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Development of a spherical solar collector with a cylindrical receiver

Khaled Mahdi [1,2*] and Nadir Bellel [1]

[1] Laboratory of Physics Energy, Department of Physics
Mentouri University of Constantine, Algeria
[2] Hydrometeorology Institute of Formation and Research, Oran, Algeria

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Abstract - *Solar energy can be used for substitution of the depleting fossil fuels in thermal applications and electricity generation through thermal route. For medium and high temperature applications, a system for collecting solar energy at high temperatures was developed and built in this research work. The system, built at the center of development of renewable energy of the Algiers, consists of a 2* $\theta_m = 60°C$ *included angle,* $R_0 = 0.90$ *m diameter spherical reflector with a cylindrical receiver filled with water, tracking reflector which moves into the focus following the sun's movement. The system is capable of heating water or other fluids to temperatures above 350 °C, thus making it possible to obtain process heat for domestic use and to store solar energy in a compact and economical way. An analysis of the system's optical characteristics was performed to aid in the design of the spherical reflector and cylindrical receiver. The thermal performance of the system was analyzed. The effects of mirror reflection, concentration ratio, heat transfer to the fluid (water), incidence angle, size and form of the cylindrical receiver, environmental conditions (wind, ambient temperature), have been studied by means of thermal model. The performance of the spherical reflector was tested by the temperature of the water. Total efficiencies (solar to thermal) of* η_{th} *= 60% - 70% were obtained for a wide range of temperatures up to 350 °C. The results of the present study show that it is possible to use the spherical reflector for systems requiring process heat and make possible substantial utilization of solar energy and considerable savings relative to fossil energy in the sunny countries of the world.*

Résumé - *L'énergie solaire peut être utilisée en substitution des carburants fossiles dans les applications thermiques et la production d'électricité par voie thermique. Pour les applications de moyennes et hautes températures, un système de collecte de l'énergie solaire à haute température a été développé et réalisé dans le cadre de ce travail de recherche. Le système, intégré au Centre de Développement des Energies Renouvelables d'Alger, se compose d'un réflecteur sphérique de* $R_0 = 0.90$ *m de diamètre, de* $2\theta_m = 60°C$ *angle inclus, et avec un récepteur cylindrique rempli d'eau, suivant à la trace le réflecteur qui se déplace dans le centre suivant le mouvement du soleil. Le système est capable de chauffer de l'eau ou d'autres liquides à des températures supérieures à 350 °C, ce qui permet d'obtenir la chaleur de processus à usage domestique et pour stocker l'énergie solaire de manière compacte et économique. Une analyse des caractéristiques optiques du système a été effectuée pour faciliter la conception du réflecteur sphérique et du récepteur cylindrique. Le rendement thermique du système a été analysé. Les effets de la réflexion miroir, le ratio de concentration, le transfert de la chaleur au fluide (eau), l'angle d'incidence, la taille et la forme du récepteur cylindrique, les conditions environnementales (vent, température ambiante), ont été étudiés au moyen de modèle thermique. La performance du réflecteur sphérique a été testée par la température de l'eau. Les rendements totaux (solaires pour thermique)* η_{th} *= 60% - 70% ont été obtenus à partir d'une large palette de températures de plus de 350°C. Les résultats de l'étude*

[*] khaled_mahdi@yahoo.fr

montrent qu'il est possible d'utiliser le réflecteur sphérique pour les systèmes nécessitant la chaleur et de rendre possible l'utilisation substantielle de l'énergie solaire et par conséquent, des économies considérables par rapport à l'énergie fossile dans les pays ensoleillés du monde.

Keywords: Spherical reflector - Circle of least diffusion - Cylindrical receiver - Optical characteristics - Thermal characteristics.

1. INTRODUCTION

All systems, which harness and use the sun's energy as heat, are called solar thermal systems. These include solar water heaters, solar air heaters, and solar stills for distilling water, crop driers, solar space heat systems and water desalination systems. Temperatures far above those attainable by flat-plat collectors can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. This is done by interposing an optical device between the source of radiation and the energy absorbing surface. Concentrating collectors exhibit certain advantages as compared with the conventional flat-plate type, Planar and non-concentrating type which provides concentration ratios of up to four and are of the flat plate type. Line focusing type produces a high density of radiation on a line at the focus. Cylindrical parabolic concentrators are of this type and they could produce concentration ratios up to ten. Point focusing types generally produce much higher density of radiation in the vicinity of this point. A paraboloïd reflector is example of point focus concentrators. Spherical solar collector is an attractive method to concentrate direct beam radiation which converts it to thermal energy in a useful form for electrical power generation [1]. Solar thermal power plants with concentration technologies are important candidates for providing the bulk solar electricity needed within the next few decades. Four concentrating solar power technologies are developed: parabolic trough collectors, linear Fresnel reflector systems, power towers or central receiver systems and dish engine systems [2]. The design of a receiver of solar heat in the operating temperature range (150 °C – 500 °C) requires the study and the optimization in order to characteristize the receiver absorber surface using the heat balance. The optical properties of absorbing receiver are important for characterizing the type of solar radiation concentrator, the geometric concentration ratio defined as the ratio of the apparent surface of the mirror and apparent surface receptor absorber to home mirror is used, for a given operating temperature. The thermal efficiency increases not practically beyond a certain value of the concentration ratio and this is likely to facilitate the recovery of heat and limit technological difficulties when performing the mirror concentrator. The choice of the latter requires knowing the values of concentration ratio as a function of tolerance of various kinds like, that induced by the automatic tracking of the sun. It is for this reason that we apply such a calculation mirror ball from a cylindrical receiver two different positions are proposed in our study, the first dealing with the heat exchange surface side wall and the second heat exchange surface receptor at the lower diffusion circle. The spherical concentration presented a second type of compound curvature collector using spherical geometry instead of parabolic geometry. Figure 1 shows ray traces in a plane of symmetry for normal incidence (tow axis tracking) on a spherical concentrator. The parallel rays in this case are focused along a line which extends from the surface of the mirror to a distance of $R_0 / 2$ from this surface, as in the case of other compound curvature mirrors. It is also clear that rays intercepted near the cylindrical receiver base intercept the absorber at very large incident angles. Therefore, an absorber envelope with very low reflectance or no envelope at all is used to avoid severe penalties to the optical efficiency, in our research work, the second choice is used.

2. MATHEMATICAL MODEL

2.1 Optical model and analysis

The optical scheme of a spherical concentrator in the axial section coincides with the scheme of circular cylindrical reflector. An arbitrary point of the spherical concentrator the radius R that is defined by the angular coordinate θ reflects the incident ray that is parallel to the optical axis at the angle $\pi/2-2\theta$ to the abscissa axis (Fig. 1).

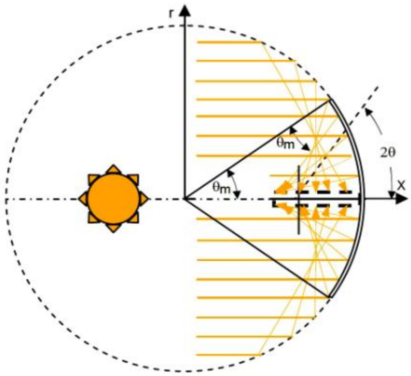

Fig. 1: Optical scheme of spherical concentrator

The equation of the reflected ray has the form:

$$x = \frac{R}{2}\left[1-\left(\frac{r}{R}\right)^{2/3}\right]^{1/2} \times \left[1+2\left(\frac{r}{R}\right)^{2/3}\right] \tag{1}$$

The family of the reflected rays with the parameter θ forms the envelope of these rays, which is described by the parametric equations

$$x = \frac{R}{2} \times \cos\theta\left[1+2\sin^2\theta\right] \tag{2}$$

$$r = R\sin^3\theta \tag{3}$$

When the incident rays are inclined on the axis of the mirror, the situation is much more complicated.

The concentration of the parabolic dish is greater than the spherical concentration. the concentration of a parabolic dish increases with the aperture angle of the dish, on the other hand the spherical dish is better in the aperture angle of 22° where the concentration is maximum [2, 7]. The spherical mirror is preferable because of its simplicity of realization.

$$2\pi\times\rho_m\times I_N\, x\ dx = \pi\times D_r\times Q_c(x)\times dr \tag{4}$$

Finally Heat flux distribution is given by:

$$Q_c(x) = \frac{2\rho_m \times I_N \times x}{D_r} \times \frac{dx}{dr} \qquad 0.45 < x < 0.9 \tag{5}$$

The relatively large cylindrical receiver required in the spherical reflector system may be partially offset in some applications by the non uniform energy distribution along the "line" focus. For a constant diameter, circular cylinder is used as the absorber with a reflector having a rim angle varying between 0° and 90°, the ratio of the local heat flux on the receiver Q_r to the average I_N when the sun's rays are normal to the aperture is:

$$Q_c(x) = \frac{\rho_m \times I_N}{2D_r} \times \frac{1}{x^3} \tag{6}$$

$Q_r(x)$ is the cylindrical receiver incident flux by spherical reflector given by equation:

$$Q_r = A_a \eta_0 \frac{\rho_m \times I_N}{2D_r} \times \frac{1}{x^3} \times \cos i \tag{7}$$

Where,

$$\eta_0 = \rho \times \gamma \times \alpha \tag{8}$$

η_0, is the optical efficiency, is the product of ρ, α and τ. A spectral reflectance ρ is between 0. 85 and 0.9 is typical for high quality mirrors. The solar absorptance α of a selective surface characteristically lies between 0.85 and 0.95. The use of a cover plate seems illogical due to the high reflective loss for rays at large angles of incidence, γ is the intercept factor.

As shown in figure 2, the cylindrical receiver surface flux increases with non-uniform energy distribution along the 'line' focus, a line which extends from the surface of the mirror to a distance of $R/2$ from this surface. Hence, an absorber which is to intercept all of the specularly reflected energy from such a spherical mirror must have a length of approximately $R/2$. We notice that on the abscissa of line focus the least diffusion circle incident flux is maximal.

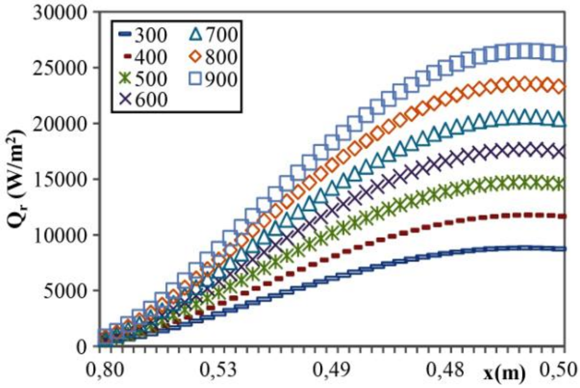

Fig. 2: The Influence of line focus on cylindrical receiver flux for different incidents solar radiation

2.2 Thermal model and analysis

In this first effort to describe the solar spherical collector, we selected the simplest thermodynamic model of the system (1st thermodynamic law). The model comes from an energy balance done on the thermodynamic system we defined (Fig. 10).

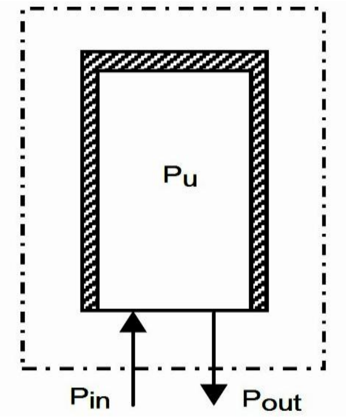

Fig. 3: Boundary of the thermodynamic system

The thermodynamic system is closed system composed of the cylindrical receiver made of steel and water that gives form to the absorber. Under these assumptions, the general energy balance is given by:

$$P_u = P_{in} - P_{out} \tag{9}$$

Where P_u is the instantaneous change in internal energy of the system, P_{in} is the energy by unit time that arrives at the boundary of the system and P_{out} is the loss of energy by unit time that leave the boundary of the system.

The incoming energy is given by the only energy source, the solar radiation concentrated by the spherical reflector. The amount of energy the concentrator can provide the system is

$$P_{in} = C \times \alpha \times \rho \times A_a \times I_N \tag{10}$$

Where C is the geometric concentration parameter for the spherical reflector, which is dimensionless and defined as the surface area of the concentrator over the surface area of the concentrated image, A_a (m^2) is the surface area that is used up by the image that the mirror over of the cylindrical receiver for first experience and for second experience over lateral wall of cylindrical receiver, finally I_N (W/m^2) is the instantaneous irradiance, which can be measured using a horizontal global by pyranometer from station meteorological of CDER. The heat loss P_{out} from the receiver with the simplifying assumptions the losses of the system are given by:

$$P_{out} = h \times A_r \times (T_r - T_a) + \sigma \times \varepsilon \times A_r \times (T_r^4 - T_s^4) \tag{11}$$

The form of the differential equation that the program solves is shown in Eq. (5).

$$(m_s C_s + m_w C_w)\frac{dT_r(t)}{dt} = C\alpha A_s I_N - hA_c(T_r - T_\infty) - \varepsilon\sigma A_c(T_r^4 - T_\infty^4) \tag{12}$$

In order to evaluate the model we use the values presented in **Table 1**. The instantaneous irradiance and the average ambient temperature that was used in the program were measured experimentally. The experimental setup is presented in the next section.

We used a scheme of order one (1) backward to evaluate the time derivative and a centered scheme of order two (2) for the second derivative in space. The temperature with iteration $(n+1)$ is given by:

$$\left(1+2F_0\right)\times T_{r,i}^{t+\Delta t} - \beta\left(T_{r,i+1}^{t+\Delta t}+T_{r,i-1}^{t+\Delta t}\right) = T_{r,i}^{t} \qquad (13)$$

Where,

$$F_0 = \frac{\alpha_f \times \Delta t}{\Delta x^2}$$

F_0 - Fourier number dimensionless.

And,

$$\alpha_w = \frac{\lambda_w}{\rho_w \times C_w}$$

α_w is the thermal diffusivity.

i varying from 1 to $(n-1)$. It was found that the unknowns at iteration $(n+1)$ are connected by an implicit method (hence the name of the method). At each iteration the vector of discrete unknowns is determined by solving a linear system in the matrix form, the Gaussian elimination algorithm (based on Gaussian elimination method) is often used. The algorithm is written in Fortran.

Table 1: Optical and dimensional characteristics values used in the theorical model program

Item	Symbole	Value
Weather conditions for Algiers (10/05)	T_{min}	25 °C
	T_{max}	32 °C
The spherical reflector	ρ_m	0.9
	η_{th}	60 %
	Γ	-
Transversal aberration	δ_t	10.7e-2
Latitudinal aberration	δ_l	6.18e-2
Aperture area	A_a	0.636 m^2
Reflector area	S	0.681 m^2
Maximal Aperture angle	θ_m	30 °
Focal distance	f	0.45 m
Maximal Aperture angle		0.681 m^2
Aperture area		0.636 m^2
Diameter	D_a	0.9 m
Receiver aperture	A_r	0.0078 m^2
Receiver Height		0.2 m
Receiver area	S	0.681 m^2

The useful heat delivered by a solar collector is equal to the energy absorbed by the heat transfer fluid minus the direct or indirect heat losses from the surface to the surroundings. When neglecting the losses the useful energy collected from a reflector can be obtained from the following formula:

$$P_u = C_w \dot{m} (T_0 - T_i) \tag{14}$$

Where P_u is the rate of useful energy delivered by solar dish concentrating collector in W, C_p is specific heat at constant pressure in J/kgK, $\dot{m}$ is working fluid mass flow rate in kg/s, and T_i, T_0 is temperatures of fluid entering and leaving the receiver in °C [2].

Since the aperture area of the solar spherical concentrator A_a is a relevant indicator of the concentrated sun rays, the efficiency equation based on A_a.

$$\eta_{th} = \frac{Q_u}{I_N \times A_a} = \frac{C_w \dot{m} (T_0 - T_i)}{I_N \; A_a} \tag{15}$$

Where I_N is the beam normal solar radiation in W/m2 and A_a is aperture area of the solar spherical concentrator in m^2 [1].

3. MEASUREMENT AND ANALYSIS

The experiments have been done at Center of Development of Renewable Energy-CDER Bouzareah (latitude 36.8° North, longitude 3° East, Altitude 345 m) in Summer's season with clear sky conditions.

The experiment is made at 5 August, from 11 h to 14 h. To determine the space-time evolution of the cylindrical receiver temperature, two thermocouples were installed in equidistant positions along its diameter (Fig. 6, 7**)**.

3.1 Analysis of experimental data

Data acquisition system makes it possible to follow the evolution of the Temperature given by each thermocouple every five minutes, solar radiation flux and the ambient temperature are given by a weather station installed in situ. The values given by the pyranometer represent the solar flux on horizontal surface (Fig. 12). Figure 13 represents global solar flux variation measured by the meteorological station of the site during the sunny period of the day. The horizontal global solar flux density measured by the pyranometer using an estimated solar altitude h to obtain incident solar flux I_N on the spherical reflector each time during the experiment. The relation is given by the following expression:

$$I_N = \frac{G_h}{\sin(h)} \tag{16}$$

3.2 Experimental study

For our experiment we have dealt only with the second case, the reflector of our experimental device consists of a spherical concentrator of 0.9 meter aperture diameter. Its interior surface is covered with a reflecting layer (mirror) that reflects solar rays on the face of a receiver placed at the focal position. The concentrator is placed on a directional support according to two axes to ensure the follow-up of the sun. The characteristics of the solar concentrator are shown in **Table 1**. The reflecting film covering the surface of the spherical reflector is a silver layer with a reflecting coefficient near 0.9.

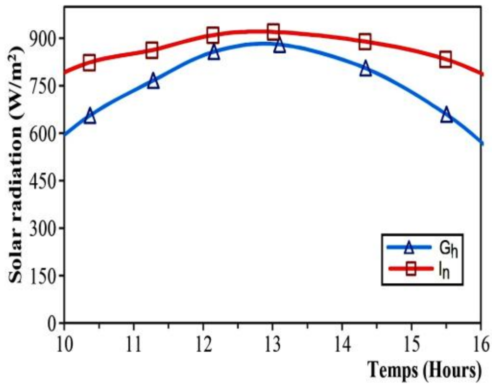

Fig. 4: Variation of solar radiation during the test period on 5 August

Fig. 5: The solar spherical reflector used in the experiment [12]

The first experience the receiver has a diameter of 0.1 m, and is covered with a thin coat of black paint having an absorption coefficient near 0.9 and is located in a circle of least confusion (the focal zone) of the concentrator equals to 0.02394 m. The receivers' characteristics are shown in **Table 1**. The horizontal global radiation measured during the test and the estimated beam radiation is presented in Fig. 13.

4. RESULTS AND DISCUSSION

Figure 8 shows the correspondence between the points measured by thermocouples and thermal stratification calculated by the model. The thermo physical characteristics of steel are different from those of water, $\lambda_W = 0.6\,W/mK$, $\lambda_S = 48\,W/mK$, $C_W(t) = [4180-5700]\,J/kgK$, $C_S = 465\,J/kgK$ and this means that heat transfer by conduction is more significant in the walls of the absorber than in the water inside the receptor. We note that the theoretical curve and the measured levels (thermocouple) have practically the same shape. However, we notice a slight increase at the extremity of the curve which is due to the difference between the physical characteristics of steel (absorber) and those of water such as thermal conductivity and calorie capacity.

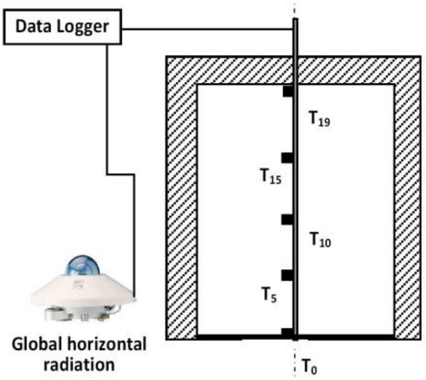

Fig. 6: The cylindrical receiver schematic diagram and data acquisition system

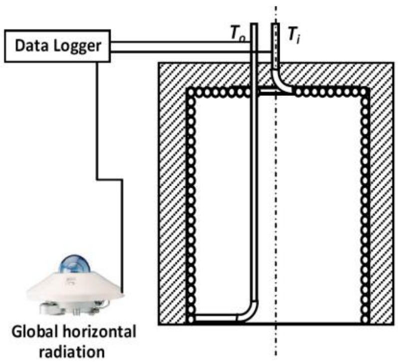

Fig. 7: The cylindrical receiver with coil schematic diagram and data acquisition system

However, we notice a slight increase at the extremity of the curve which is due to the difference between the physical characteristics of steel (absorber) and those of water such as thermal conductivity and calorie capacity. In fact, the spread of heat by conduction in the absorber (steel) is faster than in water. As a result, the upper part of the absorber becomes a source of heat, hence the increase in temperature. According to figure 10, for $t = 0$ s the difference between the initial tap water temperature and temperature at the coil exit ($T_i = T_0$) is nil. But theoretically the difference is different from zero because the net power which depends on direct solar radiance. We note that the estimation follows the measurement with some fluctuations due to many factors pertaining to the experiment, such as the temporal variation of direct solar illumination because of the passage of clouds.

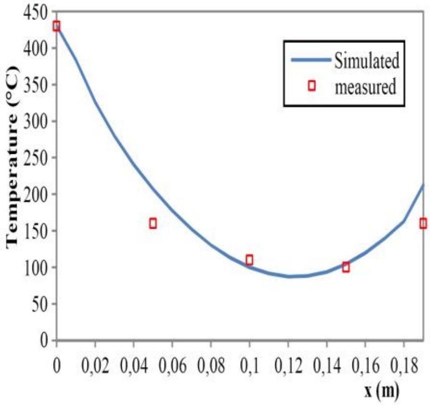

Fig. 8: The cylindrical receiver with coil schematic diagram and data acquisition system

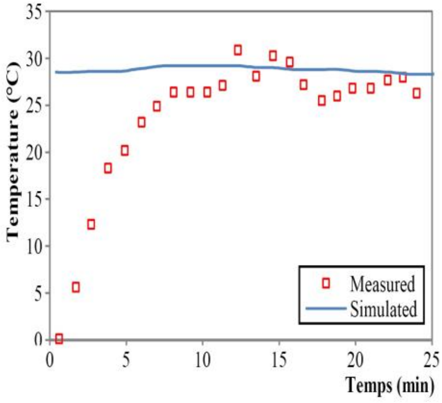

Fig 9: Comparison between the variations in difference regarding measured and estimated Temperatures for $\dot{m}$ = 0.0007 kg/s on August 5th

5. CONCLUSION

Spherical reflectors are the simplest type of concentrator and are easy to build and use. It is easy to focus sun rays, and if one opts for a moving vessel to meet the focus, cooking can also be done very easily. However, the study highlighted the importance of the cylindrical receiver position, the optimal geometry of the spherical reflector and the cylindrical receiver position for the solar energy concentrated converted to thermal energy are particularly function. Average concentrations of the area may be that of the production of electricity by thermodynamics (steam), but also photocell, by concentrating solar radiation onto solar cells, Production of heat the energy conversion photochemical and photovoltaic.

NOMENCLATURE

A_r - Absorber area, m^2	A_a - Aperture area, m^2
D - Diameter of spherical reflector, m	D_a - Diameter of receiver absorber, m
R - Radius of spherical reflector, m	S - Mirror area, m^2
T_r - Receiver temperature , °C	T_i - Temperatures of fluid entering
T_∞ - Ambient temperature, °C	T_0 - Temperatures of fluid leaving
$\dot{m}$ - Working fluid mass flow rate, kg/s	P_u - Useful energy, W
P_{in} - Solar radiation concentrated energy, W	C - Collector concentration ratio $[A_a / A_r]$, factor
P_{out} - Loss of energy, W	G_h - Global horizontal radiation, W/m^2
h - Solar altitude	I_N - Incident normal radiation, W/m^2
α - Absorbance	θ - Angle rim of mirror
θ_m - Maximal angle rim of mirror	ρ_m - Mirror reflectance
δ_t - Transversal aberration	η_o - Optical efficiency
δ_l - Latitudinal aberration	η_{th} - Thermal efficiency
Δt - Step time, s	Δx - Step space, m
α_w - Thermal diffusivity of water, m^2/s	Δt - Therm. conductivity water, W/mK
ρ_w - Density of water, kg/m^3	c_w - Specific heat of water, m^2/s
λ_s - Therm. conductivity of steel, W/mK	C_s - Specific heat of steel, J/kgK
ε - = 1	F_0 - Fourier number dimensionless

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