Analysis of scientific research conducted to improve the efficiency of solar concentrator systems

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Abstract. The article presents a scientific analysis based on scientific research conducted in the field of solar concentrators in leading institutions of the world. Parabolocylindrical concentrators with a free surface have been shown to be more efficient. concentrator model with free surface shape is proposed and based on its ability to solve problems in the design and analysis of optical systems, including boundary surfaces of arbitrary shape.

1 Introduction

To date, the main goal of research in the field of solar energy is to create new types of highly efficient devices based on the theories being developed and to increase the efficiency of solar energy use. When analyzing scientific research conducted in this area and the results obtained in the design of optimal designs for concentrating surfaces of solar power plants, assessing their parameters, increasing the efficiency of using solar energy on radiant heat pipes, studying the composition of coolants moving in heat pipes, increasing the possibility of using for different seasons of the year, it is clear that such issues as the enrichment of the chemical composition and the use of nanofluids as heat carriers in the system are relevant. The world's leading research institutions in the field of solar energy device designs, especially the use of solar concentrators, including Taiwan National Chung Cheng University, Iran University of Science and Technology, Russian "Federal Scientific Agro-Engineering Center VIM", a number of research institutes in Morocco, Ataturk University in Turkey, University of Cagliari in Italy. Many scientific studies are carried out by scientists from scientific institutions such as the State University of India and the Central Research Institute of Salt and Marine Chemistry, Shanghai Jiao Tong University in China, Hamdard Institute of Engineering Technology in Pakistan.

2 Materials and methods

In a study by Chung-Yu Tsai, a researcher at National Chung Cheng University in Taiwan, on the design of a free-form tubular concentrator for a solar thermal concentrator system based on a quadratic Bezier curve [1], in a scientific study by Italian scientists Mario

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Petrollese et al., pump storage systems thermal energy with integrated solar energy concentrating sections, a conceptual design was developed [2]. The studies of Kajal J. Sareriya, Jigar K., and Andhari [3] comprehensively analyzed the evaluation of the thermal performance and design parameters of Scheffler concentrators in medium-temperature solar thermal devices, and the research papers of Fazlay Rabbi, Lihan Das et al. [4] analyzed the use of oil-based nanofluids in thermal collectors of solar concentrators. Research on nanofluids is also presented in the scientific works of Mahyar Tafavog, Alireza Zahedi [5]. The research is supposed to develop a new type of encapsulated nanomaterials to increase the thermal efficiency of geothermal/hydropower/biomass/solar/wind hybrid systems based on renewable energy sources. The scientific studies of Shauei Chai, Jian Yao et al. [6] analyzed the heat transfer and thermal performance of vacuum tube solar collectors using solar-coated internal reflective concentrators, and the scientific works of Atazaz Hassan, Chen Xuanfan et al. [7] carried out thermal analysis of structures of paraboloid solar-optical, cylindrical and conical light receivers made of copper tubes for concentrators. Russian scientists A.A. Taran and S.M. Voronin [8] studied the efficiency of using solar concentrators in photoelectric converters. A. Habchi, B. Hartity et al. [9] investigated the feasibility study and thermal/electrical performance of smart hybrid systems using a parabolic trough collector with a tubular thermoelectric generator.

On designing an arbitrary-shaped tubular concentrator for a solar thermal concentrator system based on a quadratic Bezier curve, in [1] for designing an arbitrary-shaped tubular concentrator system in a solar concentrator, an optimization method based on mathematical theory is proposed.

It is noteworthy that the continuity (or discontinuity) of the shape of the surface created by this method appears in the free state. To get closer to the optimal design solution, it is necessary to determine the redundant design points. According to ZEMAX simulations, compared to traditional cylindrical and parabolic tubular concentrators, the free-form tubular concentrator achieves the efficiency of even distribution of radiation on the surface of the heat pipe. It is easy to program on a computer because it is based on a purely algebraic approach to freeform hub modeling.

As fuel and energy resources are depleted, more and more attention is paid to solar thermal systems at stages from small water heating systems for domestic needs to steam production at large thermal power plants [10]. In a study by Wan et al., a calculation model was proposed to estimate the thermal stress and fatigue of steam-water receivers of solar concentrating power plants [11-12] proposed a series of combined cycles to increase the production capacity and efficiency of a 250 MW steam turbine plant by combining it with a gas turbine, an absorption cooler, and various forms of photovoltaic and photothermoelectric devices. The combination of solar thermal power plants with critical CO_2 cycles has led to increased interest in improving the global efficiency of solar energy conversion systems. In [13], a thermomechanical model of a heat exchanger used in such power plants was developed.

Proposed an approximate control approach based on a general lighting model for maximizing the heat output of parabolic solar power plant concentrators. An efficient solar concentrator is one of the key elements of all solar energy systems. [15], the author of the work proposed a system of solar concentrators with a large fixed reflector with a focal point located on the surface of the heat pipe and a small reflector for tracking the trajectory of the sun. Kalogirou conducted a scientific study of the environmental and economic benefits of a number of solar collectors.

In systems with a solar concentrator, the even distribution of heat over the surface of the heat pipe not only reduces the likelihood of breakdowns due to localized heat accumulation, but also increases the heating efficiency. That is why there are many proposals to increase the spread of radiation in research conducted around the world. In, a numerical simulation

was carried out to optimize the characteristics of a parabolic trough concentrator with a variable focus and it was determined that the heating efficiency increases with an improvement in the uniform distribution of light intensity on the heating surface of the tube when a fixed amount of sunlight is absorbed. In a research paper by Nilson et al., concentrator designs based on microstructured surfaces were proposed to ensure the uniformity of the light flux and improve the concentration coefficient in stable asymmetric parabolic cylindrical concentrators. In, the ray tracing method was used to optimize the design of parabolic trough concentrators with an asymmetric combination. As a result, it was found that the obtained tilt angles in the range of 55~77° make it possible to provide a more uniform distribution of radiation over the surface of the pipe in comparison with the reception of direct radiation beams. The authors of developed a concentration system consisting of a flat reflector and a parabolic trough reflector to achieve an even flow on the surface of the light receiving tube.

A 2D bubble Fresnel lens for use as heat transfer inside a vacuum tube or inside photovoltaic devices was developed by Loyts et al. A solar collector based on modular multi-angle Fresnel lenses was developed by K. Rue et al. to improve the process of light absorption in solar concentrator systems. In, the authors used a concentrating spherical ring to place the lens and mirrors in order to create a fixed amount of light distribution.

Used the method of metaheuristic optimization and multifocal modules to improve the flow of solar energy. Rabady and Andraves used the solution of a second-order differential equation to develop a concentrator that provides a uniform distribution of energy on the glass surface.

Most research on the design of light-receiving surfaces of arbitrary shape is based on the principle of conservation of energy and uses special methods for determining the normal vectors and structural points on the surface. However, for different initial parameters or design variables, different constraints apply, and the free surface design results must also be different. Then, if traditional methods are used to design a free surface, non-uniform solutions can be obtained that reduce the optical performance and efficiency of the surface as the surface profile gradually changes.

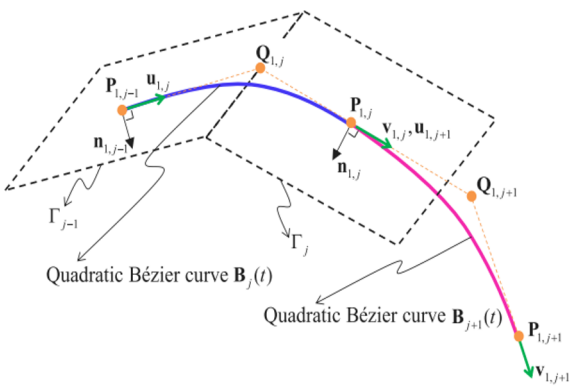

Fig. 1. Connection of quadratic Bezier curves.

As shown in f figure 1, when constructing a compound curve from several continuous quadratic Bezier curves, if the last point of the Bezier curve $B_{(j)}(t)$ coincides with the first point of the neighboring Bezier curve $B'_{(j)}(t)$, the line of the two curves C_0 is continuously connected.

In general, the results show that the method of creating a free-form surface requires only small structural points to achieve an optimal solution.

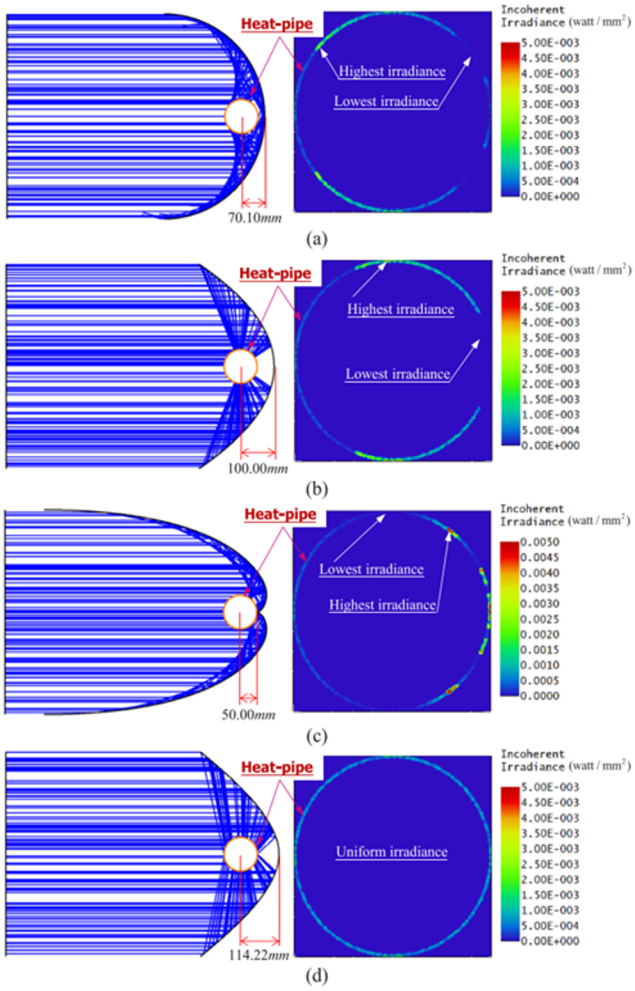

Fig. 2. Radiation calculation results for four types of concentrator structures using the ZEMAX program.

Figures 2(a) and 2(d) show the simulation results obtained for solar concentrator systems including SC, SP, CPC and FF reflectors respectively. To ensure a fair comparison between different systems, the radius of the heatpipes was set to 50mm in each case, and the inlet spherical width of each hub was set to 300mm.

Because all solar concentrators are concave with the same cross section, the beam flux is theoretically independent of the length of the concentrator. Thus, for simplicity and without loss of generality, the concave groove length of the concentrator has been set to only 1 mm in each case. The half angle of natural sunlight is about 0.27°. Thus, a certain light source with an angle of inclination of 0.27° is considered. In addition, 1,000,000 rays were considered for all concentrators, and the surface of the concentrator was located at a distance of 700 mm from the center of the heat pipe. The concentrator surface power is assumed to be 1 kW/m^2, so the total power is 0.6 W. In the SC concentrator, when the distance between the center of the heat pipe and the edge of the concentrator is 70.10 mm, the number of rays reaching the surface of the heat pipe reaches its maximum value, and in the concentrator SP, the maximum value of the rays incident on the surface of the heat pipe is reached at this distance, equal to 100 mm (Figure 2 a, b). For the CPC concentrator, the

maximum value of rays falling on the heat pipe surface was achieved by optimizing the distance between the pipe and the concentrator surface to 50 mm (Figure 2c). The value of the optimal size of the surface of the TF concentrator is determined to be 114.22 mm (Figure 2d).

3 Results and Discussion

According to the conclusions made in figure 2, the radiation distribution in the FF concentrator system is qualitatively superior to that in the SC or SP concentrator system. On Figure 3 shows the radiation distributions of ideal concentrators, SK, SP, CPC, and FF, respectively. The ideal distribution shown in the figure has the form of a horizontal straight line, i.e., it has the same radiation index. A deviation of the radiation distribution of the concentrators SC, SP and CPC from the ideal is observed. Then the performance of the FF type concentrator is very close to the ideal distribution. Table 1 shows the number of beams obtained for each of the four concentrators, as well as the corresponding values calculated by equation (2).

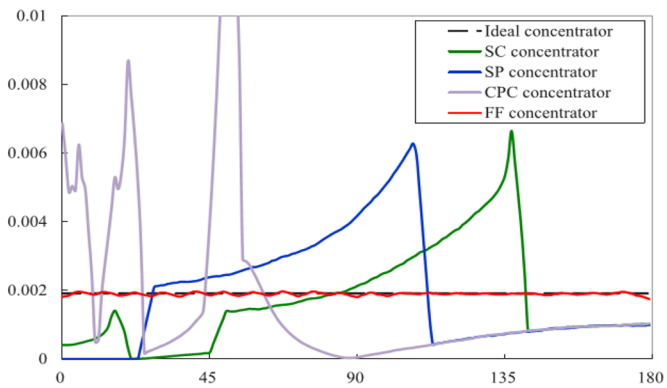

Fig. 3. Dependence of the angular position of concentrators of different designs on radiation.

In [1], a two-stage optimization method based on the mathematical theory of a quadratic Bezier curve is proposed for designing a solar concentrator system consisting of an arbitrary-shaped solar concentrator and a heat pipe. At the first stage of the proposed methods, the distance between the light sources and the distribution of light on the surface of the heat pipe were calculated based on the principle of conservation of energy.

Table 1. ZEMAX Simulation Results for Optical Characteristics of Four Concentrator Types.

The angle of inclination of the incident sunlight	The concentrator	The number of rays received	The value of the efficiency coefficient η_{rms}. (see equation 33b)	Uniformity improvement
0.27°	SC	859,007 (85.9%)	0.729 (86.0%)	14.3%
	SP	995,500 (99.6%)	0.847 (100%)	0%
	CPC	1,000,000 (100%)	1.475 (174.1%)	−74.1%
	FF	996,595 (99.7%)	0.045 (5.3%)	94.7%

At the second stage of optimization, based on the results obtained at the first stage, the direction of the incident and returning energy of solar radiation from the smooth surface of the concentrator FF is calculated. Four basic parameters (slope, curvature, symmetry, and flatness) are proposed for optimization methods, and these parameters are combined in the optimization process.

It is noteworthy that the fragmentation or integrity of the surface of the concentrator FF created by the proposed method does not affect the function of reflection from the source. Consequently, there is more freedom in designing (manufacturing) the reflective surface of the concentrator.

4 Conclusion

Based on the ZEMAX simulation program, the following conclusions were drawn:

- SC concentrators have a relatively simple shape, but their light absorption coefficient is 85.9%.
- SP and CPC concentrators have almost 100% light absorption, but the light distribution on the surface of the heat pipe is not very good.
- Directs the beam of light incident on the surface of the TF concentrator onto the surface of the heat pipe. In addition, compared with them with the SP concentrator, the flatness (uniformity) of the beam distribution is improved by about 94.7%.

In order to choose the shape of the concentrator in the proposed free-surface FF-type optimal design, the calculation of densely located multi-point systems is required. Naturally, a pure algebraic approach is used in the calculations, and such an approach allows easy calculation results with the help of programming packages. In general, the free-surface concentrator model can be an effective computational tool for solving a wide range of problems in the design and analysis of optical systems, including arbitrary-shaped boundary surfaces.

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