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View Factor of Solar Chimneys by Monte Carlo Method

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Abstract

A typical solar chimney power plant (SCPP) system mainly contains three components, namely, solar collector, tower and turbine. The collector heats up ambient air entering to the system by buoyancy force. Updraft airflow is then generated in the chimney and drives the pressure-staged turbine in the chimney base to generate electricity or ventilation of buildings. A part of the solar radiation is absorbed by solar collector directly, which is greater than which reflected by collector to the tower. But this amount of reflection can enhance the efficiency of the system. Determining more precise view factor between collector and the tower is essential for solving heat transfer equation. In this study, results obtained by Monte Carlo method are compared with analytical method which is available in literature for calculating the view factor. With increasing the ratio of the length to the radius of the tower, configuration factor increases slightly. Also, at higher radius of the collector, supposing length and outer radius of the chimney are unchanged, the view factor decreases. This behaviour can also be seen by analytical solution, but the result of analytical solution is much lower than that one obtained by Monte Carlo solution. It is suggested to designers and researchers to use the results obtained by Monte Carlo method, which seems to be more accurate.

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Keywords: Radiation; View factor; Monte Carlo method; Analytical solution; Solar chimney, Heat transfer.

1. Introduction

One of the important ways to energy transfers at high temperatures is heat radiation. Radiation heat transfer depends on the orientation of the surface relative to each other. To account the effects of orientation on radiation heat transfer between two surfaces, one parameter is defined that called view factor, which is a purely geometric quantity and is independent of surface properties and temperature.

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For complex geometries and when the arrangement of surfaces and shapes is arbitrary, it is unavoidable to compute the configuration factors for the particular geometry and arrangement of surfaces at hand. For such cases, approximate techniques using numerical algorithms and computers must be used [1]. One of the most efficient commonly used numerical solutions is Monte Carlo method. The use of Monte Carlo method in radiation heat transfer goes back as far as the paper by Howell and Perlmutter [2]. Monte Carlo method is a class of numerical techniques based on the statistical characteristics of physical processes, or analogous models that imitate physical processes. The analysis of previous works shows that Monte Carlo offers a beneficial method for finding the values of configuration factors as it is able to incorporate all important effects in a radiative heat transfer simulation without approximation [3]. Monte Carlo method has some drawbacks, such as the immense requirement for computer time and the statistical fluctuation of the results [4]. Maltby and Burns [5] investigated performance, accuracy and convergence in a three-dimensional Monte Carlo radiative heat transfer simulation with a code including capabilities mixing specular and diffuse reflection models, banded spectral material properties, transmission through external surfaces, and simulation of beam radiation. Also, Miyahara and Kobayashi have developed new numerical method for calculating the configuration factors for an axially symmetrical geometry [6]. It was compared with the area integration and Monte Carlo methods for concentric coaxial cylinders, and was seen to be 19 times and 3 times faster than them, respectively. A two dimensional Monte Carlo method by Qualey et al. [7] was applied to a classic radiant energy exchange problem that models the interior of an industrial furnace. The configuration involved a source as an infinite radiating plane and the heat sink as parallel rows of infinitely long tubes. With developing this method and after two years, Hong and Welty used Monte Carlo simulation of radiation heat transfer in a three dimensional enclosure containing a horizontal circular cylinder [8]. A fast Monte Carlo scheme was presented in the research by Mazumder and Kresch [9]. The basic algorithm was the classical surface to surface ray-tracing algorithm. In addition, a modified form of the binary spatial partitioning (BSP) algorithm was implemented to speed up ray tracing by at least a factor of 3. The results demonstrated a high level of accuracy with fairly low computational cost. Chai et al. [10] applied finite volume method to calculate configuration factors between surfaces of control volumes. In a study by Xia et al. [11] through discretizing the medium into many sub layers and employing a linear refractive index approximation for each sub layer, a curve Monte Carlo method was developed to solve the radiative heat transfer in an absorbing and scattering gradient-index medium. In some researches, Monte Carlo was implemented for combined radiative and conductive heat transfer. For instance, Schweiger et al. [12] applied this method for combined conduction and radiation heat transfer in honeycomb type transparent insulation materials. In their work a good agreement between numerical and experimental results was shown. Mirhosseini and Saboonchi [13] applied Monte Carlo method to determine configuration factor for the plate including strip elements to circular cylinder. The analysis displayed the differences between the numerical results obtained and analytical solutions for the 20, 30, and 45 element discretized figures and for (30^4) , (50^4) and (70^4) rays per element. Also, Mirhosseini and Saboonchi [14] determined configuration factor for the plate including strip elements to two parallel circular cylinders as a case in industrial heating and cooling processes. Details can be observed in these two researches completely. Hajji et al. [15] used three methods for calculating view factor of a strip to in-plane parallel semi-cylinder. They reported high difference between results obtained by Monte Carlo method and the analytical solution.

In our investigation, determining more precise view factor between collector (base plate) and the tower of solar chimney is considered because of its importance for solving heat transfer equation. In this study, Monte Carlo method is implemented by a code plus analytical method which is available in the literature.

2. Solution methods

In fact, view factors represent the fraction of radiant energy leaving any given surface that is incident upon a reference surface and dependent upon problem geometry via the solid angle subtended by one surface upon the

other. For calculation of shape factor, several methods exist that are introduced in brief. Some methods that called “special methods” compute view factor indirectly. Actually these methods calculate shape factor with geometrical restrictions and just implemented for special geometries. “Crossed strings method”, “unit sphere method” and “inside sphere method” are some of them. Other methods that have no limitation for using are statistical methods like “Monte Carlo method”.

2.1. Analytical method

For determining view factor between collector (base plate) and the tower of solar chimney, an analytical solution has been offered by Naraghi and Chung available in [16]. It should be noted that in the reference, the relation for calculating the view factor of ring fin to the truncated cone has been reported. Therefore, the equation will be applicable for obtaining configuration factor of circular base plate to the circular cylinder (zero or \approx zero angle truncated cone) as shown in Fig. 1.

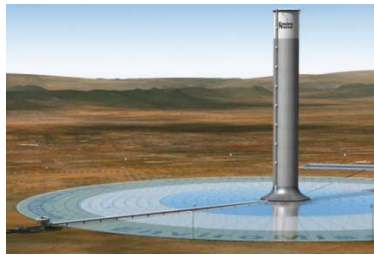


Fig.1. Photograph of a solar chimney power plant

2.2. Monte Carlo method

Monte Carlo method is based on statistical approach that can be implemented for shape factor calculation. Theory of this method is based on laws of probability (i.e. chance). The basic characteristic of Monte Carlo method is that energy emitted by a finite area is substituted with a total number of N rays, where each ray carries the same amount of energy. Different origins for the rays coming from an element surface can be used, e.g. random [17] or all rays emanating from the centre of the finite element face. Some of the rays will hit another surface while others will fail to do so. The view factor, which links finite elements i and j , can be simply represented by:

$$F_{i-j} = \frac{m}{N} \quad (1)$$

Where N is the total number of rays emitted from surface i and m the total number of rays hitting surface j . In Fig. 2, general scheme of a truncated cone object is observed with its geometric parameters, which used for calculating the view factor by this method in a special angle that is equal to zero. Primarily the program is written to calculate the view factor of tower to the ring plate, due to its easier procedure. Then for presenting the view factors of the ring plate (collector) to the solar chimney in order to compare with the analytical results, reciprocity relation is used.

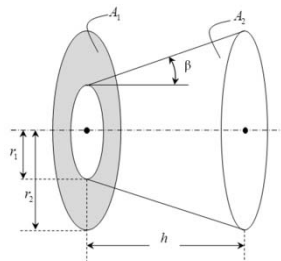


Fig.2. Scheme of the truncated cone and disk fin with their geometric parameters

For better understanding physics of the problem, a truncated cone with a ring disk fixed at the base of the cone is shown schematically in Fig. 3. According to that, any oblique line tangent to the cone can only views as maximum, portion of the ring fin area that is in its front, then it is not necessary that calculations are done for whole of lateral area of the cone. The assumption point (1), as shown in the figure, is on the oblique line tangent to the cone, and also only the front part of the ring area can be seen by each point on the oblique line. The points (2) and (3) are on the ring plate horizontally. The angle of θ can vary between 0 to 180 degrees.

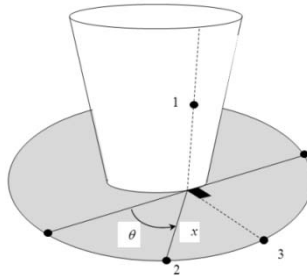


Fig.3. Situation of tangent oblique line on truncated cone, variation range of θ angle and 'x'

In Fig. 4, the oblique line in the vertical plane, and the angle of θ and the length of 'x' in the horizontal plane, can demonstrate the simple geometric parameters of the problem.

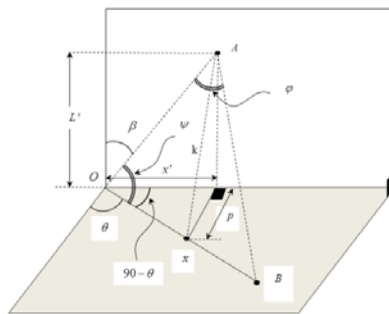


Fig.4. Defining required parameters for Monte Carlo method

By dividing the height of the truncated cone to some point elements, equations related to the limitation of striking to the disk fin are obtainable. As mentioned above, the point (1) is on the oblique line tangent to the truncated cone, and also it is on the vertical plane. Also, the point (2) and (3) are on the ring plate. Choosing different situations on the tangent oblique line on the truncated cone and different θ angles on the surface of ring plate, and portion of ring area which the energy emitted packs can strike it, help for simplifying to write mathematical relations. When $\theta=0$, the angle between the tangent oblique line on the truncated cone and the length of 'x' is equal to 90° . By increasing the angle of θ leading to 180° , the mentioned angle changes permanently. Therefore, the mathematical relations can be found for these behaviours. These relations will give the space angle between the oblique line and the line that creates the angle of θ .

3. Results and discussion

Parameters such as length and radius of the chimney and also radius of the circular planar collector are considered by defining dimensionless parameters to show generalized comparing between results obtained by two mentioned methods. As shown in Fig. 5, with increasing the ratio of the length to the radius of the tower, configuration factor increases slightly. This fact has physical vindication, when the height of the tower increases, collector can see bigger

area of the tower and thus the fraction of incident rays divided into total emitted rays will increase. Furthermore, at higher radius of the collector, supposing the length and the radius of the chimney remain unchanged, the view factor decreases. This behaviour can also be seen in analytical solution, but the results of analytical solution are much lower than those obtained by Monte Carlo method. It must be noted that in higher (L/r_1), just a small difference is observed between the results of each method, in spite of that the difference between the results of two methods is noticeable. According to the above discussion, the amount of radiation reflected from the collector to the chimney is estimated to be higher than the analytical results that have been used up to now in the related designs. It can have undeniable effects to improve solar chimneys design. In below figure for more obvious comparison, results have been shown in three domains of r_2/r_1 , separately.

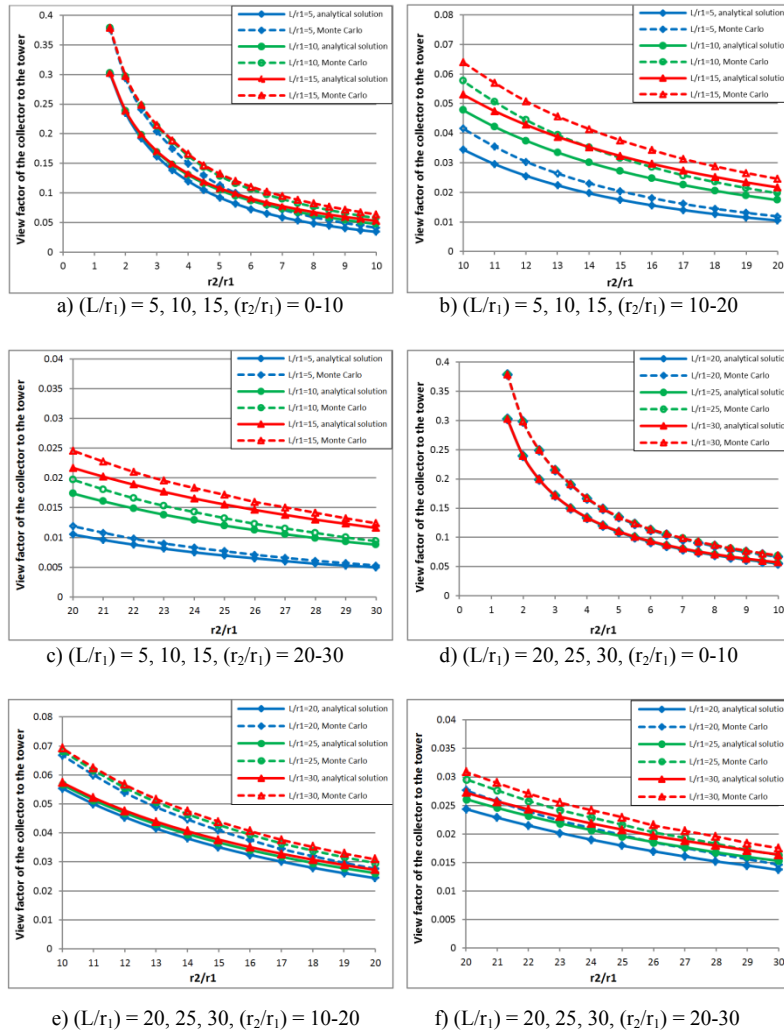


Fig.5. View factor versus (r_2/r_1) calculated by Monte Carlo and analytical method

For comparing the results presented in Fig. 5, percentage of difference as $[(F_{\text{Monte Carlo}} - F_{\text{Analytical}}) / F_{\text{Analytical}}] \times 100$ is used to show the difference between analytical view factor values and the values obtained by Monte Carlo method. The maximum and minimum difference percentage for $L/r_1=5$ is equal to 25.2% (in $r_2/r_1=1.5$) and 6.85% (in $r_2/r_1=30$), respectively. It means in lower r_2/r_1 , the analytical results have about 25% error.

4. Conclusions

In this study, the performance of Monte Carlo method for view factor calculation was investigated. This method is well known to produce accurate results if enough sample packets are used. Monte Carlo method is always used to validate the results of other methods. Presumably, the single most difficult problem in using this method is the inborn barter between statistical accuracy and computational volume. To calculate radiation view factor of solar chimney, geometric parameters such as length and outer radius of the chimney and also radius of the circular planar collector were considered by defining dimensionless parameters to compare results obtained by two mentioned methods. With increasing the ratio of the length to the radius of the tower, configuration factor increases slightly. Also at higher radius of the collector, supposing other parameters are unchanged, the view factor decreases. In all cases, the results of analytical solution are much lower than those obtained by Monte Carlo solution. The amount of radiation reflected from the collector to the chimney is estimated to be higher than the analytical results that have been used up to now in the related designs. Percentage of difference as $[(F_{\text{Monte Carlo}} - F_{\text{Analytical}}) / F_{\text{Analytical}}] \times 100$ was used to show the difference between analytical view factor values and the values obtained by Monte Carlo method. The difference percentages showed linear trends with negative slopes by increasing r_2/r_1 (from 1.5 to 30). Accurate calculation of the view factor can have important effects to improve solar chimneys design. The direct and probably most urgent advantage of optimum system design is in cost savings. A solar chimney that is well designed will not require oversized collector or tower, and would thus significantly reduce costs associated with system sizes.

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