J. Wind Eng. Ind. Aerodyn. 142 (2015) 82–92

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Numerical simulations of wind-driven rain on building facades under various oblique winds based on Eulerian multiphase model

Hui Wang*, Xiaozhen Hou, Yangchen Deng

School of Civil Engineering, Hefei University of Technology, Hefei 230009, PR China

ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form
21 January 2015
Accepted 26 February 2015

Keywords:
Wind-driven rain
Eulerian multiphase model
Wind directions
Catch ratio
Building complex

ABSTRACT

Wind-driven rain (WDR) is an important factor affecting the hygric behavior and durability of building facades. In recent years, CFD simulations of WDR impinging on building facades almost have been focusing on isolated buildings for wind directions perpendicular to the facades. Very few efforts have been made towards study of complicated WDR on buildings considering group effect and the effect of varying wind direction. By virtue of the WDR simulation approach based on the Eulerian multiphase model, this paper presented a validation study of CFD simulations of WDR for an array of low-rise building models provided by recently field measurements. The simulation results suggested that CFD simulations can provide fairly accurate estimates of WDR for complex situations by the present method. And simulations of WDR are performed for a single building and building complex, analyzing the characteristics of catch-ratio distribution with various wind directions and focusing on the impact of group effect and varying wind direction on WDR. The differences of WDR distribution on the building facades are presented and discussed by comparing the results of the single with those of the complex. The conclusions in this paper can provide references for further research of WDR and design of engineering.

1. Introduction

Wind-driven rain (WDR) is oblique rain with a horizontal velocity component due to the result of driving force by wind (Blocken and Carmeliet, 2004). WDR is one of the most important moisture sources on building facades that lead to a series of engineering problems, such as weathering, salt damage and frost damage at exterior wall surfaces. It affects the hygrothermal behavior and durability of building facades, etc. (Aykut Erkal, 2012; Cornick and Alan Dalgliesh, 2009; Carlos Lopez and Bolton, 2011). Therefore, the distribution characteristics of WDR on building facades obtained is the important foundation to carry out related research (Blocken and Carmeliet, 2004). Currently, three methods exist for determining the amount of WDR: measurements, semi-empirical methods and numerical simulations based on Computational Fluid Dynamics (CFD) (Blocken and Carmeliet, 2004). Generally, measurements are quite difficult, time-consuming and easily suffer from large errors. In recent years, only a limited number of researchers, such as Blocken, Abuku, Kubilay, respectively conducted the WDR measurements on the windward facades for different building models (Blocken and Carmeliet, 2005; Abuku et al., 2009; Kubilay et al., 2014). Semi-empirical model in the ISO Standard for WDR (ISO) and the semi-empirical model by Straube have great limitations in application. Many researchers have been using CFD to assess the WDR amounts falling on building facades. The CFD simulations to estimate distribution of WDR were developed by Choi (1991, 1993, 1994). Hangan (1999), vanMook, Tang and Davidson (2004), Blocken and Carmeliet (2007), Abuku et al. (2009) studied the distribution of WDR amounts for a single building. Their studies showed good agreement between numerical results and corresponding WDR measurements. It is shown that CFD simulations can provide fairy accurate calculation of WDR for a single building (Kubilay et al., 2013).

Currently, CFD simulations of WDR are almost all based on the Euler–Lagrange model. Although that method is useful and valuable, it is quite difficult to adapt WDR simulations for complex situations. In order to simplify calculation, Euler–Euler model is introduced so that WDR research can be performed for complex WDR field. In recent years, Huang et al. and Kubilay et al. performed validation study of CFD simulations of WDR by WDR measurement dataset. The simulation results showed there are many advantages of WDR simulations based on the Euler–Euler model (Kubilay et al., 2013; Huang and Li, 2010; Kubilay et al., 2014). With the development of computing resource and computational algorithms, this method will gradually be the main means for research of WDR impinging on building facades in the future (Lixing, 2008).

WDR is governed by a wide range of parameters, such as building geometry, group effect, environment topography, wind speed, wind direction, rainfall intensity (Blocken and Carmeliet, 2002). In spite of the large amount of work done in the past years, it is an urgent need

* Corresponding author.
E-mail address: hfutwh@sina.com (H. Wang).

http://dx.doi.org/10.1016/j.jweia.2015.02.006
0167-6105/

to conduct further study of WDR on buildings as the basic research subject (Blocken and Carmeliet, 2004). Up to now, CFD simulations of WDR almost have been focused on isolated building under wind directions perpendicular to the facade. In reality, buildings seldom stand alone and wind direction is oblique to the building facade. However, very few efforts have been made towards studies of complicated WDR on buildings considering group effect and various oblique wind (Abuku et al., 2009; Blocken et al., 2009). The difference of the WDR between a single building and building complex still lacks further and systemic research.

In this paper, the content is arranged as follows: in Section 2, numerical simulation method will be established in the Euler–Euler frame. Validation study of CFD simulations of WDR is performed for a building complex model supported by a high-resolution experimental WDR datasets by Kubilay et al. in Section 3, verifying the accuracy and reliability of the WDR simulation approach for building complex with various wind directions. In Section 4, the simulations are conducted for a single high-rise rectangular building with various wind directions, analyzing the characteristics of catch-ratio distribution for various oblique winds. And CFD simulations of WDR are performed for building complex under various oblique winds, focusing on the distribution of catch ratio with various oblique winds and comparing the difference of the of catch ratio distribution on the windward facades between a single building and building complex. Finally, Section 5 and Section 6 provide a general discussion and conclusion, respectively.

2. Numerical wind-driven rain simulation method

2.1. Multiphase flow governing equations

The different phases are treated as interpenetrating continuum for WDR with Eulerian multiphase model. Each phase is solved by a set of the governing equations including N momentum and continuity Equations. Phase volume fraction a_k (a_k the space occupied by each phase) introduced, mass conservation equation and momentum conservation equation for each phase are established and the realizable k–ε turbulence model is adopted (Carlos Lopez and Bolton, 2011).

2.1.1. Rain phase

For rain phase, rain is divided into N phases based on different diameter sizes of raindrops. The range of raindrops diameters of each phase is in $[d_k-(\mathrm{d}d/2), d_k+(\mathrm{d}d/2]$, $k=1, 2, \ldots, N$. a_k represents volume fraction of the Kth phase. The governing equations of the Kth phase are as follows (Huang and Li, 2010):

$$\frac{\partial \rho_w a_k}{\partial t}+\frac{\partial(\rho_w a_k u_{kj})}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \rho_w a_k u_{ki}}{\partial t}+\frac{\partial(\rho_w a_k u_{ki} u_{kj})}{\partial x_j}=\rho_w a_k g_i+\rho_w a_k \frac{3\mu C_d \mathrm{Re}_p}{4\rho_w d_k^2}(u_i-u_{ki}) \tag{2}$$

where ρ_w denotes the density of raindrops, u_{ki} (i being x, y, z) the velocity component of the Kth phase, g_i the component of gravity in the i direction, Re_p the relative Reynolds number, C_d the raindrops drag coefficient, u_i the velocity component of wind in the i direction, and μ the viscosity coefficient of air. a_k represents the volume fraction of kth rain phase, and g_i is the gravity in ith direction.

2.1.2. Wind phase

For wind phase, 3D Steady RANS with the realizable k–ε model is used in the present study (Huang and Li 2010)

$$\frac{\partial \rho_a}{\partial t}+\frac{\partial}{\partial x_i}(\rho_a u_i)=0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_a u_i)+\frac{\partial}{\partial x_j}(\rho_a u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ji}}{\partial x_j}+S_{li} \tag{4}$$

$$\frac{\partial}{\partial t}(\rho_a k)+\frac{\partial}{\partial x_j}(\rho_a k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho_a\varepsilon \tag{5}$$

$$\frac{\partial}{\partial t}(\rho_a \varepsilon)+\frac{\partial}{\partial x_j}(\rho_a \varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho_a C_1 S\varepsilon-\rho_a C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}} \tag{6}$$

where ρ_a denotes the physical density of air, τ_{ji} the Reynolds stresses, G_k the generation of turbulent kinetic energy, σ_k the turbulent Prandtl number for k, σ_ε the turbulence dissipation rate for ε, and S_{ij} the momentum contribution of rain to wind phase, which is calculated as follows:

$$S_{li}=-\sum_{k=1}^{N}\rho_w a_k \frac{3\mu C_d \mathrm{Re}_p}{4\rho_w d_k^2}(u_i-u_{ki}) \tag{7}$$

2.2. Boundary conditions

The computational domain is determined according to the guidelines by Tominaga et al. (2008) and Franke et al. (2011). The buildings are positioned at a distance 5H (H the height of the tallest building) from the inlet, top and side boundaries. The outlet plane is set 15H behind the building.

2.2.1. Wind phase

The inlet profile of mean wind speed is defined with the typical power-law expression in the atmospheric boundary layer. U_{10} (U_{10} the velocity at 10 m height) and α (α power-law exponent) in the present study are set to be 10 m/s and 0.20, respectively. Turbulent boundary is established by turbulent kinetic energy and turbulent dissipation rate (Bencai and Congjun, 2008).

The standard wall functions by Launder and Spalding are imposed at the ground surface and the building surfaces (Launder and Spalding, 1990), with appropriate roughness modification (Cebeci and Bradshaw, 1977). A frictionless slip wall conditions are imposed at the top boundary conditions. Symmetry conditions are applied on both sides of the domain. The outlet boundary is set to be a constant static gauge pressure of 0 Pa.

2.2.2. Rain phase

For rain phase, it is quite difficult to consider raindrops of all diameters. Therefore, the raindrops are grouped based on the raindrop size spectrum, and several representative classes are chosen and calculated. In this paper, a modified gamma distribution by de Wolf is used (de Wolf, 2001), which is calculated as

$$N(d,R)=N_0 d^{\alpha}\exp(-\Lambda d) \tag{8}$$

where $N(d,R)$ is the differential number of raindrops with diameter d per unit volume and per differential diameter range dd. α is a constant 2.93. N_0 and Λ are the function of rain intensity R. N_0 and Λ can be calculated as follows:

$$N_0(R)=1.98 \times 10^{-5}R^{-0.384}\left[1.047-0.0436\ln(R)+0.00734(\ln(R))^2\right] \tag{9}$$

$$\Lambda(R)=5.38R^{0.186} \tag{10}$$

Based on the size spectrum, the raindrop diameters less than 2.0 mm take relatively major proportion when the rainfall intensity is less than 5 mm/h. In the present study, d_k=0.5–2.0 mm are determined with an incremental step 0.5 mm.

The local force equilibrium between gravity and drag force is assumed. Thus the inlet velocity component along the direction of