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Design and Performance Analysis of Conical Solar Concentrator

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Abstract

Purpose: The objective of this study is to evaluate the performance of the conical solar concentrator (CSC) system, whose design is focused on increasing its collecting efficiency by determining the optimal conical angle through a theoretical study. **Methods:** The design and thermal performance analysis of a solar concentrator system based on a 45° conical concentrator were conducted utilizing different mass flow rates. For an accurate comparison of these flow rates, three equivalent systems were tested under the same operating conditions, such as the incident direct solar radiation, and ambient and inlet temperatures. In order to minimize heat loss, the optimal double tube absorber length was selected by considering the law of reflection. A series of experiments utilizing water as operating fluid and two-axis solar tracking systems were performed under a clear or cloudless sky. **Results:** The analysis results of the CSC system according to varying mass flow rates showed that the collecting efficiency tended to increase as the flow rate increased. However, the collecting efficiency decreased as the flow rate increased beyond the optimal value. In order to optimize the collecting efficiency, the conical angle, which is a design factor of CSC, was selected to be 45° because its use theoretically yielded a low heat loss. The collecting efficiency was observed to be lowest at 0.03 kg/s and highest at 0.06 kg/s. All efficiencies were reduced over time because of variations in ambient and inlet temperatures throughout the day. The maximum efficiency calculated at an optimum flow rate of 0.06 kg/s was 85%, which is higher than those of the other flow rates. **Conclusions:** It was reasonable to set the conical angle and mass flow rate to achieve the maximum CSC system efficiency in this study at 45° and 0.06 kg/s, respectively.

Keywords: Collecting efficiency, Conical solar concentrator, Optimum flow rate, Performance analysis, Solar energy

Introduction

Currently, fossil fuels, such as coal and oil, are used as main energy sources. In recent years, these fuels have significantly contributed to environmental pollution, global warming, and resource depletion. Because of these problems, it is necessary to improve the efficiency of technologies that take advantage of renewable energy sources (Al et al., 2016; Ruelas et al., 2017; Jaramillo et al., 2016; Meng et al., 2016). It is well known that solar energy, as a source of renewable energy, is currently one of the most important energy sources and has received increasing attention in several heat applications, because it is clean, inexhaustible, and abundant but has minimal negative environmental impact (Lee, 2013; Hussein, 2016; Ustaoglu et al., 2016; Cakici et al., 2017). Moreover, solar energy is the largest and cheapest energy resource on earth (Imtiaz and Lee, 2015a). Numerous researchers have continuously studied the use solar energy in industry as well as various shapes of solar concentrators. In particular, a study is being conducted on a concentrating solar collector that can achieve higher temperatures than flat-plate collectors. High-temperature solar collectors employ mirrors and lenses (Vijayan et al., 2013; Meiser et al., 2015, Tang et al., 2016; Imtiaz and Lee, 2016). The conical solar concentrator (CSC) system is one of the mirror types of thermal solar concentrator for condensing solar energy into energy sources. This system consists of

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a conical solar reflector, double tube absorber, and heat storage tank. The solar energy entering the aperture of the concentrator is redirected through the reflector, and the energy is condensed on the surface of the absorber. The condensed energy transfers heat to the operating fluid flowing inside the absorber and is converted into thermal energy. It uses a domestic solar thermal field, which includes solar water heating, solar-powered heating, and solar drying. Togrul et al. (2004) examined solar air heaters with varying conical collector angles between the main tube and horizontal surface in the range 28.4–38.4°. Exit air temperatures reached 150℃, which allow the utilization of the device under high-temperature applications. Hussain (2016) presented a thermal performance evaluation of a conical solar water heater integrated with a thermal storage system, seeking to compare the collecting efficiency of the concentrator employing a double tube absorber, with and without a vacuum glass. Nevertheless, because of the minimal amount of research conducted on CSC design so as to achieve high efficiency, no definitive answer has been provided for a CSC with a critical conical angle. In this investigation, the optimal angle was identified based on theoretical studies, such as that which considers heat loss and concentration ratio. The objective of this study was to design a CSC with minimum heat loss and high collecting efficiency. The heat loss in the conical solar concentrator was minimized by using an optimal conical angle of 45°, which was determined by theoretical means. A performance analysis of the optimally designed CSC at various mass flow rates was conducted. In this work, the CSC system consists of a conical reflector, double tube absorber, and heat storage tank. The conical solar reflector was made of an aluminum sheet with high reflectivity. The double tube absorber was positioned at the center of the reflector along its focal axis so as to obtain a uniform concentration of the solar flux. The CSC system, which is a closed-loop system, was equipped with a thermal storage tank for water heating so as to monitor the continuous temperature rise of the operating fluid. For the thermal storage tank, excellent insulating materials, such as high-pressure double urethane and polyethylene were used to minimize heat loss. The systems were equipped with a dual-axis tracking system to increase solar flux.

Materials and methods

Conical solar reflector design

In the conical reflector design, the analysis of the effect of the conical angle provides a very appropriate approach for high-efficiency solar energy solutions. The optimization of a CSC is based on half of the conical angle of the system. To analyze the effect of the conical angle directly on the system, the following design parameters were defined as fixed variables in Eqs. (1), (2), and (3) (Fig. 1): the

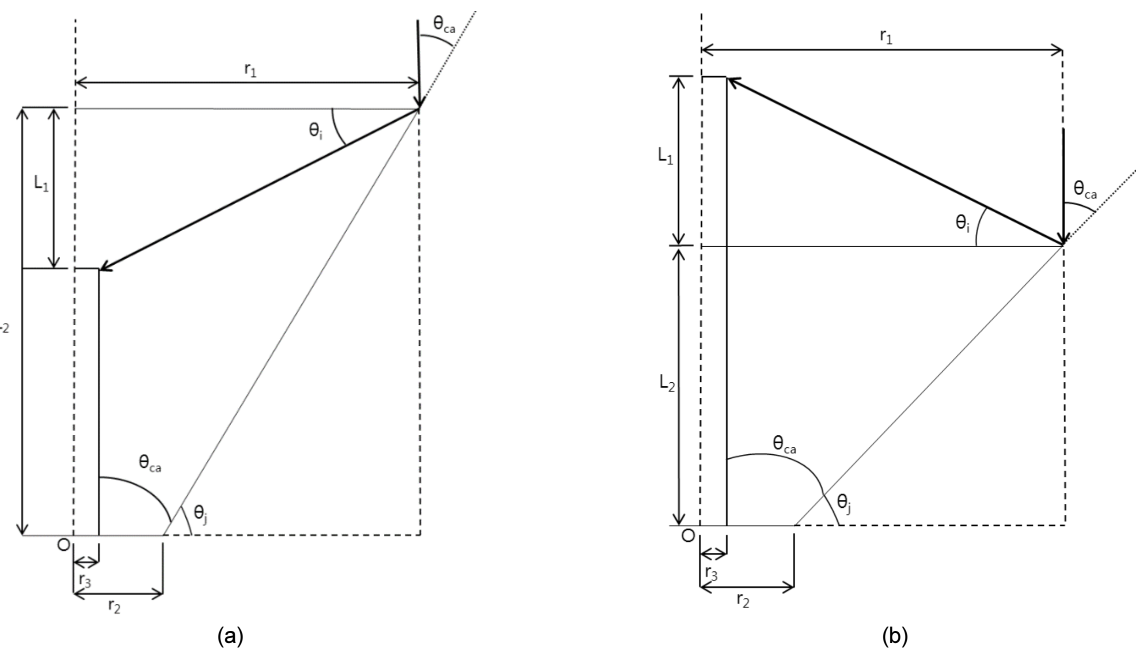

Figure 1. Geometrical structure of conical solar reflector (a) $0^\circ < \theta_{ca} \leq 45^\circ$ (b) $45^\circ \leq \theta_{ca} < 90^\circ$.

aperture radius(r_1), conical reflector bottom radius (r_2), double tube absorber width(r_3), and design variable of the conical angle (θ_{ca}). With these formulas, the length of the double tube absorber is expressed as $L_{ab} = L_2 + L_1$ when the conical angle is $0^\circ < \theta_{ca} \leq 45^\circ$, and $L_{ab} = L_2 - L_1$ when $45^\circ \leq \theta_{ca} < 90^\circ$. The case of the conical angle being of 45° is possible in both cases. The above equations are basic to the conical reflector design, and the variables must be set according to the capacity of the system.

$$L_1 = \tan(\theta_i)(r_1 - r_3) \tag{1}$$

$$L_2 = \tan(\theta_j)(r_1 - r_2) \tag{2}$$

$$\begin{cases} \theta_i = |90^\circ - 2\theta_{ca}| \\ \theta_j = 90^\circ - \theta_{ca} \end{cases} \tag{3}$$

Heat loss in CSC design

One of the factors that affect the efficiency of a solar concentrator system in its design is the heat loss that occurs as a result of absorption, reflection, and so on. To overcome these problems, an optimal design must be considered based on a theoretical analysis. The heat loss of the CSC design, which depends on the conical angle, occurs as shown in Figure 2. The colored region indicates the heat loss area. In the range $0^\circ < \theta_{ca} < 45^\circ$, the solar radiation reflected from the bottom portion of the reflector is blocked by the floor surface of the concentrator. Consequently, the solar flux could not reach the double tube absorber. At $45^\circ < \theta_{ca} < 90^\circ$, although the solar radiation redirected from all portions

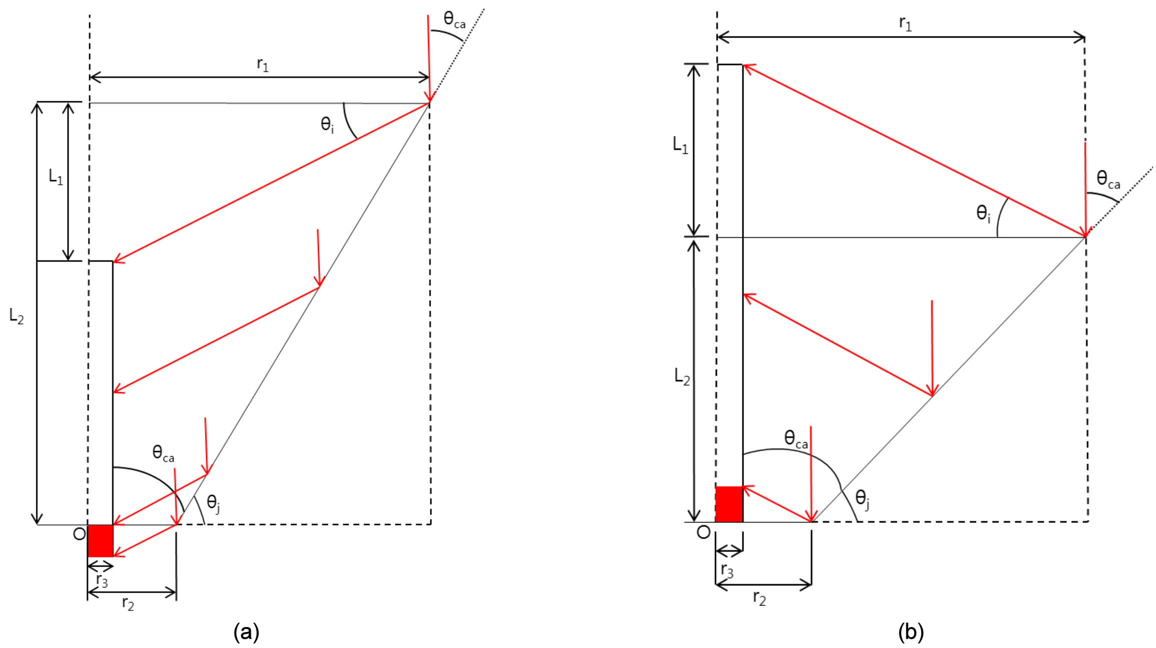

Figure 2. Diagram of conical solar reflector heat loss (a) $0^\circ < \theta_{ca} < 45^\circ$ (b) $45^\circ < \theta_{ca} < 90^\circ$.

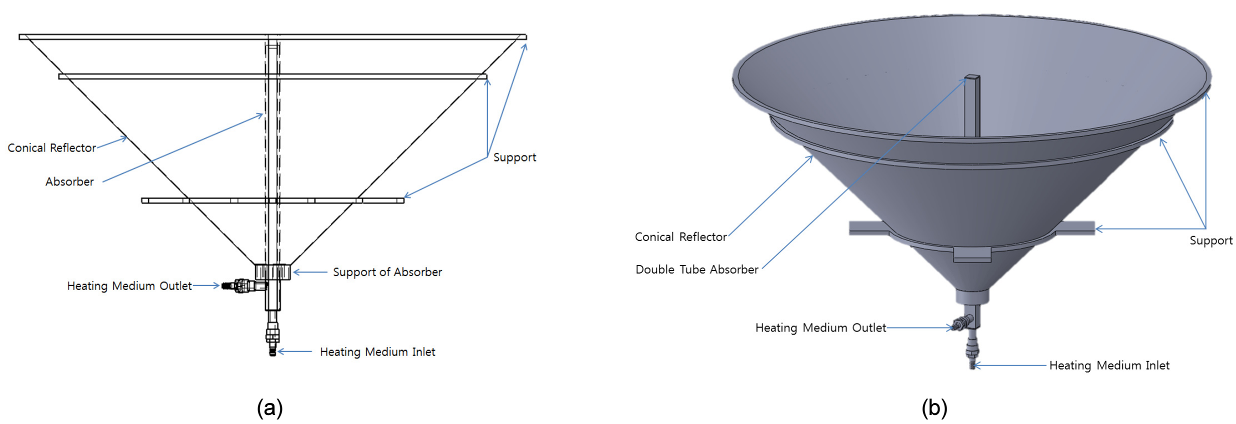

Figure 3. Graphical representation of a conical solar reflector (a) two-dimensional (b) three-dimensional

of the reflector can reach the double tube absorber, there is no solar flux transmitted to the bottom portion of the absorber. Within this range, the height of the double tube absorber is longer than that of the reflector. Thus, the heat lost to the atmosphere is greater. Considering such heat loss, if the length of the double tube absorber is reduced, then the area of the densest portion is reduced and efficiency is further decreased. In the case of 45°, as shown in Figure 3, the reflected solar radiation is collected vertically on the absorber, minimizing the heat loss that could occur based on the design. Because θ_{ca} is closer to 45°, theoretically, the concentration ratio (C) values approach the maximum value. The concentration ratio, C, for CSC is to be calculated in a similar way as that given in Eq. (3). This can be obtained by dividing the area of the absorber (A_{abs}) that receives the solar flux by the aperture area (A_{ape}) of the conical solar reflector.

$$C = A_{ape}/A_{abs} \tag{4}$$

Table 1 lists the C values according to conical angles using the fixed variables for the experiment given in Eq. (4). These variables were assumed to be appropriate for the purpose of the experiment. A prototype of the conical solar reflector was fabricated and experiments were conducted on it. The design shown in Figure 3 was drawn with the aid of AutoCAD and Solid Works software.

For the circulation of the operating fluid, the double tube absorber was fabricated by using two copper tubes having different diameters and located at the center of the conical solar concentrator. Moreover, the collected energy in the heated surface of the absorber is conveyed to the operating fluid flowing within the absorber with the aid of a circulation pump. This is particularly true because the material used for the absorber is copper, which has high thermal conductivity and resistance to corrosion. To improve the performance of the absorber, its surface is painted black to increase absorption, as shown in Figure 4.

Experimental set up

The CSC system consists of five parts (Table 2): a conical solar reflector, double tube absorber, heat storage tank, sun tracking system, and data collecting devices, as shown Figure 5. The conical reflector was made of an aluminum sheet with high reflectivity. To prevent twisting and deformation, steel hoops were welded at the top, bottom, and center of the conical reflector. The double tube absorber was made of two

Table 1. Geometric parameters of CSC

Conical angle (°)		$L_{ref}(mm)$	$L_{ab}(mm)$	Concentration ratio
$0^\circ < \theta_{ca} \le 40^\circ$	5	5257.82	2493.07	3.1487
	10	2608.79	1269.39	6.1841
	15	1716.74	872.37	8.9985
	20	1263.84	682.56	11.4958
	25	986.47	577.41	13.5952
	30	796.74	515.59	15.2341
	35	656.95	479.51	16.3709
	40	548.21	462.25	16.9822
$\theta_{ca} = 45^\circ$	45	460	460	17.0652
$50^\circ \le \theta_{ca} < 90^\circ$	50	385.99	471.95	16.6331
	55	322.10	499.53	15.7148
	60	265.58	547.04	14.3500
	65	214.50	623.56	12.5834
	70	167.43	748.41	10.4889
	75	123.26	967.63	8.11261
	80	81.11	1420.51	5.5262
	85	40.24	2805.00	2.7986

Note, 1) Fixed variables: aperture radius (r_1), bottom radius of conical reflector (r_2), double tube absorber width (r_3).
2) Design variable: conical angle (θ_{ca}).
3) Assumptions: $r_1 = 500(mm), r_2 = 40(mm), r_3 = 12.5(mm)$

(a) (b)

Figure 4. Double tube absorber (a) two-dimensional drawing (b) three-dimensional drawing.

copper tubes with different diameters to circulate the operating fluid. It was painted black for high absorption and positioned at the center of the reflector along its focal axis so as to obtain a uniform concentration of the solar flux. To minimize heat loss, an optimal absorber length, considering the laws of reflection, was selected. For the thermal storage tank, excellent insulating materials, such as high-pressure double urethane and polyethylene were used to minimize heat loss. Resistance temperature detectors (RTDs) were installed at the top, bottom, and center of the thermal storage tank to measure the operating fluid temperature. For data collecting devices, a data logger (GL800, GEAPHTEC, USA) was used to record temperature readings of the operating fluid through the absorber at 60-s intervals. The incident direct solar radiation on the concentrator surface was measured with a pyrheliometer (EQ-08, Middleton solar, Australia). Ambient temperature and wind speed data were collected using a weather station (Vantage Pro2Plus, Davis Instruments Co., USA) at 60-s intervals. The collected data that affected the efficiency were used for the performance analysis of the solar system based on a 45° conical-shaped concentrator. The analysis was conducted under different mass flow rates of 0.03, 0.06, and 0.1 kg/s. A series of experiments utilizing water as the operating fluid was performed under a clear and cloudless sky. For an accurate comparison of the effect of the mass flow rates, three equivalent systems were tested under the same operating conditions. The systems were equipped with a dual-axis tracking system (V 3.3, Hanul Corp., Rep. Korea) to increase the capture of solar flux and provide sustained solar radiation. A slew driver and linear actuator tracked the altitude and azimuth angles, respectively, and were operated using a tracking sensor and controller. The driving cycle of the tracking system was 6 s and the incident angle error of tracking was 0.025°.

Table 2. CSC Specifications

Description	Conical Solar Concentrator
Conical Solar Reflector	Material : Aluminum Aperture area : 0.785 m^2 Conical angel : 45 ° Height : 460 mm Average CR : 17.07
Double Tube Absorber	Material : Copper Height : 460 mm
Heat Storage Tank	Cylindrical vertical Capacity : 70 L
Solar Tracking System	Dual axes
Data collecting system	Temperature : RTD (GL800) Direct solar radiation : Pyrhelimeter (LI19)

Figure 5. Experimental setup of CSC systems.

Table 3. CSC accuracy

Description	Error	Sensitivity
Solar tracking sensor	0.025°	
Direct pyrheliometer		$10\mu v/(W/m^2)$
Data logger (LI-19)		$15\mu v/(W/m^2)$
Thermocouple (T-type)	±0.15℃+0.002℃	
RTD (PT100Ω)	±0.05%+1.0℃	
Data logger (GL800)	±1.0℃	
Flowmeter	±2%	

Error sources in CSC systems

The error sources are based on collected measured data, such as the incident solar radiation, temperature of the operating fluid and mass flow rates during the experiments. All measured data were recorded at 60-s intervals. In order to reduce measurement errors, temperature sensors were attached at two points after calibration, and the mean of the temperature values at these points was used. The errors of the collecting devices are given by the manufacturer's specifications. The errors in all experimental results in this study are listed Table 3. These errors appear to be at an acceptable level (Imtiaz and Lee, 2015b; Imtiaz et al., 2015).

Concentrator collecting efficiency

In this study, the thermally collected useful energy of CSC can be written as

$$Q_t = \dot{m}c_w(T_o - T_i) \tag{5}$$

where Q_t is the thermally collected useful energy of the

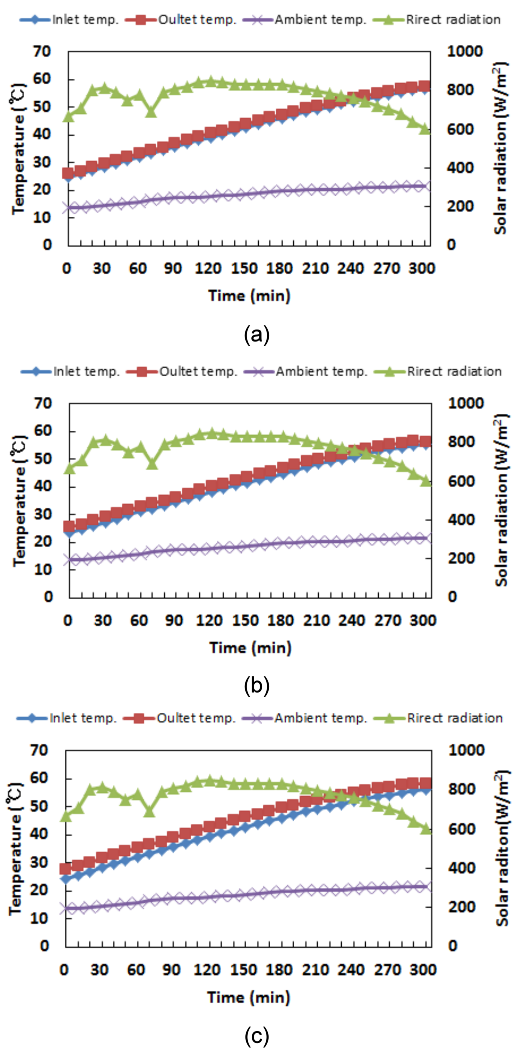

Figure 6. Daily variations of operating conditions at flow rates of (a) 0.1 kg/s (b) 0.06 kg/s (c) 0.03 kg/s.

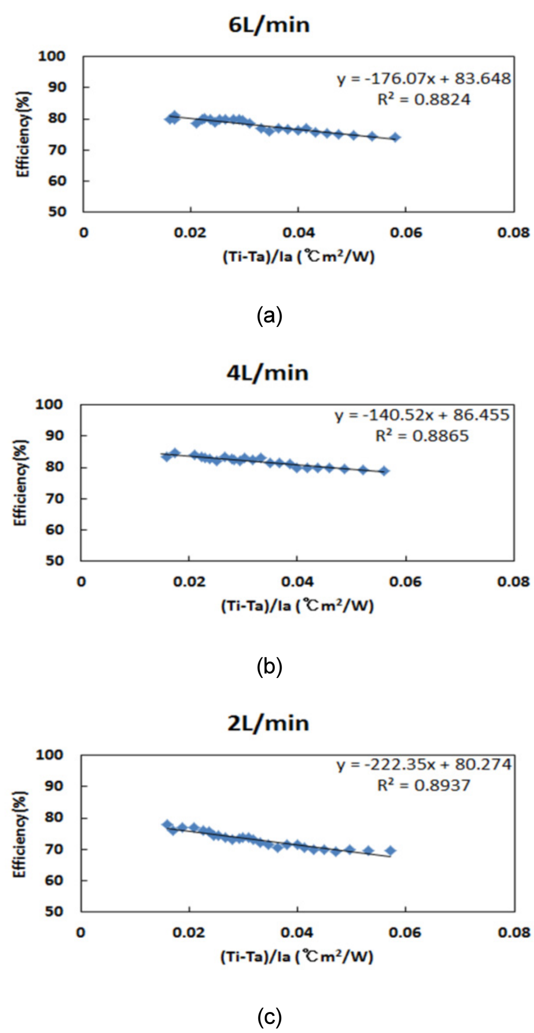

Figure 7. Collecting efficiency against $(T_i - T_a)/I_a$ at flow rates of (a) 0.1 kg/s (b) 0.06 kg/s (c) 0.03 kg/s.

CSC system, $\dot{m}$ is the mass flow rate, c_w is the specific heat of the thermal fluid, and T_i and T_o are the inlet and outlet temperatures of the heat operating fluid, respectively. The collecting efficiency of the CSC system during the experimental time is calculated using Eqs. (6) and (7) (Imtiaz and Lee, 2014; Ali, 2017).

$$\eta_t = \dot{m}c_w(T_o - T_i)/A_{ape}I_a \tag{6}$$

$$\eta_t = \eta_o - a(T_r - T_a)/I_a \tag{7}$$

where η_t is the concentrator instantaneous efficiency, A_{ape} is the area of the concentrator, I_a is the incident direct solar radiation, T_r is the mean temperature of the heat operating fluid, a is the heat loss of the concentrator, and η_o is the maximum efficiency of the concentrator.

Results and discussion

Performance analysis

A thermal performance analysis of CSC systems was conducted by using different values of mass flow rates, such as 0.03, 0.06, and 0.1 kg/s. Figure 6 indicates the daily variations of operating conditions at different values of the incident direct solar radiation, ambient temperature, and inlet and outlet temperatures measured at 60-s intervals. Figure 7 shows the collecting efficiency according to $(T_i - T_a)/I_a$. The collecting efficiency decreased with increasing inlet temperature and difference in ambient temperature. It is considered that heat is lost because of increases in convection as the operating fluid temperature increases. This system can achieve high collecting efficiency and temperature than a low temperature collector. Additionally, if the size of the system is increased, it can be used in a field requiring higher temperatures, such as in an industrial system (Kang MC et al., 2006; Son PH et al., 2007, Park BJ and So YS, 1997).

In the experiment, it was found that the factors that influence the CSC system are the incident direct solar radiation, inlet temperature of the operating fluid, and ambient temperature (Fig. 8). As the inlet and ambient temperatures increased, the heat loss through convection increased and collecting efficiency gradually decreased. This is because the rate of increase of the inlet operating temperature is higher than the rate of increase of the ambient temperature.

Through the use a thermal imaging camera (Thermo Gear G100, NEC, Japan), the surface temperature of the double tube absorber and inlet temperature at an optimal mass flow rate of 0.06 kg/s were obtained (Fig. 9). The temperature of the inlet was successively taken as 30, 40,

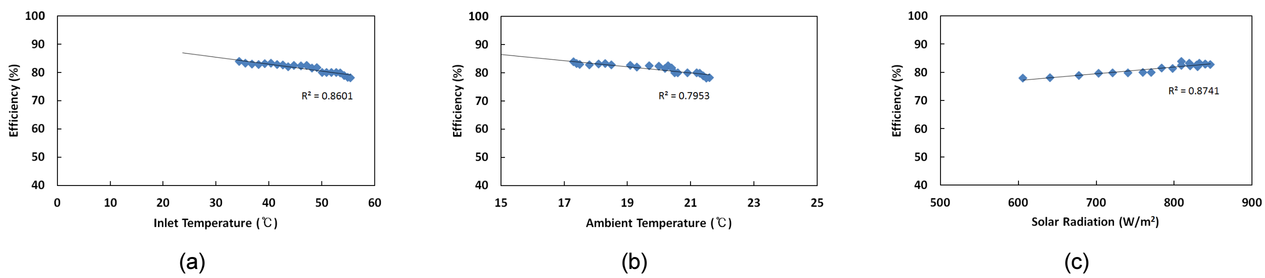

Figure 8. Collecting efficiency according to influential factors. (a) Inlet temperature (b) Ambient temperature (c) Solar radiation.

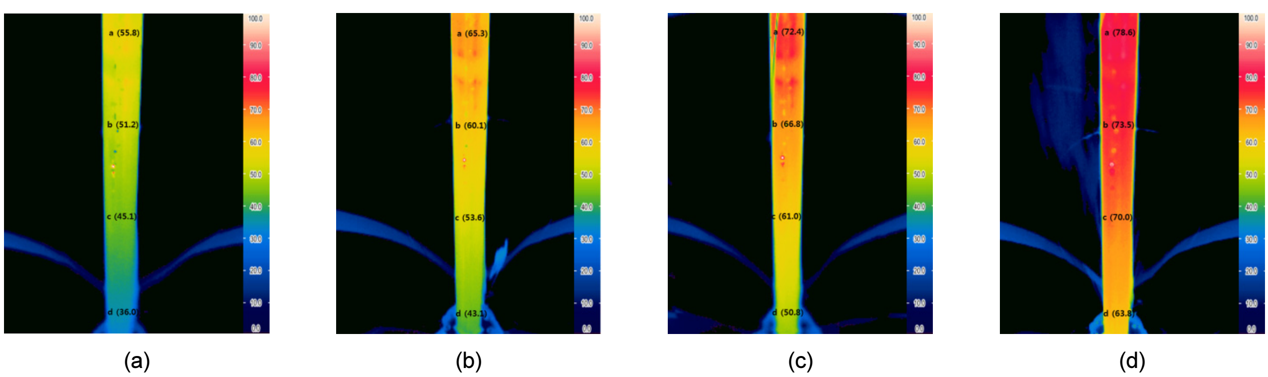

Figure 9. Surface temperature of double tube absorber according to the inlet temperature (a) 30℃ (b) 40℃ (c) 50℃ (d) 60℃.

50, and 60℃. The CSC is characterized by the gradual decrease in the concentration ratio because of the reduction in the aperture area from the upper part to the lower part of the conical reflector. Accordingly, it was confirmed that the surface temperature of the double tube absorber became lower at its bottom section. Moreover, as the inlet temperature increases, the surface temperature rise of the absorber decreases because of heat loss through convection to the atmosphere. Early and later stages of the experiment time are somewhat shorter because of low direct solar radiation.

Conclusions

In this study, the effects of changes in the mass flow rate and CSC design on the collecting efficiency of a CSC system are analyzed based on a theoretical approach. The correlation between high efficiency and design factors was further analyzed to determine the influence of the optimal conical angle. The conical angle, which is a design factor of the CSC, was selected to be 45° based on low heat loss in order to optimize the collecting efficiency. Furthermore, as θ_{ca} closely approximates 45°, theoretically, the concentration ratio (C) approaches the maximum value. A performance analysis was conducted keeping all conditions constant except for the mass flow rate. The experimental results indicate the following conclusions. Influential factors, such as the incident direct solar radiation, ambient temperature, and initial inlet temperature have a significant effect on the collecting efficiency of the CSC system. The collecting efficiency was observed to be at its lowest and highest when the mass flow rates were 0.03 and 0.06 kg/s, respectively. All efficiencies were reduced over time because of variations in ambient and inlet temperatures throughout the day. The maximum efficiency calculated at an optimum mass flow rate of 0.06 kg/s was 85%, which is higher than those of the other flow rates. It was found that the optimal performance of this CSC system can be obtained at that flow rate.

Conflict of Interest

The authors have no conflicting financial or other interests.

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