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Wind engineering analysis of parabolic trough solar collectors: The effects of varying the trough depth

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ABSTRACT

Wind affects parabolic trough solar collectors on both the structural and performance levels. With the need for higher temperatures, larger apertures of the troughs are required to increase the concentration ratio, however, this also increases the wind loads on the structure. Additionally, airflow around the receiver tube adversely affects the performance of the plant by increasing convective heat losses.

This paper presents the results of research into the effects of the wind on parabolic trough solar collectors. The airflow is investigated in a parametric study aiming at a reduction of the wind loads and thermal losses in the receiver tubes to provide a basis for higher concentration ratios and thus higher efficiencies of parabolic trough power plants. Validated against experimental data from wind tunnel tests and previous studies on the wind effects on parabolic troughs, a series of three-dimensional simulations was conducted using the commercial CFD program ANSYS ® CFX 14.5. The parameter that was varied is the depth of the trough, i.e. the focal length of the paraboloid. Simulations were performed over a large range of pitch angles for three different trough geometries as periodic simulations of an individual trough, representing a single collector row. Time-averaged data on aerodynamic loads and heat transfer are presented.

While a deep trough leads to higher forces than a shallow trough, when facing the wind, due to increased curvature, the wind speed around the receiver is significantly lower with a lower focal length, which can minimise the heat loss in the receiver tube leading to overall higher efficiencies due to higher possible temperatures in the solar field.

1. Introduction

With the ever-growing need for sophisticated renewable energy technologies, concentrating solar power (CSP) is becoming an increasingly important contributor to clean energy, especially in countries with abundant solar resources. The technology has largely been neglected for more than a decade after the initial large-scale plants were built in the Mojave desert in the 1980s (Kearney, 1989), however, CSP has received renewed attention from 2005 onwards, particularly in Spain. By far the most developed and sophisticated form of CSP are parabolic trough collectors (PTC), representing over 95% of the worlds installed capacity of CSP plants (Lovegrove, 2013). Recently heliostat field or power tower technology has received much research attention due to the extremely high temperatures possible in this point focus technology. However, PTC technology has scope for further development, and reaching higher temperatures in the solar field, leading to higher overall plant efficiencies, is a major goal for the technology.

In PTC plants, large parabolic reflectors point at the sun and concentrate the solar energy onto a receiver tube that is located along the focal line of the parabola. The energy is absorbed in the form of heat and is transported via a heat transfer fluid (HTF), which is pumped through the solar field. The heat is then transferred to a steam generator, where it generates superheated steam driving a steam turbine. Due to limitations in size, heat losses, and operating temperatures of the HTF, current PTC plants do not exceed temperatures of 400 °C in the solar field, but higher temperatures have large potential to make the power block more efficient and thus reduce the cost of the generated electricity.

PTC requires accurate tracking of the sun, since it relies on direct normal irradiance (DNI), so the opening of the parabola always needs to directly face the sun. With the need for higher temperatures larger apertures of the troughs are required to increase the concentration ratio. High wind loads can therefore be a factor that negatively impacts the system performance. Larger collectors will also cause an increase in the wind loads and therefore the requirements on the structural strength.

The wind effects on PTC structures have been investigated in wind tunnel experiments by Peterka et al. (1980) at small model

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scale with varying trough geometry. Peterka compared PTC structures with varying focal length regarding wind induced force and moment. Later Hosoya et al. (2008), using a similar model, performed measurements of the wind effects at different positions in the solar field. More recently some numerical studies have been published about the wind effects on PTCs. For example, Naeeni and Yaghoubi (2007) and Zemler et al. (2013) conducted two-dimensional numerical simulations, both focusing on one particular trough shape varying wind speed, and in the latter case also the trough aperture. Hachicha et al. (2013) examined the wind effects on the Eurotrough (Lüpfert et al., 2001) collectors with periodic three-dimensional simulations studying both loads and thermal effects of the wind. None of these numerical studies investigated and compared the effects of different geometries of the parabolic trough. A comprehensive review of previous studies about wind loads on PTCs was provided by Sun et al. (2014).

The present study aims at optimising the shape and layout of the parabolic troughs to minimise the wind loads, as well as the wind speeds around the receiver tube to reduce thermal losses due to forced convection. Validated with wind tunnel experiments and results from the above-mentioned studies, a series of parametric simulations were conducted with computational fluid dynamics (CFD) tools. For a given aperture of the trough, variations of the focal length of the parabola were applied and the effects on the air flow around the PTC were analysed. Initial results of this study were presented in a conference paper at the Solar 2014 Scientific Conference (Paetzold et al., 2014).

Section 2 of this paper describes the methodology, the set-up and conditions of the simulations, as well as the experimental and computational procedure. Section 3 gives an overview of the results focusing on force and moment coefficients and flow fields. Section 4 provides a discussion of the results and Section 5 presents the conclusions of the study.

2. Computational and experimental procedure

2.1. Computational set-up and procedure

The simulations for this paper were conducted using the commercial CFD program ANSYS ® CFX 14.5. Most were performed as steady-state Reynolds averaged Navier Stokes (RANS) simulations with the shear stress transport (SST) turbulence model (Menter, 1994). This turbulence model is based on a blending of the two-equation eddy viscosity models k–ε and k–ω, thus providing an accurate simulation of the turbulence in both the free stream (k–ε model active) and the near wall region (k–ω model active). Therefore, the SST model was chosen to simulate the turbulent airflow of the atmospheric boundary layer, as well as the regions close to the rough wall boundary on the ground of the domain and the smooth surfaces of the parabolic reflector and the receiver element. The model has been used extensively in various studies and its suitability was demonstrated in several validation studies (e.g. by Bardina et al., 1997).

The air flow around PTCs was simulated both at full scale and in a scaled down version representing the dimensions and conditions of the wind tunnel experiments, as described in Section 2.2. While the latter is used for validation purposes, the main parametric studies are conducted on full-scale troughs with an aperture D of 5 m. In the parametric studies the focal length of the parabola, f, was varied from $D/3$ (shallow trough), which is a common layout of PTC plants, through $D/4$ (medium trough), to a deep trough at $D/5$. Fig. 1 shows the size and layout of the computational domain. The x-axis is oriented in the direction of the flow, the y-axis runs laterally through the trough, and the z-axis is vertical, with the origin of the system defined at the centre of the receiver tube in the mid-plane of the domain. An orientation of the opening of the trough facing straight upwards in the positive z direction is defined as 0° pitch angle, with positive pitch angles moving the concave side of the trough into the wind, as shown in Fig. 2. The fluid used in the simulations was air, considered as incompressible, at a temperature of 25 °C. The air velocity was set at the inlet in the form of a logarithmic boundary layer profile to simulate the atmospheric boundary layer of category 2 terrain according to AS/NZS1170.2:2011. This category represents 'open terrain, grassland with few, well-scattered obstructions having heights generally from 1.5 m to 10 m' (Standards Australia Limited/Standards New Zealand, 2011):

$$\frac{u}{u^*} = \frac{1}{0.4}\ln\left(\frac{z}{z_0}\right) \tag{1}$$

with the aerodynamic roughness height $z_0 = 0.02$ m as given in the standard, and the friction velocity $u^* = 0.8$ m/s defined based on a reference velocity of 10 m/s at the reference height of 3 m (height of receiver tube). The turbulence intensity at the inlet was set to 0.17 with an eddy viscosity ratio of 1. The outlet had an average relative static pressure of 0 Pa (ambient pressure: 1 atm). A sand grain roughness of 2 mm was applied to the ground of the domain assuming a relatively smooth ground surface around the solar field. The trough and receiver tube were defined as smooth walls, as they represent a highly polished reflective surface and a glass tube. The wall temperature of the glass tube was set to 100 °C. The top boundary was a free slip wall, and the lateral sides of the domain were treated as periodic boundaries, thus, simulating a row of collectors. With an aperture of the trough of $D=5$ m, the width of the individual trough was $2D$, while a gap of $0.05D$ was applied on either side of the trough, so the simulated collector row had a spacing of $0.1D$ between each other. The Reynolds number based on the trough aperture and the inlet velocity at the height of the receiver tube was 3.2×10^6.

The full domain consisted of approximately 6 million mesh nodes. An unstructured mesh was employed with a high level of refinement close to the surfaces of trough, receiver and ground by means of an inflated boundary with 20 mesh layers. The region around the trough and in the wake up to $2D$ behind the trough had a maximum sizing of 80 mm, whilst a sizing of 400 mm was defined from the inlet up to $4D$ behind the trough. This sizing provides adequate resolution of the atmospheric boundary layer and ensures that the velocity profile from the inlet is carried along to the trough. Additionally this mesh setting smoothly coarsens the mesh away from the trough. The largest element size in the domain was 3000 mm. Mesh independency tests were conducted with a finer mesh (ca 15 million nodes, significant mesh dimensions almost halved), and coarser meshes (ca 2–4 million nodes, significant mesh dimensions at least doubled), the results of which are presented in Section 3.1. For each trough geometry presented in this paper a total of 17 simulations were performed varying the pitch angle from −90 ° to 90 ° in increments of 15 °, and in increments of 5 ° between −15 ° and 15 ° pitch angle.

For the wind induced forces on the PTC structure, the main focus of the analysis was on the determination of the force coefficients in the flow as well as in the vertical direction. These will be called drag and lift coefficient (C_D and C_L) in accordance with the naming convention for forces on aerofoils, i.e. the force in the positive x direction is the drag force F_D, while the force in the positive z direction is the lift force F_L. The coefficient of the total force C_F was determined in the same way based on the total force F_{total}. The force coefficients are defined as

$$C_D = \frac{2F_D}{\rho v^2 A} \tag{2}$$

$$C_L = \frac{2F_L}{\rho v^2 A} \tag{3}$$