oil

The volumetric flow rate of heat transfer oil gradually increased up to ~13 $\ell \cdot min^{-1}$ during Trials A and B in which the incident solar radiation was concentrated by solar CPC reflectors (Figures 7a and 7b).

(a)



(b)



(c)

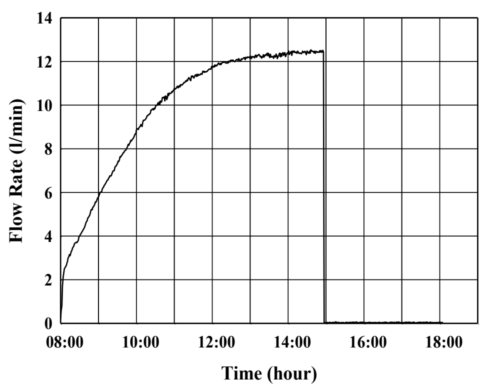


Figure 7. The volumetric flow rate values of heat transfer oil over time (a: Trial A, b: Trial B, c: Trial C)

The increase of heat transfer oil temperature decreased the viscosity but increased the volumetric flow rate of the heat transfer oil. The increase of the volumetric flow rate values slowed down due to the fact that the increase of heat transfer oil temperature slowed down around 11:00 am. On the other hand, the volumetric flow rate of heat transfer oil increased slowly over time in Trial C than in Trials B and C because of the differences in their temperatures (Figure 7c). The volumetric flow rate of heat transfer oil gradually increased up to ~12.5 ℓ·min^{-1} during Trial C.

3.4. Temperature values of distillation water and steam at the different points of distillation unit

The temperature values of distillation water and steam at the different points of distillation tank were plotted over time in Figure 8.

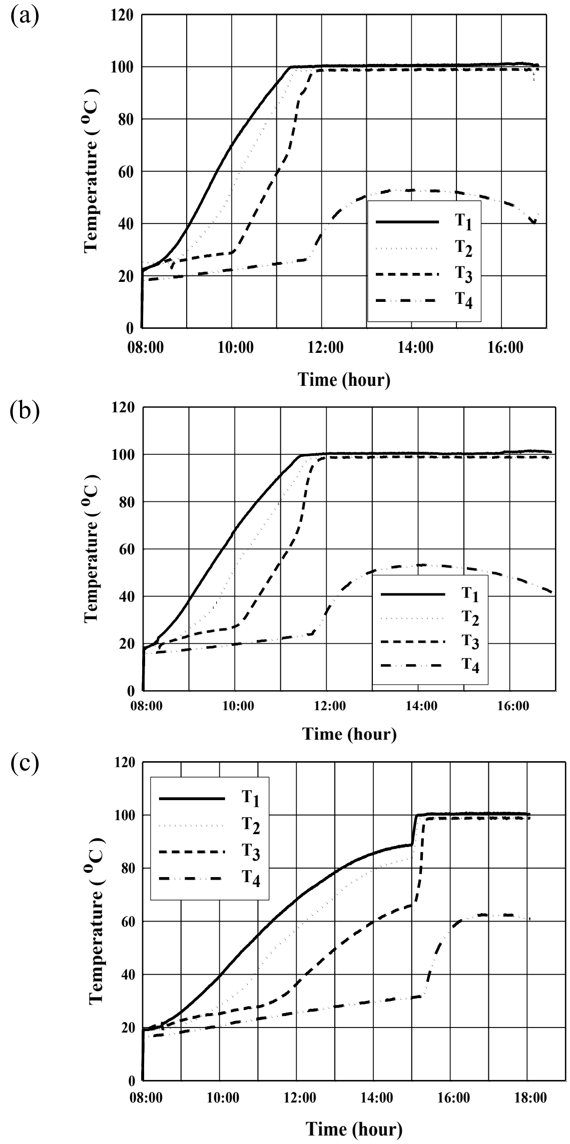


Figure 8. Temperature values at the different points of distillation unit over time (a: Trial A, b: Trial B, c: Trial C)

The temperature (T_1) of distillation water at the bottom of distillation tank gradually increased up to its boiling point (~100°C) at 11:00 am-11:30 am stayed constant at its boiling point for Trials A and Trials B (Figures 8a and 8b). The temperature (T_2) of steam in the steam chamber, which was the section between the free surface of distillation water and the bottom of distillation basket, the temperature (T_3) of steam leaving the distillation tank followed the temperature of distillation water but showed time delays. After T_3 reached to the water boiling temperature value, the circulation pump of condenser was turned on to have the cooling water lose heat to the ambient air. The cooling water temperature (T_4) reached up to ~53°C and began to decrease because of the decrease of solar radiation intensity in the afternoon. These results showed that the condenser unit was good enough to condense precisely the steam of distillation water and the essential oil of peppermint plants. The decrease of solar radiation intensity reduced the amount of distillation water getting vaporized and then reduced the amount of heat that had to be removed from the cooling water. The distillation water temperature reached up to only 88.6°C during solar heating for Trial C in which the incident solar radiation was not concentrated (Figure 8c). After the electrical heater was turned on at 15:00, the temperature (T_1) of distillation water reached rapidly its boiling point for Trial C. The temperature (T_2) of steam in the steam chamber and the temperature (T_3) of steam leaving the distillation tank also reached the boiling points with a short time delay after electrical heating started. The temperature (T_4) of cooling water increased up to ~62.5°C (Figure 8c). The electrical heating increased more the temperature of cooling water since it accelerated the vaporization of distillation water compared to Trials A and B in which electrical heating was not used or shortly used.

3.5. Thermal performance of solar CPCs

The amounts of insolation on the total aperture area of solar CPCs (Curve 1) were calculated by multiplying solar radiation intensity with the total aperture area of solar CPCs and numerically integrating them in one-minute-time interval and plotted over time in Figures 9a, 9b and 9c for Trial A, Trial B and Trial C respectively. The amounts of insolation on the total diffuse reflection area of evacuated tubes (Curve 1) were calculated by multiplying solar radiation intensity with the total diffuse reflection area of evacuated tubes and numerically integrating them in one-minute-time interval and plotted over time in Figures 9c for Trial C. When the incident solar radiation was concentrated by solar CPC reflectors, the total aperture area of solar

CPCs was considered to calculate the amount of insolation arriving on the solar CPCs. On the other hand, when the incident solar radiation was not concentrated by solar CPC reflectors, the total diffuse reflection area of evacuated tubes was considered to calculate the amount of insolation arriving on the solar CPCs. The amounts of insolation on the aperture area of solar CPCs followed a similar trend to the solar radiation intensity plots given in Figure 5. The occurrence of clouding reduced drastically the amount of insolation arriving on the total aperture area of solar CPCs (Figure 9a). The amounts of heat energy gained from insolation by solar CPCs in one-minute-time interval (Curve 2) were also given in Figures 9a, 9b and 9c for Trial A, Trial B and Trial C, respectively. The amounts of heat energy gained from insolation by solar CPCs in one-minute-time interval were calculated by multiplying the difference between the collector entering and exiting temperatures of heat transfer oil with the mass flow rate and the specific heat capacity of heat transfer oil. The increase of the difference between the collector entering and exiting temperatures of heat transfer oil increased the heat gained by solar CPCs per minute. The curve (Curve 2) of heat gained by solar CPCs in one-minute-time interval showed fluctuations and ripples during the trials. These fluctuations and ripples could be caused by the heat energy charge and discharge of distillation unit parts (pipes, the distillation tank, heat transfer oil, etc.), the measurement errors of the temperature sensors and the flow rate meter, the heat losses from the unit to ambient and the irregularities in the flow of heat transfer oil due to its friction and expansion. The heat gain in one-minute-time interval was correlated with the amount of insolation arriving on the total aperture area of solar CPCs per minute. The maximum values of heat gain in one-minute-time interval were 25.13, 23.95 and 8.80 kcal for Trials A, B and C, respectively. Trials A and B had much higher heat gains in one-minute-time interval since the incident solar radiation was concentrated for these trials compared to Trial C. The total amount of insolation having arrived on the aperture area of solar CPCs was 22245 kcal for Trial A until it was completed. The total amount of insolation having arrived on the aperture area of solar CPCs was 23133 kcal for Trial B until the electrical heater was turned on. The total amount of insolation having arrived on the diffuse reflection area of evacuated tubes was 6175 kcal for Trial C until the electrical heater was turned on. The total amount of heat gained by solar CPCs was 7620 kcal for Trial A until it was completed. The total amount of heat gained by solar CPCs was 7368 kcal for Trial B until the electrical heater was turned on. The total amount of heat gained by the evacuated tubes was 1722 kcal for Trial C until the electrical heater was turned on. The percentage values of the total amount of heat gain to the total amount of insolation were 34.3%, 31.8% and 27.9%, for Trials A, B and C, respectively. These results show that the concentration of incident solar radiation.

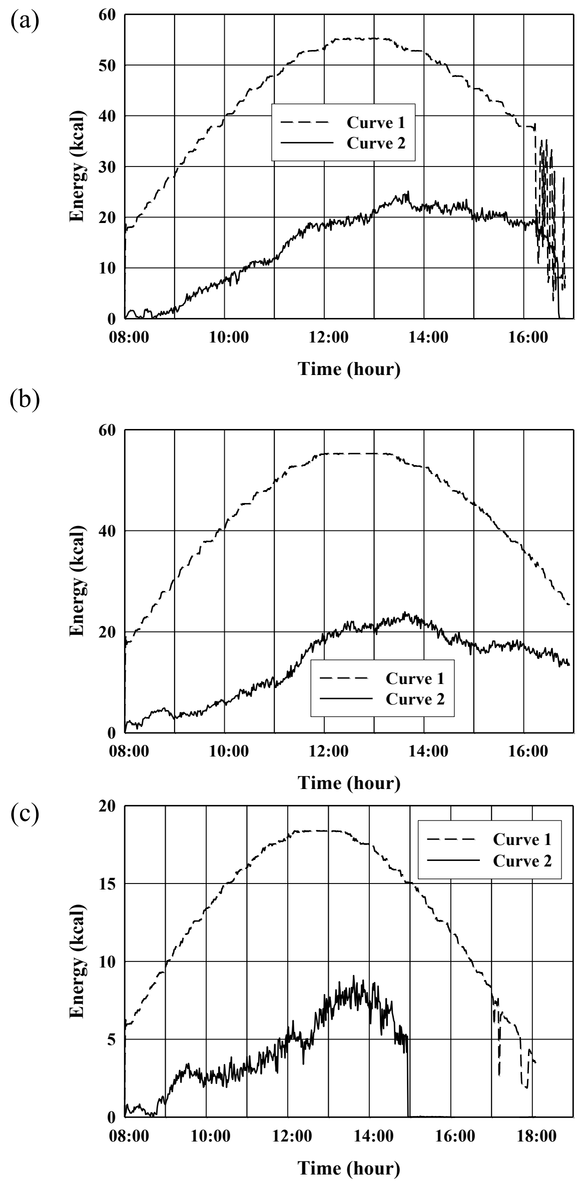


Figure 9. The amounts of solar energy arriving to CPCs and collected by the CPCs per minute (a: Trial A, b: Trial B, c: Trial C)

4. Conclusions

A unique essential oil distillation system with solar CPCs gaining its thermal energy from solar energy was developed and its performance was experimentally tested. This essential oil distillation system consisted of seven solar Compound Parabolic Collectors (CPCs) to convert solar energy to heat energy and a water-steam distillation unit to extract essential oil from the peppermint plants by steam. The overall efficiency of solar CPCs ranged from 27.9% to 34.3%. The distillation system was able to distill essential oil from 5 kg newly-harvested peppermint plant by evaporating 5 kg distillation water without needing electrical heating when no clouding was observed during distillation process. However, the occurrence of clouding during the distillation process made electrical heating necessary to evaporate 5 kg distillation water. Concentrating incident solar radiation by solar CPC reflectors increased the total heat gain and the overall efficiency of solar CPCs. A versatile automation system needs to be developed to keep the performance of this unique essential oil distillation system high and consistent under varying weather conditions.

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