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Research Article

Study on Concentrating Characteristics of a Solar Parabolic Dish Concentrator within High Radiation Flux

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Concentrating characteristics of the sunlight have an important effect on the optical-thermal conversion efficiency of solar concentrator and the application of the receiver. In this paper, radiation flux in the focal plane and the receiver with three focal lengths has been investigated based on Monte Carlo ray-tracing method. At the same time, based on the equal area-height and equal area-diameter methods to design four different shape receivers and numerical simulation of radiation flux distribution characteristics have also been investigated. The results show that the radiation flux in the focal plane increases with decreasing of the focal length and the diameter of the light spot increases with increasing of the focal length. The function of the position with a maximum of radiation flux has been obtained according to the numerical results. The results also show that the radiation flux distribution of cylindrical receiver has the best performance in all four receivers. The results can provide a reference for future design and application of concentrating solar power.

1. Introduction

With the rapid development of global economy, the challenges for environment and energy are more and more important to the human. Concentrating solar power (CSP) is regarded as an effective way to solve energy problem [1, 2]. The main idea of CSP is that the sunlight hits the surface of the earth and concentrates on the receiver, where the fluid is heated from the energy [3–6]. A large number of CSP projects have currently been developed or proposed in many countries, particularly in China, Spain, and USA. As we know, the concentrating characteristics of the sunlight in CSP plant have very huge effect on the efficiency and cost of the power. The concentrating types of CSP plant often have four contributions: solar power tower, solar parabolic dish, parabolic tough collector, and linear Fresnel reflector. Solar parabolic dish system has the best concentration ratio in all four types and the radiation flux has maximum. Therefore, the investigation of concentrating characteristics of a solar parabolic concentrator with a high radiation flux is very necessary and can provide a reference to the state-of-the-art design of CSP plant.

A large number of advancements have taken place in recent years in an effort to make radiation flux of the receiver more uniformly and effectively. As for the CSP system, there are some researches that focus on the solar radiation, conversion efficiency, and storage tank [7–9]. Ji et al. have experimentally investigated the application and the efficiency in solar optical-thermal and PV fields, that is, solar heating water and heat pump, and have obtained some important results [10–14]. Shuai et al. have applied the Monte Carlo ray-tracing method and coupled with optical property to simulate the performance of a solar parabolic dish system. They have proposed an upside-down pear cavity receiver based on the concept of equivalent radiation flux. The results show that uniformity performance of the wall flux is compared with five traditional geometries [15]. Clausing has presented an analytical model to calculate convective loss for a receiver. The analytical results and experimental evidence in the research have indicated that the convective

loss for the receiver is appreciable [16, 17]. Nithyanandam and Pitchumani have integrated the cost and performance model of an encapsulated phase change materials thermal energy storage and latent heat to study the dynamic thermal energy system performance [18]. Emes et al. have assessed the influence on the levelized cost of electricity of the design wind speed [19]. Desai and Bandyopadhyay have reported extensive energy and economic analysis of CSP plant [20].

In the above literatures, these researches focus on the energy conversion efficiency and the concentrating types, but the effect of the local length of parabolic dish and geometrical configuration of the receiver on the radiation flux and the system's efficiency is limited. In this paper, the concentrating ways of sunlight firstly have been established based on Monte Carlo ray-tracing method. After that, the effect of the local length on the radiation flux in the local plane and the receiver has been investigated. Finally, the effect of the geometrical configuration of the receiver on the radiation flux distribution has been simulated. The present study can provide a reference for the future design and application of CSP plant.

2. Monte Carlo Ray-Tracing Method

The Monte Carlo ray-tracing method, referred to as MCRT, is a popular tool with high accuracy in this field [21, 22]. Therefore, MCRT method has been employed for calculating radiation performance for all cases in present study. As we have known, the idea of this method is that the transfer process of the solar radiation is divided into four subprocesses, that is, emission, reflection, absorption, and scattering, and every subprocess has an occurrence probability [23–27]. The object of the study is divided into many surface units and mathematical functions can stand for them. The MCRT method used in this paper is to assume every surface emits a certain quantity of light rays, after which each ray is tracked and judged based on whether it is absorbed by the material, interface, or escapes from the system. In the numerical simulation, each sunlight ray carries the same amount of energy and has a specific direction determined from the appropriate probability function. What happens to each of these sunlight rays depends on the physical parameters of the materials of the system, which is described by a set of statistical relationships. The computer code for MCRT method has been written in FORTRAN language in-house. The detailed description of this model can be inferred from the literature [3]. The outer surface of the receiver is considered to be adiabatic. The receiver is located at the focal plane of the parabolic dish system.

3. Results and Discussions

3.1. Effect of the Local Length on the Radiation Flux Distribution. In this study, the radiation flux distributions of the local plane and receiver within three local lengths, that is, 2500 mm, 3250 mm, and 4000 mm, have been obtained. In simulation process, the basic parameters are as follows: incident solar irradiation in the air is 1100 W/m^2, system error is 0 mrad, radius of the parabolic dish concentrator is 2600 mm, height of the parabolic dish concentrator is 520 mm, reflectivity of the parabolic dish concentrator is 0.9, radius of the cylindrical receiver is 100 mm, and height of the cylindrical receiver is 260 mm.

Light spot performance of the local plane in different local lengths has been simulated and shown in Figure 1. It can be seen from the figure that the light spot is circle and radius of light spot increases with increasing of local length. The results show that the diameter of light spot is about 22.4 mm and radiation flux of light spot is about 30.46 MW/m^2 when the local length is 2500 mm. Meanwhile, the results show that the diameter of light spot is about 30.0 mm and radiation flux of light spot is about 21.80 MW/m^2 when the local length is 3250 mm. The results also show that the diameter of light spot is about 37.0 mm and radiation flux of light spot is about 18.58 MW/m^2 when the local length is 4000 mm.

3D radiation flux distribution of the receiver in different local lengths has been simulated and shown in Figure 2. It is very obvious that the positions with the maximum flux are about 60 mm, 127 mm, and 160 mm when the local lengths are 2500 mm, 3250 mm, and 4000 mm, respectively. It also can be found that the position with the maximum flux increases with increasing of local length. This distribution has indicated that local length has important effect on the concentrating characteristic of sunlight. When sunlight hits the wall of the receiver, almost all sunlight rays can be absorbed by the receiver.

Figure 3 shows the curve of the position along the wall, the diameter of light spot, and the radiation flux of light spot in different local lengths. It can be obtained from the figure that the optimal design is essential for the system. When the radius of the receiver is more than the radius of light spot, the sunlight can enter into the receiver. However, when the radius of the receiver is less than the radius of light spot, part of sunlight rays cannot enter into the receiver, which produces optical heat loss. According to the above results, the function of the position along the wall and the local length with an error of 5% can be proposed and given as follows:

$$\tan\theta = 10.10 - 5.05 \times 10^{-3} \times p + 0.67022 \times 10^{-6} \times p^2, \quad (1)$$

where θ is an angle of the axis direction of the receiver and inlet direction of the sunlight and p is local length with unit of mm. For this equation, it can only be used for the same concentrating system and the cylindrical receiver. Also, when the parameters of the concentrating system change, the results can accordingly be obtained from the computer code for MCRT method.

3.2. Effect of Geometrical Configuration on the Radiation Flux Distribution. To investigate the effects of the geometrical configurations on the radiation flux distribution, four receivers (i.e., frustum, inverted frustum, cylindrical, and conical receivers) shown in Figure 4 have been designed and simulated. The parameters of the receiver are given based on the equal area-height and area-radius method and shown in Tables 1 and 2, respectively.

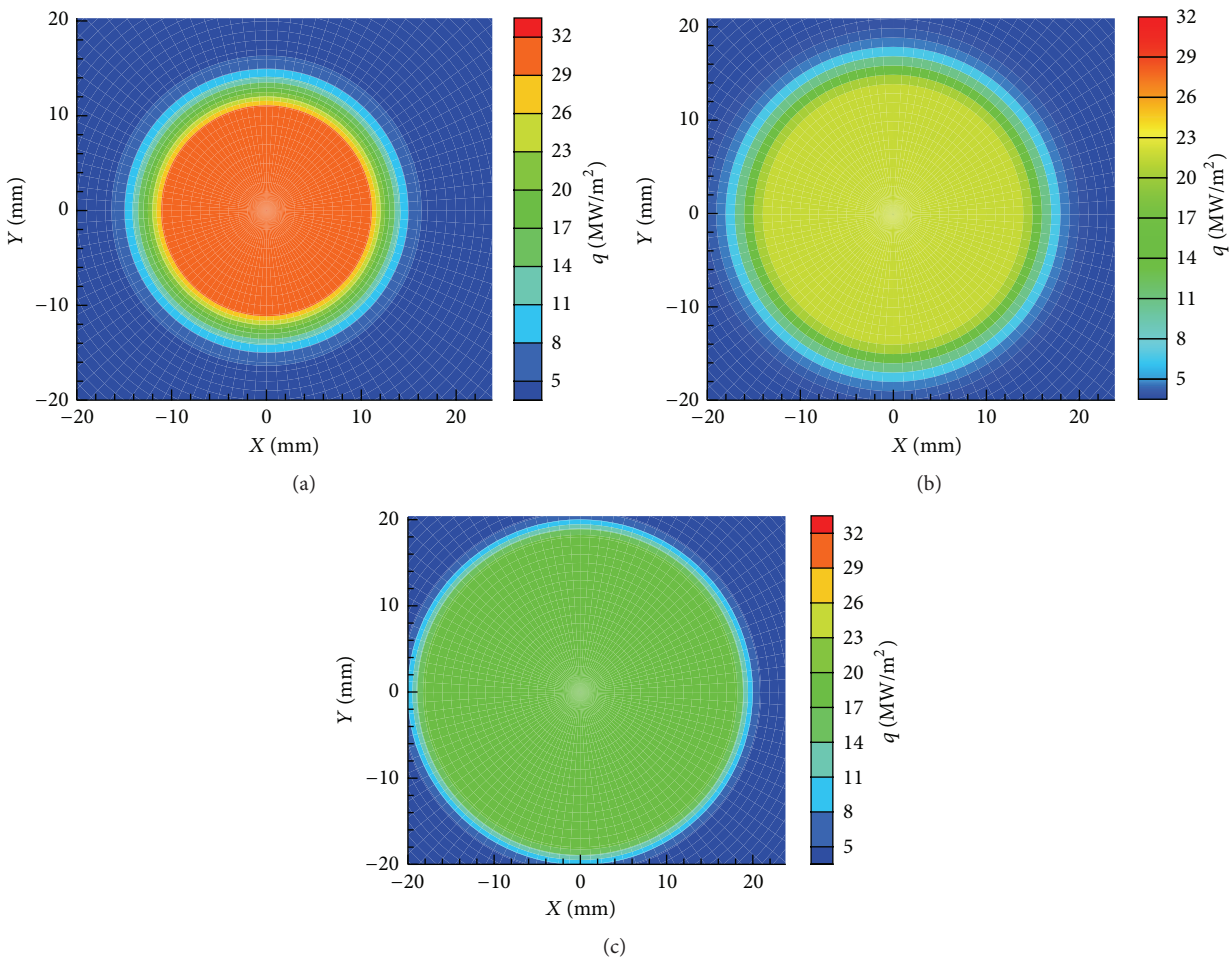


Figure 1: Radiation flux distribution in focal plane with different focal lengths: (a) 2500 mm; (b) 3250 mm; (c) 4000 mm.

Table 1: Design parameters of the receiver based on equal area-height method.

Shapes	Height (mm)	Radius in the bottom (mm)	Radius in the top (mm)
Frustum	260	120	78
Inverted frustum	260	78	120
Cylindrical	260	100	100
Conical	260	168	0

Table 2: Design parameters of the receiver based on equal area-radius method.

Shapes	Height (mm)	Radius in the bottom (mm)	Radius in the top (mm)
Frustum	235	100	120
Inverted frustum	285	100	80
Cylindrical	260	100	100
Conical	510	100	0

Figure 5 shows the radiation flux distribution of the receiver based on equal area-height method. It can be seen from the figure that (1) the radiation flux is symmetrical along the circumferential direction; (2) the performance for the radiation flux distribution in the conical receiver is the worst; (3) the characteristics of the radiation flux distribution in the cylindrical receiver are similar to frustum and inverted frustum receiver.

Figure 6 shows the radiation flux distribution of the receiver based on equal area-radius method. It also can be seen from the figure that (1) the radiation flux is also symmetrical along the circumferential direction; (2) the performance for the radiation flux distribution in the conical receiver is the worst. All radiation flux almost focuses on the middle of the receiver and a little radiation flux in the top and bottom of the receiver; (3) the radiation flux distribution in the cylindrical receiver obviously priors to other receivers. For getting the higher efficiency of the system, the higher radiation flux is necessary for the receiver.

4. Conclusions

In this paper, radiation flux in the focal plane and the receiver with three focal lengths has been investigated based on

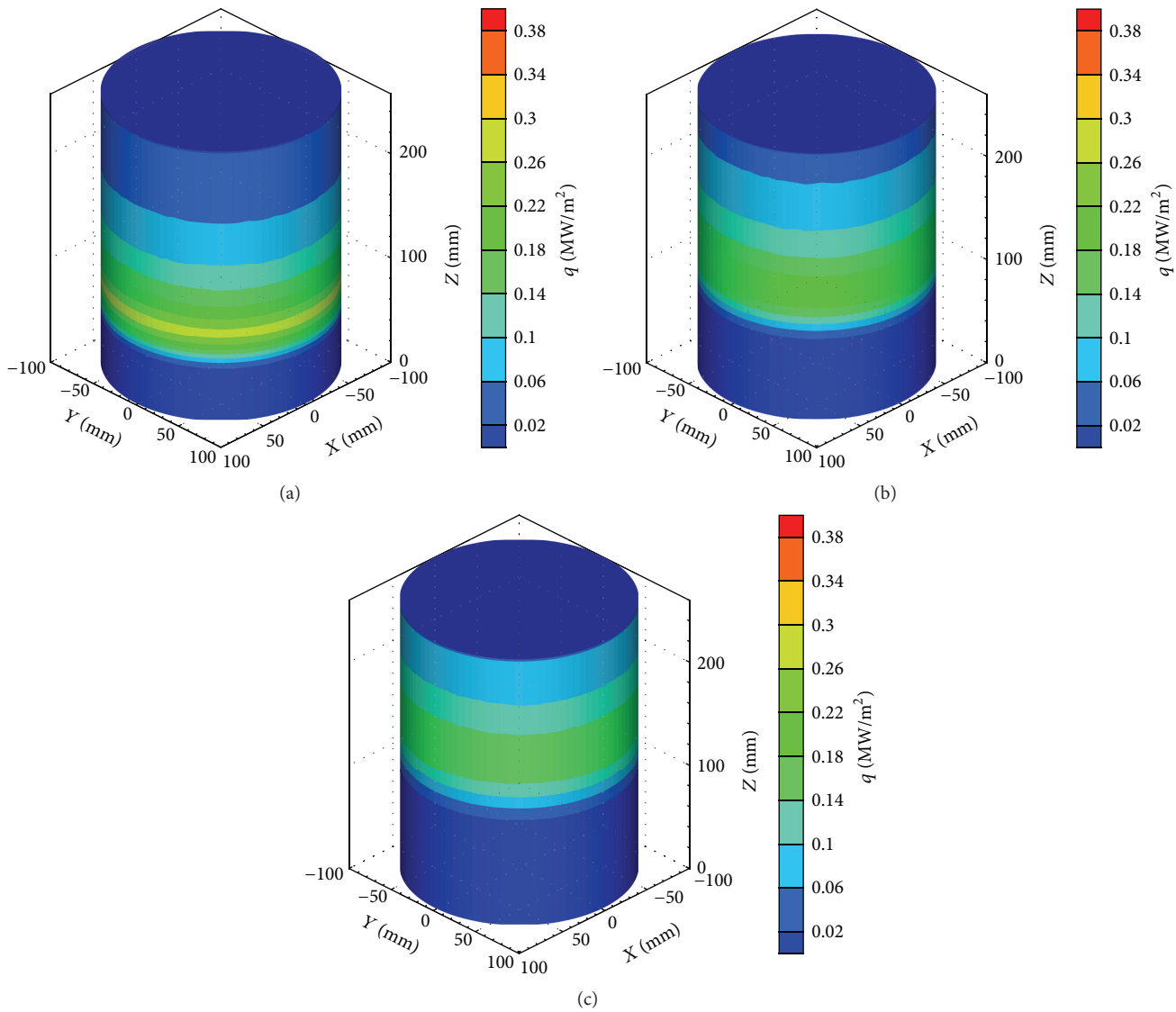


Figure 2: Radiation flux distribution in the receiver with different focal lengths: (a) 2500 mm; (b) 3250 mm; (c) 4000 mm.

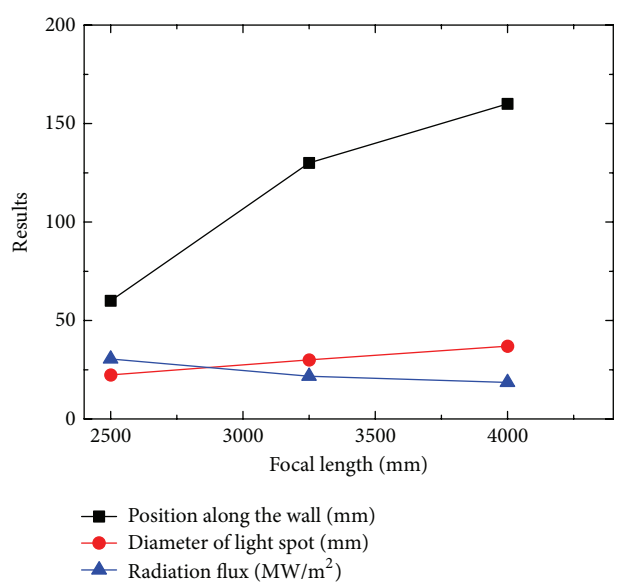


Figure 3: Effect of the focal length on the performance of concentrating characteristics.

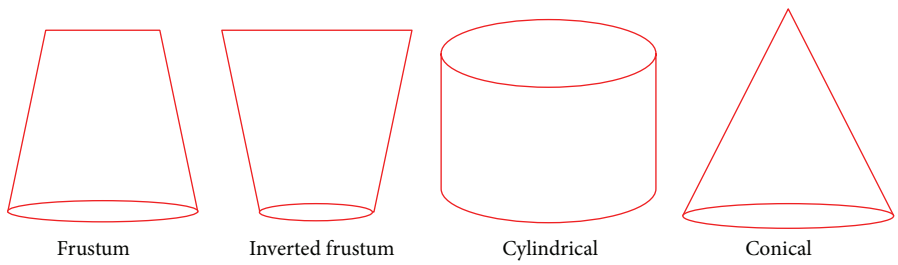
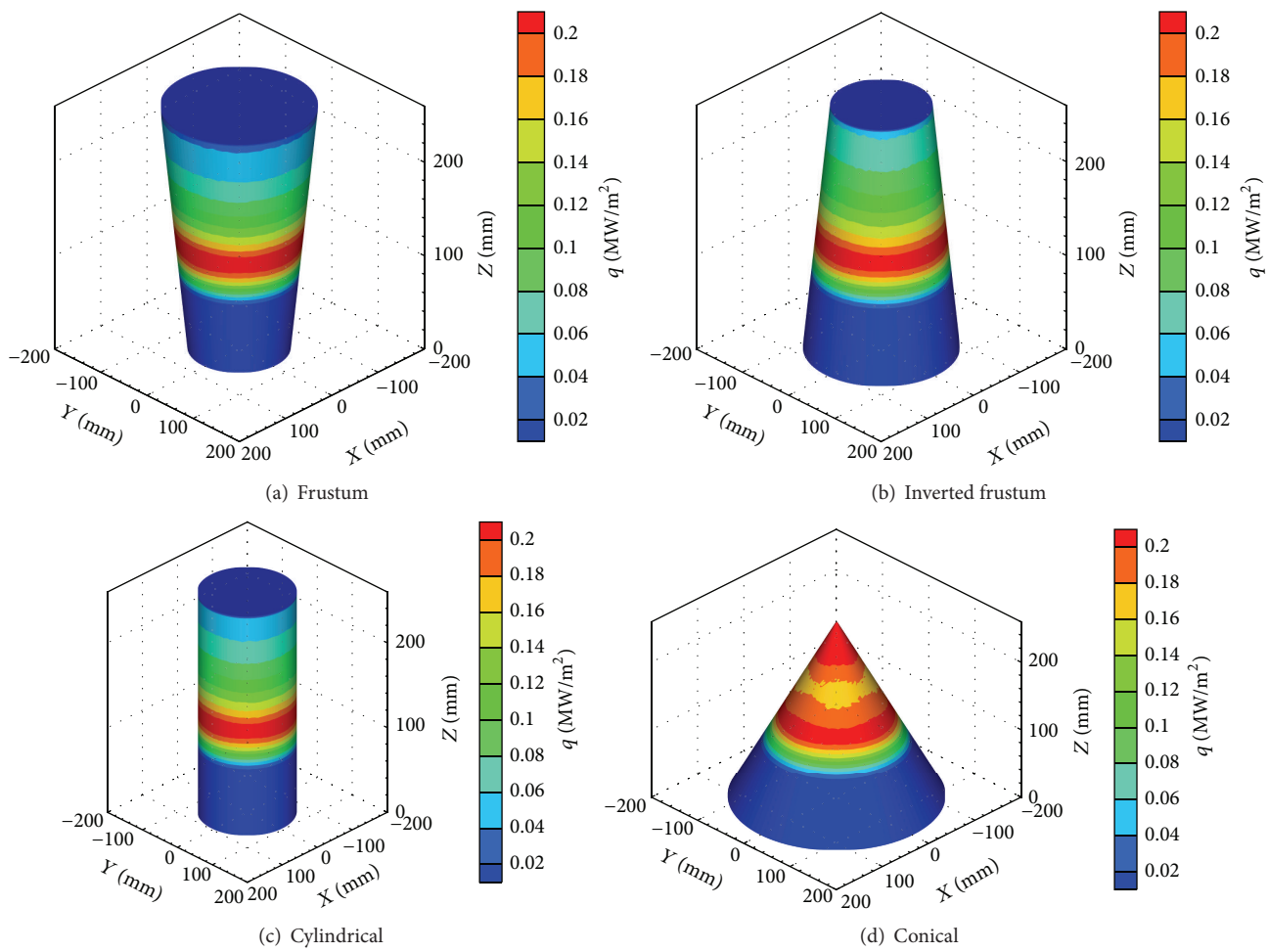


Figure 4: Four types of the receiver.



(a) Frustum (b) Inverted frustum

(c) Cylindrical (d) Conical

Figure 5: Radiation flux distribution based on equal area-height method.

MCRT method. Also, four different shape receivers have been designed and simulated based on the equal area-height and equal area-diameter methods. The main conclusions can be given as follows:

(1) The radiation flux in the focal plane increases with decreasing of the focal length and the diameter of the light spot increases with increasing of the focal length.

(2) The positions with the maximum flux are about 60 mm, 127 mm, and 160 mm when the local lengths are 2500 mm, 3250 mm, and 4000 mm, respectively. The function of the position with a maximum of radiation flux has been obtained according to the simulation results in this paper.

(3) The results show that the radiation flux distribution of cylindrical receiver has the best performance in all four receivers, which will result in a higher efficiency of the system.

This paper aims to know the characteristic of radiation flux distribution for the receiver in different focal lengths

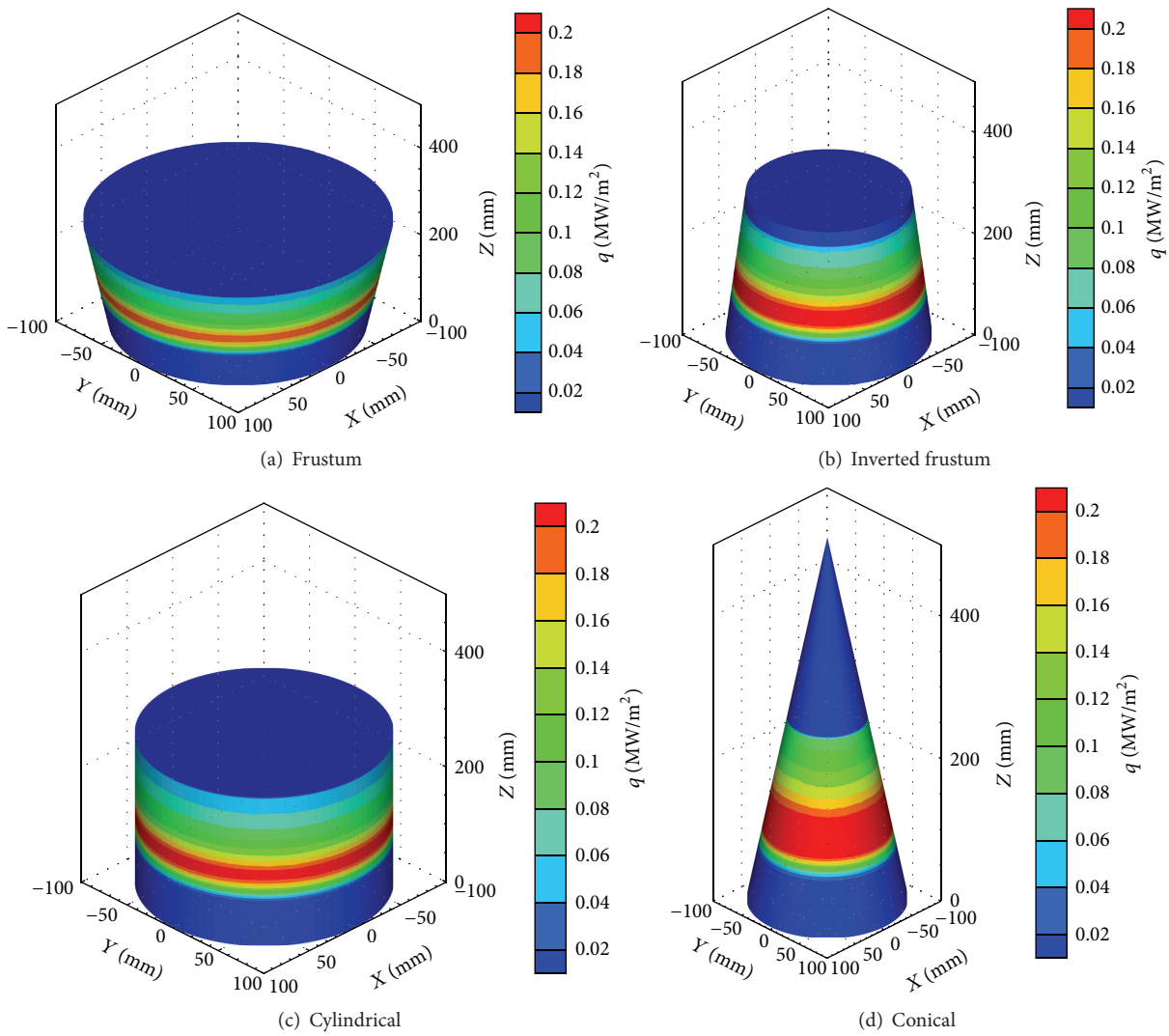


Figure 6: Radiation flux distribution based on equal area-radius method.

and geometrical configurations and make a starting point to motivate future investigation in this field.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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