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Numerical simulation of wind flow around a parabolic trough solar collector

A.A. Hachicha, I. Rodríguez, J. Castro, A. Oliva *

Centre Tecnològic de Transferència de Calor, Universitat Politècnica de Catalunya, ETSEIAT, Colom 11, 08222 Terrassa, Barcelona, Spain

HIGHLIGHTS

- A numerical aerodynamic and heat transfer model based on LES modelling of PTC is proposed.
- The numerical model is verified on a circular cylinder in a cross-flow.
- The instantaneous and time-averaged flows are studied for an Eurotrough solar collector.
- A comparative study of the heat transfer coefficients around the heat collector element is carried out.

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ABSTRACT

The use of parabolic trough solar technology in solar power plants has been increased in recent years. Such devices are located in open terrain and can be the subject of strong winds. As a result, the stability of these devices to track accurately the sun and the convection heat transfer from the receiver tube could be affected. In this paper, a detailed numerical aerodynamic and heat transfer model based on Large Eddy Simulations (LES) modelling for these equipments is presented. First, the model is verified on a circular cylinder in a cross-flow. The drag forces and the heat transfer coefficients are then validated with available experimental measurements. After that, simulations are performed on an Eurotrough solar collector to study the fluid flow and heat transfer around the solar collector and its receiver. Computations are carried out for a Reynolds number of $Re_W = 3.6 \times 10^5$ (based on the aperture) and for various pitch angles (θ = 0°, 45°, 90°, 135°, 180°, 270°). The aerodynamic coefficients are calculated around the solar collector and validated with measurements performed in wind tunnel tests. Instantaneous velocity field is also studied and compared to aerodynamic coefficients for different pitch angles. The time-averaged flow is characterised by the formation of several recirculation regions around the solar collector and the receiver tube depending on the pitch angle. The study also presents a comparative study of the heat transfer coefficients around the heat collector element with the circular cylinder in a cross-flow and the effect of the pitch angle on the Nusselt number.

1. Introduction

Parabolic trough solar collectors (PTC) constitute a proven device of thermal energy for industrial process heat and power generation. Currently, PTC is one of the most mature and prominent technologies for solar energy for production of electricity. The majority of the parabolic trough plants deployed operate at temperatures up to 400 °C using synthetic oil as heat transfer fluid (HTF) [1]. Parabolic trough collectors are built in modules that are supported from the ground by simple pedestals at either end. A PTC is basically constructed as a long parabolic trough-shaped mirror that reflects direct solar radiation and concentrates it onto a heat collector element (HCE) located in the focal line of the parabola. The HTF runs through the receiver tube and absorbs the concentrated sunlight. The surface of the absorber is covered with a selective coating which has a high absorptance for solar radiation and low emittance for thermal radiation. A glass envelope is used around the absorber tube to reduce the convective heat losses with vacuum in the space between the absorber and the glass cover. The PTC is aligned to the north–south axis and tracks the Sun from east to west as it moves across the sky using a tracking mechanism system.

In practice, the array field of solar collectors is located in an open terrain and it is sensitive to strong winds [2]. The surrounding air is usually turbulent and can affect the optical performance and wind resistance of the PTC, as well as, the heat exchange between

* Corresponding author. Tel.: +34 93 739 8192; fax: +34 93 739 8101.
E-mail address: cttc@cttc.upc.edu (A. Oliva).
URL: http://www.cttc.upc.edu (A. Oliva).

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Nomenclature

Greek symbols
α azimuthal angle
β thermal expansion coefficient (1/K)
κ thermal diffusivity (m^2/s)
κ_{SGS} Subgrid scale diffusivity (m^2/s)
ν kinematic viscosity (m^2/s)
ν_{SGS} Subgrid scale viscosity (m^2/s)
ρ density (kg/m^3)
τ stress tensor (m^2/s^2)
θ pitch angle

Roman letters
D diameter (m)
g gravity (m/s^2)
n normal direction vector
Nu Nusselt number (hD/k)
p pressure (Pa)
Pr Prandtl number ($\mu C_p/\kappa$)
Pr_t Turbulent Prandtl number $Pr_t = \frac{\nu_{SGS}}{\kappa_{SGS}}$
Ra Rayleigh number ($g\beta\Delta T\, D^3/(\nu\kappa)$)
S rate-of-strain (1/s)
T temperature (K)
t time (s)
u velocity (m/s)
W aperture (m)

Subscripts
amb ambient
avg average
g glass envelope
max maximum
min minimum
n normal

Abbreviations
CFD Computational Fluid Dynamics
CV Control Volume
HCE Heat Collector Element
HTF Heat Transfer Fluid
LES Large Eddy Simulations
PTC Parabolic Trough solar Collector
RANS Reynolds-Averaged Navier–Stokes
SGS Subgrid Scale
VMS Variational Multiscale
WALE Wall Adapting Local Eddy viscosity

the glass outer surface and the ambient air. Wind flow analysis is then required to understand the aerodynamic loading around the parabolic reflector, as well as, the convection heat transfer from the HCE.

Several numerical and experimental studies have been performed to determine the thermal performance and heat transfer characteristics of PTC [3–7]. However, only few studies of wind flow around the PTC have been published. 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. From March 2001 to August 2003, Hosoya et al. [12] conducted a series of wind tunnel tests about a PTC with different configurations in which they included the peak load and the local pressure across the face of the solar collector and, investigated the effect of the location of the PTC in the collector field, as well as, the use of a porous fence. Gong et al. [13] performed field measurements on the Yan Qing solar collector in China to determine the boundary layer wind characteristics and the effect of wind loads on solar collectors for different configurations.

On the other hand, numerical studies for studying wind flow around solar collectors are rare. Naeeni and Yaghoubi [14,15] developed a turbulent model based on resolving the Reynolds-averaged Navier–Stokes equations (RANS) to analyse the fluid flow and heat transfer around a parabolic trough solar collector from Shiraz solar power plant. They investigated the recirculation regions around the collector for different configurations and calculated the Nusselt number around the receiver tube. Christo [16] developed a numerical model for a solar dish using FLUENT CFD package and validated it with the wind-tunnel experiments on PTC by Hosoya et al. [12]. He studied the transient flow behaviour and vortex-shedding characteristics around the dish and calculated trajectories of dust particles on the surface of the dish.

Up to now, the turbulence modelling of the fluid flow and heat transfer around the PTC has been solved using RANS models which suffer from inaccuracies in predictions of flow with massive separations and vortex shedding [17,18]. The lack of precision of RANS models in these situations and the increase of computer power, together with the emergence of new high-efficiency sparse parallel algorithms, motivated the use of more accurate turbulent models such as Large Eddy Simulation models (LES). In LES, the largest scales of the flow are solved and requires modelling only for the smallest ones, while RANS models are focused on the mean flow and the effects of turbulence on mean flow properties.

In the present work, detailed numerical simulations based on LES modelling of the flow field and heat transfer around a full-scale parabolic trough solar collector are presented. The main objectives of this study are to demonstrate the capabilities of LES models for quantifying the fluid flow and the aerodynamic coefficients for various pitch angles, as well as, to identify the recirculation zone and vortex-shedding around the PTC and the HCE The thermal field and convection heat transfer around the HCE are also determined.

2. PTC numerical model

2.1. Mathematical model

The methodology used for solving the fluid flow and heat transfer around the PTC is similar to that of bluff body flow described in [19]. In this context, LES models have been proven to yield accurate results in flows with massive separations, reattachments and recirculations and they have been widely tested to simulate turbulent flow around obstacles [20–23].

All the simulations are carried out using the CFD&HT code Termofluids [24], which is an unstructured and parallel object-oriented code for solving industrial flows. In Termofluids, the incompressible filtered Navier–Stokes and energy equations are written as

$$\nabla \cdot \overline{\mathbf{u}} = \mathbf{0} \tag{1}$$

$$\frac{\partial \overline{\mathbf{u}}}{\partial t} + (\overline{\mathbf{u}} \cdot \nabla)\overline{\mathbf{u}} - \nu\nabla^2\overline{\mathbf{u}} + \rho^{-1}\nabla\overline{\mathbf{P}} + \overline{\mathcal{F}} = (\overline{\mathbf{u}} \cdot \nabla)\overline{\mathbf{u}} - \overline{\mathsf{C}(\mathbf{u})\mathbf{u}} \approx \nabla \cdot \tau \tag{2}$$

$$\frac{\partial \overline{\mathbf{T}}}{\partial t} + (\overline{\mathbf{u}} \cdot \nabla)\overline{\mathbf{T}} - \kappa\nabla^2\overline{\mathbf{T}} = (\overline{\mathbf{u}} \cdot \nabla)\overline{\mathbf{T}} - \overline{\mathsf{C}(\mathbf{u})\mathbf{T}} \approx \nabla \cdot \tau_T \tag{3}$$