NUMERICAL STUDIES ON CAPABILITY TO FOCUS SOLAR RADIATION WITH MIRRORS OF DIFFERENT CURVATURES

by

Zuzanna KACZOR**, Zbigniew BULINSKI, and Sebastian WERLE

Institute of Thermal Technology, Gliwice, Poland

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The article presents the methodology and results of a parametric analysis performed to investigate the effects of changes in the curvature of the solar concentrator mirror on its ability to focus the radiation. Working conditions of the concentrator, i. e. possible values of radiation intensity, were adopted according to irradiance typical for Poland, and, therefore, similar to the conditions in many European countries.

The curvatures of examined mirrors were obtained by modification of a parabolic curve. The calculations were conducted for two cases: when the Sun radiation falls completely directly and when it's half diffuse.

The 2-D simulations were conducted in ANSYS FLUENT 18.2 software. Discrete ordinates model was employed to simulate radiation phenomenon. Also, a sensitivity analysis was carried on discrete ordinates model parameters and density of the computational mesh.

The results allow stating that some of the new curvatures provide only slightly worse focus than the classical parabolic shape, but also show greater insensitivity to the increasing share of diffusive part of radiation.

The presented model is a quick and proven tool for testing new curvatures of solar concentrator mirrors.

Keywords: *solar, concentrator, mirror, curvature, radiation, CFD, parametric analysis, collector*

Introduction

Currently, technologies allowing the use of solar energy are very diverse and easily available. Even simple homemade heating installations based on the solar collectors can provide hot water for household needs. The ease of employing solar energy immensely contrasts to the complexity of solar radiation phenomenon.

Solar radiation is just a part of the spectrum of electromagnetic radiation, which represents the energy emitted by matter as a result of the changes in the electronic configurations of the atoms or molecules [1].

Electromagnetic radiation has a dualistic corpuscular-wave nature, which means that depending on the conditions, it may behave as a wave or as a beam of particles [2]. Such a duality of nature causes that in different situations, certain properties can be better described

* Corresponding author, e-mail: zuzanna.kaczor@polsl.pl

using the physical laws typical for waves, some can be expressed using physical laws derived for the matter, while other features can be described by both methodologies [3].

As mentioned earlier electromagnetic radiation is a beam of particles called photons, but also a term *a beam of quanta (portions) of energy* can be met. The interchangeability of these determinations can be justified by the principle of equivalence of mass and energy [4], described by Einstein with the famous formula:

$$\Delta E = \Delta mc^2 \tag{1}$$

where E [J] is the indicates energy, m [kg] – the mass, and c [ms^{-1}] – the speed of light in the vacuum.

An example of situation, in which the radiation behaves simultaneously as a wave and as a beam of particles is Sun rays reflection from the mirror of the solar concentrator. The surface of the mirror is not perfect, it is not characterized by reflectivity equal to 1, moreover in the whole spectrum of radiation. Therefore, a part of radiation falling on the surface of the mirror is reflected at an angle equal to the angle of incidence, so it behaves like a wave, while some of the radiation is absorbed by the surface of the mirror, causing its heating up. In this situation, the radiation behaves like a stream of energy quanta. In addition, for other wavelength ranges and other temperatures of the radiation source the proportions between the reflected and absorbed part of radiation is different, according to the course of spectral reflexivity of the mirror surface.

Irradiance in Poland

Around $1.75 \cdot 10^7$ W of radiative power from the Sun reaches the Earth. On the outer surface of the atmosphere, calculated per unit of surface perpendicular to the incident radiation, it gives 1367 W/m^2 what is the value of so-called solar constant. Passing through the atmosphere, part of the radiation is absorbed or scattered by the gaseous components of the atmosphere and dust suspended in the air [5].

As the effect of absorption, air particles receive portions of energy transported by the wave and raise their own energy, which results in an elevated temperature of the atmosphere. Scattering occurs due to absorption of radiative energy and immediate reemission but yet in random directions. In addition, as a result of position changes of the Sun in the sky, the distance from the external surface of the atmosphere to the earth's surface also changes. So the way that radiation has to pass is different and an amount of scattered and absorbed radiation changes. This is expressed by so-called optic air mass.

The solar radiation reaches the Earth's surface, partly falling directly from the Sun, in a straight line connecting the Sun with a given surface, being the direct irradiance, and partly in a scattered form, from different, random directions, as diffuse irradiance. In addition, on the selected surface falls also radiation reflected from other elements of the environment. Figure 1 presents what happens with Sun's rays before they rich surface of th Earth.

It should be emphasized that when determining the amount of radiation energy falling onto a certain surface, two terms with a similar meaning are being used, which should not be applied interchangeably: *irradiance* [W/m^2], which expresses the intensity of radiation (global irradiance equals the sum of direct and diffuse irradiance and *irradiation* [J/m^2] expressing the amount of energy that reached the selected surface within a given time interval (global irradiation determines the sum of direct, diffuse and reflected irradiation). Values of global irradiation are important in assessing the energy efficiency of systems using solar radiation.

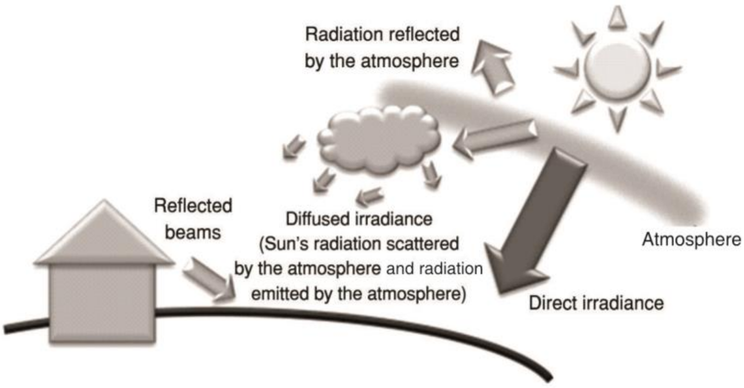

Figure 1. Solar conditions on the Earth

An important factor is also so-called *insolation*, *h*, expressing the time when the Sun's rays fall directly onto the ground. Insolation and irradiance are affected by the geographical position (latitude), as well as the state of the atmosphere and cloudiness [5].

According to measurements carried out regularly since the 1950s, in Poland insolation equals averagely 18% of the year (which gives 1580 houres). Direct irradiance is usually 600-800 W/m^2, temporarily reaching 1200 W/m^2 (1250 W/m^2 of global irradiance), usually however not exceeding 1000 W/m^2. Global irradiance during the year equals 3600 MJ/m^2. The part reflected and absorbed by the atmosphere constitutes about 55-62% of radiation falling from the Sun onto Earth's atmosphere. In Poland, averagely, annual direct irradiation accounts for approximately 52% of global irradiance (30% in the winter and 57% in the summer). For comparison in tab. 1 are summarized data for Poland and selected locations on Earth [5].

Table 1. Solar conditions in selected locations on the Earth

Location	Global irradiation, [MJm^{-2}]	Insolation, *h*
Helsinki	3362	1740
Poland	3600	1580
Rome	4968	2445
Arizona	8460	3842
Sahara	8460	3900

Currently, the market offers many methods of using solar energy. One of them is concentration of radiation that further is used in many different ways. The basis of focusing installations is a mirror or a set of mirrors and a receiver in mirror focus. Mathematics offers many curves that could be used as a curvature of mirrors. Most common solution is trough- or disc-shape parabolic mirror that provides focus on the line or on one point, respectively. Systems of many separate flat mirrors are also popular. Sometimes, in some solutions a parabolic disk in combination with a hyperbolic dish is used.

Unfortunately, literature offers very few works regarding adopting curvatures different than a parabola for mirrors. Available sources present extensive summarisations of parabolic concentrator technologies or examinations of issues related to their operation. An example of such work is the paper of Fernandez-Garcia *et al*. [6]. The article presents an overview of existing parabolic concentrators constructions and prototypes currently being designed around the world. Review prepared by Hafez *et al*. [7] summarizes researches on parabolic trough collectors. The paper collects methods of design of such systems and presents a summary of so far developed mathematical model used for simulation of concentrators operation. Arancibia-Bulnes *et al*. [8] summarized methods for evaluating the efficiency of solar concentrators and presented vastly sources of mirror imperfections. Salgado Conrado *et al*. [9] summarized data on thermal performance of parabolic trough solar collectors and reviewed simulation works on the concentrators.

Research papers usually focus on a chosen aspect of operation, mainly of parabolic concentrators. Antonelli *et al*. [10] conducted a CFD investigation on heat transfer around the receiver. Cagnoli *et al*. [11] performed numerical research on influence of geometry and air-flow on performance of central tower solar plant. Chen *et al*. [12] modeled concentrator consisting of paraboloidal and hyperboloidal disks to investigate the influence of parabola shape and its focal length on collector effectiveness. Hachicha *et al*. [13] presented a CFD simulation of fluid flow around parabolic solar concentrator.

It is not without reason that the parabola is used most often - if the radiation falls parallel to the symmetry axis of the mirror, it is concentrated in one particular point, with a location determined by a simple formula. However, as aforementioned, in Polish conditions statistically per year, even a half of the radiation can be diffuse, which means that it falls onto the mirror surface not parallel to its axis, but from random directions. In this case it is not sure any more whether parabolic collectors are still the best.

The aim of this work is to examine this problem by carrying out the parametric analysis of the concentrator shape, to verify the possibility of finding better mirror shape for solar radiation concentrators.

Analysis and modeling

To perform the numerical investigation of focusing ability of differently shaped mirrors ANSYS FLUENT 18.2 software was used. Simulations considered mirror and a fragment of space above it. As a mirror curvature basic parabola was initially adopted, which was further systematically modified.

First simulations were performed to obtain distributions of incident radiation within the area above the mirror and to identify spots with the highest values. Therefore, no receiver was included in the geometry of the computational domain. Secondly, for chosen cases, in spot of maximum value of incident radiation an opening representing pipe receiver was added to verify possibilities of receiving the radiative energy.

Both analyses were conducted for two cases: with completely directed and with 50% diffuse irradiance.

Geometry

The initial mirror shape was a parabola of equation $y = 0.5x^2$. Parabola was created by determining nine points of which the top and both ends were fixed. The other three pairs of points were symmetrical to each other. So the curvature of mirror can be changed by changing position of actually only three point. All points were connected with 2nd order spline. The model geometry is shown in fig. 2. Dimensions are expressed in meters.

Mathematical focus of basic parabola limited the size of mirror. The co-ordinates system is defined classically, positive X direction is directed to the right, positive Y direction is directed up. Origin of the system is the top of parabola. The X co-ordinate of all points were fixed. Co-ordinate in Y direction of three movable points, named $h1$, $h2$, $h3$ were being changed by moving the spline nodes by specified distance in the downward or upward Y direction. The size of the spatial step was assumed equal to 1 cm. This methodology allowed us

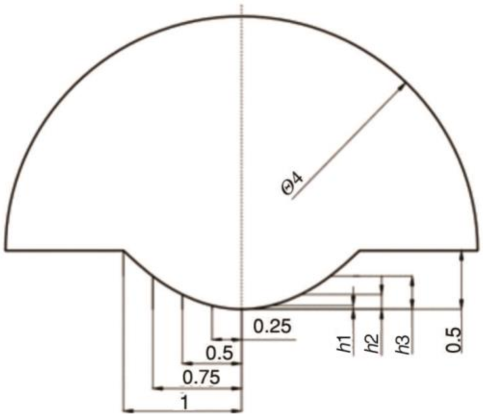

Figure 2. Basic geometry

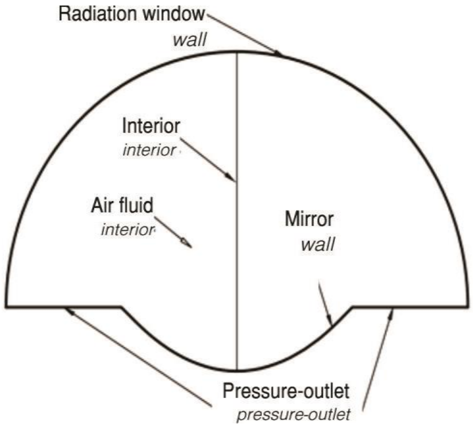

Figure 3. Geometry elements with assigned boundary conditions

to parametrize the mirror shape in the discreet way, namely, to three parameters (Y position of the spline nodes) three different values could be prescribed, this resulted in 3^3 = 27 different mirror shape configurations.

In fig. 2 the receiver that was added in the second part of calculations is not marked due to its small diameter, adopted equal to 1.5 cm. Position of the opening corresponded with the region of the highest values of incident radiation distribution specific for each case separately.

Boundary conditions

In the analysis perfect conditions were assumed: it has been adopted that the mirror is a perfect mirror with a reflectivity equal to 1, the air absorption and scattering coefficient equal to 0 and that Sun's beams fall perfectly parallel to mirror axis of symmetry. Geometry elements with assigned boundary conditions are presented in fig. 3.

Sun's rays entre the domain through a semicircular wall *radiation window* defined as semitransparent (which in fact is defined to be completely transparent). In the first and second series of calculations intensity of radiation was adopted accordingly: A) direct irradiance: 1000 W/m^2, B) direct irradiance: 500 W/m^2 and diffuse irradiance: 500 W/m^2.

To simplify calculations of energy balance and thus to simplify assessing the accuracy of calculations, it was assumed that the only source of energy in the model would be solar radiation, which is why the surroundings temperature was defined as 0 K. Thus, the radiation enters the domain through the semi-transparent wall, then partly falls on the openings named *pressure outlet* where it leaves the domain irretrievably, and partly reflects from the mirror and leaves the domain also through the semi-transparent wall.

In the second part of the calculation, in which a receiver in a form of pipe was added to the geometry, pipe walls were defined as perfectly absorbing. The heat receiving conditions inside the pipe were assumed: heat transfer coefficient equal to 1000 W/m^{2}K and bulk fluid temperature cooling the pipe inside was assumed equal to 300 K.

Calculation assumptions and adopted models

Pressure based solver was enabled for calculations. All cases were calculated in a steady-state. To simulate radiation the discrete ordinates model was chosen for the calculation. To find appropriate values of the DO model parameters, which would provide reasonably accurate results in reasonable computational time. The conducted sensitivity analysis comprised influence of the angular discretization of the radiative transport equation on the computational results. Especially, influence of these model parameters on the maximum value of the incident radiation in the domain, was verified. Obtained results are collected in figs. 4(a) and 4(b).

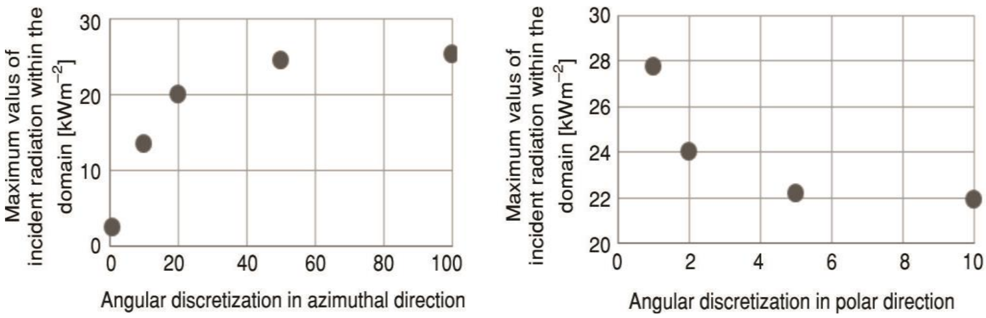

Figure 4. Influence on calculation accuracy of angular discretization in (a) azimuthal and (b) polar direction

It can be seen that the influence of the azimuthal angle (the angle on the computational plane for the 2-D model) discretization is definitely more significant than the discretization of the polar angle (the angle measured in the plane perpendicular to the computational plane in 2-D model). In order to obtain discretization independent solution at least 50 angular discretization steps in the azimuthal direction needed to be generated while in case of the polar direction around 5 discretization steps was enough.

The discretization in the polar direction is actually out of the computational plane in the 2-D models, so it is less important for us since it does not bring any new information into the solution. It only influence the absolute value of incident radiation but once the integration of the incident radiation over whole sphere to obtain value of the transferred radiative heat is carried out its influence disappears completely. Therefore, based on analysis results, angular discretization in azimuthal direction was set to 100 to achieve high accuracy of the radiation field in the computational plane and angular discretization in polar direction was set to 1 as it is out of plane direction and practically does not influence radiative heat transfer at all.

Computational mesh

To identify appropriate density of numerical mesh, the sensitivity analysis was performed. For different maximum element size, results of energy balance calculations were observed. Due to adopted values of radiative power entering the doman (as the only source of energy) and geometrical dimensions, calculation should give following results:

– Through the *radiation window* 4000 W of power enters the domain (4 m^2 ·1000 W/m^2 = 4000 W) but also 2000 W reflected from the mirror leave the domain (2 m^2 of the mirror projection · 1000 W/m^2 = 2000 W). So the balance should give +2000 W on the *radiation window* surface (4000 W –2000 W = 2000 W).
– Through *pressure outlet* 2000 W leave the domain (2 m · 1000 W/m^2 = 2000 W) so –2000 W should be calculated on *pressure outlet* surface.

Results collected in tab. 2 show that even for mesh with relatively big element, the energy balance calculation are correct. Therefore, for simulations was chosen element size equal to 0.5 cm.

Table 2. Energy balance results for different mesh element size

Maximum element size [cm]	5	2	1	0.4	0.3
Number of mesh elements [–]	3466	21119	83200	511040	948499
Radiative heat flux [W]					
Pressure outlet	–2000.6	–2000.7	–2001.1	–2001.5	–2001.6
Radiation window	2000.6	2000.7	2001.1	2001.5	2001.6
Net	5.0E-12	3.0E-12	3.0E-12	5.0E-12	5.0E-12

Results

All 27 cases with different mirror shapes were calculated for two assumed conditions of irradiance: pure direct solar irradiance and half diffuse solar irradiance. The most important results were the distributions of radiation intensity in the domain and the position of the highest intensity value.

The radiation intensity distributions were investigated in terms of the values but also in termsof the location of the maximum value intensity and shapes of the intensity fields. In fig. 5 chosen distributions are presented. For easier evaluation of the distributions shapes, the results are given at various, automatically colour scales, because when adopting one common scale some distributions would become almost monochromatic.

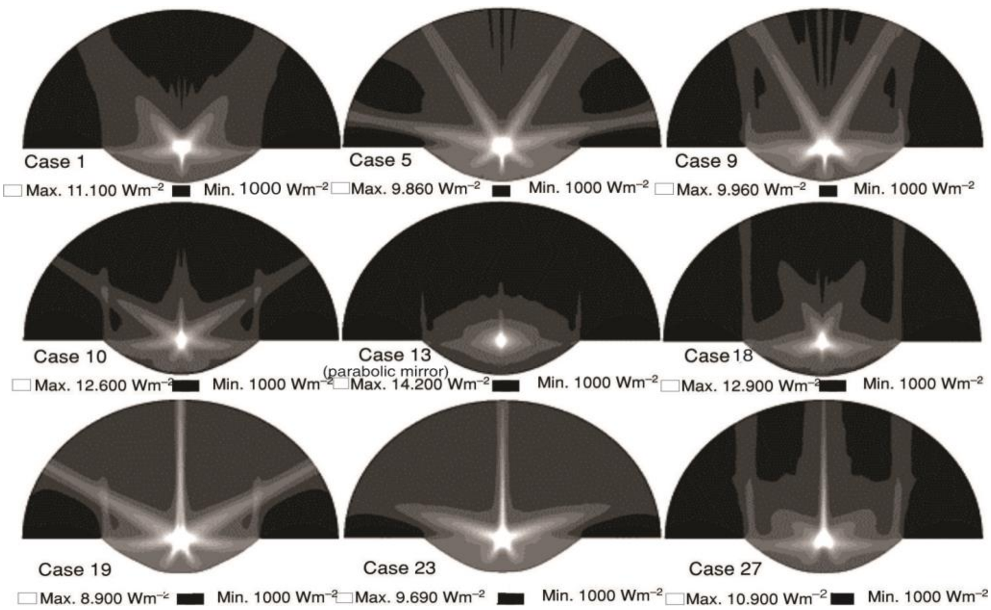

Figure 5. Distribution of incident radiation for irradiance; direct 500 W/m^2, diffuse 500 W/m^2 for selected cases

Maximum values obtained in the distributions of radiation intensity are presented in the diagrams in fig. 6. Case number 13 is considered as a basic mirror shape – the parabolic one.

In the next step, the mentioned receiver was added to the geometry of 10 chosen cases to verify the real capability of absorbing solar energy. Cases were selected based on the highest values in incident radiation distributions. In some of them two spots of maximum values were observed. For such a cases two receiver pipes were applied. Results of heat-flow rates at the pipes walls for chosen cases are shown in fig. 7.

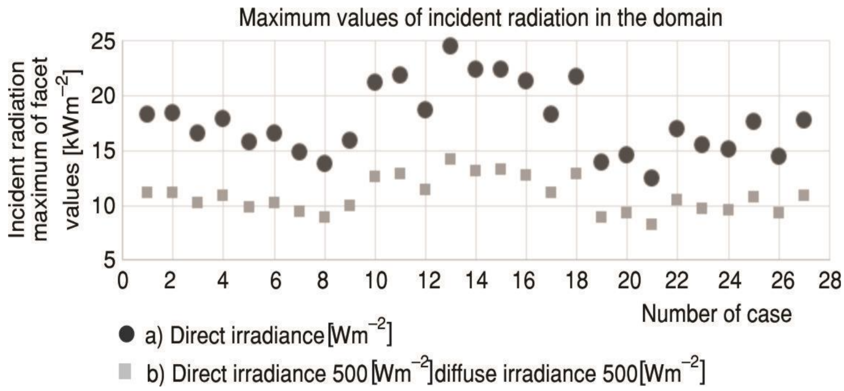

Figure 6. Maximum values of incident radiation

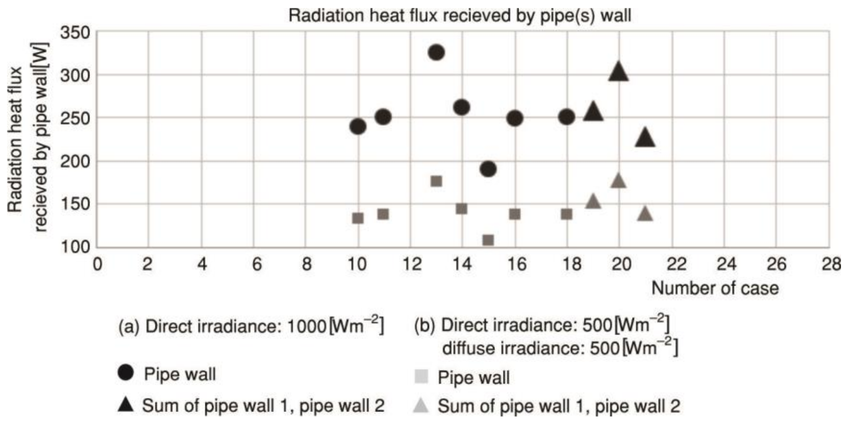

Figure 7. Heat flux received by pipe(s) wall

Moreover, to assess potential to make use of the diffuse irradiance, the ratio of maximum incident radiation values obtained for fully direct irradiance to the maximum incident radiation obtained for half diffuse irradiance were calculated. Table 3 summarizes these calculations and presents the assumptions adopted in geometry and the results of maximum values of radiation intensity.

Based on the carried out computations following issues can be noticed:

– parabolic shape gives the best focus, however, after changing a bit the curvature, results are very similar to those provided by the parabolic mirror,
– mirror shapes obtained in the same series of changes revealed some similarities in the distribution and levels of maximum values,
– for cases revealing two spots of maximum incident radiation values, the results were calculated as a sum of them, this gives values almost equal to result for the parabola, and
– for case in which half diffuse irradiance is considered, mirrors were focusing on average around 60 % of the energy focused in case of pure direct irradiance, for the parabolic mirror shape this factor was the lowest among all analysed cases, while for cases 19-21 the factor was the highest.

Table 3. Calculation results and geometry settings for cases without radiation receiver

No. of case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Geometry	$h1$	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125
	$h2$	0.135	0.135	0.135	0.125	0.125	0.125	0.115	0.115	0.115	0.135	0.135	0.135	0.125	0.125
	$h3$	0.04125	0.04125	0.04125	0.04125	0.04125	0.04125	0.04125	0.04125	0.04125	0.03125	0.03125	0.03125	0.03125	0.03125
Maximum values of incident radiation [Wm^{-2}]	A) Direct irradiance 1000 [Wm^{-2}]														
	AF	18243	18415	16526	17867	15731	16524	14802	13829	15934	21211	21881	18737	24513	22363
	B) Direct irradiance 500 [Wm^{-2}] diffuse irradiance 500 [Wm^{-2}]														
	AF	11114	11199	10261	10926	9860	10258	9399	8914	9964	12598	12931	11363	14249	13173
	Calculations														
	Ratio (B/A) × 100%														
		60.9	60.8	62.1	61.2	62.7	62.1	63.5	64.5	62.5	59.4	59.1	60.6	58.1	58.9

No. of case		15	16	17	18	19	20	21	22	23	24	25	26	27
Geometry	$h1$	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125	0.28125	0.29125	0.27125
	$h2$	0.125	0.115	0.115	0.115	0.115	0.115	0.115	0.125	0.125	0.125	0.115	0.115	0.115
	$h3$	0.03125	0.03125	0.03125	0.03125	0.03125	0.03125	0.03125	0.02125	0.02125	0.02125	0.02125	0.02125	0.02125
Maximum values of incident radiation [Wm^{-2}]	A) Direct irradiance 1000 [Wm^{-2}]													
	AF	22435	21366	18329	21774	13875	14587	12531	16917	15452	15123	17590	14492	17798
	B) Direct irradiance 500 [Wm^{-2}] diffuse irradiance 500 [Wm^{-2}]													
	AF	13210	12675	11156	12881	8930	9280	8263	10452	9719	9555	10788	9239	10894
	Calculations													
	Ratio (B/A) × 100%													
		58.9	59.3	60.9	59.2	64.4	63.6	65.9	61.8	62.9	63.2	61.3	63.8	61.2

AF – Air fluid

Conclusions

The paper presents numerical investigations on the effects of changes in the shape of the mirror on their focusing abilities. Based on the results, the following conclusions can be made:

- Since similar changes in geometry give similar distributions of radiation intensity as result, it is possible to predict the effects of certain changes, and significantly narrow the field of searching for the best mirror curvature.
- Proposed factor defined as a ration of maximum incident radiation in mixed case (half diffuse and half direct irradiance) to the maximum incident radiation in case of pure direct irradiance is simple and effective quantity to measure mirrors ability to concentrate diffuse

radiation. As it turns out new shapes showed greater ability to focus scattered radiation and thus less sensitivity to variation in diffusivity of solar irradiance.

- Mirrors providing two spots of focus can find applications in projects of new, more compact and cheaper installations.
- Presented methodology is a proven and quick tool for multiparameter studies of the curvature of mirrors.

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