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Streamlined CFD Simulation Framework to Generate Wind-Pressure Coefficients on Building Facades for Airflow Network Simulations

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ABSTRACT

Energy modeling packages such as EnergyPlus and TRNSYS come with capable airflow network solvers for natural ventilation evaluation in multi-zone building energy models. These approaches rely on pressure coefficient arrays of different wind directions based on simple box-shaped buildings without contextual obstructions. For specific sites, however, further attention is needed to avoid geometric oversimplification. In this study, we present an automated and easy-to-use simulation workflow for exterior airflow simulation based on OpenFOAM to generate pressure coefficient arrays for arbitrary building shapes and contextual situations. The workflow is compared to other methods commonly used to obtain pressure coefficients for natural ventilation simulation.

KEYWORDS

Natural Ventilation, Airflow Networks, Pressure Coefficients, Computational Fluid Dynamics.

INTRODUCTION

Due to urbanization and population growth, the United Nations expects a construction demand that is equivalent to 750 times the size of Rome (Heilig, 2012). This may be a unique opportunity to improve the built environment and quality of life through an integrated design process that utilizes Building Energy Modeling (BEM) to create high-comfort habitats with low carbon footprints. The majority of the construction volume is expected to take place in warmer, subtropical and tropical climates. Here, studies have shown that natural ventilation (NV) can be an effective method for space cooling and can lead to significant energy savings compared to mechanical ventilation (Cardinale, Micucci, & Ruggiero, 2003; Oropeza-Perez & Ostergaard, 2014). BEM packages like *Energy Plus* and *TRNSYS* come with capable airflow network (AFN) solvers for NV evaluation in multi-zone BEMs. These solutions rely on pressure coefficient (c_p) arrays of different wind directions and exterior simulation nodes. For simple, box-shaped buildings without contextual obstructers, lookup tables and fast methods for surface-averaged pressure coefficient generation exist, such as the work of Swami and Chandra (Swami & Chandra, 1988) now implemented in *EnergyPlus,* or the wind-pressure distribution model *CpCalc+* developed for *COMIS* (Grosso, 1992). Since then, many attempts have been made to deal with air flow sheltering effects for simplified urban geometries and there is an evolving literature about pressure coefficients for sheltered buildings that are summarized by (Costola, Blocken, & Hensen, 2009). However, for specific sites such as dense urban environments, further attention is needed to avoid geometric oversimplification (Cheung & Liu, 2011). In such cases, computational fluid dynamics (CFD) analyses are required. CFD is a numerical method to calculate the desired flow variables on a number of grid points within a simulation domain by solving discretized Navier-Stokes equations (NSE).

However, the expertise, the modeling effort, and simulation overhead required to perform such analyses often hinder a wider dissemination of AFN-based NV studies. To facilitate modeling of NV in early design processes at urban and complex architectural scale, the authors introduce

Eddy, an easy-to-use tool, that utilizes OpenFOAM to conduct isothermal exterior airflow simulations to generate pressure coefficient (c_p) arrays for the AFNs. The framework is fully automated and generates c_p arrays for arbitrary building shapes and contextual situations using a novel cylindrical domain approach to avoid expensive re-meshing of the domain for different wind directions. Further, a case study for an urban building is presented to compare CFD-based c_p values against the wind pressure distribution model of *CpCalc+* and *EnergyPlus'* internal c_p calculation method called "Average-Surface Calculation" (Swami & Chandra, 1988). The c_p results of each method are subsequently passed on to an *EnergyPlus* BEM with an AFN to evaluate the differences in NV potential using the different NV simulation modes provided by *EnergyPlus*.

METHODS

Overview: Usually, five steps are required to compute c_p arrays for AFN simulations: (1) modeling the building geometry and context with CAD software; (2) defining the simulation domain and meshing of the building geometry and topography; (3) conducting isothermal airflow simulations for a set of wind directions using appropriately assigned boundary conditions; (4) post-processing the CFD data and extracting pressure values on openings for multiple directions and (5) setup of energy model and AFN while providing c_p arrays for all openings in the model. In most cases, these steps are conducted manually and tend to be tedious and error-prone, especially when they have to be repeated multiple times. For step 2 and 3, several best practice guidelines propose adequate domain dimensions, convergence criteria, and relaxation factors. For basic urban CFD simulations, it is considered best practice to construct a box-shaped virtual wind tunnel with predefined dimensions with respect to the building geometry that shall be simulated. A widely used best practice proposed by (Tominaga et al., 2008) suggests the size of the simulation domain to be $z = 6H_{max}$, $l = 20H_{max}$ and w given by a blocking ratio of ≤ 3 %, where z, l, and w are the dimensions of the domain and H_{max} is the height of the tallest building in the building agglomeration. The blocking ratio is defined as the ratio of building area perpendicular to the inlet to the total area of the inlet. A visual representation of those suggestions is illustrated in Figure 1 (A). For cases where symmetry cannot be exploited and where the weather does not have strongly pronounced predominant wind directions, the steps 2-4 would have to be repeated at least eight times to cover approaching wind in 45° increments. However, interpolating the remaining in-between directions often results in significant errors (Cheung & Liu, 2011). This can only be overcome by further increasing the wind direction increments, resulting in greater meshing, simulation, and post-processing time.

Cylindrical simulation domain: To circumvent re-meshing of the simulation domain for every wind direction and to reduce manual and computational overhead, a cylindrical mesh is used to facilitate the simulation of arbitrary wind directions, see Figure 1 (B). The modeling approach has been validated against three cases with measured data showing insignificant differences compared to the best practice box-domain approach (Kastner & Dogan, 2018). Furthermore, the proposed method automates the setup of boundary conditions so that a significant amount of time will be saved to change the boundary conditions in case of an annual wind analysis. More specifically, every lateral cylinder patch represents an adjustable and therefore sufficiently small circular sector and can be assigned to either inlet (blue) or outlet (red) conditions depending on the wind direction of interest, see Figure 1 (B).

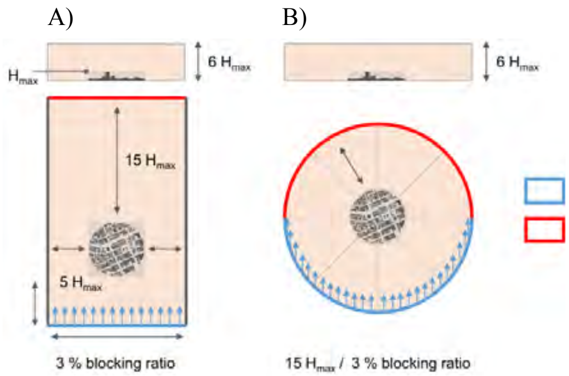

Figure 1: Top view of the (A) of a typical simulation domain for an arbitrary urban area; (B) top view of proposed cylindrical simulation domain accounting for the same best practice requirements.

Figure 2: CAD model of the test case. Case one is simulated without contextual obstructions. Case two is simulated as depicted. Red highlights the zone that was modeled in EnergyPlus.

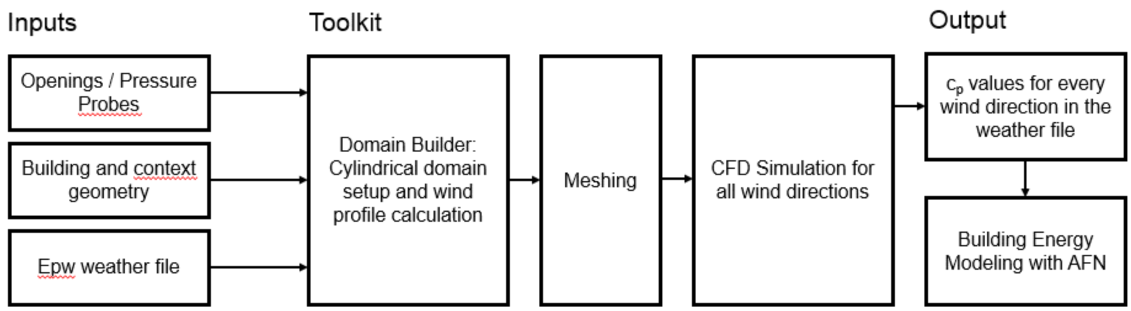

Figure 3: Flow-chart for proposed c_p generation methodology

Implementation: The procedure above has been fully automated and implemented in C# as a plugin for Rhino v5 (Robert McNeel & Associates, 2016b) and Grasshopper (Robert McNeel & Associates, 2016a) for seamless design workflow integration. The developed tool, called *Eddy*, consists of the following main components: (1) the Domain-Builder sets up the cylindrical simulation domain by analyzing the input geometry and applying best practice rules. The Domain-Builder organizes geometric and non-geometric input data and manages the setup of all cases required to model different wind directions (2). The Meshing-Component creates one circular domain mesh that can be used for all wind directions. (3) The CFD-simulation component executes the simulations and encapsulates the result processing routines and probes data for a given slice, envelope or point (figure 4). c_p values are then automatically calculated for all façade openings. A coupling to the Archsim interface for *Energy Plus* (Dogan, 2018) is provided. All simulation framework components and the flow of inputs and outputs are illustrated in Figure 3. Numerical simulations are based on the open source CFD library *OpenFOAM*, using its steady-state RANS models and solvers in combination with a $k{-}w{-}SST$ turbulence model. Pressure and velocity were coupled with the SIMPLE algorithm using three non-orthogonal correctors. Buoyancy effects were neglected due to the domain-decoupled approach and the given air velocities that are well above 1.8 *m/s* (Ramponi & Blocken, 2012; Tecle, Bitsuamlak, & Jiru, 2013). The framework uses a combination of a logarithmic, exponential or uniform profile as introduced by (Bueno, Roth, Norford, & Li, 2014). Further, we assumed that convergence was obtained when reaching residuals of 1e-4 for p and 1e-5 for the remaining parameters. The relaxation factors were chosen to be 0.7 for p and 0.3 for U, k, and ω. Relative wind pressure coefficients (c_p^*) are defined as the difference of the wind pressure coefficient with respect to the inlet condition as given in equation (1) (ASHRAE, 2013). The subscript *(i)* labels the inlet condition. The pressures c_p and $c_{p,i}$ are obtained from CFD simulation results. The reference velocity ($u_{\mathrm{ref,nv}}$) is mainly used to normalize the nodal pressure, and can therefore be set as the largest freestream velocity at the top of the modeling domain. Further, (ρ) is the density of air given in kg·m-3. Those pressure differences can be utilized to calculate flow rates and air changes per hour, thus in turn estimating the NV potential.

$$c_p{}^* = c_p - c_{p,i} = \frac{p - p_{atm}}{\frac{1}{2}\rho u^2{}_{ref,nv}} - \frac{p_i - p_{atm}}{\frac{1}{2}\rho u^2{}_{ref,nv}} = \frac{p - p_i}{\frac{1}{2}\rho u^2{}_{ref,nv}} \quad (1)$$

Case study: Figure 2 shows the case study (Architectural Institute of Japan, 2003) used for the coupling of CFD-based c_p values with an *EnergyPlus* energy model using an AFN. The scale ratio used for the simulations in this paper is 100:1. The c_p values generated with the proposed CFD workflow are compared to *CpCalc+* and the Swami & Chandra model implemented in *EnergyPlus*. The latter only calculates surface-averaged c_p values for orifices with respect to the incident wind angle. The obstructed case shown in Figure 2 is compared to an unobstructed case for which all eight surrounding buildings have been removed. Further, a single zone on the third floor with two opposing orifices (red) is modeled in *EnergyPlus* to compute indoor temperatures, air change rates, cooling loads, and the ASHRAE 55 Adaptive Comfort model. For this zone, a hybrid NV system is assumed that switches to full mechanical cooling if the outdoor air temperature increases beyond 28°C. For each variant, the zone is modeled based on either a residential, classroom or office setting using SIA space templates (SIA, 2006) as well as based on heavy mass or lightweight structure with an average envelope U-Value of 0.4 [W/m2K]. Using weather data from Darwin, Cairo, Hyderabad, Mumbai, New Delhi, Nairobi, Mexico City, Karachi, Manila, Bangkok, Tunis, Izmir, Taipei, Caracas, Cape Town, Melbourne, and Singapore — each variant was further tested yielding a total 102 simulation variants.

RESULTS

Figure 4 compares the c_p values retrieved from the CFD simulation and *CpCalc+*. Without the surrounding buildings, both methods are in good agreement. With surrounding obstructions, *CpCalc+* exceeds its confidence interval and is neither able to estimate c_p distributions nor pressure differences between facades. A comparison of the c_p values of all three methods for eight wind directions is given in Figure 5. The results show that both *CpCalc+* and Swami & Chandra consistently overestimate the c_p arrays. This overestimation leads to significantly deviating air change rates calculated by the AFN in *EnergyPlus* as shown in Figure 6 (left and middle). However, this influence is less significant with respect to the comfort hours where the majority of predictions fall within a ± 5 % interval (Figure 6 (right)). Nonetheless, significant outliers exist when the cooling potential of NV reaches its limit and is thus more dependent on high flow rates.

DISCUSSION AND CONCLUSION

The study has shown that it is possible to automate and streamline CFD-based c_p generation and the coupling with AFN workflows. The juxtaposition of c_p values calculated with different methods reveals that NV modeling is still subject to great uncertainty. Especially in denser environments where contextual building geometries change wind patterns, the current user-friendly tools significantly overestimate wind-induced air flow rates and NV potential. It should be noted that a fairly simple building geometry was used for the case study. It is therefore likely that the performance of the methods by *CpCalc+* and Swami & Chandra will be worse for geometries for which symmetries cannot be exploited. Thus, they are not recommended for (1) geometries that differ from cuboids, (2) projects that are sited in hilly topography (3) buildings with significant contextual obstructions such as urban areas. For such cases, the tool introduced provides a viable alternative that may be used for NV analysis in case of complex building geometries and dense urban sites. It is worth noting that both the setup of the presented study as well as the coupling with the annual AFN simulation took less than 10 minutes. Further, the CFD simulations converged in less than one hour on consumer hardware. As such, it is the authors' hope that the presented tool facilitates the use of CFD-based NV analysis for sustainable and passive design strategies.

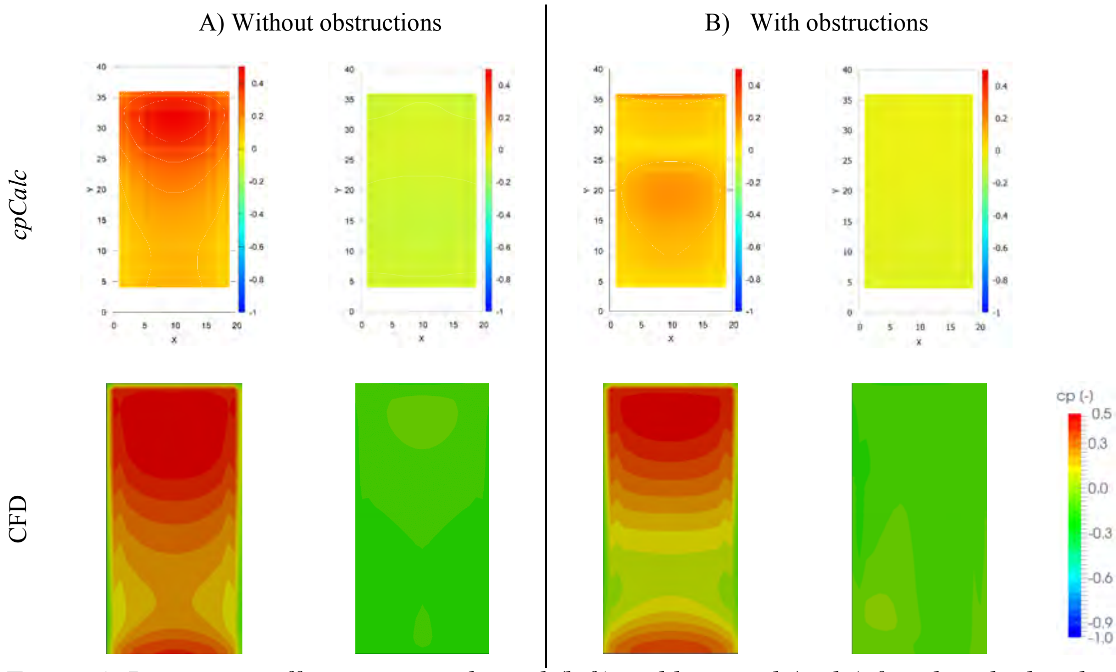

Figure 4: Pressure coefficients at wind-ward (left) and lee-ward (right) façade calculated with CpCalc+ and CFD. The left plots refer to the simulation without obstructions (single building), the right plots to the simulation with obstructions (10 buildings).

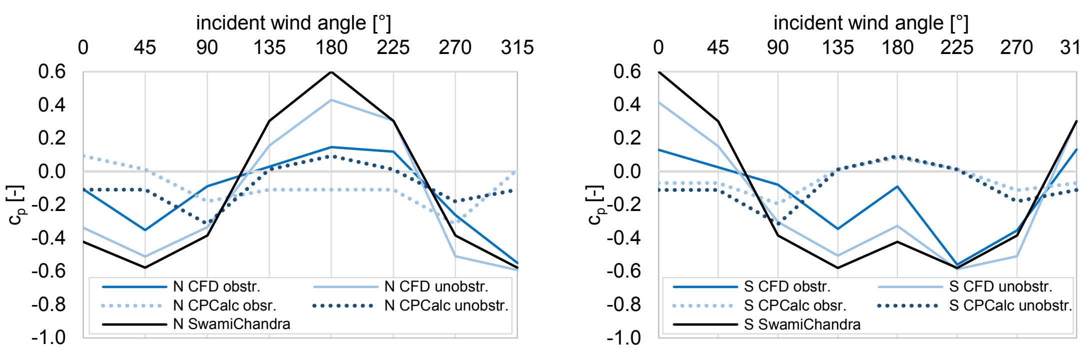

Figure 5: c_p arrays by method for window 1 (left) and window 2 (right).

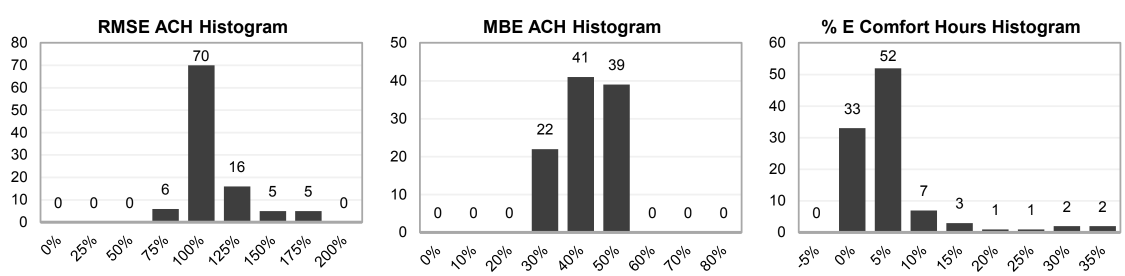

Figure 6: Histograms quantifying the RMSE (left), mean bias error and the difference between c_p values generated by EnergyPlus (auto-calculation) and the CFD simulation (right).

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