IJE TRANSACTIONS C: Aspects Vol. 28, No. 6, (June 2015) 940-948

International Journal of Engineering

Journal Homepage: www.ije.ir

A Numerical Investigation on Aerodynamic Coefficients of Solar Troughs Considering Terrain Effects and Vortex Shedding

Z. Baniamerian [a], R. Mehdipour *[a], F. Kargar [b]

[a] *Department of Mechanical Engineering, Tafresh University, Tafresh, Iran*
[b] *Department of Energy & Environment Research Center, Niroo Research Institute, Tehran, Iran*

PAPER INFO

Paper history:
Received 09 January 2015
Received in revised form 05 March 2014
Accepted 30 April 2015

Keywords:
Solar Trough Collector
Aerodynamic Coefficient
Numerical Analysis
Vortex Shedding

ABSTRACT

Recently, increase in the cost of fossil fuels and taking into consideration the environmental effects of exploiting them, caused many researchers and governments to find some ways to make use of renewable energies more cost-effectively. Solar energy is a category of renewable energies which could be harvested via several technologies. One of the most practical methods is using parabolic troughs. In solar power plants, many parabolic troughs are set in parallel rows in order to concentrate the solar power onto a tube absorber. In designing and manufacturing parabolic troughs and their structures, it is essential to take into account the wind force. Any negligence in considering the wind force could be concluded in losing the accuracy and efficiency. In this article, the aerodynamic coefficients of parabolic solar troughs have been investigated using CFD methods. The variations of aerodynamic coefficients considering terrain effects, the angle of collectors and the gap between mirrors have been studied. Also, it will be demonstrated that in order to properly align trough collector in solar farms, it is essential to study the vortices shed created at the behind of parabolic troughs and its effects on collectors' structures in the result of wind interaction. At the end and as an illustration, the drag and lift coefficients of collectors have been calculated in Yazd power plant.

doi*: 10.5829/idosi.ije.2015.28.06c.15*

NOMENCLATURE

C_{ave}	Average Force Coefficient	q	Kinematic energy of wind
C_{dp}	Differential Pressure Coefficient	t	Time
C_{max}	Maximum Force Coefficient	U_{mean}	Target mean wind velocity
C_{mean}	Mean Force Coefficient	U_{ref}	Reference height wind speed
C_p	Pressure Coefficient	$\vec{v}$	Velocity vector
C_x	Horizontal Force Coefficient	W	Aperture width
C_z	Vertical Force Coefficient	x, y, z	Coordinate system
f	Focal Distance	Z	Target elevation
F_x	Horizontal Force	Z_{ref}	Reference elevation
F_z	Vertical Force	α	Pitch angle
g	Gravitational Acceleration	β	Yaw angle
I	Identity Matrix	μ	Viscosity of fluid
L	Aperture Length	ρ	Density of fluid
n	Power Law Exponent (Roughness Definition)	$\bar{\bar{\tau}}$	Stress tensor
p	Pressure		

*Corresponding Author's Email: mehdipour@tafreshu.ac.ir (R. Mehdipour)

Please cite this article as: Z. Baniamerian, R. Mehdipour, F. Kargar, A Numerical Investigation on Aerodynamic Coefficients of Solar Troughs Considering Terrain Effects and Vortex Shedding, International Journal of Engineering (IJE), TRANSACTIONS C: Aspects Vol. 28, No. 6, (June 2015) 940-948

1. INTRODUCTION

In the recent years, the energy crisis and several pollution effects of fossil fuels lead to an increasing tendency toward exploiting renewable energies. However, the high cost of energy production via these kinds of energies comparing to fossil fuels is still a matter of concern. One of the potential energies assumed to be cost-effective in the near future is solar energy.

A frequent method to absorb solar thermal power is utilizing solar collectors. A solar collector is a heat-exchanging device that transforms solar radiation into thermal energy that can be used for power generation [1]. Based on the methods of solar power concentration and the geometry of collectors, the solar power plants are categorized into linear parabolic troughs [2, 3], linear Fresnel reflectors, central tower receivers or parabolic dish collectors [4]. Among all these technologies, linear parabolic troughs aligned in parallel rows forming a solar farm seem to be more viable. During the last years, there is a tremendous growth in producing electric energy via linear troughs in several countries [5, 6]. So far, the parabolic troughs represent the most mature solar thermal electricity technology [7]. These parabolic troughs can be used in direct, indirect or hybrid cycles in order to produce steam for power generation [8].

One of the considerations in designing parabolic troughs is the proper design and construction of their supports and structures. Since in solar farms many parabolic troughs are utilized, the improper design of trough structures can affect the solar farm economically. To elaborate more, the design of supports and structures should be based on accurate knowledge of wind forces and its effects on the collectors' structures. This is because the wind force is a critical parameter in selecting an optimum reliability factor which significantly, influences the manufacturing costs. Evidently, the higher the reliability factor, the more the manufacturing cost.

In solar trough collectors, all the mirrors have parabolic curvatures which have been aligned beside each other. Although the parabolic profile has the capability of absorbing maximum possible solar power, it is assumed to be a considerable obstacle for wind, and as a consequence, the structures of collectors tolerate significant drag forces. Hence, in a solar farm, the structure beneath the parabolic mirrors should be designed in a way that not only could bear substantial drag forces caused by wind fields, but also has a relative low manufacturing cost in order to make the solar farm economically acceptable. Optimum designing of the collectors' structures could end in significant saving in total establishment cost of solar farms. Another important issue regarding solar trough collectors is the method of installation and alignment of mirrors on their structures. Usually, parabolic mirrors are connected to the structures using specific resins. In addition, durability and structure deformation in the result of possible stresses are important concerns which should be taken into account during the design phase. If the mirrors deform more than maximum allowable limit, the efficiency of solar collectors diminish significantly. In designing the structure of solar collectors, total wind loads, pressure distribution upon the bowl structures, interior flow field within the bowl, flow field on the exterior of the bowl and bowl vibration caused by vortex shedding should be kept in mind [9].

In order to obtain the wind loads on structures, it is essential to calculate the drag and lift coefficients. To evaluate the drag force, it is suggested to use either static or dynamic methods. In static analysis, it is assumed that the structure is under the maximum wind load. On the other hand, in the dynamic methodology, the fluctuations of the structure in the result of vortices created in downstream of flow field and vibration of collectors' structures caused by these vortices are monitored. The most important advantageous of static models are their simplicity. Usually, it is proposed to use static methods for structures lower than 50 meters high. Using static methods for higher or elastic structures are not recommended [10].

Since the solar trough collectors have a parabolic geometry and keeping in mind the fact that various parameters can affect the wind flow and its total load, many researchers tend to study collectors' characteristics in wind tunnel tests [11-16]. To reach this end, collectors are usually installed on moving planes in a wind tunnel which can rotate and make it possible to investigate the effects of different wind flow directions on troughs' structures. Another way to test the wind characteristics and drag forces is field measurements. Recently, a very comprehensive in-field study has been carried out installing anemometers and wind pressure transducers on front and back sides of solar trough collectors in order to measure the speed and direction of the wind and pressure on solar troughs in Beijing, China by [17].

There are comprehensive studies which investigate the forces on flat, parabolic troughs and dish collectors and can be found in [11, 14, 15] and [18]. In wind tunnel tests, due to the limited number of examinations, all the phenomena could not be inspected and in some cases dimensional differences between the prototypes and models and limitations in providing the required velocity for the wind, makes it impossible to equalize dimensionless variables. This hindrance is reported for Reynolds numbers in [9] and [16]. Although experimental investigations are more precise and give a realistic understanding of the subjects under investigation, they are generally expensive and time consuming. Utilizing numerical methods along with or before experimental investigations could reduce the cost and time of analyses in a great deal.

Naeeni and Yaghoubi [19] investigate the aerodynamic of 2D solar collectors and obtained the aerodynamic forces. In this study, it is demonstrated that the gap between the two sections of parabola at midsection and the gap between the collector and ground affects both flow field and pressure distribution around the collector considerably, while the effect of absorber tube is negligible.

Shademan and Hangan, [20] carried out a numerical investigation of wind effects on flat collectors and studied the mutual effects of collectors or technically, sheltering effects. Furthermore, an experimental study has been performed to analyze the sheltering effects of a building on a solar collector by [21].

Another important issue regarding the solar collectors is creation of vortex shedding at the behind of them in the result of wind flow. Vortex shedding causes a kind of fluctuating force on collectors. If the frequency of the force coincides with the natural frequency of collector's structure, it will be demolished [9]. The analysis of flow field around microwave dish antennas has similarities to solar collectors. Lamboradi [22] and Holmes et al. [23] depicted that the maximum wind force on dishes occurs when the flow field is normal to dish and does not change until 30 degrees rotation.

The structure's materials and manufacturing process is described in [24]. Using frequent standards in manufacturing structures with typical geometry is widely accepted. Also, in some standards the procedure of combination simple geometries in order to construct complicated structures is explained. Holmes et al. [25] calculated the wind force on buildings using 15 different standards and concluded that different standards result in significant fluctuations in evaluating wind forces. Therefore, the structures in solar collectors should not be designed in accordance with these standards and it is more acceptable to use CFD methods or wind tunnel experiments.

In this study, first, the variations of wind flow as the result of interaction with solar collectors are investigated via numerical methods. Moreover, the creation of vortices at the behind of collectors and its impact on other collectors installed in the solar farm are studied. The results show that creation of vortices causes drag forces in both directions fluctuate in time. Hence, it is an essence to carry out transient simulation in order to calculate drag and lift coefficients. Also, the effects of terrain on variation of wind profile and consequently, its impact on the drag forces have been analyzed. In addition, the effect of gap size on variation of aerodynamic coefficients has been considered. It is demonstrated that increase in gap size causes the drag force to decrease. At the end and as an illustration, the aerodynamic coefficients of Yazd solar farm have been presented.

2. MATHEMATICAL MODELING

2. 1. Geometry of the Collectors Generally, in Fluid-solid heat coupling method, the solar collectors have a parabolic curvature. Considering the thermal efficiency, the following profile shows the best performance [10]:

$$z = x^2/4\,f \qquad f = 1.71 \tag{1}$$

2. 2. Governing Equations In aerodynamics, the angles are defined with respect to wind's direction. Figure 1 illustrates the angles used in calculations schematically. Regarding the definition of pitch and yaw angles with α and β respectively, the aerodynamic coefficients could be obtained via following equations:

$$C_x = F_x/q\,L\,W \tag{2}$$

$$C_z = F_z/q\,L\,W \tag{3}$$

$$C_{tot}^2 = \sqrt{C_x^2 + C_z^2} \tag{4}$$

The kinematic energy of wind (q)in the above equations can be obtained via the following equation:

$$q = 0.5\,\rho\,U^2 \tag{5}$$

The local drag coefficient can be defined as follow:

$$C_p = p/q \tag{6}$$

The final drag coefficient can be calculated as follow: [12]:

$$C_{dp} = p_f - p_b/q \tag{7}$$

In the reference [12], it has been demonstrated that in Reynolds higher than 46000, the drag coefficient is independent of Reynolds numbers and hence, in this study the analysis has been carried out in velocities correspondence to Reynolds equal to 46000.

In order to calculate drag forces, it is an essence to identify the velocity and pressure fields in the domain of study. The governing equations for the problem include mass conservation and 2D Navier-Stokes equations. The mass-conservation and Navier-Stokes equations can be defined as follow:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\,\vec{v}) = 0 \tag{8}$$

$$\frac{\partial}{\partial t}(\rho\,\vec{v}) + \nabla\cdot(\rho\,\vec{v}\,\vec{v}) = -\nabla\,p + \nabla.\left(\bar{\bar{\tau}}\right) + \rho\,\vec{g} + \vec{F} \tag{9}$$

The stress tensor in the above equation can be defined via the following formulation:

$$\bar{\bar{\tau}} = \mu\left[\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right) - (2/3)\nabla . \vec{v} I\right] \tag{10}$$

Near the collectors, the flow regime is turbulent. In order to model the dynamic viscosity of turbulence, the well-known k-ε method is used.

Creation of vortices in the vicinity of collectors makes the necessity of considering both transient and steady-state solutions for the problem. In the transient solution, the effects of vortices and also, the load's frequency and amplitude on the collectors could be defined. A preliminary simulation of the problem demonstrated that considering the wind as an incompressible fluid is not appropriate and it is better to simulate the wind as a compressible flow. Also, the perfect gas equation is used to take into account the variations of density. After solving these equations using numerical methods, the drag forces could be obtained utilizing Equations (2) to (7).

2. 3. Geometry of the Collectors The quality of meshing is a key factor in computational fluid dynamics. In modeling the vortices created at the behind of the collectors the mesh quality as well as the object's distance from the upper and exit boundaries play an important role in obtaining more precise results and therefore, should be chosen properly. The 2D and 3D views of a solar farm are shown in Figure 2. The 2D view illustrated in the figure is the physical domain of the problem. In order to observe the vortices, the width and length of the domain should be approximately 10 and 50 times of collector's length. A sample of generated grids is shown in Figure 3. The meshes have the required uniformity with aspect ratios equal to 1.7. The meshes are finer in the vicinity of collectors. Figure 3 illustrates the approximated number of 700000 generated meshes in the environs of two collectors. Also, in Figure 3, the meshes around one collector have been shown with more resolution.

The boundary conditions in the problem have been illustrated schematically in Figure 2. At the inlet of the domain, the wind velocity profile has been specified considering terrain effects. In other words, the terrain adjacent to the solar farm defines the amount of wind, its profile and turbulence intensity. Generally, to estimate the wind speed near the earth surface, the data of synoptic meteorological masts is used. Since wind data is measured in 10 meters high, the extrapolation of data will be necessary to the desired elevation which collectors are installed. In order to extrapolate the data, the power law Equation (11) is utilized. The exponent *n* depends on the type of terrain in which collectors are located and can be obtained from Table 1. The inlet turbulence intensity is considered equal to 0.15 which is suitable for desert terrains.

$$U_{mean}/U_{ref} = \left(z/z_{ref}\right)^{n} \tag{11}$$

It should be noted that considering the maximum wind velocity over-designs the structures and supports, while considering average wind velocity may end in destruction of collectors in a possible high velocity wind flow. Generally, in designing collectors' structures and supports, it is suggested to use the maximum wind velocity that has the probability of 5% occurrence over 50 years available data [20]. In order to define boundary layer condition, the wall function method is employed. Using this method has the advantage of exploiting coarse meshes in the vicinity of wall boundary conditions.

2. 4. Discretization Method Central discretization is used to discretize the governing equations. Moreover, the time dependent terms are discretized using implicit discretization. Finally, SIMPLE algorithm is exploited to solve the flow field.

2. 5. Code Validation To validate the code, the results for maximum drag coefficients in x direction for different pitch angles and zero yaw angle obtained from a single collector simulation have been compared with experimental data of [13] (Figure 4). The comparison proves that the numerical results are in good agreement with experimental data. The maximum discrimination occurs at 30 degrees pitch angle.

3. RESULTS

3. 1. Velocity and Pressure Contours The results obtained from numerical analysis clearly show that the flow field could be modeled accurately around the collectors using CFD methods. Figures 5 and 6 show the velocity and pressure fields around a single collector without any gaps between mirrors. As it can be clearly observed from the figures, pressure distribution and velocity field at the behind of collectors vary continuously with time. With the aid of these contours, the pressure distribution could be calculated on every spot on the trough collector. Definition of pressure distribution stipulates the force magnitude on mirrors and resin sub-layers. In these figures, the pressure and velocity contours have been defined for 15 m/s wind velocity. Vortex fomation as well as vortices motion are demonstrated in Figure 5. Precise modeling of the formed vortices provide conditions for accurate computation of drag coefficient. In the other hand, the oscilations of the exerted force may define the collector lifetime and fatigue. Vortices movements and their increase in size can be seen in furthe distances from the collector.

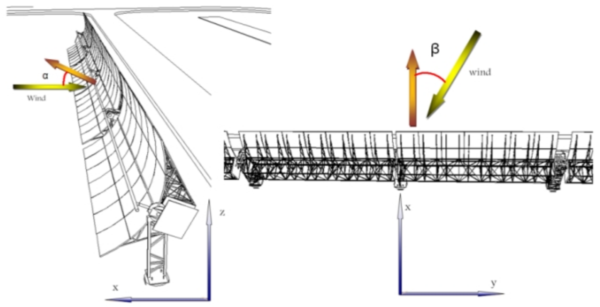

Figure 1. Schematic of solar trough collectors with aerodynamic angles of wind (α and β for pitch and yaw angles, respectively)

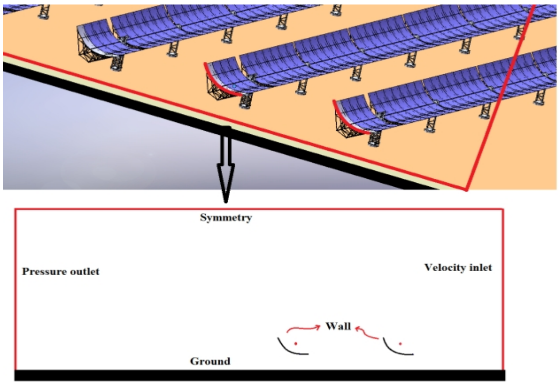

Figure 2. Geometry and boundary conditions

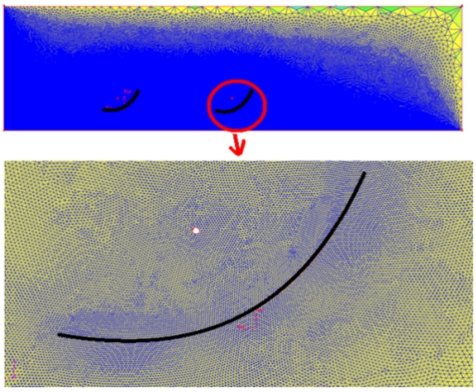

Figure 3. Meshing around the collectors

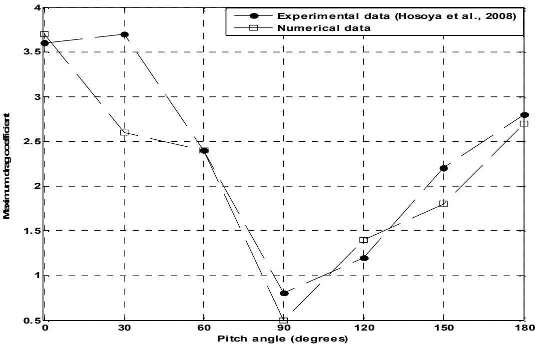

Figure 4. Comparison between numerical study and experimental data acquired from wind tunnel tests on trough collectors

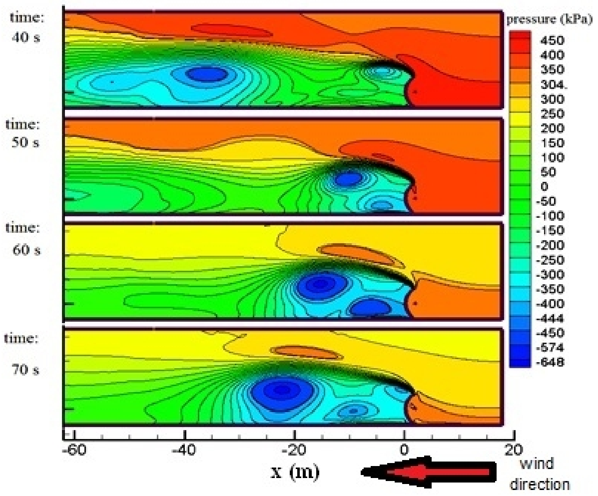

Figure 5. Pressure distribution in different time steps around a collector with inlet wind velocity of 15m/s (α and β = 0)

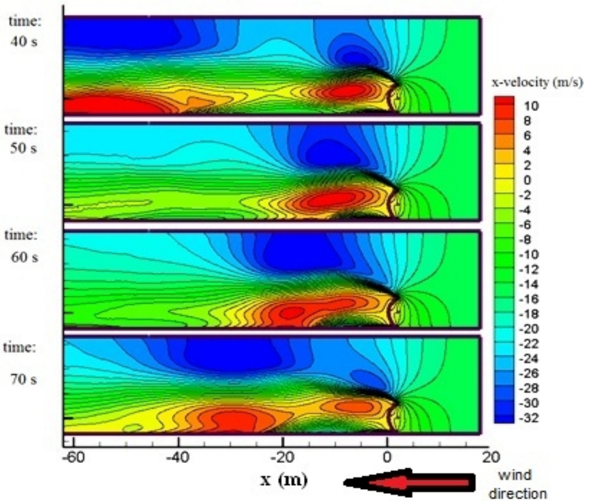

Figure 6. Velocity fields in different time steps around a collector with inlet wind velocity of 15m/s(α and β = 0)

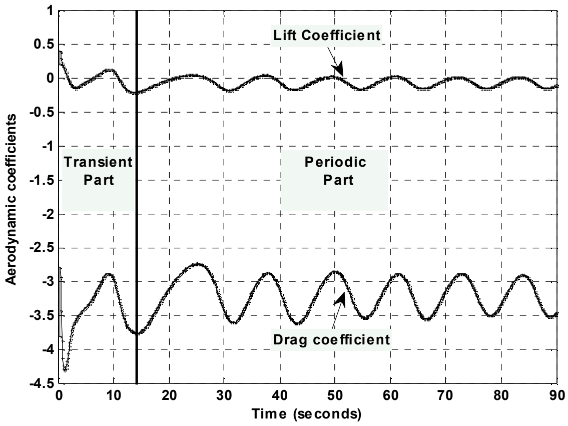

Figure 7. Drag and lift variations with time for a single collector(α and β = 0)

TABLE 1. Earth [26]

Terrain category	Power law exponent, n
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22-0.24
small towns and suburbs	0.28-0.30
Urban areas with tall buildings	0.4

3. 2. Calculation of Drag and Lift Forces

Creation of vortices in the vicinity of collectors cause drag and lift coefficients to fluctuate. Variations of drag coefficient in time are plotted in Figure 7. As it can be observed in Figure 7, the results are comprised from two sections which have been divided by a line. The first section begins at $^{t=0}$ until the mentioned line contains transient results. Since at the first steps of numerical analysis, the results are greatly influenced by numerical initial conditions, the first section could not be interpreted physically. In the second section, the results are fluctuating. From these figures the minimum, maximum, average and frequency of the wind loaded on collectors could be obtained.

In Figure 7, the exerted force on the collector with angle of 0^{o} is demonstrated. As can be seen in Figures 5 and 6, the formed vortices behind the collector flows along the wind flow and cause a relative vacuum zone in behind and in turn a considerable pressure gradient along the flow which is a source for oscillation. Regarding the lift force, since the vortices that formed at the bottom and on the above of the collector detaches from the collector with a small interval, an asymmetry condition is governed which result in lower pressure gradient compared with what occurred for the drag force. The numerical analysis also has been carried out for different pitch angles and the results are listed in Table 2. These results are valid for a single collector without any gaps between mirrors. Simulation of vortices provides us with the capability to evaluate the minimum and maximum drag coefficients. Exploiting methods based on steady-state assumptions could not model the created vortices and as a consequence, unable to calculate the maximum drag coefficient.

3. 3. Gap Effects

So far, the pressure and velocity fields around a single collector without any gaps between mirrors have been studied and aerodynamic coefficients have been obtained. Actually, considering manufacturing constraints, it is impossible to put mirrors beside each other without any gaps. Figure 8 shows the impact of gaps on velocity vectors around a single collector in horizontal position at different time steps. In this figure, there is a gap of size 200 mm in the center line of solar troughs which causes upper and lower mirrors separate from each other. As it is clearly observed from the figure, the gaps cause the vortices to be more asymmetric.

Moreover, the effect of gaps on aerodynamic coefficients have been analyzed and presented in Figure 9. Obviously, increasing the gap size will end in drag force reduction on solar troughs. However, increasing the gap size reduces the thermal efficiency. Therefore, definition of optimum gap size is a tradeoff between thermal efficiency and the magnitude of drag force on collectors. Generally, it is acceptable to take 200 mm gaps for solar troughs considering manufacturing and installation restrictions. In addition, as it is obvious in Figure 9, the variation of drag force in the range of 100 to 200 mm is small. The analyses show that increasing the gap size causes the vortices to shrink and separate more rapidly from the back side of the collectors.

3. 4. Yazd Solar Farm trough Colle Ctors

Yazd solar farm is located in 31°56' N and 54°02' E. Yazd power plant is an integrated solar combined cycle (ISCC) with an area of 104640 m^2 and 474 MW nominal capacity in which 128 collectors are designed to be installed in 32 parallel rows and proposed to produce 17 MW solar electrical energy out of total electric energy production. The aerodynamic coefficients of solar collectors installed in Yazd solar farm have been analyzed and are listed in Table 3. These results are obtained for the first row, since the troughs in the frontier rows bear drag forces approximately twice the back collectors due to sheltering effects. In calculating the aerodynamic coefficients presented in the table, the effects of earth terrains (desert), gaps between mirrors and sheltering effects have been considered. According to the results, the maximum wind force occurs at zero pitch angles. Hence, the design of supports and structures are based on drag and lift coefficients obtained at horizontal positioning of solar troughs.

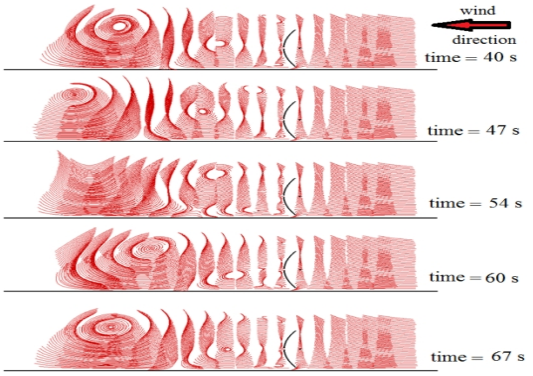

Figure 8. Velocity vectors in different time steps around the collector for inlet velocity of 15 m/s (α and $\beta = 0$)

TABLE 2. Aerodynamic coefficients for different pitch angles (β = 0)

Pitch angle	|Cx,max|	|Cx,ave|	|Cy,max|	|Cy,ave|	Ctot
0	3.70	3.20	0.20	0.10	3.71
30	2.60	2.20	1.65	1.40	3.08
60	2.40	1.70	2.90	2.20	3.76
90	0.50	0.30	1.70	1.30	1.77
120	1.40	1.10	0.10	0.20	1.40
150	1.80	1.40	0.10	0.20	1.80
180	2.70	2.30	0.20	0.25	2.71

TABLE 3. Aerodynamic coefficients for Yazd collectors

Pitch angle	|Cx,max|	|Cx,ave|	|Cy,max|	|Cy,ave|	|Ctot|
0	2.10	1.80	0.12	0.04	2.10
30	1.10	0.80	0.60	0.30	1.25
60	0.80	0.70	1.50	1.30	1.70
90	0.40	0.20	0.90	0.60	0.98
120	0.70	0.50	0.10	0.20	0.71
150	0.90	0.80	0.10	0.00	0.91
180	1.20	0.90	0.10	0.00	1.20

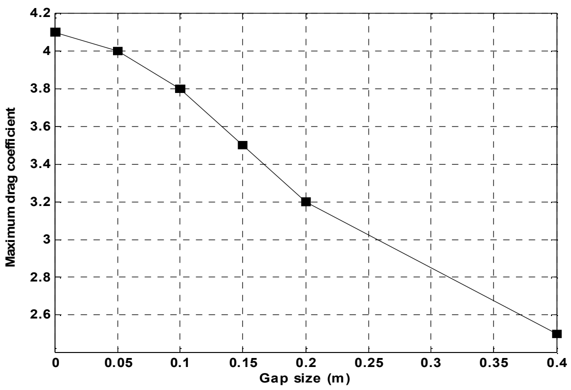

Figure 9. Effect of gap size on maximum drag coefficient(α and β = 0)

4. CONCLUSION

In this study, a numerical analysis has been carried out in order to evaluate the wind forces and aerodynamic coefficients of solar trough collectors. To this end, the earth terrains, gap size effects and creation of vortices at the behind of collectors have been studied thoroughly. In brief, the following deductions could be summarized regarding the numerical study of solar troughs:

- The results show that all mentioned parameters are key factors in designing and manufacturing collectors' supports and structures. The numerical results demonstrate that the terrain unevenness and gaps between the mirrors cause the vortices to be asymmetric at the behind of collectors.

Increasing the gap size causes the drag force to reduce. However, increasing the gap size lessen the thermal efficiency. Therefore, to define the optimum gap size the tradeoff between thermal efficiency and the magnitude of drag force on collectors should be taken in consideration. Generally, 200 mm gaps for solar troughs are suitable considering manufacturing and installation restrictions.

- The study shows that the troughs on back rows bear less drag forces relative to the first row due to the sheltering effects. As a case study, the troughs in Yazd solar farm have been studied thoroughly. The results show that the collectors at first row bear drag forces approximately twice the back collectors.
- A preliminary estimation of wind force on the first row of the collectors based on the results obtained from this study clearly shows that in order to reduce the wind force, the solar farm is better to be surrounded by fences or porous walls. Using these elements all around a solar farm could reduce the wind loads on collectors in a great deal.

At the end, the aerodynamic coefficients have been obtained for Yazd solar power plant and observed that the maximum drag force occurs at the horizontal pitch angle. This result is in conflict with the experimental results obtained from wind tunnel tests by [13] which show the maximum drag force happens at 30 degrees pitch angle. One of the reasons in order to interpret this discrimination is that in the experimental investigation the gaps between mirrors have not been considered.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge Monenco Iran Consultant Company for the financial supports in order to true fulfillment of this study.

6. REFERENCES

1. Azad, E., "Interconnected heat pipe solar collector", ***International Journal of Engineering Transaction A: Basics***, Vol. 22, No. 3, (2009), 233-242.
2. Dhass, A., Natarajan, E. and Lakshmi, P., "An investigation of temperature effects on solar photovoltaic cells and modules", ***International Journal of Engineering Transaction B: Applications*** , Vol. 27, No. 11, (2014), 1713-1722.
3. Kouhikamali, R. and Hassani, M., "The possibility of using flat plate solar collector based on the best calculated tilt angle in the city of rasht as a case study", ***International Journal of Engineering Transaction B: Applications***, Vol. 27, No. 8, (2014), 1297-1306.
4. Barlev, D., Vidu, R. and Stroeve, P., "Innovation in concentrated solar power", ***Solar Energy Materials and Solar Cells***, Vol. 95, No. 10, (2011), 2703-2725.
5. Wang, Z., "Prospectives for china's solar thermal power technology development", ***Energy***, Vol. 35, No. 11, (2010), 4417-4420.
6. Poullikkas, A., "Economic analysis of power generation from parabolic trough solar thermal plants for the mediterranean region—a case study for the island of cyprus", ***Renewable and Sustainable Energy Reviews***, Vol. 13, No. 9, (2009), 2474-2484.
7. Mills, D., "Advances in solar thermal electricity technology", ***Solar Energy***, Vol. 76, No. 1, (2004), 19-31.
8. Giostri, A., Binotti, M., Astolfi, M., Silva, P., Macchi, E. and Manzolini, G., "Comparison of different solar plants based on parabolic trough technology", ***Solar Energy***, Vol. 86, No. 5, (2012), 1208-1221.
9. Foran, R.K., "Vibration and flow field characteristics of a hemispherical solar concentrator", Texas Tech University, (1984).
10. EU-FP, E., "Wind loads on solar energy roofs", ***Heron***, Vol. 52, No. 3, (2007), 201-222.
11. Rhee, J., Nguyen, C., Grace, M. and Thu, A., "An effective, low-cost mechanism for direct drag force measurement on solar concentrators", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 99, No. 5, (2011), 665-669.
12. Hosoya, N., Peterka, J., Gee, R. and Kearney, D., "Wind tunnel tests of parabolic trough solar collectors", ***National Renewable Energy Laboratory Subcontract Report NREL/SR-550-32282***, (2008).
13. Peterka, J., Hosoya, N., Bienkiewicz, B. and Cermak, J., Wind load reduction for heliostats., Colorado State Univ., Fort Collins (USA), (1986).
14. Peterka, J.A., Tan, L., Bienkiewcz, B. and Cermak, J., Mean and peak wind load reduction on heliostats, Colorado State Univ., Fort Collins (USA), (1987).
15. Peterka, J.A., Tan, Z., Bienkiewicz, B. and Cermak, J., "Wind loads on heliostats and parabolic dish collectors", Solar Energy Research Institute, Paper SERI/STR-253-3431, Vol. 89,(1988).
16. Ewald, R., Peterka, J.A. and Cermak, J.E., "Heliostat-array wind-tunnel study, Fluid Mechanics and Wind Engineering Program, Fluid Dynamics and Diffusion Laboratory, Department of Civil Engineering, Colorado State University, (1979).
17. Gong ,B., Wang, Z., Li, Z., Zhang, J. and Fu, X., "Field measurements of boundary layer wind characteristics and wind loads of a parabolic trough solar collector", ***Solar Energy***, Vol. 86, No. 6, (2012), 1880-1898.
18. Pfahl, A., Buselmeier, M. and Zaschke, M" ,.Wind loads on heliostats and photovoltaic trackers of various aspect ratios", ***Solar Energy***, Vol. 85, No. 9, (2011), 2185-2201.
19. Naeeni, N. and Yaghoubi, M., "Analysis of wind flow around a parabolic collector (1) fluid flow", ***Renewable Energy***, Vol ٣٢ . , No. 11, (2007), 1898-1916.
20. Shademan, M. and Hangan, H., "Wind loading on solar panels at different inclination angles", in 11th Conference of American Society of Wind Engineers, San Juan, Puerto Rico., (2009).
21. Lee, B. and Evans, R., "The measurement of wind flow patterns over building roofs", ***Building and Environment***, Vol. 19, No. 4, (1984), 235-241.
22. Lombardi, G., "Wind-tunnel tests on a model antenna rotating in a cross flow", ***Engineering Structures***, Vol. 13, No. 4, (1991), 345-350.
23. Holmes, J.D., Banks, R. and Roberts, G., "Drag and aerodynamic interference on microwave dish antennas and their supporting towers", ***Journal of Wind Engineering and Industrial Aerodynamics***, Vol. 50, (1993), 263-269.
24. Arasu, A.V .and Sornakumar, T., "Design, manufacture and testing of fiberglass reinforced parabola trough for parabolic trough solar collectors", ***Solar Energy***, Vol. 81, No. 10, (2007), 1273-1279.
25. Holmes, J., Tamura, Y. and Krishna, P., "Comparison of wind loads calculated by fifteen different codes and standards, for low, medium and high-rise buildings", in Proceedings of 11th American Conference on Wind Engineering, San-Juan, Puerto Rico, (2009).
26. Ray, M., Rogers, A. and McGowan, J., "Analysis of wind shear models and trends in different terrains", University of Massachusetts, Department of Mechanical and Industrial Engineering, Renewable Energy Research Laboratory, (2006).

A Numerical Investigation on Aerodynamic Coefficients of Solar Troughs Considering Terrain Effects and Vortex Shedding

Z. Baniamerian[a], R. Mehdipour[a], F. Kargar[b]

[a] *Department of Mechanical Engineering, Tafresh University, Tafresh, Iran*
[b] *Department of Energy & Environment Research Center, Niroo Research Institute, Tehran, Iran*

PAPER INFO

Paper history:
Received 09 January 2015
Received in revised form 05 March 2014
Accepted 30 April 2015

Keywords:
Solar Trough Collector
Aerodynamic Coefficient
Numerical Analysis
Vortex Shedding

چکیده

در سالهای اخیر، افزایش قیمت سوختهای فسیلی در کنار مشکلات آلودگی ایجاد شده در اثر استفاده ی فزاینده از آنها، بسیاری از محققین و دولت ها را ترغیب کرده است تا روش هایی مقرون به صرفه برای استفاده از انرژی های تجدیدپذیر بیابند. در میان انرژی های نوین، انرژی خورشیدی می تواند به وسیله ی روش های مختلفی مورد بهره برداری قرار بگیرد. یکی از عملی ترین و مقرون به صرفه ترین روشها برای این امر استفاده از کلکتورهای سهموی خطی است. در نیروگاه های خورشیدی سهموی خطی، بسیاری از این کلکتورها در صفوف موازی در کنار هم قرار می گیرند تا نور را بر روی گیرنده های لوله ای شکل متمرکز نمایند. در طراحی و ساخت این کلکتورها و پایه های نگهدارنده ی آنها، ضروری است تا نیروی وارد شده از طریق باد بر روی این کلکتورها محاسبه گردد؛ چراکه هر گونه خطا در محاسبه ی میزان نیروی باد می تواند باعث از دست رفتن دقت و راندمان این کلکتورها گردد. در این مقاله، ضرایب ایرودینامیک این کلکتورها با در نظر گرفتن تأثیرات ناهمواری های زمین، زاویه ی کلکتور نسبت به وزش باد و فاصله ی آینه های نصب شده بر روی کلکتور از یکدیگر بررسی شده است. همچنین نشان داده شده است جهت تنظیم و قرار دادن بهینه ی این کلکتورها در مزارع خورشیدی، ضروری است تا گردابه ی حاصل از وزش باد که در پشت این کلکتورها تشکیل می گردد و تأثیر آن ها بر روی ساختار و پایه های نگهدارنده ی آنها مورد بررسی قرار گیرد. در پایان، ضرایب درگ و لیفت کلکتورها برای نیروگاه یزد محاسبه شده است.

.***doi***: *10.5829/idosi.ije.2015.28.06c.15*