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Numerical simulation of wind loads on a parabolic trough solar collector using lattice Boltzmann and finite element methods

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ABSTRACT

In this study, we evaluate lattice Boltzmann and finite element methods for wind load estimation of parabolic trough solar collectors. Mean, root-mean-square (RMS) and peak values of aerodynamic load coefficients of an isolated collector are estimated using large-eddy simulation and compared with experimental results obtained in a boundary layer wind tunnel. Despite their fundamental differences, the two numerical approaches yield similar values for the drag, lift and pitching moment indicating that the results are essentially independent of the numerical schemes. Time-varying inlet boundary conditions are obtained using an efficient synthetic generation technique. The statistics of the numerical boundary layer are investigated by comparing mean and turbulence intensity profiles at varying distances from the inlet as well as the spectra and autocorrelation at the position of the structure. Through appropriate modelling of the boundary layer, the numerical models are shown to reproduce the mean, RMS and peak load behaviour measured in the wind tunnel.

1. Introduction

The parabolic trough solar collector (PTSC) is an established technology used in a number of solar thermal power plants around the world. Design relevant aspects of such plants include the estimation of wind induced effects on the plant's performance as well as the PTSC's ability to withstand peak wind loads. Ongoing research and development efforts into the accurate assessment of wind loads on PTSCs are motivated by the goals of improving plant reliability and performance while lowering investment costs.

Initial wind tunnel data including mean loads on PTSCs were reported in Peterka et al. (1980) and Randall et al. (1980, 1982) under contract from Sandia National Laboratories. In order to account for the dynamic behaviour of wind loads, peak load coefficients are estimated from mean load coefficients using a gust factor approach (see, e.g., Liu, 1990). In Hosoya et al. (2008), a more recent wind tunnel investigation sponsored by the National Renewable Energy Laboratory (NREL), wind tunnel measurements of peak loads were provided, thus eliminating the need for the gust factor assumption. However, problems arising from size restrictions and scaling requirements have limited the extent to which arrays of PTSCs can be modelled in the wind tunnel. Additionally, the available aerodynamic load coefficients are restricted to specific geometries, configurations and load conditions. Any design modifications require a new set of tests which can be time-consuming to set up and may not be feasible in the design phase.

Since the first wind tunnel tests of PTSCs in the 1980s, computational fluid dynamics (CFD) has made significant progress towards becoming a more effective and reliable tool in wind engineering. Greater access to computing power has made large-eddy simulation (LES) a suitable candidate for the numerical prediction of wind loads on structures. For buildings, Tamura et al. (2008) concluded that time-dependent methods such as LES are required for numerical wind load estimation since they allow for the prediction of peak loads and pressures. Meanwhile, an abundance of discretization and LES modelling approaches have been proposed whose suitability for computational wind engineering (CWE) has yet to be investigated.

Despite its potential, only a small number of CFD investigations of PTSCs can be found in the literature. Mean loads were simulated using Reynolds-averaged Navier–Stokes (RANS) models in two (Naeeni and Yaghoubi, 2007; Zemler et al., 2013) and three (Paetzold et al., 2014) dimensions. Hachicha et al. (2013) estimated mean loads from an LES of a geometrically two-dimensional PTSC with a periodic boundary in the spanwise direction and a steady, uniform approach flow. Time-varying inlet boundary conditions were first used with LES in Mier-Torrecilla et al. (2014) to estimate both mean and root-mean-square (RMS) wind loads of a three-dimensional model. Through appropriate modelling of the atmospheric boundary layer, the mean loads were shown to be within

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10% of experimental reference data. Slightly larger differences in RMS values were attributed to difficulties in simulating the correct turbulence intensity values close to the ground.

In this contribution, we present new developments in the numerical simulation of wind loads on PTSCs using lattice Boltzmann (LBM) and finite element methods (FEMs), including:

- Assessment of a procedure for generating time-varying inlet boundary conditions which, compared to the procedure used in Mier-Torrecilla et al. (2014), results in better modelling of the turbulence intensity and closer overall agreement with RMS loads measured in the wind tunnel.
- A comparison of mean velocity and turbulence intensity profiles as well as spectra and autocorrelation functions in the simulated atmospheric boundary layer.
- The prediction of peak loads, which have not previously been compared in a numerical study of PTSCs, in addition to mean and RMS loads.

Because the focus of the current study is on the evaluation of design wind loads at high wind speeds, it is assumed that the atmospheric boundary layer is neutrally stable, hereafter referred to as NABL, and any thermal effects are neglected. For simplicity, we further assume a uniform roughness of the upstream fetch. For a non-uniform upstream fetch, a more sophisticated model of the mean velocity profile such as the model proposed in Wang and Stathopoulos (2007) may be more suitable.

The close agreement between LBM and FEM results presented in this study demonstrates their independence of the underlying numerical schemes and the reliability of the current modelling approach for estimating wind loads on PTSCs. The two numerical schemes are further validated using results from a boundary layer wind tunnel experiment reported in Terres-Nicoli et al. (2013).

An important aspect of the current modelling approach is the combination of three-dimensional LES with time-varying inlet boundary conditions to model the NABL. These modelling choices determine to a large extent the resulting RMS and peak wind loads. Therefore, the evolution of the simulated NABL within the LBM and FEM domains is studied in detail by comparing mean velocity and turbulence intensity profiles close to the ground in an empty channel simulation. Additionally, the spectra and autocorrelation functions of the turbulent fluctuations are compared at the position of the structure. Both techniques are shown to correctly model the NABL near the position of the structure with slightly better agreement in mean velocity and turbulence intensity obtained using the FEM. Mean, RMS and peak loads are shown to be in good agreement with experimental data. A preliminary investigation into the suitability of different modelling choices for wind load estimation was presented in Andre et al. (2014).

In Section 2, we explain the procedure for generating inlet data along with the LBM and FEM formulations used for this study. Section 3 discusses the wind tunnel experiment and computational set-up. Numerical results for the empty channel simulation and isolated collector are presented in Section 4 and conclusions are made in Section 5.

2. Numerical models

2.1. Generation of inlet data

Accurate modelling of the NABL is an important prerequisite for estimating structural wind loads using LES. One of the main challenges lies in assigning appropriate time-dependent inflow boundary conditions. In Tabor and Baba-Ahmadi (2010), several techniques for modelling inlet conditions for LES are reviewed. The techniques are divided into precursor simulation and synthesis methods. In contrast to synthesis methods, precursor simulations use CFD to generate inlet fluctuations either before or during the intended LES simulation. Synthesis methods, on the other hand, rely on simplified models. They are faster to compute and the statistics of the generated turbulence such as mean velocity, turbulence intensity and spectra can be more easily controlled. However, while the synthesized inlet fluctuations may look like turbulence, they are not consistent with the CFD model. This leads to the undesirable situation where the boundary layer immediately after the inlet is not in equilibrium. Therefore, changes in turbulence statistics downstream of the inlet need to be accounted for.

In this work, we use the algorithm presented in Mann (1998) to generate inflow data for both LBM and FEM methods. This choice follows from the work of Michalski (2010) and Michalski et al. (2011) who used the same model as a synthesis method for the simulation of large-span umbrellas. The prescribed mean velocity, $\overline{\mathbf{u}} = (\overline{u}_1, 0, 0)$, varies vertically according to the standard log-profile

$$\overline{u}_1(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right), \qquad (1)$$

with z the height above the ground, u_* the friction velocity, $\kappa \approx 0.4$ von Karman's constant and z_0 the surface roughness length. The time-varying inlet velocity is then computed as the sum of the mean and fluctuating components

$$\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}'. \qquad (2)$$

The fluctuations are generated in a box with side lengths L_i, $i = 1, 2, 3$ on $N_1 \times N_2 \times N_3$ grid points with coordinates $x_i = n\Delta L_i$, $0 \le n \le N_i$, $\Delta L_i = L_i / N_i$. At each grid point, their values are defined by the discrete approximation of the inverse Fourier transform

$$\mathbf{u}'(\mathbf{x}) = \sum_{\mathbf{k}} \hat{\mathbf{u}}'(\mathbf{k}) \exp(i\mathbf{k} \cdot \mathbf{x}) \Delta\mathbf{k}. \qquad (3)$$

Here $\sum_{\mathbf{k}}$ is the sum over discrete wave vectors with components $k_i = 2\pi m / L_i$, $0 \le m \le N_i$ and $\Delta\mathbf{k} = (2\pi)^{3/2} / \sqrt{L_1 L_2 L_3}$. Using this definition, the Fourier coefficients are calculated as

$$\hat{\mathbf{u}}'(\mathbf{k}) = \frac{\sqrt{L_1 L_2 L_3}}{(2\pi)^{3/2}} \mathbf{C}(\mathbf{k}) \mathbf{n}(\mathbf{k}), \qquad (4)$$

with $\mathbf{C}(\mathbf{k})$ a 3×3 matrix of model coefficients and $\mathbf{n}(\mathbf{k})$ independent Gaussian complex random vectors of unit variance. The basic components of the simplified model for the fluctuations include a model for the spectral tensor of isotropic turbulence, a set of linearized equations describing the stretching of turbulent eddies due to a constant shearing of the mean flow and an eddy lifetime model. Three modelling parameters are used to control the statistical properties of the synthesized turbulence including anisotropy or stretching of the eddies, a length scale of the isotropic turbulence and the turbulence intensity.

Several possibilities for choosing these parameters are analysed in Mann (1998). The general procedure consists of selecting a reference set of one-point spectra (i.e. spectra computed from a time series of velocity at a single point in space) and solving a least squares curve fitting problem of the model spectra to the reference spectra (Mann, 1994). This approach has a practical significance since measurement data is only required for a single point. Furthermore, codes such as the ESDU International (1985) provide single point data including spectra which can be used to configure the model. Once the model parameters have been selected, the coefficients of $\mathbf{C}(\mathbf{k})$ are fixed. Their definitions are provided by Mann (1998).

In this study, the wind tunnel velocity data used to configure the model was limited to a time series of the velocity modulus, $u = \sqrt{\mathbf{u} \cdot \mathbf{u}}$, and the degree of anisotropy in the wind tunnel was