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Technical note

Numerical study of wind forces on parabolic solar collectors

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ABSTRACT

Concentrated solar power is an established technology for megawatt-scale power generation. Recent advances in lower-cost and lighter materials have made kilowatt-scale concentrated solar power applications feasible. Despite the importance of designing support structures for solar collectors, very little reliable work has been done to investigate the forces of the wind on parabolic solar collectors. In the present study, two-dimensional numerical turbulent flow simulations around parabolic solar collectors are performed. Force and torque data are presented for several collector orientations and for wind speeds 8.9 m/s (20 mph) $\leq V \leq$ 49.2 m/s (110 mph). The aperture width of the parabola, which corresponds to aperture widths used for kilowatt-scale as well as some megawatt-scale applications, is also varied from 1.2 m (4 ft) $\leq a \leq$ 3.7 m (12 ft).

1. Introduction

Concentrated solar power (CSP) systems convert the radiant energy from the sun into consumable power such as electricity. CSP is an established technology for utility-scale (megawatt-scale) power generation. Previously, parabolic troughs were made from glass, which is expensive to manufacture and requires heavier rotating support structures. However, recent innovations in highly reflective thin-film materials have reduced the manufacturing costs and allowed for much lighter support structures. These lower costs have made kilowatt-scale CSP applications feasible. Since kilowatt-scale CSP is now being considered, forces and torques from the wind acting on collectors of that size is needed to design the support structures.

Despite the importance of designing parabolic solar collector support structures for extreme wind conditions, only a small amount of literature on the subject exists. Radu and Axinte [1] experimentally determined pressure coefficients for wind forces acting on flat-plate solar collectors. Naeeni and Yaghoubi [2,3] investigated the force of the wind on a parabolic trough with an aperture of 3.1 m and a length of 25 m. A two-dimensional computational fluid dynamics (CFD) simulation was performed for several different wind velocities acting on the trough. Furthermore, the orientation of the trough was parametrically varied. Force results are presented in Newtons, even though the simulations were two-dimensional. Naeeni and Yaghoubi provide a trough length of 25 m; however, their results in Newtons match more closely with the drag force calculated on a rectangle that is 3.1 m tall by 1 m wide suggesting that their force data is actually per unit meter.

Arasu and Sornakumar [4] investigated the forces on a fiberglass reinforced trough by means of analytical wind load testing. Chung et al. [5] also investigated the wind load on flat-plate residential solar collectors and their accompanying storage tanks. Bakic et al. [6] performed CFD simulations for arrays of flat-plate solar collectors at different angles of inclination for wind speeds of 1, 5, and 10 m/s. Another study on wind-interaction analysis is by Christo [7]. In that investigation, numerical simulations were used to determine the wind-flow patterns surrounding a paraboloidal dish in order to track the trajectory of dust particles.

A series of reports, sponsored by Sandia National Laboratories and published in the 1980s and 1990s, on wind loads on parabolic solar troughs have been widely used to estimate forces in practical situations [8–11]. More recently, in 2008, a National Renewable Energy Lab (NREL) subcontract report on wind tunnel tests of parabolic solar collectors was published [12]. These reports used wind tunnel tests to experimentally determine wind loads on a scale model of a parabolic-trough solar collector. In the most recent report [12], a 1:45 model was used of a 7.9-m-long collector with an aperture width of 5 m. Experiments were conducted in order to determine the horizontal force, vertical force, and pitching moment on both isolated troughs and troughs situated in array fields for

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varying pitch angles and wind speeds. Also given in this report were maximum and minimum force and momentum load coefficients.

Although the subcontract reports from Sandia National Laboratories and NREL provide the best-available estimate for wind loads on parabolic solar collectors, there are several issues that should be noted. First, the data which appears in Ref. [12] is widely spread for certain cases (i.e., force coefficients varied greatly across multiple measurements). The spread will be discussed more specifically later. Furthermore, parabolic-trough collectors have curved surfaces, and objects with curved surfaces such as cylinders, automobiles and airplanes should be modeled at near-full scale to produce accurate results [12]. Future studies of the full-scale model for comparison to the 1:45 wind tunnel model are recommended by the authors of the NREL subcontract report.

The present study examines, via numerical experiments, the force of the wind on full-scale CSP parabolic troughs of varying aperture widths. The parabolic trough is modeled as two-dimensional and as an isolated structure in order to obtain baseline loading. The aperture width of the trough is varied between 1.2 m (4 ft) and 3.7 m (12 ft). A parametric model of the forces and torques are given for these aperture widths and for wind speeds between 8.9 m/s (20 mph) and 49.2 m/s (110 mph). The collector is modeled in four orientations: facing the wind or normal to the wind (0°), 30° and 60° from the wind direction, and inverted. Numerical results will be compared with available experimental data in Ref. [12].

2. Physical model

The force due to the wind on a parabolic trough with a rim angle of 90° and a varying aperture width $1.2\ \text{m} \le a \le 3.7\ \text{m}$ is modeled in four orientations (a) facing the wind (0°), (b) 30° from the wind, (c) 60° from the wind, and (d) inverted as shown in Fig. 1. A diagram of the dimensions of the trough is shown in Fig. 2.

For a rim angle of 90°, the focal length f of the parabola is related to the aperture width a by the following equation.

$$f = \frac{a}{4} \tag{1}$$

The parabolic collector is situated so that the bottom edge of the collector is 0.129 m off the ground when oriented so that it is facing the wind. When the collector is oriented in the 30°, 60°, and inverted position, the position of the vertex, with respect to the solution domain, remains the same as when the collector is normal to the wind.

The parabolic collector is modeled as two-dimensional. It is assumed that since the length of the collector is much greater than the aperture width, end effects can be neglected. The collector is modeled as a thin body since the thickness of the collector is assumed to have negligible impact on the flow field and resultant forces. Moreover, the effect of the receiving tube on the fluid flow is also neglected. The solution domain is chosen such that the boundaries do not interfere with the flow near the solar collector. Several solution domains were tested and the final height of the solution domain was $H = 30$ m and the width was $W = 90$ m (Fig. 3). The solution domain was extended 14.105 m from the leading edge of the collector to the entrance when the collector is oriented normal to the flow.

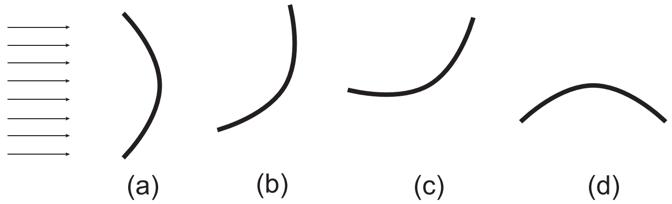

Fig. 1. Schematic diagram of the wind velocity in relation to the parabolic solar collector (a) facing the wind (0°), (b) 30°, (c) 60°, and (d) inverted.

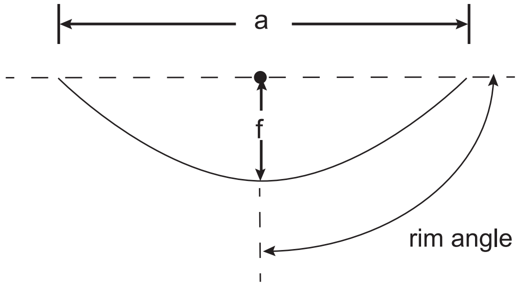

Fig. 2. Geometry of a parabolic solar collector with a rim angle of 90° where a is the aperture length and f is the focal length.

The material properties for air used in the fluid simulations are $\rho = 1.185\ \text{kg/m}^3$ and $\mu = 1.831 \times 10^{-5}$ kg/m s.

3. Governing equations

The wind flow is inherently turbulent. The turbulence model chosen for the current study is the Shear Stress Transport (SST) Reynolds-averaged Navier–Stokes (RANS) model [13,14]. The SST model is an excellent predictor of separated flows and is an appropriate choice for low-speed turbulent flow around objects. The equations for turbulent, steady-state, incompressible, Newtonian flow using the SST model are as follows:

Conservation of Mass:

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0 \tag{2}$$

Conservation of Momentum:

$$\frac{\partial}{\partial x}\left(\rho \bar{u}_i \bar{u}_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) \tag{3}$$

In these equations, $\bar{u}_i$ and $\bar{u}_j$ are the mean velocity components, x_i and x_j are coordinates, P is the pressure, μ is the dynamic viscosity, ρ is the density, and $\overline{u_i' u_j'}$ is the Reynolds stress tensor. The Reynolds stress tensor is related to turbulent viscosity by

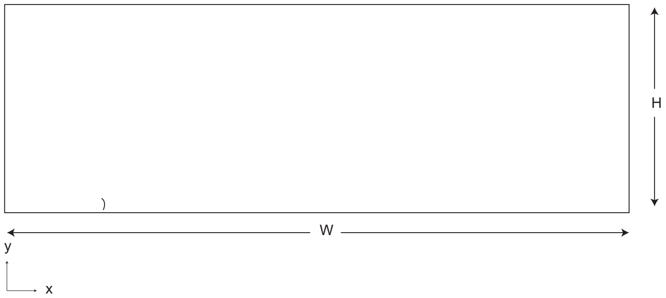

Fig. 3. Solution domain.