Developing a methodology to model trees for CFD in outdoor comfort

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1. Introduction:

Today, 55% of the world's population lives in urban areas which is expected to increase to 68% by 2050. Studies show that the existing population from rural to urban areas could add another 2.5 billion people in the urban areas by 2050. This will lead to major growth and changes in the cities around the world (United Nations, 2018). Architects and urban planners must cater to these growing needs, and design to create comfortable outdoor spaces despite these changes. Another factor that affects the built environment is trees, in both managing the air quality and wind comfort. (H Akbari, 2001)

2. Objective:

To develop a methodology to model and incorporate trees in computational fluid dynamics (CFD) simulation and analysis for pedestrian comfort. This will impact the wind flow pattern in locations with presence of trees, as a result affecting pedestrian wind comfort. The image below depicts how the presence of trees affects the wind flow in an urban scale. Elevated wind speeds and cornering effects are noticeable in the Figure 1, and the decrease of the same can be seen in Figure 2 with trees. (Girin, SIMSCALE, 2020)

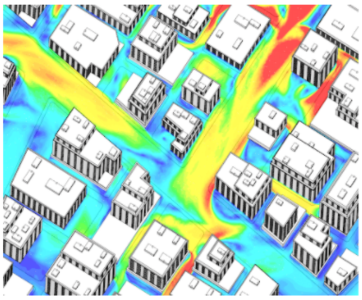


Figure 1-CFD simulation without trees with the cornering effect. Reference (Girin, SIMSCALE, 2020)

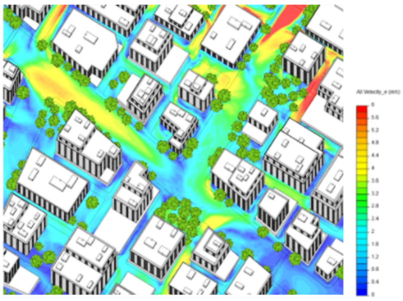


Figure 2-CFD simulation with trees and the cornering effect reduced Reference (Girin, SIMSCALE, 2020)

Modelling a tree for the purpose of analyzing wind comfort and CFD simulation includes several steps. The first step is, building a three-dimensional tree model as per the nature of trees present on the project site. Modelling a simple tree model as seen in Figure 4 will be a cuboid boundary with the porosity properties of a tree. Other ways to model a tree are making a detailed model with the various tree components i.e., individual leaves, branches, and bark Figure 3. Details added to any model, in this case the tree components will make the meshing process during CFD simulation tedious and time consuming. Using such heavy tree models in a large-scale project with multiples trees will slow down the analysis process and will increase the errors during simulation process, this will affect the analysis of pedestrian wind comfort. Hence modelling a complicated tree model will not be an efficient way to analyze the wind comfort.

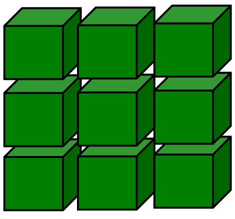


Figure 3-Modelling porous approximation of elements result in simple CFD mesh

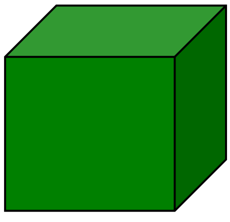


Figure 4-Modelling individual elements result in complex CFD mesh

3. Problem Statement:

- To determine the pressure drop across the trees by verifying the appropriate leaf area volume and drag coefficient.
- To identify the relevant method of modelling a tree for the purpose of outdoor comfort analysis using CFD from the following three methods:

1. Sphere shape with one porosity value for the entire tree
2. A cuboid model with different porosity for each Z axis layer
3. Staggered shape with different porosity for each Z axis

The cuboid model with different LAD for each Z axis layer is feasible to be used further in this study, as this model captures the properties of a tree by each layer in the Z axis.

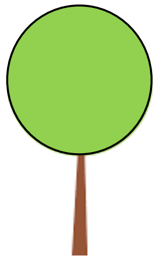


Figure 5- Sphere shape with one LAD value for the entire tree

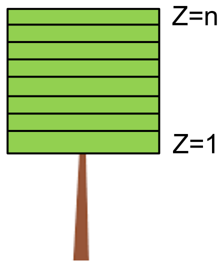


Figure 6- A cuboid model with different LAD for each Z axis layer

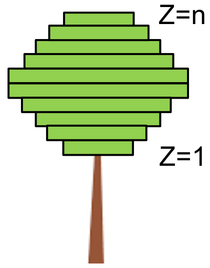


Figure 7- Staggered shape with different porosity for each Z axis

4. Identifying pressure drop across a tree

Pressure drop is defined as the difference in total pressure between two points of a fluid. Pressure drop across objects such as buildings and trees that are part of a built environment impact the wind velocity and pattern. Wind speed being one of the major factors that affect thermal comfort of occupants, accurate analysis of the same is essential while designing comfortable built spaces.

Trees are often excluded from wind analysis such as CFD, as modelling trees close to their natural properties can be complicated. Given the different varieties and changing properties according to climate, identifying the right volume of the tree is an important aspect of modeling trees for CFD.

The difference in pressure across the trees is essential in pedestrian comfort analysis and CFD simulation as it contributes to changing the wind pattern. The tree objects are momentum sinks within individual grid cells that require drag coefficient that is appropriate to the local conditions (Falkenstein-Smith, McGrattan, Toman, & Fernandez, 2019).

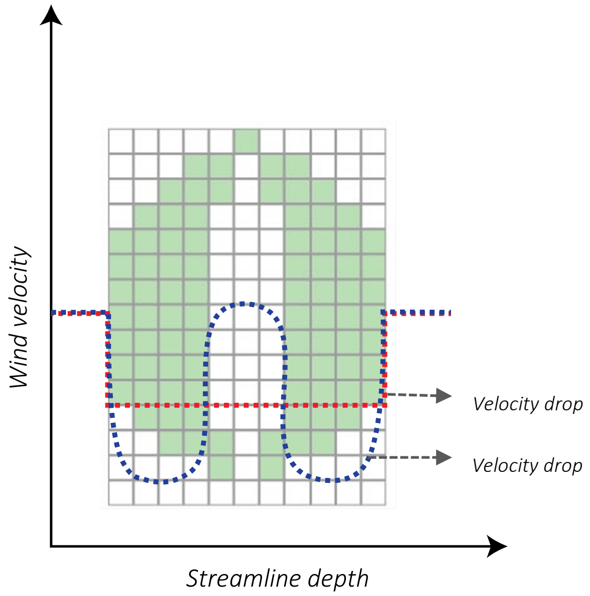
4.1. Factors that affect pressure drop:

The three factors that affect the pressure drop across a tree object are the following:

1. Leaf area density (LAD)
2. Drag coefficient

3. Streamline depth of each z axis level

The LAD and streamline depth is being adapted from Envimet – Albero. Sectional drag is a constant depending on the aerodynamic features of vegetation (Ryan Falkenstein-Smith, 2019).



Graph 1-Velocity profile of the two methods of modelling of LAD in trees

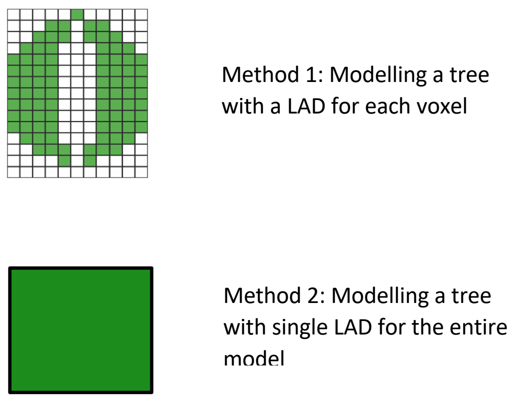


Figure 8- Two methods of LAD modelling

4.2. Methods of modelling a tree with LAD:

LAD for streamline depth of each z axis level can be modelled in two methods. Method 1 is to model the tree with the empty voxel in the center at the location of the bark. This method could be used for projects or research that is done to analyze the wind flow below the tree, as the shape of the tree may alter the wind flow patter below the tree. Method 2 is to model a tree with an average LAD for each Z axis level. This method is applicable for analyses in which the wind flow across the tress is important. We will be using the second method. The difference in wind flow pattern results can be identified in further studies and verified.

Drag coefficient is the resistance of an object in fluid medium. Lower drag coefficient means the object has less aerodynamic resistance. It varies for different shapes according to the surface area. Drag coefficient of a single trees may vary between 1.35 to 2.8, and that of a tree belt will vary between 0.162 to 0.276. Considering the correct drag coefficient value is influential in CFD simulations of trees. For this research a drag coefficient value of 2.8 will be considered. (Falkenstein-Smith, McGrattan, Toman, & Fernandez, 2019)

5. Estimating CFD inputs:

To estimate the inputs for the CFD simulation in Openfoam i.e. Darcy and Forchheimer values, the difference in pressure loss across the tree object has to be calculated. This can be calculated using LAD and drag coefficient from equation 1.

5.1. Calculating pressure loss:

Pressure loss is given by the following formula:

$$\boldsymbol{\lambda = LAD * C_d [m^{-1}]} \quad \textit{Equation 1}$$

Where,

λ – Pressure loss

LAD – leaf area density

C_d – Sectional drag (drag coefficient)

LAD value is derived from the library of software Envimet – Albero. Hence, pressure loss estimated from the Equation 1 is inputted in Equation 2 to calculate the static pressure difference between the windward and leeward side of the porous object.

$$\boldsymbol{\lambda = \frac{\Delta P_{static}}{\left(\left(\frac{1}{2}\right)\rho u^2\right) l}} \ [\boldsymbol{m^{-1}}] \quad \textit{Equation 2}$$

Where,

λ – Pressure loss

ΔP_{static} – Static pressure difference between the windward and leeward side of the porous object

l – depth of the material

ρ – viscosity of the fluid

u^2 – Wind velocity

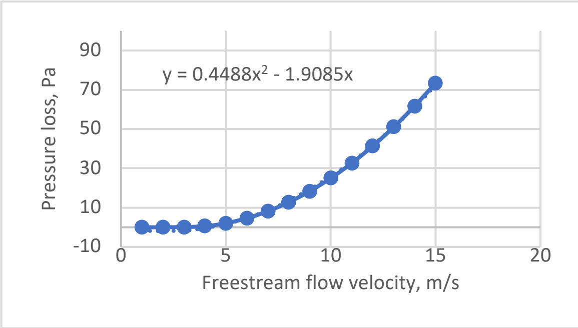
$$\boldsymbol{\Delta P_{static} = \lambda * \left(\left(\frac{1}{2}\right)\rho u^2\right) l \, [m^{-1}]} \quad \textit{Equation 3}$$

5.2. Plotting pressure loss and wind velocity:

The pressure loss estimated from the formula above and the wind velocity for which the calculation is done is then plotted on a linear graph to get the equation Y=mx^2-nx. The values for the Darcy Forchheimer equation which is the input for the CFD simulation is derived from this equation. This model allows us to add the porosity of an object in the fluid domain.

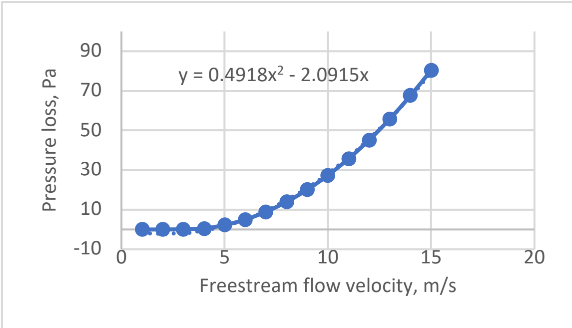
Level of z axis - 2

Wind velocity (u)	Pressure loss(ΔP)
0.1	0.00509832
0.5	0.127458
1	0.509832
2	2.039328
3	4.588488
4	8.157312
5	12.7458
6	18.353952
7	24.981768
8	32.629248
9	41.296392
10	50.9832
11	61.689672
12	73.415808



Level of z axis - 8

Wind velocity (u)	Pressure loss(ΔP)
0.1	0.0055872
0.5	0.13968
1	0.55872
2	2.23488
3	5.02848
4	8.93952
5	13.968
6	20.11392
7	27.37728
8	35.75808
9	45.25632
10	55.872
11	67.60512
12	80.45568



Estimation of Darcy Forchheimer value from the above table can be found in the table below:

Z axis level	C2 (Fluent) (pressure loss term "λ")[m−1]	1/alpha (Fluent) (viscous loss term) [m−1]
1	0	0
2	35.12027491	1217.948718
3	45.2233677	1570.512821
4	35.12027491	1217.948718
5	38.48797251	1335.470085
6	38.48797251	1335.470085
7	38.48797251	1335.470085
8	38.48797251	1335.470085
9	38.48797251	1335.470085
10	38.48797251	1335.470085
11	38.48797251	1335.470085
12	35.12027491	1217.948718
13	45.2233677	1570.512821
14	42.33676976	1463.675214
15	52.91408935	1837.606838

6. Conclusion:

The components that play an important role in outdoor wind comfort includes trees, which plays a major role in modifying the wind path in and around the built environment. This research highlights the importance of considering the correct values for a CFD simulation that includes trees. The leaf area density and drag coefficient are the two important values which must be considered depending on the type and number of trees considered for simulation. Drag coefficient of a single trees may vary between 1.35 to 2.8, and that of a tree belt will vary between 0.162 to 0.276. By modelling a tree with a cuboid model with different porosity for each Z axis layer, with the appropriate values of LAD, drag coefficient and streamline depth of each z axis, a tree model with the natural properties of a tree can be modelled. After the estimation of pressure loss and plotting it with the wind velocity relevant to the location, this model allows us to add the porosity of an object in the fluid domain. Further, the values stated in this research must be verified by parametric CFD analysis for different methods of modelling and various kind and shape of trees.

7. Reference:

Girin, A. (2020, October 9). *SIMSCALE*. Retrieved from https://www.simscale.com/blog/2020/03/model-trees-cfd-porous-media/

(2018, May 16). Retrieved from United Nations: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

Falkenstein-Smith, R., McGrattan, K., Toman, B., & Fernandez, M. (2019). *Measurement of the Flow Resistance of.* National Institute of Standards and Technology.

H Akbari, M. P. (2001). *Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas.* Elsevier.

Nations, U. (2018, May 16). *United Nations*. Retrieved from United Nations: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

Girin, A. (2021, April 14). *SimScale*. Retrieved from SimScale: https://www.simscale.com/blog/2020/03/model-trees-cfd-porous-media/

J. P. Bitog, I.-B. L.-S.-H.-W.-H. (2011). A wind tunnel study on aerodynamic porosity and windbreak drag. *Forest Science and Technology*, 10.

G.J.Mayhead. (1973). Some drag coefficients for british forest trees derived from wind tunnel studies. *Elsevier*, 123-130.

Ryan Falkenstein-Smith, K. M. (2019). Measurement of the Flow Resistance of Vegetation. *National Indtitute of Standards and Technology* (p. 34). US: National Indtitute of Standards and Technology.

(n.d.). Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html