Building and Environment 114 (2017) 68–81

Contents lists available at ScienceDirect

Building and Environment

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

Analysis of time-resolved wind-driven rain on an array of low-rise cubic buildings using large eddy simulation and an Eulerian multiphase model

A. Kubilay [a, b, *], D. Derome [b], J. Carmeliet [a, b]

[a] Chair of Building Physics, Swiss Federal Institute of Technology ETHZ, Zurich, Switzerland
[b] Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland

A R T I C L E I N F O

Article history:
Received 29 September 2016
Received in revised form
25 November 2016
Accepted 5 December 2016
Available online 8 December 2016

Keywords:
Wind-driven rain
Raindrop behavior
Computational fluid dynamics (CFD)
Eulerian multiphase model
Large eddy simulation (LES)

A B S T R A C T

Time-resolved wind-driven rain (WDR) load is investigated on an array of low-rise cubic buildings using an Eulerian multiphase (EM) model together with large eddy simulation (LES). The influence of wind-flow unsteadiness on the unsteady behavior of raindrops and the WDR intensity is discussed in detail. The wind-flow field predicted with LES has been validated with wind-tunnel measurements. The mean WDR intensity values obtained using the EM model are found to be in agreement with in-situ WDR measurements. The time-resolved simulations show that the instantaneous specific catch ratio values of smaller droplets fluctuate a lot around their mean values due to higher influence of turbulence. Instantaneous specific catch ratios for the smallest raindrops are mainly dictated by local turbulent structures present in the shear layer or below the rooftop level. On the other hand, the motion of larger raindrops is mainly influenced by the larger-scale motions above the cubes. It is also shown that, running means of the specific catch ratio over a time window of 100–300 s of physical time stabilize to a constant value.

1. Introduction

Wind-driven rain (WDR) is the type of rain which has a horizontal velocity vector due to the effect of wind flow occurring at the same time. WDR is one of the most important moisture sources that influence the hygrothermal performance and the durability of building facades with potential negative effects. Rain can lead to film runoff on building facades, which may cause leakage, or be absorbed by the facade, which may transport moisture to internal layers of the facade causing moisture damage. Through such mechanisms, several undesired phenomena in buildings can occur, such as frost damage at exterior wall surfaces [22,47], erosion of building materials [19,44], moisture-induced salt migration [14,22], discoloration by efflorescence [22], surface soiling [16,20] and biological growth such as algae growth on the exterior [3] and mold growth on the interior wall surfaces [2], etc. Accurate prediction of raindrop behavior in the air has the potential to improve the understanding of such phenomena.

WDR intensity on a building is governed by a wide range of parameters, such as building geometry, environment topography, position on the building facade, wind speed, wind direction, rainfall intensity and raindrop-size distribution [6]. A typical time-averaged surface wetting pattern shows large gradients both vertically and horizontally on a single windward facade of a simplified rectangular building [7]. In multi-building environments, the wind-flow pattern around one building is further influenced by other buildings and becomes more complex. As a result, the presence of neighboring buildings influence the WDR exposure on each other [10,34,36]. In addition to the large-scale influences of building size and shape and of surrounding environment, small-scale facade details have a considerable impact on WDR intensity [31].

The works of various researchers in the past have fundamentally contributed to a better understanding and modeling of WDR [5,9]. Computational fluid dynamics (CFD) simulations of WDR are either using a Lagrangian Particle Tracking (LPT) model where individual raindrops are tracked [1,6–8,11,15,20,21,26,43,48,49] or an Eulerian multiphase (EM) model where the rain is regarded a continuum

* Corresponding author. Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, CH-8600, Dübendorf, Switzerland.
E-mail address: aytac.kubilay@empa.ch (A. Kubilay).

http://dx.doi.org/10.1016/j.buildenv.2016.12.004
0360-1323/

[28,31,32,34–36]. A common aspect of the large number of studies based on both the LPT and EM models is that the wind-flow field around buildings is calculated using Reynolds-averaged Navier-Stokes (RANS) models. RANS models have numerical deficiencies around the windward edges and in the wake of the buildings [38,39,45,46], such as the size of the wake and the location of reattachment. Large eddy simulation (LES) is expected to calculate the Reynolds stresses more accurately and, hence, expected to give a more accurate representation of separated flows. The more accurate flow estimation by LES in separation regions can also improve the accuracy of the WDR load on downstream buildings in multi-building configurations. Furthermore, distributions of WDR intensity obtained based on RANS models are usually steady-state values, which are extended into the time domain using the method proposed by Blocken and Carmeliet [6]. WDR calculations with LES have the potential to give more insight in the transient behavior of WDR.

The calculation of WDR intensity in LPT models is usually based on the steady-state streamtube approach. The streamtube approach calculates the WDR intensity based on the conservation of mass between the two ends of the streamtube, relying on the fact that the raindrop trajectories will not intersect each other in steady-state conditions. Therefore, this approach is not applicable when unsteady WDR analyses are performed. Chang and Wu [13] performed a WDR study on different street canopies using LES with an LPT model, where they used time-averaged raindrop trajectories for their analyses. An unsteady WDR simulation with LES using an LPT model would require larger numbers of raindrop injections, increasing the computational cost significantly. In the present study, an EM model is used for WDR, where the continuity and momentum equations are solved for the rain phases which give the distribution of rain phase fraction and rain velocity in the computational domain. EM model provides a simpler integration of unsteady simulations of wind flow in WDR calculation in order to get instantaneous values for rain phase fraction and velocity. To the knowledge of authors, there is only one study so far which analyzes wind-driven rain using LES based on an EM model [27], which performs a validation study on a stand-alone low-rise building and compared WDR intensity estimated with RANS and LES on a stand-alone high-rise building.

The present study analyzes the unsteady WDR exposure of a regular array of low-rise cubic buildings using LES calculations. The geometry is similar to the one that is used for field experiments of WDR [33] and validation of the EM model based on steady RANS calculations [34]. Detailed investigation of the time-resolved wind-driven rain intensity is performed on two buildings of the array configuration. Furthermore, the response of instantaneous wind-driven rain on the local instantaneous wind-flow features is analyzed. In section 2, the governing equations of the multiphase model are presented. Section 3 presents the validation studies performed for the wind-flow field and the WDR. Section 4 describes the building geometry, the computational domain and grid, the boundary conditions, the solution strategy and the solver settings. Section 5 presents the simulation results and the main findings of the study. Finally, sections 6 and 7 provide a discussion and conclusion, respectively.

2. Numerical model for WDR simulation

2.1. Governing equations of wind

In the present study, large eddy simulation (LES) is used for the incompressible wind-flow simulations, resolving the large-scale motions while modeling the small-scale ones. In the present study, isothermal conditions are considered based on the assumption of cloudy conditions and presence of strong winds. The filtered continuity and momentum equations are as shown in Eqs. (1) and (2):

$$\frac{\partial \overline{\overline{u_i}}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{\overline{u_i}}}{\partial t} + \overline{\overline{u_j}}\frac{\partial \overline{\overline{u_i}}}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial \overline{\overline{p}}}{\partial x_i} + \nu\frac{\partial^2 \overline{\overline{u_j}}}{\partial x_i \partial x_i} \tag{2}$$

where u_i denotes the component of air velocity in the direction of the Cartesian coordinate x_i $(i = 1, 2, 3)$, p the pressure, ρ_a the density of air, ν the kinematic air viscosity and τ_{ij} the residual stress tensor. The double overbar denotes LES filtering. The residual stress tensor is modeled based on the Boussinesq approximation as follows:

$$\tau_{ij} - \frac{2}{3}k_r\delta_{ij} = -2\nu_r\overline{\overline{S_{ij}}} \tag{3}$$

where k_r the residual kinetic energy, δ_{ij} the Kronecker delta, ν_r the residual viscosity and S_{ij} the rate of strain tensor. In the present study, the residual viscosity, ν_r, is calculated using the one-equation residual stress model by Yoshizawa [52]. Transport equation models perform better than zero-equation models such as the Smagorinsky model in cases with separating and reattaching flows and boundary layers. For this, an additional transport equation is solved as shown below:

$$\frac{\partial k_r}{\partial t} + \overline{\overline{u_j}}\frac{\partial k_r}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\nu_r\frac{\partial k_r}{\partial x_j}\right) - 2\tau_{ij}\overline{\overline{S_{ij}}} - \varepsilon \tag{4}$$

where the terms on the right-hand side denote the residual turbulent transport, production and dissipation. Note that the residual stress term approaches zero in the limit of small grid spacing. As the contribution by the residual stress is smaller than the contribution by the resolved part, the modeling in LES leads to a smaller error potential, even in cases when the residual stress models are comparatively simpler than the eddy-viscosity models in RANS. The residual viscosity is calculated as follows:

$$\nu_r = C_k k_r^{0.5}\Delta \tag{5}$$

where, C_k is a model constant and Δ denotes the filter width.

2.2. Governing equations of WDR

Governing equations of WDR are solved together at each time-step with the governing equations of wind in order to estimate the unsteady WDR intensity on the buildings. Rain is considered to be composed of multiple phases, instead of a uniform phase, in addition to the air phase. Each class of raindrop size is treated as a different phase, as raindrops with similar size will interact with the wind-flow field in a similar way. For each separate rain phase defined in the Eulerian multiphase (EM) model, the following continuity and momentum equations are solved:

$$\frac{\partial \alpha_d}{\partial t} + \frac{\partial \alpha_d \overline{\overline{u_{d,j}}}}{\partial x_j} = 0 \tag{6}$$

$$\frac{\partial \alpha_d \overline{\overline{u_{d,j}}}}{\partial t} + \partial \alpha_d \frac{\overline{\overline{u_{d,i}}}\,\overline{\overline{u_{d,j}}}}{\partial x_j} + \frac{\partial \alpha_d \tau_{d,ij}}{\partial x_j} = \alpha_d g_i + \alpha_d \frac{3\mu_a}{\rho_w d^2}\frac{C_d \mathrm{Re}_R}{4}\left(\overline{\overline{u_i}} - \overline{\overline{u_{d,i}}}\right) \tag{7}$$