Numerical study and optimization of mirror gap effect on wind load on parabolic trough solar collectors

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Abstract

Parabolic trough collector (PTC) technology is currently the most proven and widely used solar thermal electric technology. These systems are usually located in open terrain where strong winds may occur and affect their stability and optical performance. As tiny deformation of collectors under the action of strong wind will influence the focusing accuracy and increase the structure demands of the collectors, it leads to the increase of the cost of collectors. It is particularly important to study the effect of wind load on parabolic trough solar collectors. In this context, different axial and radial gap sizes (0-0.06m) between the mirrors of PTC on wind load were studied numerically based on computational fluid dynamics (CFD). Wind load on collectors is decreased by around 13% with the axial gap extending from 0 to 0.06m while the effect of radial gap on wind load is small. Furthermore, the optimization model between the wind load and mirror gap was obtained by response surface methodology (RSM). The optimal gap size within 0m to 0.06m for a parabolic trough solar collector was predicted by particle swarm optimization (PSO). The result shows the optimum axial gap is 0.06m and the optimum radial gap is 0.02m.

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1. Introduction

Parabolic trough solar collectors (PTC) are currently one of the most mature and prominent solar technology for the production of electricity. Compared with other forms of solar power generation, it has the advantages of low cost and large scale. Parabolic trough solar collector systems are usually located in open terrain and subjected to the strong wind [1]. Deformation under combined effect of wind load and self-weight of collectors has an great influence on the focusing accuracy. How to decrease the effect of wind load and improve the stiffness of support structure of collectors has become an important part of the study of collectors. Simulation and analysis is the first premise for wind load of PTC.

The thermal performance and heat transfer characteristics of PTC have been studied by Several numerical and experimental studies [2-6]. The structure characteristics of PTC also has been studied. Geyer et al developed the high-performance EuroTrough parabolic trough collector models ET100 and ET150 for the utility scale generation of solar steam for process heat applications and solar power generation [7]. However, only few studies of wind flow around the PTC have been published, especially in the gap effect on PTC. In the late of 1970s and early 1980s, Sandia National Laboratories sponsored some wind tunnel tests, which were published in different reports [8-11]. These reports provided mean wind loads coefficients for an isolated parabolic trough solar collector and for a collector within an array field. Schweitzer et al. [12] measured two trough collector models with conventional minimum gaps and with enlarged staggered mirror gaps in a wind tunnel in 2011. The results found that the enlarged staggered gaps have major effects on wind loads of trough collectors. Kotter et al. [13] studied the effects of staggered gaps on wind flow around a trough collector by means of Computational Fluid Dynamics simulations in 2012.

Because of the advances in fluid dynamics, numerical schemes, the rapid growth of computing power, and the urgently demand from aviation industry over the last 40 years, computational fluid dynamics (CFD) has achieved significant progress in both theory and numerical method and has boosted many industries [14-16]. Along with the wide spreading of commercial CFD software after the 1990s, numerical simulation was widely accepted and used in many industrial applications.

One prevalent idea of cutting the collector's cost was to construct it with a larger reflective surface [17]. But this design principle brought about the predicament of wind load. For better maintenance, performance and expectation of reducing the wind load acting on the collectors, the mirrors were designed with gap. But there is no definite value of gap size of the PTC. The objective of this paper was to know whether the gap size has an remarkable impact on PTC and obtain the optimum gap size for PTC. In this paper, both axial gap (0-0.06m) and radial gap (0-0.06m) between the facets of the collectors were studied numerically by CFD software FLUENT. The results showed that the wind load decreases with the increase of axial gap size (0-0.06m), but the effect of the radial gap size was very small compared with the radial gap on overall wind load. It is necessary to take into account the axial gap size effects on the wind load during the design process of PTC, while the effect of radial gap on wind load is negligible. The best gap sizes for a parabolic trough solar collector were predicted by response surface methodology (RSM) model where the axial gap is 0.06m and the radial gap is 0.02m.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>(\theta)</td>
<td>Pitch angle of collectors</td>
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<tr>
<td>(k)</td>
<td>Kinetic energy</td>
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<tr>
<td>(\varepsilon)</td>
<td>Viscous dissipation rate of turbulent kinetic energy</td>
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<tr>
<td>(D_1)</td>
<td>Axial gap size of collectors</td>
</tr>
<tr>
<td>(D_2)</td>
<td>Radial gap size of collectors</td>
</tr>
<tr>
<td>(PF)</td>
<td>Pressure force</td>
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<tr>
<td>(V)</td>
<td>Wind speed</td>
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</table>
2. Numerical study

2.1. Model, mesh and boundary conditions

In this research parabolic trough solar collectors with EuroTrough type geometry were studied. To simulate the actual wind field, the collectors were put in a virtual wind tunnel with CFD software. In order to reduce the amount of calculation, the model is simplified with only one axial gap and one radial gap. Collectors are composed of four reflector mirrors, the opening width of collector is 5.8m, the focal length is 1.71m, mirror thickness is 0.004m and the whole computational domain is 80m long, 30m high and 30m wide. The distance from windward surface to inlet is 30m and the bottom of mirrors is 0.5m high over the ground. See Fig.1. The gap on the direction of y-axis is axial gap which is named D1 and the gap on the direction of x-axis is radial gap which is named D2. $\theta$ is the pitch angle of collectors. Fig.2 shows the pitch angles simulated.

![Fig. 1. The computational domain with boundary conditions. a. Front view. b. Top view](image)

![Fig. 2. Figure angles simulated](image)

Hybrid grids of structural and non-structured grids are used in this study, more number of grids are generated around the mirrors to simulate the intense change of wind flow around the mirrors and the gap with non-structured grids. Besides the mesh around the collectors, the other area uses the structural grids and the grids are gradually smaller from outside to inside which could contribute to a rapid production of grids and quick computing speed. See Fig.3.

The inlet at the entrance of wind tunnel is a velocity boundary and the outlet is defined as pressure outlet. The wind speed increases with height by index change at the entrance. The wall of ground is no slip wall condition and others are free slip wall condition. The standard wall function is selected to simulate the air flow around the wall.
2.2. Control equations

The control equations for a 3D steady-state incompressible fluid flow are time averaged Navier-Stokes equations and RNG-based \( k-\varepsilon \) turbulent scheme [18]. The \( k-\varepsilon \) model was of satisfactory accuracy for free shear flows, attached boundary layers and mildly separated flows. The turbulent kinetic energy is \( k \) and viscous dissipation rate of turbulent kinetic energy is \( \varepsilon \).

2.3. Solve

A segregated solver with double precision and the pressure implicit with splitting of operators algorithm are chosen. The grid dependence is conducted under several sets of grids in advance. Convergence is warranted by the residual drop to \( 10^{-4} \) for all the equations and the mass flow is balanced between the boundaries. The computation is solved in the commercial CFD software FLUENT with a computer server of 8 CPUs and 256G memory.

3. Numerical results and discussions

3.1. Effect of wind speed and pitch angle on wind load of PTC

Trough solar power generation systems are often in an open flat terrain and the current trough solar collector system design requirement is able to work normally under strong breeze and stay safe under strong gale. It is important to study the wind load of PTC on extreme conditions. Both the effect of the wind speed (0-14m/s) and the pitch angel (0-180degree) of PTC on wind load were studied. Both D_1 and D_2 were 0.020m.
Fig. 4. Pressure force for different wind speed

Fig. 4 shows pressure force on the collectors increases significantly with the increase of wind speed. This is due to the exponentially relationship between pressure and wind speed. Effect of wind load must be taken into consideration in the design process of PTC. Fig. 5 shows that collectors receive a peak wind load at pitch angle 0 degree and the lowest at 90 degree. As a result of the parabolic shape of PTC which the structure of the front and back of PTC are different, the graph in figure 4 is not symmetric and the pressure force is larger at the front of PTC.

3.2. Gap effect on wind load

Mirrors gaps are thought to be an invalid measure to reduce wind loads on heliostats [19]. However, it still should be investigated whether a similar phenomenon occurs on trough collectors. In order to obtain precise results, the whole factor numerical simulation is conducted with each of the axial and radial gap from 0m to 0.06m with 0.01m increment. Because the 0 degree is the worst position for wind load, the 0 degree pitch angle is studied and the wind speed is 8m/s.
Fig. 6 shows the correlation between the wind load and axial gap. As we can see from the figure that the pressure force on the surface of collectors decreases with the increase of axial gap. When $D_1$ is equal to 0 and $D_2$ increases from 0 to 0.06, the wind load pressure dropped by 13.7%, this value is 11.7% when $D_2 = 0.01m$, 13.0% for 0.02m, 12.7% for 0.03m, 12.8% for 0.04m, 12.5% for 0.05m, and 12.4% for 0.06m. The reason is that trough collectors have a parabolic shape, which leads to different wind flows around them against flat shape of heliostats. Parabolic shape is beneficial for catching the wind and increasing gaps between the parabolic panels. This can play a role in the variation of wind loads on them. As Bernoulli's equation shows the conservation of total energy in fluid, fluid dynamic pressure can be converted to static pressure when fluid is close to collectors [20]. Fluid velocity decreases and the pressure increases, therefore, static pressure can be converted to dynamic pressure under the action of static pressure on surface. The fluids continue to flow along the upper and lower sides of the collectors and mirror gap, as shown in Fig. 7. Due to the increase of mirror gap size, more fluids flow through clearance, thus leading to a decreased wind load.
Fig. 8 shows the correlation between the wind load and radial gap. With the increase of $D_2$, the pressure force changes slightly, even when the radial clearance is larger than 0.02m, the wind load increases slowly. The reasons behind this phenomenon is that, according to the Bernoulli equation, gas speeds up through the gap and outlet pressure of the gap decreases. Negative pressure zone is formed. This results in the increase of the drag force and the increase of radial gap will not lead to reduction of high pressure of windward, particle swarm optimization (PSO) algorithm therefore the wind load increases. But the gap size relative to the mirrors' width is very small, the increment is negligible with the increase of the load. This phenomenon is similar to wind load cases of heliostat [21].

3.3. Discussion

In this study, numerical results show that the wind load on collectors increases very small with the increasing of radial gap size from 0 and 0.06m. However, the overall wind load decreases significantly with increasing axial gap. The wind load factors of trough collectors can be reduced by 13%. Global effect for pressure force is the sensitivity of gap size to pressure force Fig 9 shows the global effect for wind load about the axial gap and radial gap, which we can see the influence of axial gap is much larger than radial gap. Consequently, axial gap should be taken into consideration for structural design of PTC, while radial gap size is negligible.

In other studies, Chen also have studied the mirror gap effect on wind load on PTC with two-dimensional model [20]. The gap effect is about 3% on wind load which is differ from this study. Because the two-dimensional model cannot accurately simulate the actual wind flow around PTC. Schweitzer at al measure two trough collector models
with conventional minimum gaps and with enlarged staggered mirror gaps in a wind tunnel [12]. The wind load factors of trough collectors can be reduced by 30% with the staggered gaps between the inner and outer mirror panels. This design can further reduce the influence of the wind load.

4. Optimization based on RSM model

For obtaining the optimal gap size of PTC, Response surface methodology (RSM) optimization model and particle swarm optimization (PSO) algorithm are used in this study. Response surface methodology is a widely accepted statistical technique used to design the experiments [22]. It has the advantages of simplifying complex problems and reducing calculation. It is very useful for modeling and predicting the response of interest affected by a number of input variables with the aim of optimizing the responses. RSM also specifies the relationships among one or more measured responses and the essential controllable input factors. RSM can find the optimal set of experimental parameters that produce a maximum or minimum value of response and can represent the direct and interactive effects of process parameters through two- and three-dimensional plots.

To predict the optimal gap size within the 0 to 0.06m, RSM optimization model is obtained in this study with the data between mirror gap and wind pressure force. The final mathematical model is given below:

\[
PF = 1520.3 - 5023.9D_1 - 1222.9D_2 + 24267.8D_1^2 + 19301.5D_2^2 + 3520.7D_1 \cdot D_2
\]

(1)

In order to validate the developed RSM model, random results obtained from the numerical simulation of CFD for the pressure force are compared with predicted results of RSM as shown in Fig.10. From the validation tests, it is obtained that the predicted error is 2.3% which is very small between the actual and predicted values and it shows a good agreement between the developed RSM models and analytical model. Therefore, these mathematical models are used for predicting the optimal gap size with significant accuracy. Optimal solution are searched within axial and radial gap size from 0m to 0.06m by PSO algorithm. Because the PSO algorithm is simple with fast convergence speed and high accuracy [23]. Besides, the concentrated loss caused by gap is limited in 3%. The results for the optimal radial gap size is 0.02m and the optimal axial gap size is 0.06m. The pressure force of PTC with the optimal gap sizes is reduced by 14.7% than no gap design.

5. Conclusions

A thorough study of the mirror gap effects on wind load on parabolic trough solar collectors was carried out through numerical simulation with different gap sizes. From these results, it was concluded that:

(1) Wind speed has a huge impact on wind load of PTC, as well as pitch angle. Wind load increases exponentially with the wind speed, and the worst position for wind load is that the pitch angle of PTC is 0 degree.

(2) For the overall wind load on collectors, the influence of the radial gap size is negligible. However, the axial
gap effect on collectors is noteworthy which can reduce the wind load by around 13% with the gap size from 0 to 0.06m. The reason is that the parabolic shape catching the wind easily which increases the static pressure on the windward surface of the collectors. In the design process of PTC, the axial gap size should be taken into account for the reduction of wind load.

(3) For the design of PTC, both the structural security and the tracking accuracy of collectors are important. In this study, it is predicted that the optimal axial gap size is 0.06m and radial gap size is 0.02m within the gap size from 0 to 0.06m. The pressure force of PTC with the optimal gap sizes is reduced by 14.7% than no gap design.

Acknowledgements

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