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Optimized Controlling System for Heliostat by Using the Configuration Factor

Dong Il Lee, Seung Wook Baek + and Woo Jin Jeon

Propulsion and Combustion Laboratory, School of Mechanical, Aerospace and System Engineering, Division of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea

Abstract. As an early stage of development, environmental friendly solar thermal generation system has many potential to increase power generation efficiency. Among them, controlling of heliostat is the most important key component. Through the optimal control, receiver can enhance the system efficiency by absorbing maximized radiation heat from heliostat. Configuration factor commonly utilized in radiation is applied to control heliostat. By using simulink program, simulation is performed how to change the angle of incidence depending on distance and season. Based on the obtained incidence angle, the angle necessary to control elevation and azimuthal angle of the heliostat is calculated.

Keywords: Solar thermal generation system, heliostat, configuration factor.

1. Introduction

As fossil fuel is depleted, new renewable energy is in the spotlight. Among the renewable energy, Solar thermal generation system (STGS) has many advantages. STGS is non-polluting and it operates indefinitely unless sun is extinct. Also, it has potential for higher efficiency because control of heliostat [1,2,3], design of receiver and storage is in development nowadays. Optimized control of heliostat will reduce radiation energy loss. In addition, well designed receiver and storage will increase the temperature of heat transfer fluid and generate power even after sunset respectively. Recent report shows the comparison of different energies costs [4]. Total cost per kWh is calculated from the sum of construction costs per kWh, production costs per kWh and decommissioning costs per kWh(nuclear only). From above research, it can be found out that STGS is competitive with other energy. Particularly its cost is much lower than solar photovoltaic.

2. Method of Optimization

2.1. Configuration Factor

In radiation theory, configuration factor is one of the most important components. Consider two surfaces, say 1 and 2, of an enclosure. Radiation from A_1 to A_2 is like eq. 1. B_1A_1 is total energy as a constant and $F_{1\to2}$ stands for fraction. So radiation flux is maximized when $F_{1\to2}$ is maximum. Eq.2 is the definition of configuration factor. Figure 1 represents a fraction of total energy leaving surface 1 intercepted by surface 2.

$$q_{1\to2} = B_1 A_1 F_{1\to2} \tag{1}$$

$$F_{1-2} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi d^2} dA_2 dA_1 \tag{2}$$

+ Corresponding author. Tel.: + 82 42 350 3714; fax: +82 42 350 3710.
E-mail address: swbaek@kaist.ac.kr.

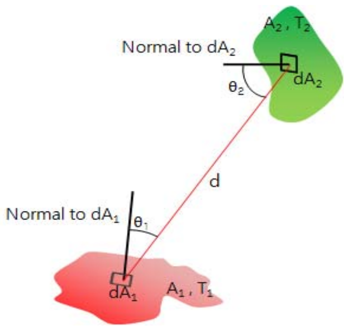


Fig. 1: Schematic diagram of configuration factor

By using eq.2, eq.3 can be derived. In eq.3, Y shows the multiplication of two configuration factors. As the distance between sun and heliostat or heliostat and receiver are constant, only incidence angle is considered in eq.3. There are two assumptions. First, θ_1 is zero because of large scale of sun. Second, incident angle of radiation on receiver surface θ_3 is predetermined by the position of heliostat. Therefore, purpose of this research is to find the maximum value θ_2 depending on movement of the sun.

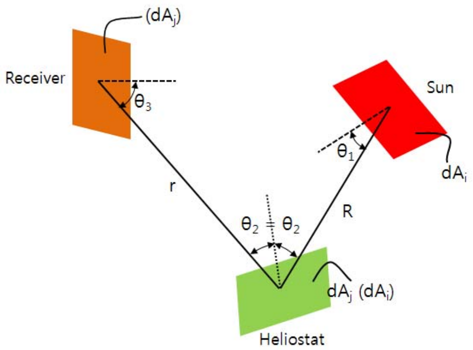
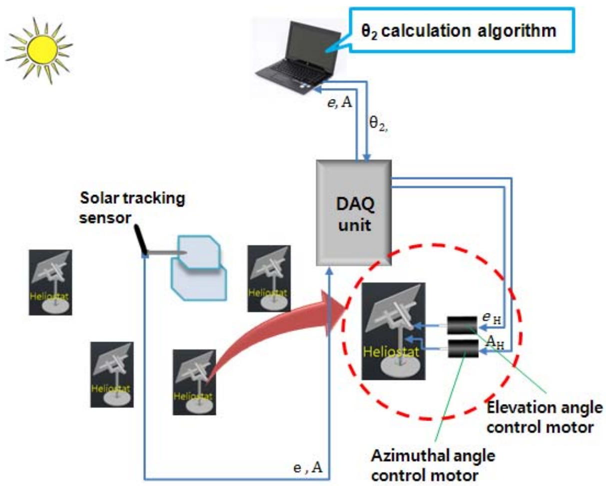


Fig. 2: Schematic diagram of two configuration factors

$$Y = \cos\theta_1 \cos\theta_2 \cos\theta_2 \cos\theta_3 \tag{3}$$

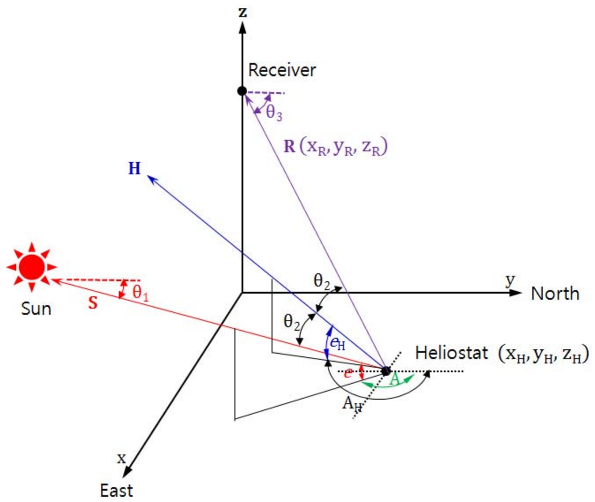
2.2. The Control System



e : Elevation angle of the sun
A : Azimuthal angle of the sun
e_H : Elevation angle of the heliostat
A_H : Azimuthal angle of the heliostat
θ_2 : Reflection angle on heliostat

Fig. 3: Control algorithm

Simulink program calculate elevation and azimuthal angle of the sun received signal from the sun sensor. After determining the location of the sun, pre-organized simulink program using equation 8 calculates θ_2 that makes maximum configuration factor. Obtained angle of θ_2 is used to calculate elevation angle of the heliostat and azimuthal angle of the heliostat. Values calculated from above are to take advantage of controlling heliostat correctly. This optimized control algorithm will enhance the system efficiency. As the sun moves from sunrise to sunset, solar sensor continuously detects the sun position and repeats above process till it finds the correct angle.



e : Elevation angle of the sun

A : Azimuthal angle of the sun

e_H : Elevation angle of the heliostat

A_H : Azimuthal angle of the heliostat

θ_2 : Reflection angle on heliostat

S : Unit vector directed from heliostat center to sun

H : Normal unit vector from heliostat surface

R : Unit vector directed from heliostat to receiver

Fig. 4: Azimuthal & elevation angle of sun and heliostat

$$S = S_x i + S_y j + S_z k = \cos e \sin A i + \cos e \cos A j + \sin e k \tag{4}$$

$$H = H_x i + H_y j + H_z k = \cos e_H \sin A_H i + \cos e_H \cos A_H j + \sin e_H k \tag{5}$$

$$R = \frac{(x_R - x_H)i + (y_R - y_H)j + (z_R - z_H)k}{\sqrt{(x_R - x_H)^2 + (y_R - y_H)^2 + (z_R - z_H)^2}} = R_x i + R_y j + R_z k \tag{6}$$

$$\cos(2\theta_2) = R \bullet S = R_x S_x + R_y S_y + R_z S_z = R_x \cos e \sin A i + R_y \cos e \cos A + R_z \sin e \tag{7}$$

$$\theta_2 = \frac{\cos^{-1}(R_x \cos e \sin A i + R_y \cos e \cos A + R_z \sin e)}{2} \tag{8}$$

Figure 4 show the azimuthal and elevation angles of sun and heliostat. By using a schematic, equations above can be induced. Equation 4, 5 and 6 represent unit vector of each direction. Eq.7 shows the dot product between unit vector directed from heliostat center to receiver and unit vector directed from heliostat center to sun. By utilizing dot product, reflection angle on heliostat θ_2 can be derived in eq.8.

$$H = \frac{R + S}{2\cos\theta_2} = \frac{(R_x + S_x)i + (R_y + S_y)j + (R_z + S_z)k}{2\cos\theta_2} \tag{9}$$

$$\sin A_H = \frac{R_x + \cos e \sin A}{2\cos\theta_2 \cos e_H} \tag{10}$$

$$\cos A_H = \frac{R_y + \cos e \cos A}{2\cos\theta_2 \cos e_H} \tag{11}$$

$$\sin e_H = \frac{R_z + \sin e}{2\cos\theta_2} \tag{12}$$

$$A_H = \tan^{-1}\left(\frac{\sin A_H}{\cos A_H}\right) \tag{13}$$

$$e_H = \sin^{-1}\left(\frac{R_z + \sin e}{2\cos\theta_2}\right) \tag{14}$$

Eq. 9 comes from the figure 4. By using eq. 4, 5 and 9, eq. 10, 11 and 12 can be induced. Eq. 13 and 14 represent azimuthal and elevation angle of the heliostat respectively. Those equations are programmed by simulink and simulation is conducted during the day with respect to different conditions depending on diverse distances and seasons.

Table 1: Data of the sun (Seoul, South Korea)

	Spring or Autumn	**Summer**	**Winter**
Elevation angle of the sun	0°~52°	0°~76°	0°~29°
Azimuthal angle of the sun	90°~270°	60°~300°	120°~240°
Sunrise time	06:35	05:11	07:43
Sunset time	18:43	19:56	17:17
Length of daytime	12h 08m 28s	14h 45m 28s	09h 33m 57s
Length of daytime(sec)	43708	53128	34437

Table 1 includes data of solar elevation and azimuthal angles, and sunrise and sunset time in Seoul, South Korea. The sun has the highest elevation angle in summer. In contrast, the sun passes through its orbit with the lowest angle in winter. Using above data, simulation is executed. As each season has different length of daytime, simulation time is dissimilar.

3. Results and discussion

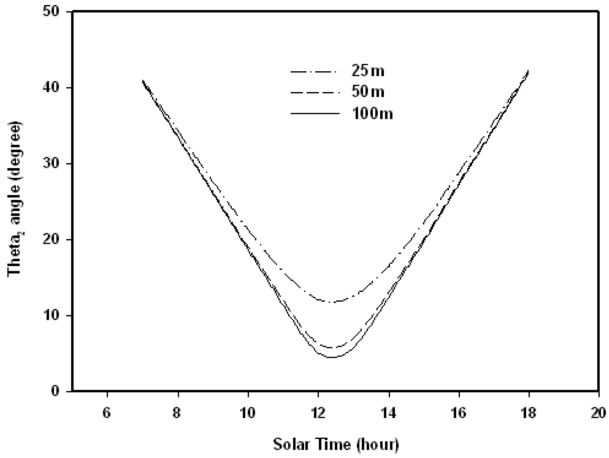


Fig. 5: Incidence angle versus solar time for different distances from receiver to heliostat (spring or autumn)

Figure 5 shows the incidence angle θ_2 versus solar time from sunrise to sunset. As the distance between the receiver and heliostat gets far, the variation of θ_2 becomes larger. That 'v' shape displays that dot product between unit vector R and unit vector S has the smallest value at meridian transit altitude. As the unit vector S becomes high, incidence angle θ_2 gets smaller on the way to meridian transit altitude.

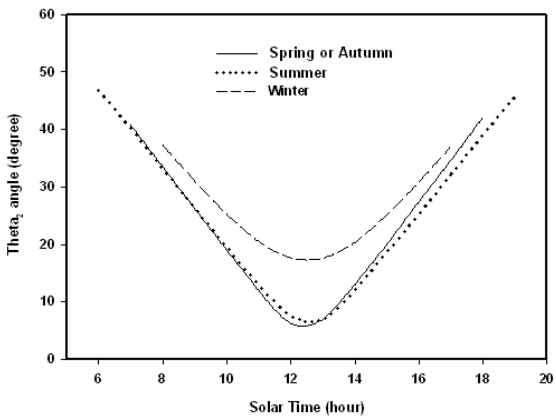


Fig. 6: Incidence angle versus solar time for different seasons, distance: 50m

Figure 6 shows the similar 'v' shape in different seasons. As the sun has the lowest elevation angle in winter, the difference of incidence angle θ_2 is the smallest. After reaching the meridian transit altitude, incidence angle θ_2 gets larger on the way to sunset. Because of different time reaching meridian transit altitude depending on the season, the time of lowest value θ_2 in winter is earlier than that of summer. The difference of incidence angle θ_2 in spring or autumn is affected due to the dissimilar size of the elevation angle.

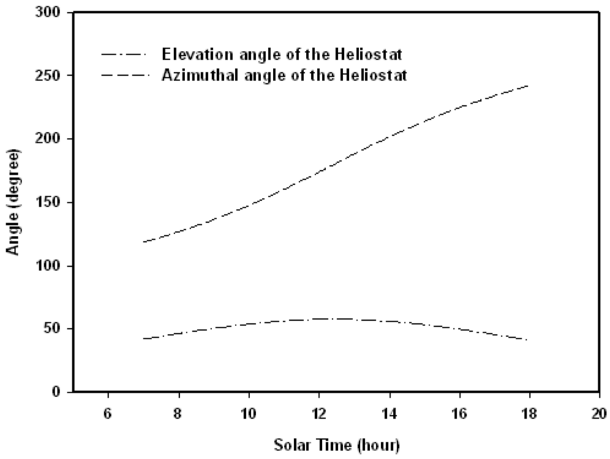


Fig. 7: Elevation and azimuthal angle of the heliostat versus solar time, season: spring or autumn, distance: 50m

By using eq. 13 and 14, simulation is done with elevation and azimuthal angle of the heliostat versus solar time. Reflection angle of θ_2 is used to calculate angles of heliostat. The difference of elevation angle between maximum and minimum is not lager than that of azimuthal angle.

4. Conclusions

Optimized controlling simulation for heliostat is conducted by using the configuration factor commonly used in radiation heat transfer.

Dissimilar distances from receiver to heliostat show interesting results. As the distance gets far, the difference of incidence angle gets larger. Also, dot product between unit vector R and unit vector S has the smallest value at meridian transit altitude.

Different seasons from spring to winter also represent notable results. As the time for reaching meridian transit altitude is different depending on the season, the time of lowest value θ2 in winter is earlier than that of summer.

Angles of elevation and azimuth needed to control heliostat can be derived by using reflection angle on heliostat.

5. Acknowledgements

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