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Impact of location of pollutant sources on air pollution dispersion around a high rise building

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Abstract

Using CFD simulations, the transmissions of aerosol particles emitted by cooling towers to a nearby high-rise building is studied. The building is exposed to a realistic wind profile and the cooling towers are located along different lines and at different distances from the building. Navier-Stokes equations for wind around the building are solved with a Standard k-ε model to simulate the turbulent flow. The Eulerian approach is also used to determine the concentration of aerosol particles on the building at different heights. The total and regional deposition fractions are evaluated and the impact of different parameters, such as location of cooling towers and shape of building, are investigated.

Introduction

Legionaries' disease is a potentially fatal respiratory illness caused by inhalation of tiny droplets which contain the Legionella bacteria. These bacteria are found in almost every moist environment. The cooling towers of air conditioning systems have been proven to provide ideal conditions for the breeding of these bacteria [1]. Cooling towers contaminated with Legionella have been identified as emission source causing infection diseases and even death [2]. In many medical publications, it is reported that residents living in different buildings near a cooling tower can be infected by Legionella, with definitive evidence that the bacteria were emitted from the cooling tower [3]. Aerosol particles are composed of mainly water droplet but contaminated by Legionella bacteria can propagate to buildings near the cooling towers [4]. The location of cooling towers is therefore an important design consideration to control the transition of this infectious and potentially fatal disease.

As aerosol particles are mainly airborne, the dispersion of air pollution is generally controlled by meteorological factors such as ambient wind speed and wind direction. There have been a number of outbreaks of Legionnaires' disease in the world in which wind strength and direction has made this phenomenon worst [5, 6]. Although many researches show that building arrays and street canyons have a significant influence on wind flow, air ventilation and pollutant dispersion within urban area, it is mostly neglected in urban design and development to consider wind-structure interaction as a dominant feature in atmospheric flows [7]. Building shape has a profound effect on the flow field as well as building arrangement. This factor can be more critical when pollutant dispersion is investigated around a specific building [8].

In this research, a numerical model has been developed to simulate the dispersion of aerosol particles transmitted from cooling towers at different locations to nearby buildings. A square-sectioned building and a crucifix form high-rise building are considered to determine the effect of building shape. The impact of wind-structure interaction is explored by numerical simulation to understand the effect of location of pollutant sources on different high-rise buildings, which may benefit urban design with guidelines for the relative location between cooling towers and buildings.

CFD model Setup

Building Geometry and Computational Model Setup

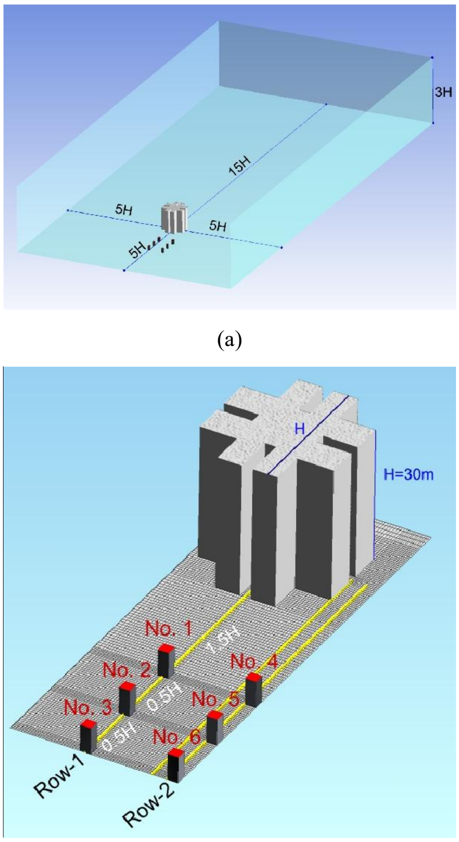
The physical model is based on a 1:30 scale model of a 10 storey high-rise building 30 m in height, which is a typical residential building in Hong Kong. The residents in one of this type of building were influenced heavily by severe acute respiratory syndrome (SARS) in 2002 and the spread of SARS virus in this building from an internal source has been studied in our previous work [8, 9,13]. The dimensions of the building model and boundary conditions were extracted from a boundary layer wind tunnel test [9] and a numerical investigation followed the experiments [8]. The range of domain size used in previous studies was considered to design the flow domain, as shown in Figure 1(a). The distance of 5H from inlet boundary to building is chosen, which is sufficient according to established guidelines [10]. The distance of lateral boundary is 5H. A distance of 15H is considered for the outlet from the building to allow for flow redevelopment behind the wake region. The blockage ratio of the constructed computational domain is about 2%, which is below the recommendation of 3% [11].

To understand cooling tower plume behaviour in the presence of the building, typical cooling towers 2.4m×2.4m square-sectioned and 6m height are considered at six tower locations upstream of the building. As shown in Figure 1 (b), they were distributed in two columns and three rows. One of the columns was located in front of the building on the centreline and the other column 20m off the building centreline which was outside the building footprint. Pollutants were emitted from the top surfaces of the cooling towers which are coloured as red in the figure. Concerning the boundary condition a constant concentration of 1 were allocated to the top surfaces of the cooling towers. Understandably, the pollutant concentration in any part of the domain could be expressed as fraction of concentration in pollutant sources.Based on the wind tunnel experimental data [9], the wind speed and turbulent intensity at the top of the building are about 3.27 m/s and 15%, respectively. Correspondingly, the following equation is prescribed at the domain inlet:

$$\frac{U(Y)}{U_{ref}} = (\frac{Y}{Y_{ref}})^{\alpha} \tag{1}$$

where U_{ref} is mean velocity at the reference height (building height), Y_{ref}, which are 3.27m/s and 1m in model scale. The power law exponent, α, is 0.2.

Other boundary conditions are considered as follows: slip wall condition at top boundary and lateral boundaries (zero normal velocity and zero normal gradients of all variables) and outflow for outlet boundary.



(a)

(b)

Figure 1. (a) Building model within the computational domain; and (b) location of cooling towers

Solution Method

A fully structured computational grid with approximately 2,000,000 cells was generated for the flow domain. The simulations were performed with CFD code ANSYS-Fluent 15.0. The 3D steady RANS equations are solved. The SIMPLE algorithm and QUICK discretization scheme are used for pressure-velocity coupling and convection terms, respectively.

Selection of proper turbulent for pollutant dispersion model has been found challenging in previous works [13, 14]. Although LES and K-ω-SST models are recognized as more precise models than others, these models are highly computationally expensive. In this research, the standard *k-ε* model has been shown to produce satisfactory results in agreement with the experimental data [8, 13]. Hence, *k-ε* model is employed to model the turbulent flow in this study.

An Eulerian approach is utilized to compute pollutant dispersion and particle transport in the domain of fluid. This approach treats the pollutant as a continuum field and assumes that the effects of pollutant particle inertia are negligible. Therefore, Eulerian method can be used for particles with such a low inertia. Large particle counts and low deposition rates can be easily simulated by this method. In this approach, the turbulent and steady form of the mass transport equation governing the convective-diffusive motion of pollutants can be written as [12]:

$$\frac{\partial(u_j C)}{\partial x_j} - \frac{\partial}{\partial x_j}\left(D\frac{\partial C}{\partial x_j}\right) = S_c \tag{2}$$

where C is the pollutant concentration and D is the effective diffusion coefficient for pollutant:

$$D = D_{lam} + D_{turb} \tag{3}$$

where D_{lam} is the molecular diffusivity of pollutant in air, and D_{turb} is turbulent diffusivity of pollutant in air, which is calculated as follow:

$$D_{turb} = \nu/0.9 \tag{4}$$

where ν is the kinematic viscosity of turbulence.

Results and Discussion

To determine the impact of distance and location of pollutant sources on the pollutant distribution around the building, in each simulation pollutants are emitted only from one source of pollutant.

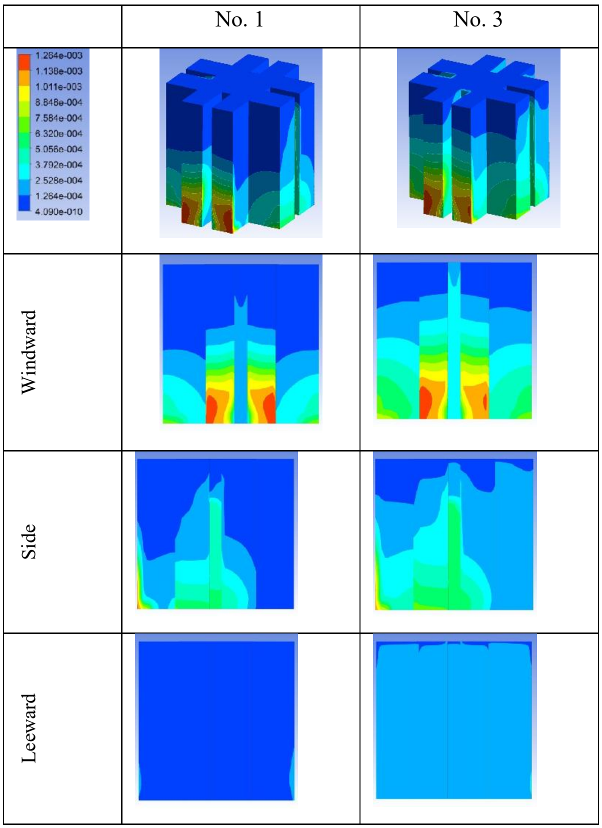


Figure 2. Contours of pollutant concentration on different facades of building

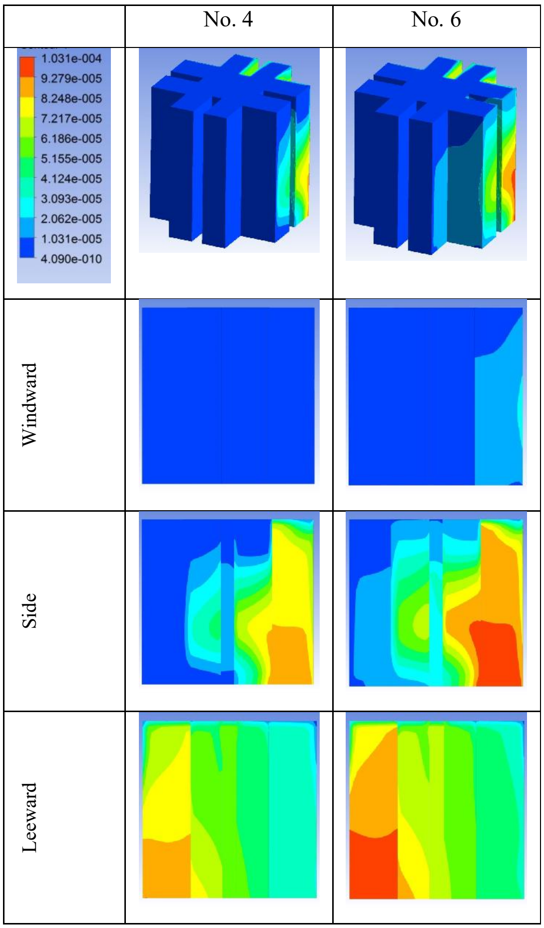


Figure 3. Contours of pollutant concentration on different facades of the building

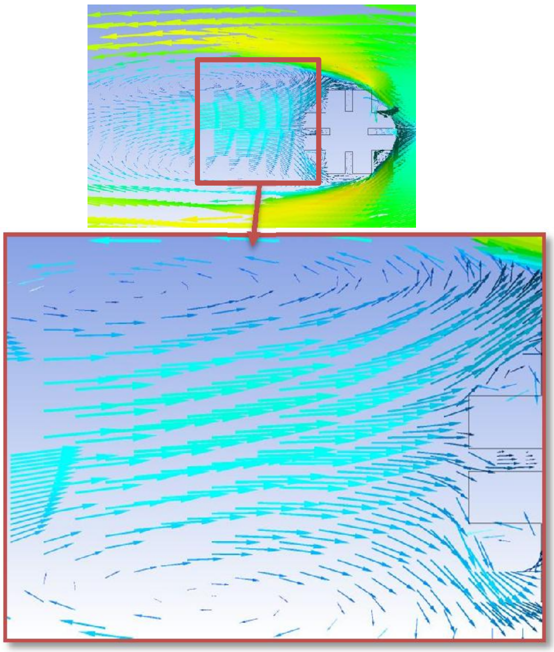


Figure 4. Recirculation zone behind the building

Figures 2 and 3 show the distribution of pollutant concentration around the building for different locations of the cooling tower (source of emission). As observed in Figure 2, when the cooling towers are in line with the building windward face (row 1), the pollutants are concentrated on the windward face. This is mainly because convective mechanism is dominant in pollutant dispersion and pollutants move with fluid particles which impinge the windward face and are dispersed primarily due to downwash. In contrast, in the case where the cooling towers are located off the building centreline, as shown in Figure 3, the upstream flow carrying the pollutants interacts primarily with the side face where the flow separates from the windward corner. The pollutants are largely entrapped within the separated shear layer and entrained into the recirculation bubble underneath the separated shear layer. Once the flow exit the side face, the intense turbulence mixing in the recirculation zone at the lee of the building, as shown in Figure 4, further delays the dispersion of the pollutants by the freestream. This causes the pollutants to be more concentrated on the leeward face. The same trend is observed when the building is replaced by a cube, as shown in Figure 5.

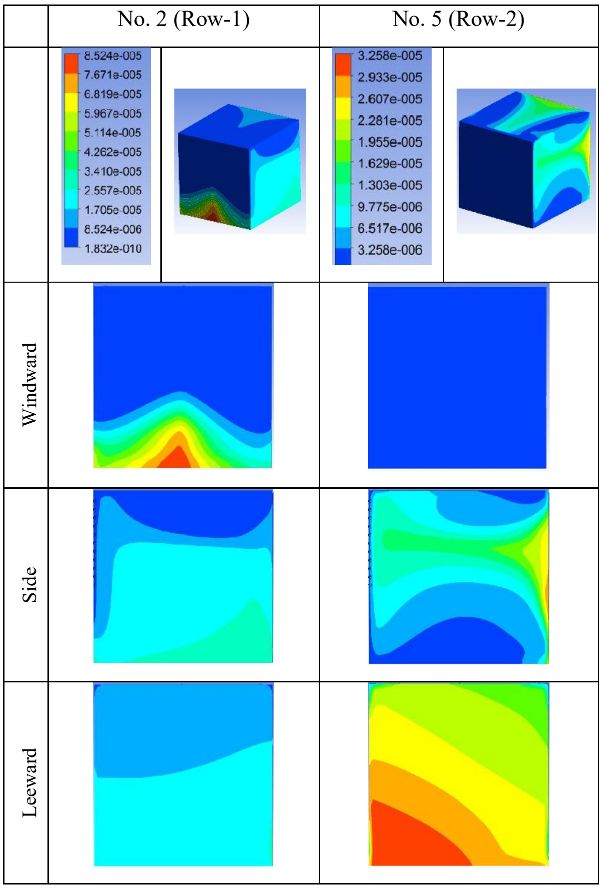


Figure 5.contours of pollutant concentration on different facades of the square-sectioned building

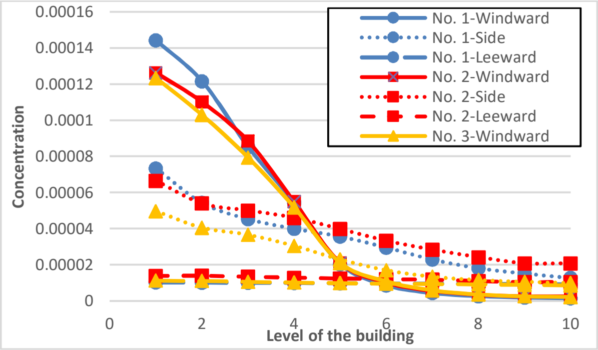


Figure 6. Particle concentration emitted from the Row-1 sources at different levels of the building

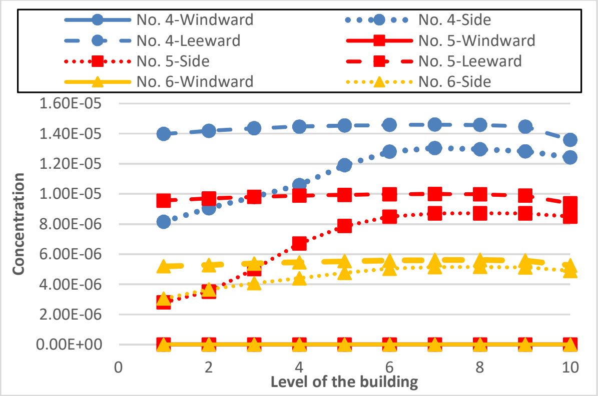


Figure 7. Particle concentration emitted from the Row-1 sources at different levels of the building

Figures 6 and 7 show how cooling tower location affects pollutant distribution around the building. Both figures show a consistent result and reveal that the cooling towers closer to the building cause a higher pollutant concentration in either windward or leeward faces. This is consistent with the natural mixing and dilution processes as pollutants are transported along the streamwise direction. Hence, closer sources of pollutants experience less dilution and mixing to create a higher deposition rate on the building.

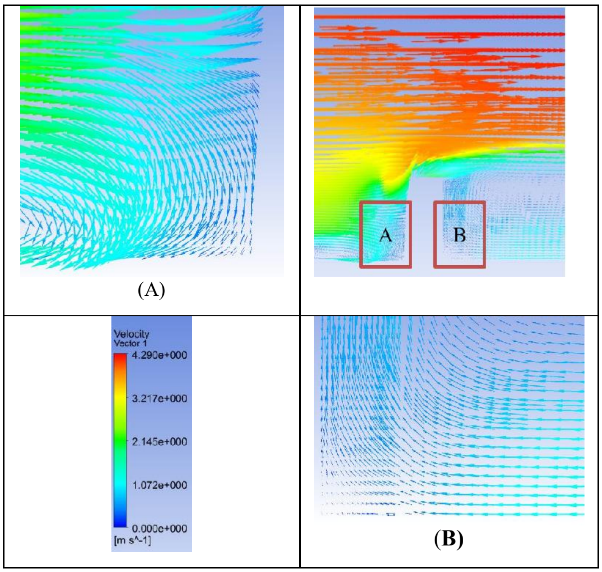


Figure 8. Vertical velocity contour across the domain centreline

Figures 6 and 7 also compare the pollutant concentration between different levels of the building. It can be seen that in contrast to the leeward face, in the windward face, lower levels have higher pollutant concentration. This trend is similar for all the locations of pollutant source, which is consistent with the flow field patterns around the building. Figure 8 shows a vertical velocity vector contour across the domain centreline. As shown in the figure, near the windward face, velocity vectors mostly show downward inclination associated with downwash, thus causing a higher pollutant concentrations at the lower levels. In contrast, in the leeward face region, the velocity vectors reflect a more turbulent flow regime with a tendency towards upward inclination, particularly at close to the leeward face, which drives pollutants to higher building levels.

Conclusions

In the paper, particle pollutant dispersion emitted from sources outside of a high-rise building has been studied using a CFD model and the effect of distance and location of these sources have been investigated through the simulations. Evidently, the pollutant concentration distribution on different faces of the building revealed that convective mechanism as a consequence of wind-structure interaction dominates the pollutant dispersion processes. As a result, two important conclusions can be drawn: firstly, the recirculation formed behind the building can change the particles' path and cause particle impingement on the leeward side of the building. Secondly, downwash in front of the building on the windward face cause higher pollutant concentration at the lower levels of the building. Along the leeward face, the pollutants drifted upward also because of wind-structure interaction.

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