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Utilization of the Fresnel principle for the concentration of solar radiation

The article deals with the use of solar energy for power engineering purposes using the concentration of solar radiation. Compound parabolic concentrators are often used for this purpose. They are characterized by high design demands. In this contribution, the possibilities of using of the Fresnel concentration principle are analyzed using the constructed model. The results show the benefits of this principle.

Keywords: solar energy, parabolic concentrator, Fresnel concentrator, solar power plants

I. INTRODUCTION

Solar energy as a renewable energy source has vital importance for life on Earth. The use of solar energy for energy purposes has its supporters, but on the other hand, it also has its objectors. It is necessary to provide sufficient space to this renewable energy source, because previously used fuels are already significantly depleted.

Solar power plants have a high perspective of becoming a strong competitor of electricity generation in conventional plants, but especially in places with a large number of sunny days per year. They are also justified in areas where the supply of conventional energy sources (coal, oil, gas, fuel oil) is expensive, and it is suitable to choose the utilization of renewable energy sources. They are ideal for reducing greenhouse gases and other pollutants. They create conditions for the electricity production on the principle of sustainability without environmental risks and environmental contamination [1], [2], [3].

II. OPTICAL CONCENTRATORS

Concentration of solar radiation is used in cases when it is necessary to reach higher temperatures, which cannot be achieved without the concentration. This is the case of the utilization of solar radiation for power engineering purposes. Without the concentration of solar radiation, the impact of light rays on the surface of small dimensions absorbers does not create the desired temperature for optimal heat of heated medium passing through the absorber. Optical concentrators are used to increase the flux density of solar radiation. They collect rays of light from a larger area and concentrate them into the small size focus point. The concentrators are characterized by the concentration factor (or ratio) *c*, which is calculated by the formula (1):

$$c = S_V / S_P \quad (–; m^2, m^2) \qquad (1)$$

where S_V – geometric projection of the inner reflecting surface of the concentrator,
S_P – receiver surface.

E.g., if the concentration factor is equal 15 then the absorption area is exposed to the 15 times higher solar radiation density than the concentrator inlet area. Solar flux density is enhanced by this way and temperature increases. For the same solar radiation power, the absorption surface can thus be smaller comparing with the case without concentration.

The concentrators are categorized according to construction design, shape, positioning method, etc. The most commonly used types of concentrators in the solar thermal power plants are:

- Linear Fresnel concentrators,
- Rotationally symmetric concentrators,
- Rotationally asymmetric concentrators,
- Compound parabolic concentrators (CPC).

Fresnel concentrator is used in various modifications as planar rotationally symmetric with spot focus – Fresnel lens (Fig. 1), or as linear with narrow band focus. The Fresnel lens is a thin transparent sheet of glass or plastic, often in the form of foil, on which Fresnel optical system behaving like a convex lens is created.

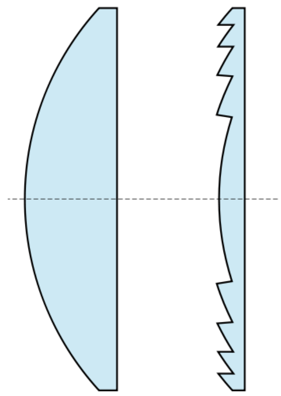

Figure 1. Cross section of a conventional lens and a Fresnel lens

Linear Fresnel lens is designed like a glass plate with correspondingly shaped set of concentric annular sections, ensuring refraction of the solar radiation to the band focus. Lens in cross section has symmetric saw shape. The design allows the construction of lenses of large aperture and short focal length without the mass and volume of material that would be required by a lens of conventional design. A Fresnel lens can be made much thinner than a comparable conventional convex lens. Large Fresnel concentrators used in solar power plants are constructed with planar or slightly curved reflecting surfaces, which are movably mounted with the horizontal axis. It allows them to optimize the optical properties and the focal length by the actual position of the Sun. The concentration ratio *c* is in the range of 8 – 80, and achieved temperatures are 260 – 400 °C.

The rotationally symmetrical solar concentrators in solar thermal power plants are mainly used in combination with the Stirling unit and with the parabolic reflector [4], [5]. Spherical or cone-shaped construction exists besides symmetrical parabolic one. The shape of the cross section curve can be described by a quadratic function. They have the highest concentration factor, more than 200. The concentration of solar rays in spot focus enables to reach the highest temperature up to 4000 °C.

The rotationally asymmetrical solar concentrators are parabolic cylindrical or parabolic trough ones. These concentrators are used in the solar thermal power plants with decentralized absorber. Concentration factor is usually in the range of 80 – 100. It is possible to reach the temperature in the range of 260 – 400 °C in their linear focus by concentration of rays. This temperature is optimal for thermal processes in solar thermal power plants. Compared with the rotationally symmetrical solar concentrators they have a simpler structure for positioning purposes. They are equipped with 1-axis trackers.

CPC concentrator is a specific type of rotationally asymmetric concentrators. Cross section of these concentrators can be described by two axially symmetric parabolic curves of the second order. The most commonly used type is the Winston concentrator. Usually, the central receiver is permanently installed to the CPC axis. Heated working medium circulates through the receiver. CPC advantage is that it does not require precise positioning. These concentrators are mainly used in applications with tubular collectors. It can be also in the linear Fresnel concentrator. There, it acts as the secondary reflector.

III. SOLAR POWER PLANTS WITH DECENTRALIZED ABSORBER

Solar power plants can be divided according to the absorber:

- Solar power plants with a central absorber (CRS – central receiver system),
- Solar power plants with a decentralized absorber (DCRS – decentralized receiver system),

DCRS solar plants are referred to the collector field, because a large number of concentration collectors situated in the solar plant area is used for heat generation. Compared with the CRS, the light rays are not focused to the central point located on the tower, but to more systematically spaced focus points of the concentration collectors. Collectors with parabolic shape, so-called parabolic troughs or linear Fresnel concentrators, are most commonly used to concentrate the sunlight. Their value of the concentration ratio is around 80.

The reflecting surface of trough concentrators is made of parabolic mirrors or curved mirror plates. A concentrator surface is not made as a single piece, but is composed of several partial sections (called lamellation). While reducing concentration factor *c*, on the other hand, easier production, and the decrease in production costs are achieved. For concentration by linear Fresnel concentrator, integrally made flat or slightly curved reflective surfaces are used. The tubular absorber for both types of concentration systems is placed in the focus line, inside vacuum glass tube to reduce heat losses. Unlike Fresnel concentrator, also the positioning of the trough concentrator absorber is realized. The concentrators positioning is performed by 1-axis Sun trackers.

Working fluid medium transferring the heat (usually oil, water) circulate in the tubular receiver and is heated to approximately 400 °C. The obtained heat is used to produce superheated steam. The steam expands in a 2-stage steam turbine and then the mechanical energy generated by the alternator is transformed into electrical energy. The average electrical efficiency reaches 11 – 16 %. In this type of solar thermal power plant, the heat storage process can be done by a salt brine medium.

IV. DESIGN OF THE FRESNEL CONCENTRATOR MODEL

The model design was proposed to allow demonstration of Fresnel principle of concentration. The model consists of a base plate and small heliostats. The base plate with dimensions of 26.5 x 40 cm enables to create various arrangements of heliostats. They can be placed to any location, to a straight line, or even to sketched three parabolic curves given by the equations:

$$y = 0.05\,x^2 \tag{2}$$

$$y = 0.1\,x^2 \tag{3}$$

$$y = 0.2\,x^2 \tag{4}$$

Heliostats were constructed with 2-axis positioning of mirrors (horizontally 0 – 360 °, vertically 0 – 270 °). All heliostats had reflecting surface with identical dimensions of a 3 x 2 cm (Fig. 2, Fig. 3).

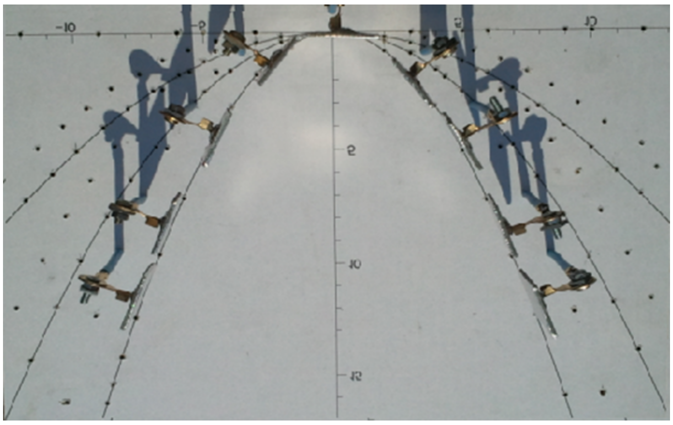

Figure 2. Heliostat models placed on a parabolic curve

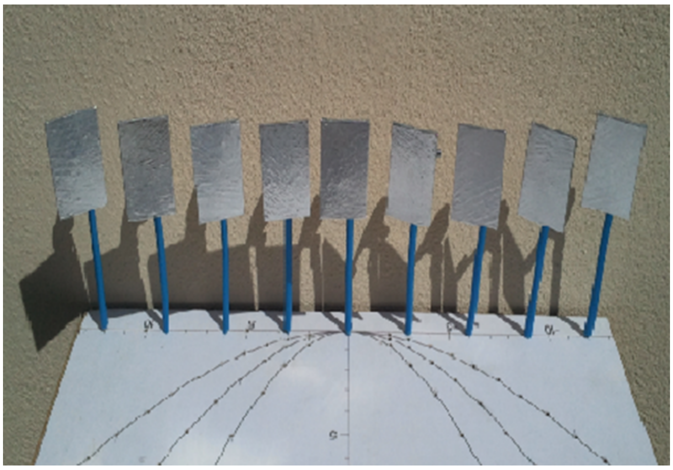

Figure 3. Heliostat models placed on a straight line

The results of measurements with the location of heliostats on the parabolic curves (Fig. 4), and also on straight line (Fig. 5) with various focal lengths, confirm the good performance of the model and the suitability of its use to demonstrate the concentration of solar radiation using Fresnel principle.

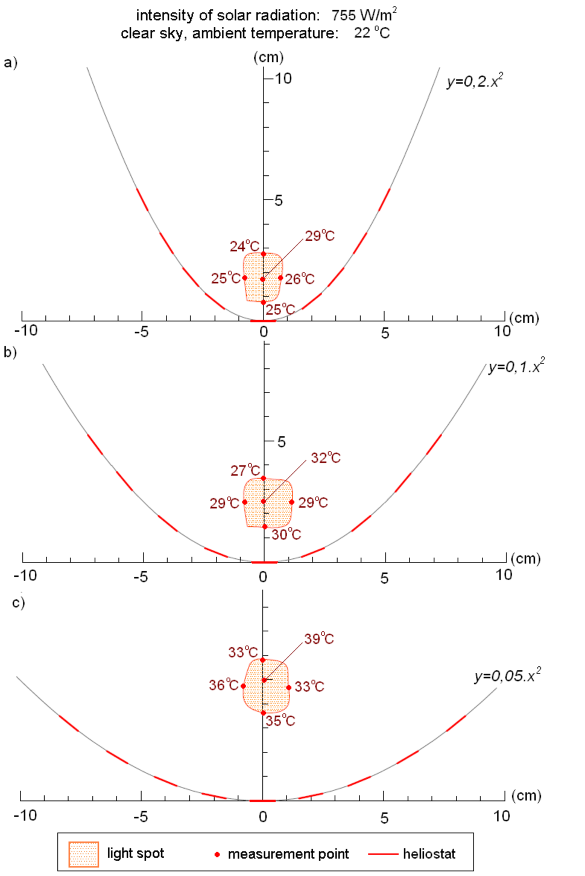

Figure 4. Temperature distribution in the focus with heliostats placed on a parabolic curve

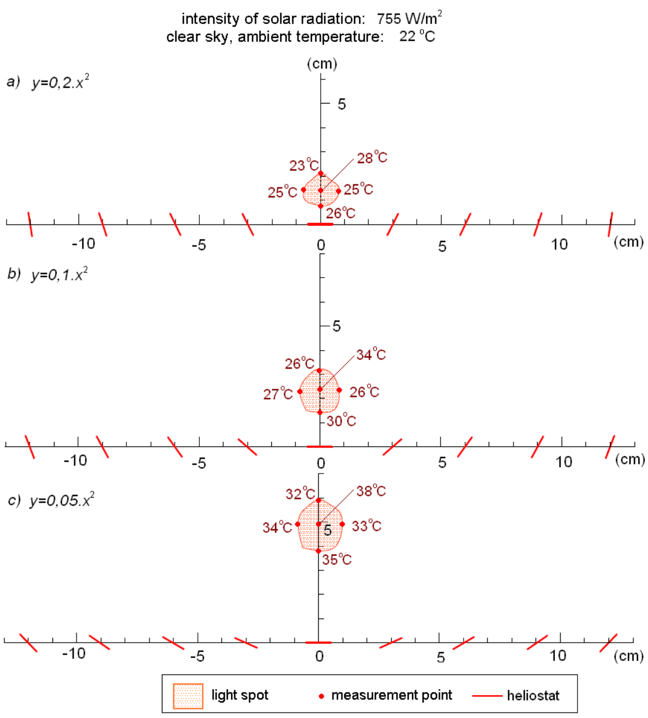

Figure 5. Temperature distribution in the focus with heliostats placed in a line perpendicular to the concentration axis

V. CONCLUSION

The measured results show that the use of Fresnel principle has great benefits to solar power engineering. It enables to replace the optical concentrators based on curves of higher order by linear plane segments. The arrangement of reflective surfaces can be optimally adapted to the surrounding terrain. Location of reflective surfaces is determined by the optical analysis based on marginal positions of the Sun towards the Earth, and by the relative positions of the particular segments to avoid their mutual shading. The highest attention in using the concentrators is paid to the optimal setting of azimuth and elevation. This setting has to be optimized for each reflective segment separately at defined moments [6], [7].

The concentration of solar radiation is very attractive, but the utilization is less efficient compared with other solar systems, because it does not allow the concentration of diffuse radiation. However, there is no alternative, if a high temperature is necessary to achieve.

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