SOLAR CENTRAL RECEIVER WITH AN IRISING APERTURE

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Abstract:

Variable sun elevation, azimuthal and declination angles with the time of day, and seasons of the year respectively, give variable projected image size defects produced by field site concave mirrors on the central cavity receiver's aperture entrance. If the aperture is small, it will be inefficient for periods when the solar isolation is inclined due to spillage. However, if the aperture is large, it will be inefficient for periods when the solar isolation is normal, due to excess heat radiation and convection losses. Thus, the fixed aperture area size is a compromise between ideal sizes for different conditions. The end result is a loss of efficiency as a function of time of day and seasons of the year. This research presents an approach to maximize the interception factor on the receiver entrance, with reducing the heat losses by radiation and convection through its aperture area. A central receiver system, having a down-looking cavity with an irises aperture is being proposed for application in rich environmental solar conditions, utilized solar flux insolation throughout the day on the city of Kuwait. Solar tower focusing collector with a cavity type receiver having a fixed area aperture at the entrance is presented for comparison with the proposed technique. This collector is proved to be less efficient than the suggested design. The isiring cavity receiver with a variable area aperture provides an approximately constant efficiency regardless of the time of day or season of the year. The end result is the proposed system shows improved performance and capability. However, over the life-time of installation these advantages of the proposed system should overweigh its disadvantages of additional cost due to extra automation.

Key words: Solar, Focusing collector, High temperature, Central receiver Irising aperture, Cavity type

1-Introduction:

Solar energy in Kuwait is promising, and there are signs of interest in building a solar central power plant in Kuwait [1], This research investigates the feasibility of available techniques their possible development. There are two groups of solar focusing collectors, low temperature and high temperature focusing collectors. *Low temperature solar focusing collectors* have an operating receiver temperature range between 100 ^{o}c and 400 ^{o}c. These are considered to be mid-temperature solar focusing collectors. They commonly have a range of concentration ratios between 20:1 and 100:1, and are classified under non-tracking and single-axis tracking collectors. Examples are Fresnel lens parabolic trough of low and high concentrations. These collectors require high performance optical refractors, or reflectors. The useful operating temperature of these systems can approach 300 ^{o}c. Problems encountered by these types of optical concentrators include the design of low cost stable structures to form and hold the reflecting optical elements and the development of corrosion resistant mirror materials to refract or reflect the solar energy. The receiver material must withstand high temperatures approaching 300 ^{o}c, and high rates of temperature change produced when the sun is obscured by a cloud is obscured by a cloud. The features of a Fresnel lens collector [2] are shown schematically in Fig.1. Fig.2 shows the efficiency of the collector as a function of its receiver temperature. Features of the parabolic trough with a moderate concentration ratio [2] are shown schematically in Fig.3. The concentrator has a moderate focal length, and a narrow aperture width. Efficiency of the collector as a function of its receiver temperature is shown in Fig.4. Fig.5 displays a comparison between various mid-temperature focusing collectors as a function of receiver temperature. It is noted that over temperature values of 200 ^{o}c and 260 ^{o}c, the parabolic trough collectors of high and low concentration ratios are more efficient than the Fresnel lens collector. The specified fixed parameters for all given collectors represent realistic practical transmittance and concentration ratios. *In high temperature focusing collectors*; the two axis tracking system is considered [2], in which solar energy is concentrated on an aperture that approaches a point. Parabolic dishes are one type where compound-curvature reflecting surfaces are utilized for focusing the incident radiation.

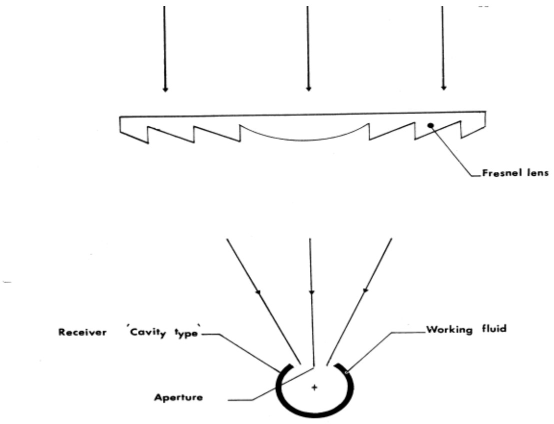

Fig.1- Principle features of Fresnel Lens Collector.

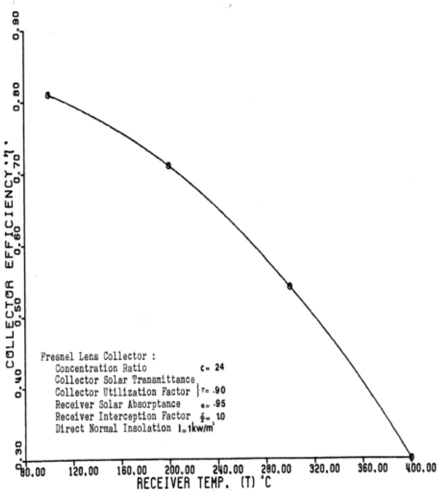

Fig.2 – Fresnel lens Collector Efficiency vs. Receiver Temperature

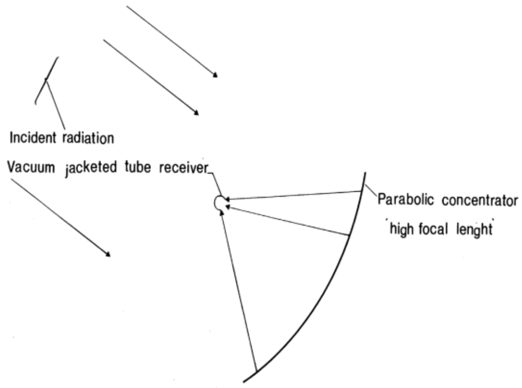

Fig.3- Parabolic Concentrator Collector.

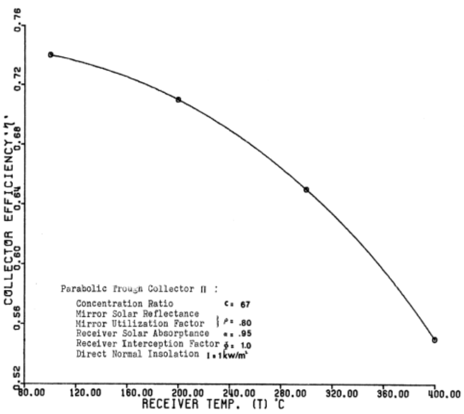

Fig.4- Parabolic Concentrator Collector Efficiency vs. Receiver Temperature.

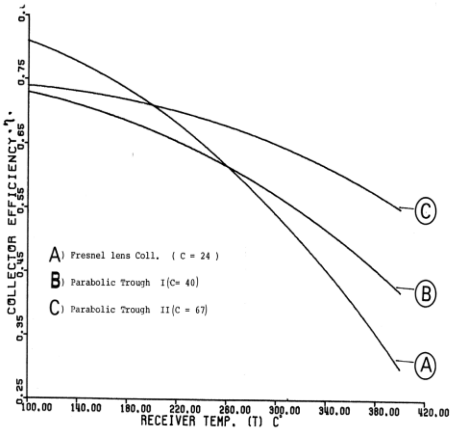

Fig.5. Efficiency of Various Collector vs. Receiver Temperature.

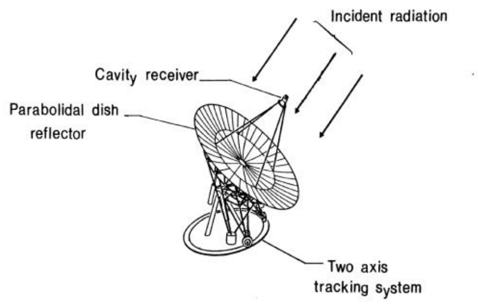

Fig.6- Parabolidal Dish Collector [2].

Heliostats are another type of two axis tracking systems. They utilize either a flat-plate reflector surface, or a compound-curvature reflecting surface. Heliostat surface concentrates the solar energy onto a central receiver. Two axis tracking systems achieve higher concentration ratios and higher receiver temperature operating between 400 ^{o}c and 1300 ^{o}c. Therefore, proceeding from the fixed orientation collectors to the single-axis tracking and finally to the two axis tracking system, collector performance improves and the receiver temperature level rises. For power system, higher receiver temperature has the advantage of providing higher thermal to mechanical energy conversion efficiencies..

Sophisticated solar collection systems are usually accompanied by higher costs per unit of collector area and this calls for additional technological development. For example,

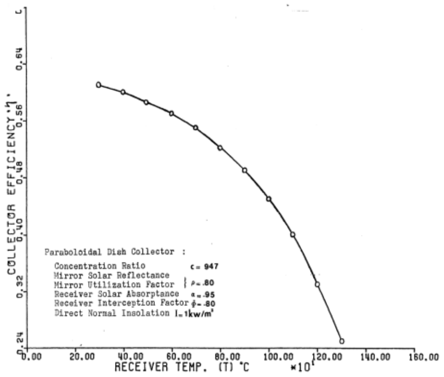

Fig.7- Parabolidal Dish Collector Efficiency vs. Receiver Temperature.

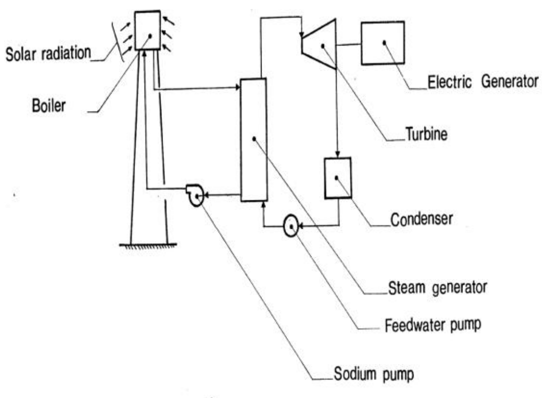

Fig.8- External Solar Central Receiver System Energy Loop.

material problems are encountered at high temperatures around 1300 ^{o}c. In addition, thermal shock problems occur at severe temperature changes resulting from cloud interferences. The complexity of high concentration systems, coupled with increasing fabrication costs per unit requires building large systems to achieve the greatest economy. The principal features of parabolic dish collector [2] are shown in Fig.6, while Fig.7 shows the collector efficiency vs. receiver temperature. One sort of central receiver systems is the external central receiver [2] shown in Fig.8. The incident radiation intercepted by the heliostat is reflected and concentrated on the external surface of the central receiver. This type of design suffers heat losses in four ways; (1) reflection (2) re-radiation (3) convection, and (4) conduction to the tower. Heat losses due to reflection are the most significant. The cavity type central receiver (Brumleve's concept) is another sort [3], where the principal features of the collector are shown by Fig.9.

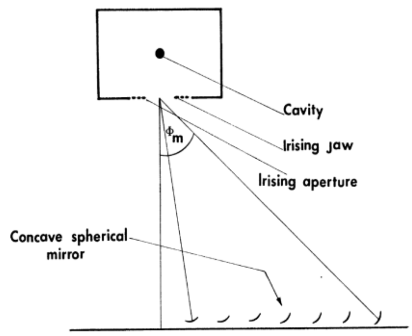

Fig.9- A cavity Type Solar Central Receiver

This central receiver has a down-looking cavity, and has a field site equipped with heliostats under a certain defined ground coverage factor. Incident radiation intercepted by the heliostats (concentrators) are reflected and focused onto the receiver aperature. The central receiver concept uses optical transmission for redirecting the incident solar energy from the field of heliostat onto a receiver located on the top of a tower. A theoretical analysis of Brumleve's concept, allowing for the image size defects produced by the field site concave mirrors is conducted [2, 3]. The analysis points out some of the critical problems encountered in the design of cavity central tower collectors. The variable azimuthal and declination angles with time of day, and with time of year give variable projected image size defects on the receiver aperture entrance [4] and variable losses by radiation and convection as a function of the time of day, seasons of the year, and changing weather conditions for a fixed aperture cavity receiver [5,6]. It is found that Brumleve's design does not have efficiencies as high as those predicted [7]. This paper is primarily concerned with the performance of the variable aperture (irising) central receiver [8]. It is a new concept for improving the efficiency of a cavity central tower system by increasing the aperture area when the image size is large and reducing it when the image size is small. Present designs utilize a constant area aperture. The irising aperture performance is presented hereby and compared to the Brumleve design. The variable area aperture is found to be superior to the fixed aperture on an overall basis.

2-Proposed Isiring Cavity Central Tower Receiver

A new proposal for the design of a central tower cavity receiver with controlled variable aperture area facing a focusing heliostat field site area is discussed. Concentration ratios and efficiencies are compared to those of a fixed aperture design.

2.1- Solar tower focusing collectors with cavity type receivers having fixed area apertures are presently in use. These collectors are less efficient than a variable area aperture considered in this paper. Variable sun elevation, azimuthal and declination angles with the time of day and time of year give variable projected image size defects produced by the field site concave mirrors on the receiver aperture entrance. If the aperture is small, it will be inefficient at periods when the solar insolation is inclined due to spillage and, if the aperture is large, then it will be inefficient at periods when the solar insolation is normal due to excess heat radiation and convection losses. However, the isiring cavity receiver with a variable area aperture provides an approximately constant efficiency regardless of the time of day or season of the year. Figure 9, is a schematic drawing for a cavity type central receiver. The receiver includes an entrance at the bottom centre with a variable aperture. The entrance faces a focusing heliostat field site, such as Brumleve’s design, which includes adjustable concave mirrors to focus the sun’s rays to the cavity entrance. Figure 10 illustrates one possible arrangement mechanism to achieve a variable area aperture. A pair of inner and outer jaws which have a U-shape in cross-sections; are moved together or apart, by rotating helical shafts. The shafts are moved in unison so that all jaws move the same distance towards or away from each other. Several types of sealing may be used between the inner jaws, the outer jaws, and the casing. The sealing prevents thermal energy transfer from the cavity receiver to the surroundings. In operation, the aperture would present its smallest area when the solar insolation is normal at noon and its largest area when the solar insolation is inclined early in the morning and late in the evening. The aperture area is adjusted between these limits during the day by a computer controlled system. The aperture size at any time would be based on the image size envelope projected by the focusing heliostats. The control system should also respond to random weather disturbances.

DU: Driving Unit, PA: Power Amplifier,
DAC: Digital to Analogy Converter,
ADC: Analogy to Digital Converter
ADMD: Accurate Displacement Measurement Device

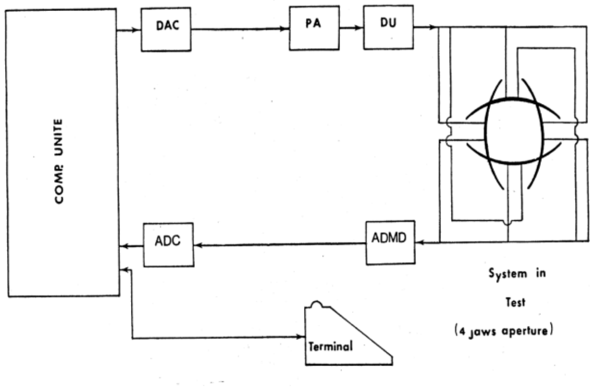

Fig.10-Control system associated with Irising Aperature

2.2- Comparison between Fixed and Irising Central Tower Receiver System

Figures 11, 12, and 15 show a comparison between fixed and irising central tower cavity receivers. Parameters that are used for the comparison are Interception factors, Concentration ratios and efficiencies. The design calculations are based on the following conditions:

- The beam width formula of Ref. [7] is used to determine the width of the reflected beam from a focusing heliostat field site area.
- Variable sun elevation, azimuthal and declination angles with the time of day, and seasons of the year is been simulated on Kuwait International Airport [7].
- The field site location is at altitude of Kuwait International Airport.
- A variable solar flux insolation throughout the day is as on the International Airport - Kuwait state [9, 10].
- A uniformly bright collector field is assumed.
- The studied field site areas are: 360° around the tower.
- The critical field site direction on 21 June, and is of the north direction for the studied field sites.
- The fixed aperture area for the cavity receiver is assumed to be based on the image size defects envelope projected on it, at noon hour.

- The heliostat is assumed to have a diameter of 6.1 m, and a spherical circular shape.
- Tower height, H = 100m.
- Heliostat solar reflectance, $\rho = 0.80$.
- Receiver solar absorptance, $\alpha = 0.095$.
- Ground coverage, $\psi = 0.447$.
- Receiver temperature, $T_r = 700°C$.
- Ambient temperature, $T_a = 25°C$.
- Parameter K, is defined by: $K = H \sqrt{(\alpha_L^2 + \alpha_G^2)}$, where H is the tower height, $\alpha_L = 0.00466$ rad for solar limb angle, and $\alpha_g = 0.0030$ rad for the guidance error.
- The practical value of ϕ_m is found to be less than 55°.

The variation of $\Phi(t, \phi_m)$ with the time of day (t), and with the maximum field site rim angle ϕ_m, for both the offered and proposed central towers on 21 June are given in Fig.11. The figure illustrates how much the proposed interception factor increased.

The fixed design concentration is given by: $C_{off.}(\phi_m) = \psi A_f / A_x(\phi_m)$

Irising design concentration is given by:

$$C_{pro.}(t, \phi_m) = \psi A_f / A_c(t, \phi_m)$$

$$C_{o,\,pro.}(t, \phi_m) = \psi \, Sin^2 \phi_m \cos^2 \phi_m$$

/

$$[4 (\frac{ras(t, \phi_m)}{H})^2 \cos^2 \phi_m + [\alpha_L^2 + \alpha_g^2]$$

Fig.12 shows a comparison between the two systems for their concentration ratios vs. the max field site rim angle vs. time of day.

The figure indicates higher concentration ratios for the proposed technique as a function of day time and the max field site rim angle. The efficiencies of both the offered and proposed central tower receiver are obtained using the relation:

$$\eta = \rho \, \alpha \, \Phi(t, \phi_m) \quad -$$

$$\left[[\varepsilon_{eff} \, \sigma \left(T_r^4 - T_s^4 \right) + (h_f + \bar{H})(T_r - T_a) \right]$$

$\times$

$$\{4[\frac{r_{as}(t, \phi_m)}{H}]^2 \cos^2 \phi_m + (\alpha_L^2 + \alpha_g^2)\} / I_0 \, \Psi \sin^2 \phi_m \cos^2 \phi_m,$$

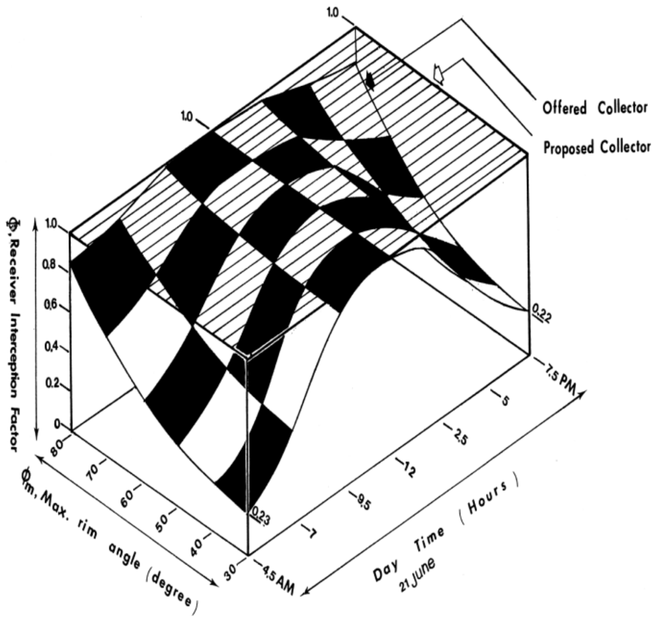

Fig.11- Receivers Interception Factor vs. max rim angle, over the daytime

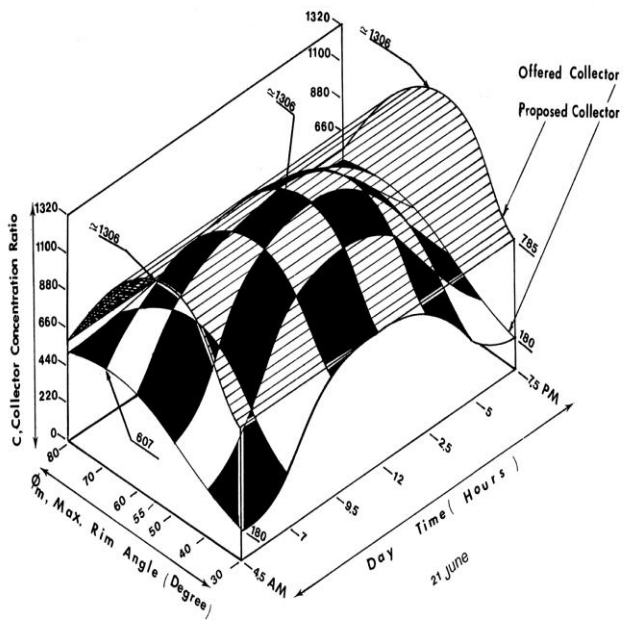

Fig.12- Collectors Concentration Ratio vs. max rim angle, over the day time

By substituting for each associated parameter's value.

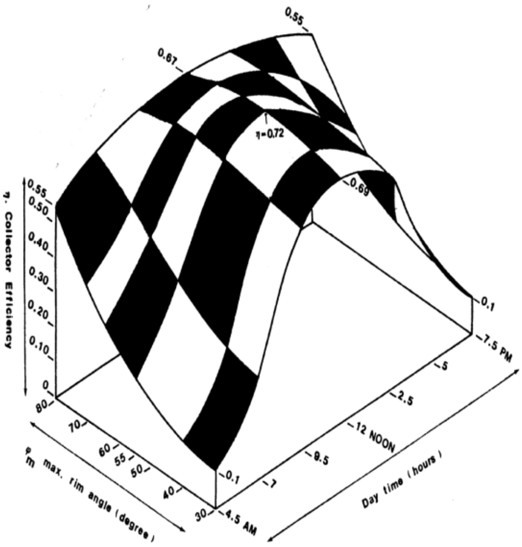

Fig.13 – Offered Collector Efficiency vs. max rim angle, over the day time

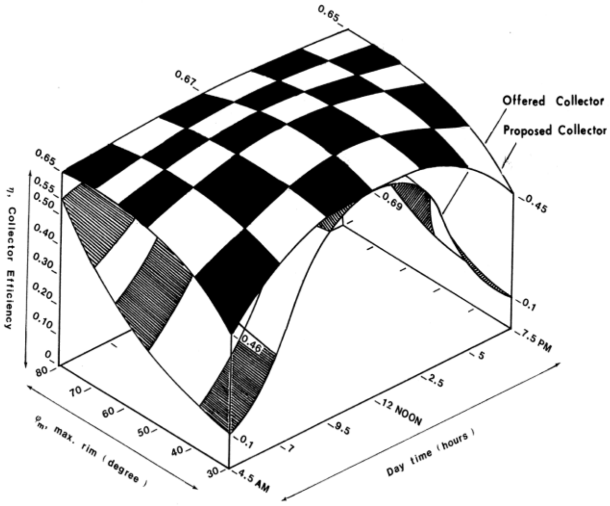

Fig.15- Comparison between Offered and Proposed Collector Efficiency vs. max rim angle, over the day time

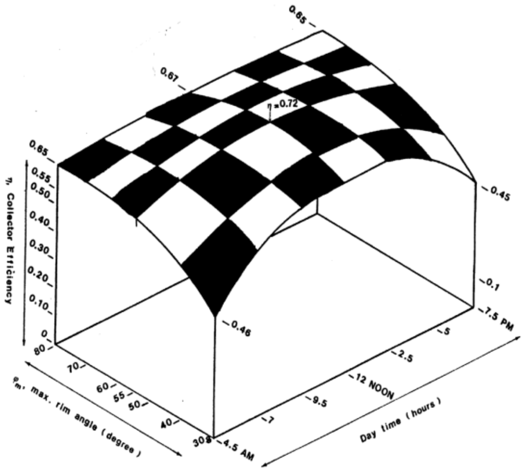

Fig.14- Proposed Collector Efficiency vs. max rim angle, over the day time

Fig.13 shows the offered collector thermal efficiency vs. the max field site rim angle vs. time of day, Fig.14 presents the variation of thermal efficiency for the proposed collector vs. the max field site rim angle vs. time of day. Fig.15 indicates the comparison between the Offered and proposed efficiencies vs. the max field site rim angle vs. time of day. The figure is demonstrating the differences, and the accomplishment achieved by the proposed technique.

3.Conclusion

Theoretical analysis for the irising cavity type central tower receiver displayed for a field site area all around the tower with a variable solar flux insolation throughout the day and with considering variable sun elevation, azimuthal and declination angles with the time of day , and seasons of the year simulated at Kuwait International Airport is done. The major effective parameters for the system's performance; the central receiver interception factor, collector concentration ratio, and collector efficiency are compared with the fixed area aperture central tower receiver system. The analysis shows the cavity type central tower receiver with irising aperture is more efficient than the available design with fixed area aperture. The efficiency of the proposed collector is found to be almost constant at the various operating conditions under consideration. Such a constant efficiency could have a dramatic impact on the central receiver heat transfer material design, since we could minimize its temperature rates of change throughout the day. Discussed application developed on this research stands as a step closer towards a useful use of the country torrential accessible Solar Energy.

NOMENCLATURE

A_c area of projected image envelope on receiver aperture, m^2
A_F area of land in the heliostat field, m^2
A_X receiver aperture area, m^2
C collector concentration ratio
C_0 concentration of the beam in absence of the terminal concentrator
C_1 collector 1 concentration ratio
C_2 collector 2 concentration ratio
C_T concentration of the beam in presence of the terminal concentrator
d heliostat slant length, m
D the concave heliostat diameter, m
D_h diameter of the lower end of the conical skirt, m
D_X diameter of the aperture, m
f fraction of the beam reflected
$\hat{f}$ average fraction of the beam reflected
H tower height or aperture height, m
I_0 direct normal insolation, 1 kw/m^2
K parameter defined as $H\sqrt{(\alpha_L^2 + \alpha_g^2)}$, m
L radius of the beam, m
q_c heat loss rate from a cavity receiver by convection, kW
q_r heat loss rate from a cavity receiver by radiation, kW
r radius of the heliostat, m
R_c the radius of irising aperture, m
r_{as} astigmatic image radius, m
R_F field site radius, m
R_X the aperture radius, m
T_a ambient temperature, °C
T_r effective cavity temperature, $R°$ in q_r and °C in q_c
T_s sky radiation temperature, $R°$
X slant length of the conical skirt, m
ϕ rim angle, degree
ϕ_m the extreme ray rim angle, degree
ϕ_0 the maximum rim angle for no reflection, degree
ϕ^* the rim angle at which the reflected ray becomes horizontal, degree
Φ receiver interception factor
ψ total ground coverage
α receiver solar absorptance
α_g guidance error, rad
α_L limb angle of the sun, rad
γ grazing angle, degree
$\theta/2$ the angle of incidence at which insolation strikes the sun tracking heliostat, degree
σ Stefan-Boltzman constant, 5.406×10^{-12} kW/m^2 − R^4
ρ mirror solar reflectance, includes utilization factor
ϵ_{eff} effective cavity emittance
β slope of the conical skirt radius, degree
η the focusing collector efficiency

REFERENCES

1. Eman Goma.2009. Kuwait set to issue tender for solar energy power plant. ENERGY/NEWS/, Kuwait, October 14.
2. T. Galal. 1982. Theoretical Analysis of a Variable Aperture Solar Tower Receiver, M.Eng. thesis, McGill University, Montreal- Quebec.
3. K. Athavaley, F. Lipps and L. vant-Hull. 1979. An analysis of the Terminal Concentrator concept for solar central receiver systems. Solar Eenrgy Journal, vol. 22, pp. 493-504.
4. L.L. Vant-Hull and A.F. Hildebrandt. 1976. Solar thermal power system based on optical transmission. Solar Eenrgy Journal, Vol. 18, pp. 31-39.
5. A.C. Skinrood, T. D. Brumleve, C.T. Schafer, C.T.Y. Okomizo, C.M. Leonard, Jr. 1974. Status report on a High Temperature Solar Energy System, Sandia Laboratory Eenrgy Report.
6. F. Biggs, C.N. Vittitor. 1979.The Helios Model for the optical behaviour of reflecting solar concentrators. Sandia Laboratory Energy Report, March.
7. T. Galal, P. Nardin, and J. Mignot. 1988. An analysis for Solar Central Receiver Systems with Terminal Concentrators or Variable apertures Solar Energy Vol. 41, No.2, pp. 147-157.
8. Mo Wang, Kamran Siddiqui. 2010. The impact of geometrical parameters on the thermal performance of a solar receiver of dish-type concentrated solar energy system", Renewable Energy, April.
9. Abdulmalik Kulaib. 1984. The Climate of Kuwait, State of Kuwait Directorate General of Civil Aviation Meteorological Department – Climatological Division,.
10. M. D. Islam, I. Kubo, M. Ohadi, and A. A. Alili, 2009. Measurement of Solar Energy Radiation In Abu Dhabi, UAE. Applied Energy Volume 86, Issue 4, pages 399-588, April.