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ENERGETICS, THE ELECTRICAL ENGINEERING, ELECTRONIC DEVICES AND INFORMATION TECHNOLOGIES

ANALYSIS OF THE OPTICAL AND THERMAL CHARACTERISTICS OF A SOLAR PARABOLIC CYLINDRICAL COLLECTOR

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АНАЛИЗ ОПТИЧЕСКИХ И ТЕПЛОВЫХ ХАРАКТЕРИСТИК СОЛНЕЧНОГО ПАРАБОЛОЦИЛИНДРИЧЕСКОГО КОЛЛЕКТОРА

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ҚУЁШ ПАРАБОЛОЦИЛИНДРИК КОЛЕКТОРИНИНГ ОПТИК ВА ИССИҚЛИК ХУСУСИЯТЛАРИ ТАҲЛИЛИ

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Abstract. *The article analyzes the optical and thermal characteristics of a solar parabolic-cylindrical collector (PCC). Effective parameters such as geometric concentration, aperture width, coverage angle, receiver diameter, and focal distance are considered. Simulation results are presented via Monte Carlo ray tracing (MCRT) method. The factors influencing the distribution of the heat flux at the receiver are revealed.*
Key words: parabolic-cylindrical collector, geometric concentration, aperture width, sweep angle, receiver diameter, MCRT.

Аннотация. *В статье анализируются оптические и тепловые характеристики солнечного параболоцилиндрического коллектора (ПЦК). Рассматриваются такие эффективные параметры, как геометрическая концентрация, ширина апертуры, угол охвата, диаметр приемника и фокальное расстояние. Приведены результаты моделирования методом Монте-Карло трассировки лучей (MCRT). Выявлены факторы влияющие на распределение теплового потока на приемнике.*
Ключевые слова: параболоцилиндрический коллектор, геометрическая концентрация, ширина апертуры, угол охвата, диаметр приемника, MCRT.

Аннотация. *Мақолада қуёш параболоцилиндрик колекторининг оптик ва иссиқлик хусусиятлари таҳлил қилинади. Геометрик концентрация, апертура кенглиги, қамраб олиш бурчаги, қабул қилгич диаметри ҳамда фокал масофа каби муҳим параметрлар кўриб чиқилган. Монте-Карло нурли кузатиш усулида моделлаштриш натижалари келтирилган. Қабул қилгичдаги иссиқлик оқимининг тақсимланишига таъсир этувчи омиллар аниқланган.*
Таянч сўзлар: параболоцилиндрик колектор, геометрик концентрация, апертура кенглиги, қамраб олиш бурчаги, қабул қилгич диаметри, MCRT.

1. Introduction

In the past two decades, concentrated solar energy technologies have received more and more attention to replace traditional energy technologies and reduce their environmental impact. Solar energy is an affordable and clean form of renewable energy used as an alternative to fossil fuels in energy production. However, maximizing the extraction of thermal energy from the sun is the most challenging task.

To meet this challenge, various concentrators have been modeled, designed, manufactured and tested to operate in various temperature ranges, such as low temperature, medium temperature and high temperature concentrators. In applications like process heat supply and steam generation, solar PCC is considered the most popular among other collectors. Numerous studies, both theoretical and experimental, have been carried out over nearly three decades to improve the optical and thermal efficiency of the system. Optical efficiency depends on material properties such as the reflectance of the mirror, the transmittance of the glass coating, the absorption coefficient, the emissivity of the receiver, the intersection coefficient, the geometric coefficient and the angle of incidence. Thermal efficiency depends on the total loss factor, which includes losses due to conduction, convection and radiation [1].

Optical characteristics in collectors with a linear focus are determined by three parameters: peak optical efficiency, modifiers of the longitudinal and transverse angles of incidence [2]. The influence of the shape of solar radiation and the angle of incidence on the optical characteristics of a solar PCC have been comprehensively investigated based on the MCRT method and theoretical analysis. It was found that the form of solar radiation has a great influence on the optical characteristics of the parabolic-cylindrical concentrator, which should be taken into account in practice. The geometrical configuration of the PCC, especially the diameter of the receiver tube, must be determined according to the energy demand based on the local conditions of the solar form (circumsolar ratio). It has also been found that the final loss due to the angle of incidence weaken the optical efficiency. A wider aperture and a smaller absorber diameter will result in large losses at a constant angle of incidence. When the absorber is long enough, the influence of the angle of incidence will be negligible. In the range of small focal lengths, the optical efficiency increases with increasing focal length, and then constantly decreases with further increasing focal length [3], [4], [5].

The rate of the local concentration coefficient on the receiver tube and the optical efficiency are determined by two main characteristics of the geometric optimization of the PCC. An increase in the coverage angle and a decrease in the width of the aperture increase the optical efficiency, an increase in the coverage angle and a decrease in the receiver diameter increase the distribution density of reflected sunlight in the focal plane [6], [7], [8].

The flow density at the absorber wall is non-uniform and complex, and the calculation of the flow distribution is key for assessing the optical characteristics of the PCC and analyzing the characteristics of the flow of liquids in a tubular absorber [9]. In addition, the geometric shape and position of the receiver affects the optical efficiency and heat flow distribution [10].

This review contains the results of a systematic analysis of current and past research to assess the optical and thermal performance of solar PCCs. Approaches to modeling and potential ways to improve the designs of solar PCC are also carried out.

2. Solar PCC systems

2.1. History of the PCC

The original idea for a solar concentrator was to use a hemispherical surface saturated with many small mirror sections. The focal point of the spherical mirror will be located at half of the spherical section, just above the top of the sphere.

The first plan was to use the derivative of the circular equation to determine the correct slope at various points along the inner surface of the sphere; then the slopes will be turned to origin. Radiation from the sun will be reflected back into focus, as in the case of a parabola. In 1870, John Eriksson (a Swedish immigrant engineer in the United States) had the first practical experience with PTC, who designed and built a manifold with an aperture area of 3.25 m^2 to generate steam to drive a small (373 W) motor [11]. In 1936, C.G. Abbott used the PCC to convert solar energy into mechanical energy and to operate a steam engine (0.37 kW). After two years in Florida, he used a similar PCC to generate (0.15 kW) a steam engine. Abbott also proved that the system should obtain a theoretical overall efficiency (15.5%) and an actual efficiency (11.7%) for steam production at (225°C) using a PCC. In 1970, Sandia National Laboratory (USA) developed the first two collectors in the USA and operated at temperatures below 250°C. In July 1975, three PCCs were designed and tested in the USA with an aperture area of 7.8 m^2 and an angle of coverage of 90°. The PTC was equipped with a 40 mm diameter chrome-plated carbon steel receiving tube with an evacuated 10 mm diameter ring.

After 1980, this technology entered the market. In particular, analysis of heat consumption by industries as a function of the temperature at which energy is used (including high-temperature processes) showed that almost 28% of the heat is consumed at temperatures up to 415°C. This temperature level can be achieved in the case of a solar power plant with PCC. The greatest success in providing heat to industrial, municipal and agricultural facilities has been achieved with the help of solar parabolic cylindrical installations in the United States. In a number of other countries of the world, including the CIS, these works are just beginning to develop. Demonstration installations are created, trial tests are carried out, and based on the test results, and new projects of practically used installations are developed.

For example, in the city of Sacramento (Calif.) At the Campbell Soup plant of the Aerotherm company, Akyurex tested a solar installation consisting of flat and PCC. The installation provides 54.0×102 liters of water per day at a temperature of 88-90°C for the washing line of the canning industry. In Mobile (Alabama), a solar parabolic-cylindrical installation was built for the production of low and intermediate pressure steam in the range of 150-290°C. The unit is designed to heat liquid fuel stored in large tanks.

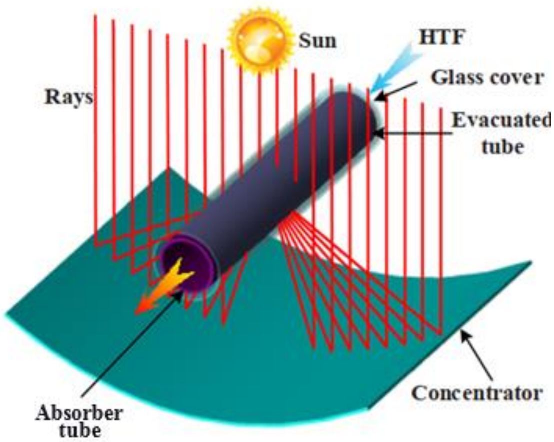

Figure: 1. Schematic diagram of the PCC [13].

Significantly more successes are expected on the path of the development of SES with PCC. The proof of this is the activity of the American-Israeli company Luz, which, despite the unfavorable environment, has created a series of highly efficient and reliable modular parabolic-cylindrical stations of industrial level with a total capacity of about 600 MW. Firm "Luz", with the construction of the SEGS, the technology was improved, the temperature of the working fluid and the efficiency of the cycle, as well as the sizes of individual collectors, increased.

Currently from hundreds of megawatts to thousands of megawatts of solar power plants are in the process of construction in the world. For example, Algeria, Egypt and Morocco have built integrated combined cycle solar power plants. While Australia, China, India, Iran, Israel, Italy, Jordan, Mexico, South Africa and the United Arab Emirates, construction or projects of solar power plants of various capacities are being completed. Today, there are more than 97 of them at different levels of development based on the PCC [12].

2.2. System Description

The solar PCC consists of three main elements: a reflector, a heat sink and a support structure with a tracking system for the sun (Fig. 1). The receiver is usually installed along the focal line of a concentrator, where a vacuum insulated receiver is mainly used. A typical evacuated receiver basically consists of a glass tubular shell and a steel absorber tube coated with a selective coating on its outer surface. The receiver tube and glass envelope are hermetically sealed with a metal bellows to form a vacuum annular gap. Typical PCCs using evacuated receivers are summarized in Table. 1 [13].

Table 1.

Parameters of a typical PCC.

Type	LS-1	LS-2	LS-3	Eurotrough	DS-1
Collector width / m	2,55	5	5,76	5,76	5
Collector length / m	6,3	8	12	12	8
Focal length / m	0,94	1,49	1,71	1,71	1,49
Receiver outer diameter / m	0,04	0,07	0,07	0,07	0,07
Geometric concentration factor	20	23	26	26	23
Hub reflectivity	0,93	0,94	0,94	0,95	0,95
Coating absorption capacity	0,94	0,94	0,96	0,96	0,96
Emissivity of the coating at 400 °C	0,3	0,2	0,1	0,1	0,1
Glass shell solar transmittance	0,95	0,95	0,965	0,965	0,965
Collector theoretical peak optical efficiency	0,734	0,737	0,772	0,80	0,80

The solar flux received by the concentrator is first reflected on the mirror reflector and then passes through the glass envelope to reach the absorber tube. The role of the glass shell is to reduce heat loss due to convection with the surrounding air. The surface of the absorber is coated with a selective material to absorb maximum solar flux. The absorbed solar flux is converted into heat and is transferred by conduction and convection to the coolant through the walls of the receiver tube [14].

2.3. Physical model

Fig. 2 shows the physical model of the PCC, where *B* is the width of the aperture, *r* is the focal length, d_T is the outer diameter of the receiver tube, d_g is the diameter of the glass envelope, α is the angle of coverage and φ is the radial angle of the sun (φ means the final size of the solar disk). The origin of coordinates *O* is the vertex of the parabola, the *XY* plane contains the cross-section of the parabolic-cylindrical reflector, the *Y*-axis passes through the vertex and focus, and the *Z*-axis passes through the apex and is parallel to the focal line [8].

Fig. 3 shows the cross section of the PCC receiver [15].

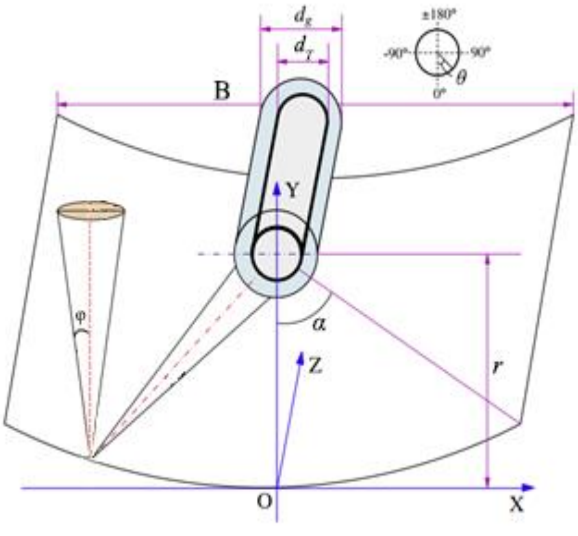

Figure: 2. Physical model of the PCC [8].

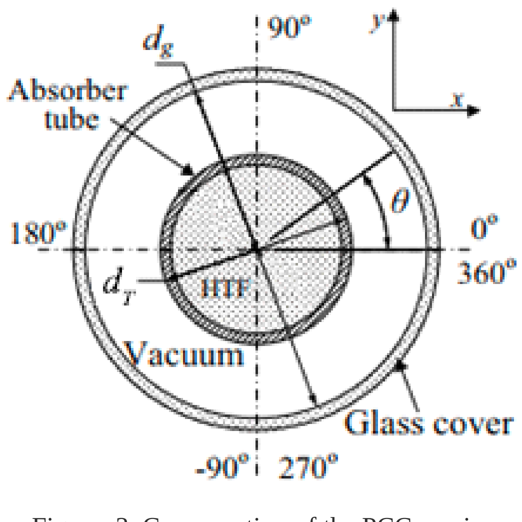

Figure: 3. Cross-section of the PCC receiver.

2.4. Geometric concentration

Geometric concentration (concentration coefficient) is the ratio of the area of the concentrator aperture to the area of the receiver, which are the main factors that increase the radiation flux on the energy-absorbing surface. Concentration ratios range from low values below one to high values 10^5 [16].

$$K_g = \frac{S_{ap}}{S_{at}} \quad (1)$$

This ratio has an upper limit, which depends on whether the hub is a three-dimensional (circular) hub, such as a paraboloid, or a two-dimensional (linear) hub, as a parabolic-cylindrical hub. If the concentrator is ideal, the maximum possible concentration factor for circular concentrators is 45000, and for linear concentrators 212 [17].

Formula (1) for PCC can be written as

$$K_g = \frac{B - d_g}{\pi \cdot d_T}, \quad (2)$$

where B is the width of the aperture, d_g is the diameter of the glass shell of the receiver, d_T is the diameter of the receiver.

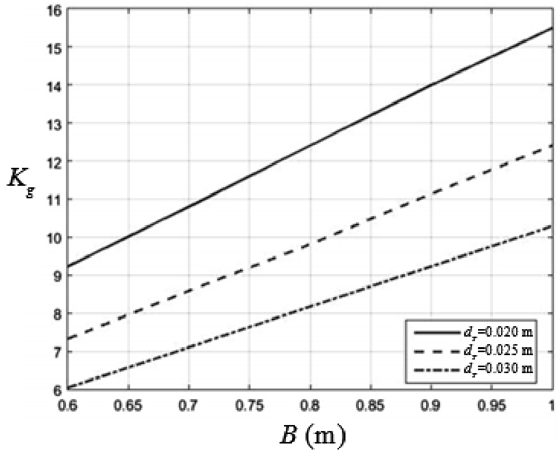

Figure: 4. Changing the concentration factor depending on the width of the aperture for different diameters of the receiver [6].

Changes in parameters such as aperture width, coverage angle, receiver diameter and focal distance significantly affect the degree of concentration factor, along with this, the optical and thermal characteristics of the concentrator. In the work [6], the solar PCC was optimized for various sizes with three design variables: receiver diameter, aperture width, and coverage angle. Fig. 4 shows that the concentration factor increases with an increase in the width of the aperture at a constant diameter of the receiver. The maximum value is associated with the receiver diameter of 0.020 m. The aperture width is 0.6 m, the receiver diameter is 0.020 m, the concentration factor is 9.23, and for a concentrator with a 1 m aperture width and 0.020 m receiver diameter, the concentration factor is 15.5.

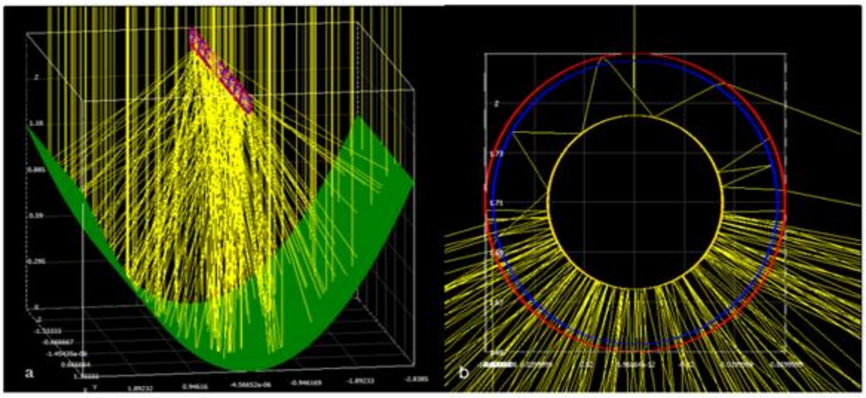

Figure: 5. Visualization of the ray tracing method [18].

In this study, we used the Monte Carlo method in the MATLAB environment. Monte Carlo is a computational algorithm that uses random sampling to compute results. The Monte Carlo method is used to simulate physical, mathematical and economic problems. Ray tracing by Monte Carlo simulation is a randomized simulation method based on probabilistic data that is used to provide accuracy and ability to solve various problems such as solar energy concentration studies.

Ray tracing is the most widely used technique for optical performance analysis, optical design and optimization of solar concentrating hubs. This method is more useful on multi-surface systems. It is essentially based on the act of tracing a ray of light through optical elements and allows you to simulate the propagation of light in various media in accordance with the properties assigned to the optical elements (see Fig. 5) [18].

Thus, a number of given photons are hitting the reflector and collide with the light emissions. These rays are reflected by impact on the reflector and directed towards the focus. Eventually, some of these photons collide with a receiver located in the center of the reflector. The greater the number of these collisions, the higher the generated heat, which leads to an increase in optical efficiency. The number of collisions at the receiver point is different from the number of collisions in other parts of the receiver. As a result, the greater the number of collisions at a point, the more heat will be generated at that point. The heat flux generated by the receiver depends on the size of the reflector surface and the magnitude of the radiation intensity [6].

A comparative and sensitive analysis of the interaction of the aperture width, coverage angle, and focal distance with the concentration factor was carried out using the Monte Carlo ray tracing method [19]. As we know, the ideal PCC can mainly be determined by focal length and aperture. In Fig. 6 we can see that the value of K_g is always proportional to B, while d_T does not change. The α and β values increase with increasing B, although they have different variations.

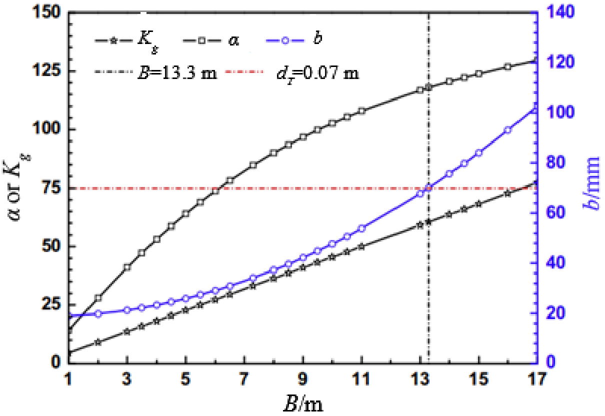

Figure: 6. Variations in the geometric concentration K_g, the coverage angle α, and the width of the focal spot b with the aperture width B [19].

Since a larger angle of coverage usually indicates a larger span of the circumferential angle of the absorber, more concentrated solar radiation from the reflector can be obtained than the original low solar radiation directly from the sun. In terms of optical performance, the absorber can collect the entire reflected beam from the reflector when B increases from a relatively small value to about 13.3 m at $b \le d_T$.

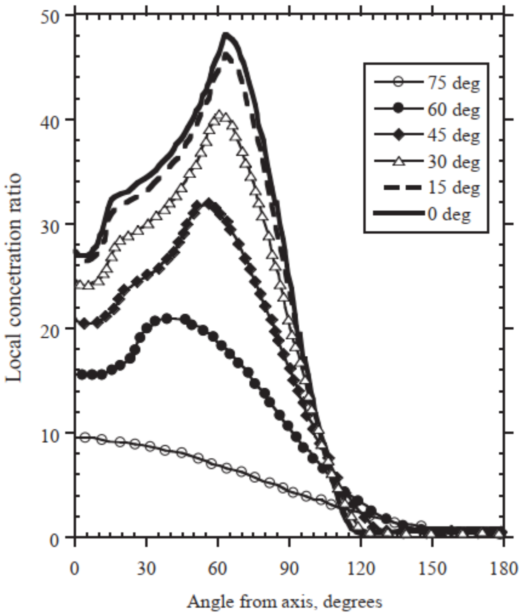

Figure: 7. Local concentration factor for an ideal PCC with a circular receiver, 90° coverage angle for a uniform sun with an angular radius of 0.0075 mrad [12].

Determining the heat flux distribution at the concentrator receiver is critical when creating an accurate thermal model of the PCC. In practice, the heat flux and temperature distribution around the receiver tube are not constant or uniform. It is known that the distribution of the heat flux at the receiver is uneven around the circumference of the absorber tube. Determining a realistic heat flow profile is critical to accurately characterizing the thermal characteristics of the PCC.

From the resulting heat flux profile, the temperature profile around the receiver can be derived. The local distribution of the heat flux around the circumference of the receiver is specified in terms of the local concentration coefficient. The use of the local concentration factor provides greater accuracy in determining the heat flux. The circumferential distribution of the local concentration factor varies with geometrical parameters such as wrap angle, concentration factor, optical errors, and angle of incidence. The incident beam radiation, in the case of a uniform solar eclipse model, strongly affects the local concentration coefficient, as shown in Fig. 7. The local concentration coefficient drops near the bottom of the receiver due to the receiver shadow, and then shows a steady rise and reaches a peak when the reflection angle is below the coverage angle [12].

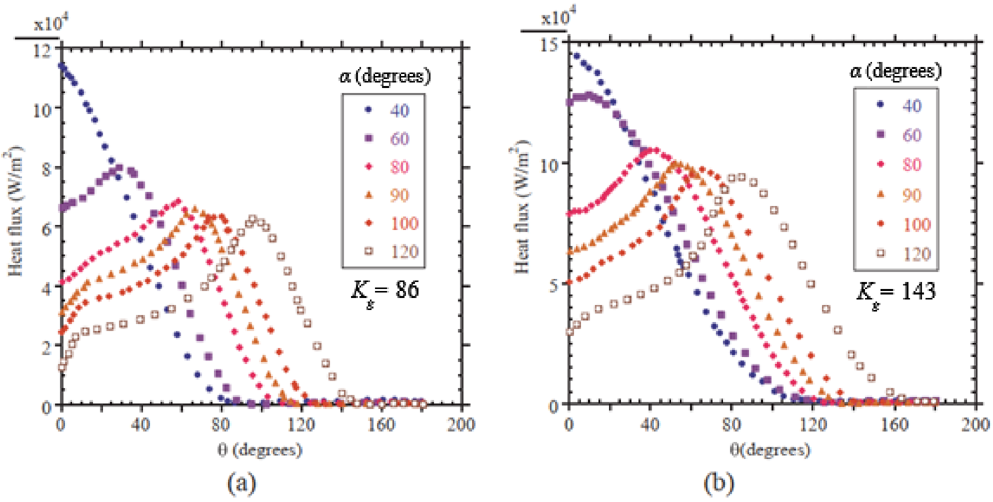

Figure: 8. Change in the heat flux around the wall of the receiver tube at different angles of coverage with the concentration factor (a) K_g = 86 (b) K_g = 143 [12].

The influence of optical errors has a significant effect on the distribution of the heat flux over the receiver. The distribution of heat flux is influenced by the intensity of the total optical errors, which acts to reduce the amount of energy collected at increasing values, and at lower values, the

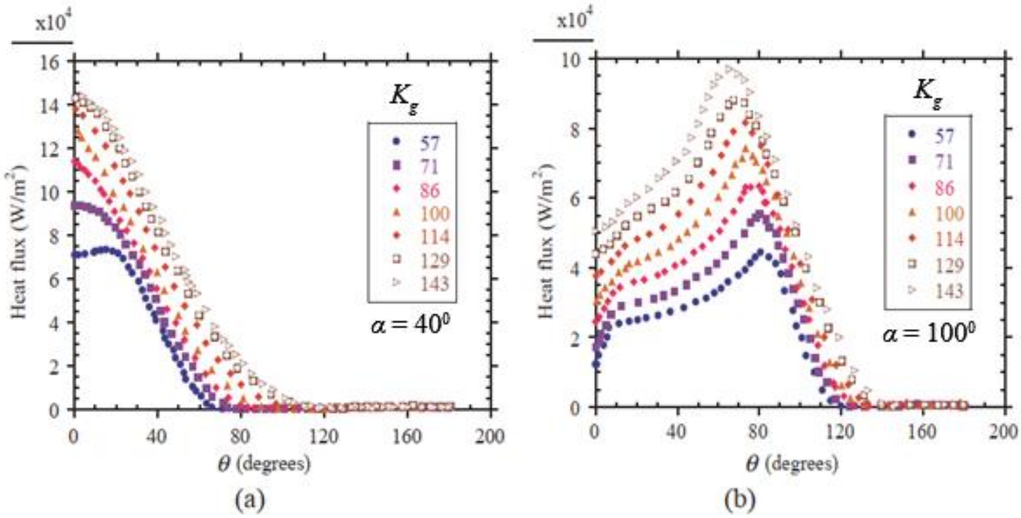

Figure: 9. Change in the heat flux around the wall of the receiver tube at various ratios of concentrations with the angles of coverage (a) α = 40° (b) α = 100° [12].

shadow effect of the receiver is quite noticeable. On the other hand, the heat flow distribution on the absorber is uneven, even if the sun is tracked correctly. The uneven distribution of solar heat flow will affect the distribution of thermal stresses and the life of the PCC. At higher values of the angle of incidence, the intensity of the heat flux will change along the length of the receiver [12].

The sweep angle is also an effective parameter for heat flux distribution and total absorbed heat flux. Determination of the appropriate value for the angle of wrap allows you to reduce the uneven distribution of heat flow and bending deflections. Larger coverage angles result in smaller deviations. With an increase in the width of the aperture, the unevenness of the circumferential heat flux increases.

Fig. 8 and 9 illustrate the variation of the heat flow profile with the sweep angle and concentration factor, respectively. The coverage angle of 110° can be considered the optimal value for maximizing the total absorbed flux at a fixed aperture width, but it may not correspond to the minimum cost of the mirror.

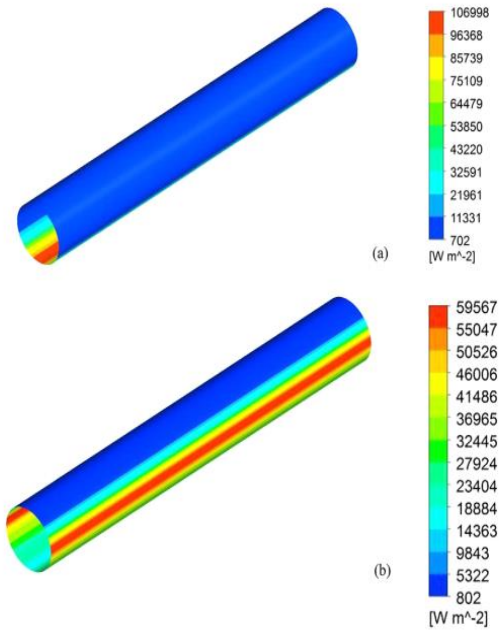

Figure: 10. Contours of the heat flux of the receiver tube at Re = 1.02 × 10, T = 400 K and K_g = 86 (a) α = 40° (b) α = 120° [20].

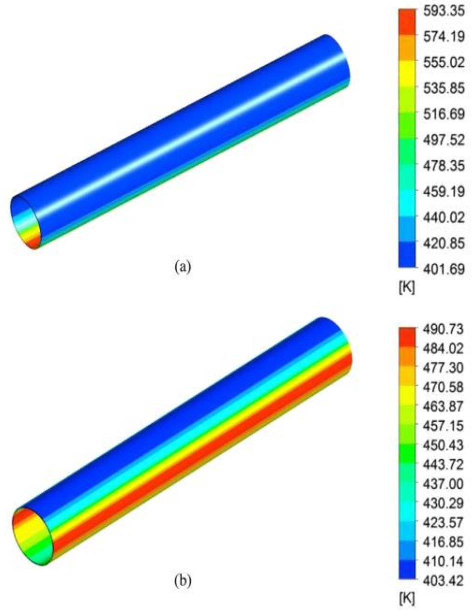

Figure: 11. Temperature contours of the receiver tube at Re = 1.02 × 10, T = 400 K and K_g = 86 (a) α = 40° (b) α = 120° [20].

However, wrap angles above 90° have some mechanical and economic disadvantages. Increasing the sweep angle requires both an increase in the size of the envelope and the mirror surface, which in turn leads to an increase in wind loads on the collector structure and a decrease in optical efficiency as a result of this condition. In order to increase the maximum heat flux at the absorber, the optimal value should be determined with respect to the assigned combination of aperture width and coverage angle [12].

At each concentration ratio, the peak heat flux increases as the sweep angle decreases. This increase in peak heat flux increases the peak temperature and therefore the final temperature difference. As for the Fig. 10 (a and b), it can be seen that the peak heat flux is higher at the lower angle of coverage (α = 40°) and lower at a higher angle of coverage (α = 120°). As shown in the figures, at small angles of coverage, only a small part of the absorber tube receives concentrated solar heat flux.

The temperature contours of the receiver at angles of coverage of 40° and 120°, respectively, with a Reynolds number of 1.02×10, T=400K and a concentration factor of 86 are shown in Fig. 11 (a and b). The temperature distribution around the circumference of the absorber tube is similar to the distribution of heat flux at each corresponding angle coverage are shown in Fig. 10 (a and b). As expected, the temperature difference in the absorber tube at 40° is higher than at 120°. The temperature difference between the absorber tube at these sweep angles for the conditions under consideration is about 192°C and 87.31°C, respectively. The temperature difference decreases with increasing flow and increasing inlet temperature due to improved heat transfer characteristics [20].

Based on the above, higher coverage angles should be used to avoid such large temperature differences, especially at low Reynolds numbers. However, the use of large sweep angles increases the requirements on the manifold material. Therefore, a trade-off must be made as to how large the wrap angle should be in order to avoid a large temperature difference while using as little material as possible. Fig. 8 (a and b), shows that above a coverage angle of 80°, the peak heat flux does not significantly decrease as the coverage angle is further increased.

3. Conclusion

The analysis performed shows that the shape (angle of incidence) of solar radiation has a great influence on the optical characteristics of the PCC, which should be taken into account in practice.

The geometric configuration, especially the diameter of the absorber tube, must be determined according to the energy demand based on the local conditions of the solar form. In addition, the final loss caused by the angle of incidence weaken the optical efficiency.

A wider aperture and a smaller absorber diameter will result in large losses at a constant angle of incidence. When the absorber is long enough, the influence of the angle of incidence will be negligible.

In the small focal length range, optical efficiency increases with focal length and then decreases steadily with further focal length.

Increasing the coverage angle and decreasing the aperture width increase the optical efficiency, while increasing the coverage angle and decreasing the receiver diameter increases the density of the reflected sunlight in the focal plane.

The concentration factor increases with increasing aperture width at a constant receiver diameter. The receiver can collect the entire reflected beam from the reflector when B increases from a relatively small value to about 13.3 m at $b \leq d_{т}$.

The heat flux generated by the receiver depends on the size of the reflector surface and the magnitude of the radiation intensity. The incident beam radiation strongly affects the local concentration coefficient. The local concentration coefficient drops near the bottom of the receiver due to the shadow of the receiver, and then shows a steady rise and peaks when the reflection angle is below the coverage angle. Larger coverage angles result in smaller deviations. With an increase in the width of the aperture, the unevenness of the circumferential heat flux increases.

Increasing the sweep angle requires both an increase in the size of the envelope and the mirror surface, which in turn leads to an increase in wind loads on the collector structure and a decrease in optical efficiency because of this condition. In order to maximize the maximum heat flux at the receiver, the optimum value must be determined with respect to the assigned combination of aperture width and coverage angle.

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