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Assessing effectiveness of physical barriers against wind-driven rain for different raindrop sizes

Chinchun Ooi*, Zhengwei Ge, Hee Joo Poh, George Xu

Department of Fluid Dynamics, Institute of High Performance Computing, 1 Fusionopolis Way, #16-16, Connexis North, Singapore 138632, Singapore

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ABSTRACT

Wind-driven rain is a major concern in the design of buildings, for the sake of occupational health and safety. In particular, for facilities such as schools, the ability to identify places at risk of wind-driven rain wetting allows for mitigation and a consequent reduction in accidents due to students slipping and falling on wet patches of corridors. In this work, we analyze a corridor previously identified as a potential area of concern by the facilities management personnel for a representative school in Singapore, and we assess possible mitigation measures for their ability to prevent wind-driven rain wetting in the problem area. By using Lagrangian particle tracking methods to simulate the wind-driven rain, we are able to assess the effectiveness of different mitigation methods such as vertical and horizontal barriers which are typically installed as down-hangs or sunshades. We show that the effectiveness of horizontal and vertical barriers is dependent on raindrop size, with vertical barriers being more effective for smaller raindrop sizes and horizontal barriers for larger raindrop sizes. In addition, we simulate the implementation of an angled barrier and show that angled barriers can be more effective than either horizontal or vertical barriers alone in resolving wind-driven rain issues.

1. Introduction

In Singapore, 450,000 students and 33,000 teachers are hosted across 366 schools. That is to say, almost 10% of the total population in Singapore spends a majority of their time in a school building or related environment over a regular work week. Therefore, a safe and comfortable learning and teaching environment can greatly improve the quality of life of students and teachers in Singapore. In particular, a tropical climate like Singapore, with 167 rain days in a year (45.7% of the year), can be particularly prone to wind-driven rain issues, and adequate and effective mitigation can lead to substantially reduced wetted areas in the school compound and consequently, minimize the risk of accidents.

Currently, the Building Construction Authority (BCA) in Singapore has launched guidelines for computational fluid dynamic (CFD) simulations for green building designs in their Green Mark for Non-Residential Buildings NRB: 2015 [1]. School buildings are also designed to mitigate the occurrence of wind-driven rain via the use of vertical and horizontal barriers (such as down-hangs and sunshades) although these are commonly employed in an ad-hoc and reactive manner.

At the same time, the scientific literature regarding the use of Lagrangian discrete phase models in conjunction with CFD to model the impact of wind-driven rain on buildings during rain events stretches back more than 2 decades since the initial pioneering work of Choi [2–5]. Much of the previous work has been thoroughly reviewed by Blocken and Carmeliet [6] with previous papers describing the use of such models in areas such as understanding the impact of wind speed and rainfall intensity on wind-driven rain [2], and the quantification of amount of water loading on the building facades from wind-driven rain [3,7–9]. Additional work by other authors further validated such a numerical simulation methodology, as they demonstrated that experimental measurements could indeed be accurately reproduced [10–14], with errors on the order of 20%–30% relative to measurements for this Laplacian particle tracing methodology. It is important to note that the majority of prior literature focused primarily on understanding and quantifying the wind-driven rain impingement on building facades, although work by Ge et al. [15] and Foroushani et al. [16] did study the effect of overhangs on the wetting of building facades.

Hence, in this work, we expand on this prior literature by further applying this same numerical simulation methodology to the assessment of wind-driven rain wetting severity in working areas such as link-ways, and more crucially, to the evaluation of efficacy of various common mitigation measures, as opposed to quantifying the impingement on the building façade per se. We conduct a CFD simulation of a representative school in Singapore with its surrounding buildings according to standard BCA Green Mark guidelines, which was developed based on best practice guidelines from Tominaga et al. [17] and Franke et al. [18], and show

* Corresponding author.
E-mail addresses: ooicc@ihpc.a-star.edu.sg (C. Ooi), ge_zhengwei@ihpc.a-star.edu.sg (Z. Ge), pohhj@ihpc.a-star.edu.sg (H.J. Poh), xu_xiangguo@ihpc.a-star.edu.sg (G. Xu).

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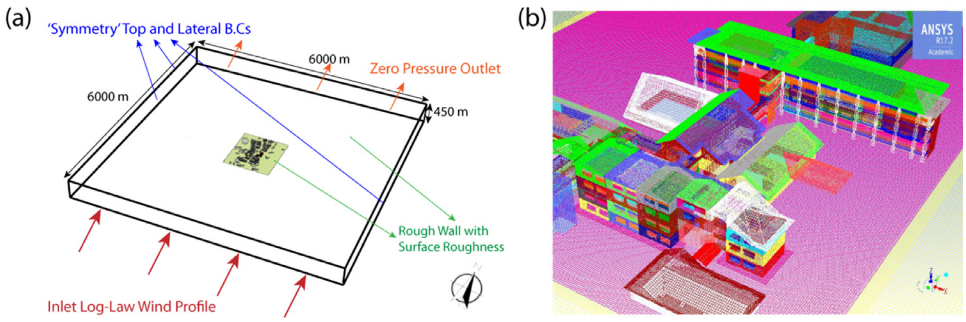

Fig. 1. (a) Schematic for the various boundary conditions used for the set of CFD simulations conducted in this work. (b) Illustration of the grid used for meshing the school compound in the domain.

that our discrete phase model can reproduce severe wind-driven rain issues at a particular corridor in accordance with the school's facilities management team's observations. We then used this methodology for assessment of mitigation measures such as the commonly used horizontal and vertical barriers [15,16], and demonstrate that such a methodology and application of discrete phase models in conjunction with urban CFD models can be of great benefit in the computational design of buildings against wind-driven rain, as it enables the digital testing of various mitigation measures before any costly implementation.

The paper is organized into the following sections. We first outline the exact computational methods used, with regards to the CFD and wind-driven rain simulation settings and choice of boundary conditions, in Section 2. In Section 3, we analyze the typical rain characteristics experienced in Singapore, and discuss this in the context of the choice of raindrop diameters to simulate, before analyzing the severity of wind-driven rain at the location of interest with and without mitigation measures in the form of horizontal, vertical and angled barriers of different lengths, and in the context of their effectiveness against different raindrop sizes. We then end with a Discussion and short Conclusion section.

2. Methods

2.1. CFD simulation settings

In this study, ANSYS FLUENT v17.2 was used to model steady-state incompressible flows under isothermal conditions for all simulations. The realizable k–ε model was used to model turbulence, with second-order discretization schemes for all variables. The pressure-based coupled solver was used for all simulations in this work, and convergence was assumed to be reached when all residuals had dipped below 10^{-4} and the area-averaged velocities across selected planes in the school compound were varying by no more than 1% over 100 iterations.

The boundary conditions are specified as illustrated in Fig. 1. Specifically, symmetry boundary conditions were specified at the top and lateral surfaces of the computational domain while a zero pressure boundary condition was specified at the outlet. The inlet boundary condition was specified with a Logarithmic Law profile, in accordance with prior work by Richards and Hoxey [19]. For the portion of the domain that was not explicitly modeled, a roughness length (z_o) of 1 m was chosen in accordance with the Davenport-Wieringa roughness classification to reflect the degree of urban build-up in the surrounding areas [20]. The inlet wind velocity, k and ε values are thus provided by the following equations:

$$U^*_{ABL} = \frac{U_{ref}\kappa}{\ln\left(\frac{h+z_0}{z_0}\right)} \tag{1}$$

$$U(z) = \frac{U^*_{ABL}}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \tag{2}$$

$$k(z) = \frac{\left(U^*_{ABL}\right)^2}{\sqrt{C_\mu}} \tag{3}$$

Table 1
Table of wind velocities across 4 wind directions (North/Northeast/South/Southeast) for a 6-month return period as used for the wind-driven rain simulations in this work.

Wind Direction	North	Northeast	South	Southeast
Wind Velocity (m/s)	6.2	7.1	6.8	6.8

$$\varepsilon(z) = \frac{\left(U^*_{ABL}\right)^3}{\kappa\left(z+z_0\right)} \tag{4}$$

where U_{ref} is the reference wind velocity at h = 15 m, κ is the von Karman constant, and C_μ is a constant value set at 0.09.

The computational domain and grid sizes were chosen in accordance with BCA's Green Mark simulation methodology and prior literature [8,17,18,21]. Briefly, surrounding buildings within 500 m of the school were explicitly modeled based on geometry derived from Open Street Maps, while the domain was extended such that the directional blockage ratio along lateral and vertical directions remained under 17%. An illustration of the grid used is provided in Fig. 1, with an extremely fine cut-cell mesh for the school (smallest dimension of 0.125 m), growing to 8 m at the furthest lateral extents of the domain, and 32 m at the largest.

2.2. Wind-driven rain simulation settings

Models were solved to convergence for flow before the discrete phase model was used to simulate raindrops for assessing wind-driven rain. Four wind directions (North/Northeast/South/Southeast) were assessed for each case as these are the prevailing wind directions for the monsoons in Singapore, and hence, are considered the most likely periods for issues due to wind-driven rain. A return period of 6 months was selected for this work after consultation with the school facilities management, as they cite a frequency of at most once every six months as their ideal maximum frequency for recurrence of wind-driven rain issues after mitigation. The reference wind speeds for a return period of 6 months for the different wind directions as presented in Table 1 are based on Singapore's National Environment Agency's 32 year historical data [1].

In our wind-driven rain simulations, 4 raindrop sizes were considered for assessment of wind-driven rain (0.5/1/2/5 mm), and each raindrop size was run independently of the others, with only one-way interaction with the wind phase. The wind is assumed to remain unaffected by the raindrops as the volume fraction of rain in air is anticipated to be very low. The raindrop equation of motion is solved with a 0.01 m length scale, and standard physical properties for liquid water are used. In addition, gravitational effects are considered for the raindrop equation of motion, with gravity being specified as a standard 9.81 ms^{-2}. Hence, the particle equation of motion solved by Fluent is given by the

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