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Simulating wind-driven rain on building facades using Eulerian multiphase with rain phase turbulence model

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ABSTRACT

Wind-driven rain (WDR) is responsible for many types of damage to building façades and contributes to storm water management problems in urban environments. Consequently there is significant interest in accurately predicting WDR using computational fluid dynamics (CFD) simulations. In this paper an Eulerian multiphase (EM) method is proposed which includes applying a turbulence model for solving the rain phase equation closure rather than a response coefficient to approximate turbulent behaviour. The simulations are conducted using AVL FIRE™ with standard $k-\varepsilon$ model and are validated against experimental data for two cases. The results produce an error ranging from 5% to 39% in the first case and from 9% to 72% in the second case. The discrepancies are attributed largely to the unsuitability of the standard $k-\varepsilon$ in predicting the flow accurately as well as the limited number of raindrop phases. While the results are not as accurate as other research has shown, the method described in this paper allows for greater flexibility when working with transient rainfall conditions and gives an alternative to the previously proposed response coefficient for modelling turbulent dispersion. The method is viable for calculating general WDR distribution patterns on a façade and can be improved to offer more accurate results.

1. Introduction

In recent decades there has been significant interest in predicting damage to building façades due to rainwater runoff, frost, vegetation growth, etc. [1]. The most prominent cause of these issues is moisture accumulation during rain events, specifically by wind-driven rain (WDR). Due to this there have been efforts in many regions on the planet to identify areas where constructions must take into account increased levels of precipitation using rainfall data. Such efforts can be found in Spain [2], Turkey [3] and Canada [4], to name a few. While there exist models describing the hygrothermal behaviour of various types of building façades [5–10]; most do not include the exterior effects of WDR such as individual raindrop splashing, pooling and wetting patterns caused by runoff. The works taking this into account include the concept CFD-HAM (heat-air-moisture) model by Blocken et al. [11], a simplified numerical model for runoff [12], a raindrop impact and evaporation model [13] and the HAM model with first order runoff, developed by Van den Brande et al. [14]. Another area of focus with relation to this problem is the acquisition of appropriate datasets for use in validation of the various models mentioned above, such as the work by Nore et al. in Norway [15].

An additional concern caused by WDR runoff lies with storm water management in urban environments. Current systems in Scandinavia are insufficient and are predicted to be further pressured with an increase in yearly precipitation level [16]. In 2014 there were several instances of flooding recorded in Stockholm and Göteborg, Sweden. Due to the nature of urban environs there are limited options for improvement of storm water mitigation and one of the most effective methods at reasonable cost has been shown to be green and blue roofs [17,18]. The issue is not unique to Scandinavia and there has been similar work on quantifying storm water mitigation using green roofs in various climatic zones such as Great Britain [19], Italy [20], Australia [21], Denmark [22] and Hong Kong [23]. These constructions require further research in terms of material performance, optimal placement, the effects on existing building micro-climates and overall impact on city-wide storm

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water runoff reduction. In more recent years as computational power has increased there have been developments in modelling these problems using computational fluid dynamics (CFD) however there is significant room for improvement. In this paper we focus upon modelling WDR impingement on building façades with increased accuracy.

The first method for calculating WDR on building façades was developed by Choi [24] [25], and utilized 3D steady-state RANS with standard $k-\varepsilon$ turbulence model for calculating the wind profile and Lagrangian particle tracking (LPT) for calculating raindrop trajectories. The process of calculating impinging WDR required the iterative calculation of precise raindrop trajectories for each wind speed, direction and raindrop diameter and was consequently computationally and temporally expensive. Blocken and Carmeliet utilized this method including validation with experimental data and expansion to the temporal domain while maintaining accurate results [26–28]. The experimental data was gathered at the VLIET test building of the Laboratory of Buildings Physics, Katholieke Universiteit Leuven in Flanders, Belgium. A study was undertaken in 2009 by Akubu et al. to determine the accuracy of the technique on WDR with wind directions oblique to the building façade [29] while Blocken et al. tested the performance of four turbulence models on capturing the wind blocking effects of two buildings on WDR distribution [30]. Foroushani et al. applied the method to determine the effect of overhangs on the WDR distribution over the building façade [31].

In 2010 Huang and Li published a paper detailing a modification to the method proposed by Choi using Eulerian Multiphase (EM) to model WDR by dividing the wind and rainfall into phases, each with its own volumetric ratio, and categorized by a specific raindrop diameter [32]. The new method allowed for calculation of WDR on all building faces simultaneously as well as reduced the user-end calculation time. It was validated against simulations and experimental data provided by Blocken and Carmeliet [33]. Kubilay et al. published a paper in 2013 [34] using the model proposed by Huang and Li wherein the turbulent dispersion term is neglected for simplicity and the results are validated against the data gathered at the Hunting Lodge St. Hubertus in the Netherlands by Briggen et al. [35]. Turbulent dispersion is characterized as the mass flux contribution from the mean turbulent flow and has the greatest effect in areas with high wind-blocking and consequently large velocity fluctuations. The accuracy of the new method was comparable to that attained using Choi's method however the user-end time was reduced by an estimated factor of 10 [34], among several other advantages [32]. One year later Kubilay et al. released two papers on the application of the EM quasi-steady method to an array of cubes in close proximity to each other and on the Hunting Lodge St. Hubertus [36,37]. In these works the turbulent dispersion term is included and the closure of each rain phase is attained by introducing a response coefficient which determines to what degree the rain phase velocity fluctuations align with those of the wind phase. The solution for the domain is attained by iteratively solving the rain phase equations until the desired residual values are reached and the catch ratio is calculated from this solution for the entire building façade. The results of the simulation on the cubes was validated against detailed meteorological data gathered from a site in Switzerland [38] and the Hunting Lodge results were compared to the previous results from the simulation without the implementation of turbulent dispersion and the accuracy was shown to improve slightly in the new model. There remains disagreement over whether the accuracy increase contribution from including turbulent dispersion is sufficient to justify the increase in model complexity and further research is necessary on this topic.

The most recent contributions to the models being used for WDR calculation come in the form of two papers, the first of which is by Kubilay et al. [39]. and applies the same technique used previously with the response coefficient on a slightly different cube configuration. The results in this paper are validated against experimental data taken from a corresponding configuration at the EMPA lab in Switzerland. The second paper is by Wang et al. [40]. and extends the cube array simulation by Kubilay to an array of high-rise structures. In the paper by Wang et al. no turbulence dispersion is included and the results are not validated.

While the results from the quasi-steady simulations performed in the above listed works have been largely accurate, the expansion of the presented techniques to full multiphase simulations and other turbulent models has not been attempted. In this paper we will present an extension of the EM method by solving the turbulent closure equations for the rain phases. In Section 2 the methodology for solving WDR using the EM method is presented. Section 3 covers the technical details of the two cases on which CFD is performed. In Sections 4 and 5 the results of the simulations and discussion are given, respectively. A brief conclusion is included in Section 6.

2. Methodology

The method used in this paper is an extension on the model first proposed by Choi [25] and modified by Huang and Li [32]. Rather than focus on the quasi-steady application we will determine the accuracy and resource requirements required by the EM method solving the full turbulence equations for all phases, including the rain phases. This approach avoids the implementation of any response coefficient and allows for the modelling of turbulent dispersion in a dynamic environment. While it is possible to run such methods in fully unsteady conditions we will focus on validation of this method on singularly chosen time steps for which we have experimental data.

2.1. Wind phase governing equations

The wind phase is solved before the rain is added in order to reduce calculation time by taking advantage of a more accurate initial condition when running the multiphase portion of the simulation. Steady-state versions of the 3D RANS and standard $k-\varepsilon$ turbulence model equations presented in Ref. [25] are used to calculate the wind profile and convergence is reached prior to the inclusion of any rain phases. In standard $k-\varepsilon$ the following model constants are used: $c_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $c_{\varepsilon 1} = 1.44$ and $c_{\varepsilon 2} = 1.92$.

2.2. Rain phase governing equations

The multiphase unsteady equations of mass and momentum conservation for the additional phases, representing the rainfall, are given by

$$\frac{\partial(\rho_w \alpha_k)}{\partial t} + \frac{\partial\left(\rho_w \alpha_k \overline{u}_{k,j}\right)}{\partial x_j} = 0, \quad (1)$$

$$\frac{\partial(\rho_w \alpha_k \overline{u}_{k,i})}{\partial t} + \frac{\partial\left(\rho_w \alpha_k \overline{u}_{k,i}\overline{u}_{k,j}\right)}{\partial x_j} + \frac{\partial\left(\rho_w \alpha_k \overline{u_{k,i}' u_{k,j}'}\right)}{\partial x_j} = \rho_w \alpha_k g + \rho_w \alpha_k \frac{3\mu_a}{(\rho_w d)^2} \frac{C_d R}{4} \left(\overline{u}_i - \overline{u}_{k,i}\right), \quad (2)$$

where α_k is the volume fraction of kth rain phase, $\overline{u}_{k,i}$ the ith