Abstract
Considerations around wind comfort and safety are important for urban planning and both wind tunnel experiments and CFD are used to predict windiness in the public realm.
Landscaping is a common wind mitigation measure because of its additional benefit in improving the streetscape. However, there is a challenge involved in the accurate modelling of the tree properties.
This paper illustrates two applications of tree modelling in CFD. A validation study is used to explore the sensitivity to foliage density and drag coefficient. A case study is then carried out to evaluate the impact of foliage density and turbulence.

Key Innovations
- The paper explores the capabilities of the recently introduced tree canopy model in OpenFOAM v2006 against wind tunnel experiments.
- The paper evaluates the effects of leaf area density and drag coefficient of a tree canopy for a generic case (isolated tree) and urban case study.
- The paper demonstrates the benefits of an accurate representation of the tree canopy in CFD including both the effects of a momentum and a turbulence term in the simulations.

Practical Implications
The findings of this paper demonstrate the noticeable effects that the inclusion of landscaping can have on the reduction of wind speeds and the differences in incorporating source terms in the turbulence transport equation.

Introduction
Modern cities are experiencing a general trend towards rapid urbanization, and tall buildings in otherwise low or medium-density cities are becoming more common. This transformation has an impact on the pedestrian wind environment, as tall buildings tend to deflect the upperlevel winds to the ground and create uncomfortable and sometimes unsafe conditions for pedestrians and cyclists (Blocken and Carmeliet, 2004). In response to this, several cities around the world (Arens et al., 1989; Boston Redevelopment Authority, 2006; City of London, 2019; White, 1992) require a pedestrian wind assessment as part of their planning process. Pedestrian wind assessments have historically been conducted using an atmospheric boundary layer wind tunnel. However, Computational Fluid Dynamics (CFD) simulations have gained popularity in the industry (Blocken and Carmeliet, 2004; Stathopoulos, 2009) to demonstrate the impact of a new development on pedestrian-level winds. An advantage of CFD over wind tunnel testing is the ability to estimate the wind conditions in all points of the computational domain and not only in discrete measurement locations. New guidelines recently published by the City of London require both studies as part of the planning process (City of London, 2019).
A key component of a pedestrian wind assessment is the design of wind mitigation measures to limit the wind energy at ground. Among others, landscaping is a particularly interesting option to combine a positive wind impact with an improvement of the city streetscape. However, there is a challenge involved in the accurate characterization of the aerodynamic properties of the trees, both experimentally and numerically (Manickathan et al., 2018). A number of literature studies discuss tree modelling using wind tunnel (Bitog et al., 2011; Gromke and Ruck, 2008; Manickathan et al., 2018) and CFD (Buccolieri et al., 2018; Gromke and Blocken, 2015; Mochida et al., 2008).
In most commercial CFD studies, landscaping is generally represented as a porous medium that acts as a momentum sink and is characterized by a drag coefficient ($C_d$) and a porosity index, such as the leaf area density (LAD). The LAD represents the total one-sided leaf area per unit volume and varies within the tree canopy (Lalic and Mihailovic, 2004). Both $C_d$ and the vertical profile of the LAD vary between species (Lalic and Mihailovic, 2004) and need to be evaluated case-by-case. Manickathan et al. (2018) has recently performed a comprehensive wind tunnel study that provides a better understanding of the tree aerodynamic properties and behaviour when exposed to the wind. The paper highlights the effect of the tree porosity on turbulence, which is often ignored by commercial CFD studies. The most recent version of OpenFOAM v2006 implements a tree canopy model that allows for a source term in both...
the momentum and the turbulence transport equation, thus enabling a simpler and more accurate process in describing the behaviour of the flow around the trees.

This paper illustrates two applications where landscape is used to mitigate adverse wind conditions in a public space. First, a validation study is carried out for an isolated tree using OpenFOAM v2006 against the experiments conducted by Manickathan et al. (2018). Then, a sensitivity study to the porosity of the trees is performed for an urban case study and used to examine the effects of representative LAD and C_d values for low-, medium-, and high-dense foliage in a public space next to a medium-rise building. Results show a significant reduction of the wind speeds when landscaping is introduced and highlight the influence of the LAD coefficient. The sensitivity to the use of turbulence sources is also tested and discussed.

Methods

Numerical model
For the urban case study, the computational domain for the CFD simulations has been defined to include the target public space and all surroundings within a radius of about 350 m. The top and sides of the domain have been placed at an adequate distance from the target to ensure that the blockage ratio is less than 10% (Franke et al., 2007). The mesh has been generated using the mesh utility snappyHexMesh, which is integrated in the OpenFOAM software library and allows for the creation of predominantly structured meshes fitted to the model geometry. The final mesh has a resolution of 23 million cells (Figure 1). A structured meshing approach has been chosen to ensure the quality of the computational mesh by using predominantly hexahedral cells of identical size and shape refined in the areas of interests to adequately capture the resolution of the wind at ground level. Cell non-orthogonality, skewness and aspect ratio are all well within acceptable limits (Ferziger and Perić, 1996).

In the case example, the CFD boundary conditions consist of an atmospheric boundary layer profile at the inlet, zero pressure outlet and symmetry at the sides and top of the domain. The inlet velocity profile is configured to replicate a suburban upwind terrain with a roughness of 0.3 m. The simpleFoam solver has been used for the analysis in both the case example and validation study to model the steady-state flow conditions in the domain with the inclusion of RANS turbulence modelling and the k-ω SST turbulence model (Li et al, 2018).

Tree modelling
The landscaping consists of 15 x 8 m tall trees, 9 of which are grouped into a larger porous zone. The usage of porous zones (zones in the domain that modify the momentum with a source term to influence the flow and if applicable affect flow behaviour through the cell region) is a common approach to model grating, louvers, porous bodies as well as foliage (e.g. Gromke and Blocken, 2015). The tree modelling in CFD is carried out by introducing velocity and turbulence source terms (for k and ω) as defined in Yangab et al. (2012). Two cases, with and without the turbulence source terms, are simulated to evaluate the impact of the additional source terms on the results. The porosity of the tree canopy in the application case study is represented in two scenarios: first, using a drag coefficient (C_d) of 0.30 and a leaf area density (LAD) of 1.5 m²/m³ and second, using a drag coefficient of 0.10 and a leaf area density of 1.0 m²/m³ for low-density foliage. In a separate sensitivity study following the experimental setup of Manickathan et al. (2018), the parameters of a model of a tree are adjusted between a range of values to examine the effects of low, medium, and high-density foliage. LAD values between 1.0 and 2.5 m²/m³ (Jeanjean et al., 2015) and C_d between 0.10 and 0.80 (Manickathan et al., 2018) are considered in this sensitivity study.

Results and Discussions

Validation study
Prior to practical application of the canopy modelling in OpenFOAM v2006 in the case study, the numerical
simulation method is first validated by replicating wind tunnel experiments conducted by Manickathan et al. (2018). In these experiments, a model tree with a canopy height of 0.12 m is mounted on a 0.4 m vertical pole. PIV measurements for wind speeds are conducted on a 0.42 m by 0.35 m cross-section plane through the middle of and behind the model tree. For the validation study through OpenFoam v2006, the dimensions of this chosen tree model are converted to full-scale with a height $H$ of 10.44 m and a diameter of 6.2 m at its widest section (approximately 15 cells spanning this length at this point). It is modelled as an elliptical sphere as a simple approximation. In a numerical domain resembling the wind tunnel, the placement of the tree setup is similar to that in the physical experiments. In lieu of mounting the tree model on a vertical pole, it is suspended from the floor of the domain by 10 m to focus the validation study on the effects of the canopy. Like the experiments, the relatively smooth flow in the simulations follows a uniform profile with a reference wind speed ($U_{ref}$) of 10 m/s and a low turbulence intensity of 0.4%.

The drag coefficient $C_d$ of this particular tree model is 0.6, as determined by Manickathan et al. (2018). The LAD has not been explicitly reported in the experimental study; therefore, it has been selected as 1.5 m$^2$/m$^3$ for the simulations. This value may approximately represent tree species commonly found in urban areas (Klingberg et al., 2015).

Vertical contours of both the simulated wind speed and the turbulent kinetic energy taken along the mid-section of the tree are presented in Figures 2 and 3. The origin has been shifted to the bottom centre point of the tree, and the axes indicating the elevation $z$ and along-wind distance $x$ have been normalized by the tree’s height $H$. Results clearly demonstrate the effects of the porous medium as flow is impeded as it approaches and passes through the tree model. As indicated by the streamlines, a region of recirculation develops behind the tree, mirroring the flow behaviour observed in the experiments by Manickathan et al. (2018). Furthermore, turbulent kinetic energy in the wake is increased due to the presence of the tree, similar to the results from the wind tunnel study.

For further comparison, the aerodynamic porosity $\alpha$ of the two-dimensional (2D) wind speed plane can be evaluated using the following Equation (1) (Manickathan et al., 2018).

\[
\alpha = \frac{\int_0^H \overline{u^2} \, dz}{U_{ref} H}
\]  

Equation (1) has been evaluated at a horizontal distance of $x/H = 0.7$. Using the wind speeds from the numerical simulations (Figure 2), this calculation is repeated at the same normalized location. The resulting 2D aerodynamic porosities at a reference wind speed of 10 m/s for this model tree of 10 m/s are similar: 0.085 from the wind tunnel experiments and 0.10 from this numerical study. Differences can be attributed to approximations of LAD in the numerical study and the reconfiguration of the branches and leaves of the tree in the wind tunnel which has not been considered in the simulations.

This simulation of the model tree has also been repeated with finer mesh sizes, all of which yield no significant differences in the results.

**Sensitivity to the tree porosity**

As a continuation of the validation study, sensitivity analyses on the LAD and $C_d$ parameters are conducted. LAD is selected from the following list 1.0, 1.5, 2.0 and 2.5 m$^2$/m$^3$ while $C_d$ is chosen from 0.10, 0.30, 0.60 and 0.80. Ranges for both parameters have been chosen to represent low-, medium- and high-density foliage (Klingberg et al., 2015; Manickathan et al., 2018). The sensitivity analyses are conducted by holding one parameter constant and repeating the simulations from the validation study for each value of the other parameter. For the $C_d$ sensitivity analysis, LAD is set to 1.5 m$^2$/m$^3$. Figure 4 presents the wind speed elevation profiles at different distances normalized by $H$ from the centreline of the tree. Matching physical expectations, trees with lower drag coefficients yield more minimal changes to the simulated wind speeds. This effect mostly continues downwind; however, potentially delayed effects due to disturbances from the additional turbulence breaks this trend at $x = 3H$. 

**Figure 2: Vertical contours and streamlines of the flow wind speed $U$ (m/s).**

**Figure 3: Vertical contours of turbulent kinetic energy $k$ (m$^2$/s$^2$).**
Figure 4. Effect of $C_d$ on wind speed profiles. $LAD$ is constant at 1.5 m$^2$/m$^3$.

The sensitivity analysis is proceeded by examining the effects of $LAD$, holding $C_d$ constant at 0.3. Figure 5 presents the resulting wind speed profiles. Once again, the profiles closest to the tree at $x = 0H$ and $1H$ exhibit a clear trend in which higher values of $LAD$ cause more greater decreases in the wind speed. As the distance from the tree increases, the reduction in wind speed diminishes, more noticeably with the higher $LAD$ simulations.

Case study

After completing the validation against physical experiments, the simulation method can be put to use in a practical application using the numerical mesh, boundary conditions and steady-state solver with turbulence as described previously. Multiple cases have been prepared to observe the changes in the surrounding flow behaviour in different scenarios. These include: a baseline scenario in which no landscaping has been modelled; one in which medium-density foliage have been modelled with the source term in the momentum equation but without the source term in the turbulence transport equation; another one with medium-density foliage but with both source terms modelled; and the final scenario, also like the previous with both source terms, but for low-density foliage. The medium-density foliage cases are characterized by $LAD$ of 1.5 m$^2$/m$^3$ and $C_d$ of 0.3, meanwhile the low-density foliage have $LAD = 1$ m$^2$/m$^3$ and $C_d = 0.1$. Winds are westerly as they are driven from the west inlet of the simulation domain. Landscaping of various shapes and heights ranging from 2.5 to 10 m tall are modelled.

Figure 5. Effect of $LAD$ on wind speed profiles. $C_d$ is held constant at 0.3.

Figure 6: Normalized wind speed contours of the four scenarios simulated for the urban case study with westerly winds.

The results are collectively presented in Figure 6 as contours of the wind speed at 1.75 m above ground which is representative of pedestrian level. The contours are presented relative to a reference wind speed of 11.7 m/s in free stream velocity at 10 m height. Figure 7 shows the streamlines that describe the wind flow through the cluster of trees. From Figure 6, the effect of including the landscaping is noticeable as several areas, notably the south corner of the outdoor open quad and the southern row of trees, exhibit reductions in wind speeds.
Comparing the low-density and medium-density foliage, the differences are not as prominent but there are certain locations, for example, within the centre of the northern group of trees in which flow appears to be more impeded and therefore redirected due to the higher values of LAD and $C_d$. As suggested from the sensitivity study, further increasing these parameters may result in lower wind speeds downwind from the trees. However, care must be taken so that the strong wind flows are not redirected to undesirable areas and that the aerodynamic characteristics of the trees are representative of the real species. In Figure 6(d), the turbulence source term is neglected in the simulations. Compared to the time needed to obtain the results for Figure 6(b) and 6(c), neglecting this term reduces the computational cost by a factor of approximately 1.5. However, including this term in the simulations provides a more realistic representation of the effect of the tree canopy on the wind flow. The results obtained without the turbulence source (Figure 6(d) and Figure 7(d)) show a distinguishable increase in the wind speeds on the sides of the cluster of trees. The trees act solely as a momentum sink, reducing the wind speed through the canopy. The corresponding results obtained with the turbulence source (Figure 6(c) and Figure 7(c)) account for the effect of the turbulence created by the foliage in dissipating some of the wind energy as the wind flows across the canopy. Overall, the results suggest that it is recommended to include the turbulence term as there may be important implications on the usage of outdoor areas with surrounding landscaping.

**Conclusion**

OpenFOAM v2006 enables accessible simulation of landscaping with different types of foliage. For validation of these newly included implementations, wind tunnel experiments of a tree model have been numerically replicated in this study. The results compare well, showing similar flow structures and changes in the wind speed as the simulated winds pass through and around the porous medium. A sensitivity study of two landscaping parameters, leaf area density and drag coefficient, demonstrate similar trends in reducing the wind speeds as these values are increased. Capitalizing on the developments in OpenFOAM v2006, a practical case study for several scenarios has been conducted. Findings demonstrate the noticeable effects that the inclusion of landscaping can have on the reduction of wind speeds and the differences in incorporating source terms in the turbulence transport equation. For this study, neglecting this source term results in higher speeds downwind from the modelled trees, which in certain circumstances may be undesirable and may dictate the planned usage or activities in an outdoor area.

The simple implementation of modelling the porous media in OpenFOAM v2006 provides many opportunities for other studies of wind flow through and around landscaping features and foliage. The sensitivity analyses presented in this study has only been preliminary and thus its continuation, preferably in conjunction with a library of leaf area densities and drag coefficients, is needed. This will be especially important for the consideration of urban trees that lose their foliage during fall and winter seasons. Additional validation against complex tree configurations and shapes rather than a single, simplified tree model will be required to further confirm the accuracy of the simulation results. These investigations will all further inform future applications of this tool in other practical case studies.

*Figure 7: Streamlines that describe the wind flow through the landscaping area for the four scenarios simulated for the urban case study with westerly winds.*
References


