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PREDICTION OF THE MAXIMUM WIND SPEED IN INDOOR ENVIRONMENTS FOR EFFICIENT NATURAL VENTILATION

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Abstract: The efficient natural ventilation in indoor environments is extremely important especially this period with the appearance of new hazardous viruses such as COVID-19. It is well known that the maximum wind speed causes the lowest individual exposure to hazardous substances in an environment (either indoor or outdoor) and as a result its reliable prediction by a numerical model (either simple or complex) becomes of utmost importance. In this study a deterministic model, that was developed for the outdoor environment, is examined as a possible candidate to predict the maximum wind speed in indoor environments. For the needs of the study a wind tunnel experiment is simulated by the LES methodology in order to acquire the maximum wind speed at various locations in an indoor environment. Then the deterministic model, without any change in its parameters, is validated successfully with the LES maximum wind speeds. The present deterministic model can be incorporated in simple methodologies (e.g. RANS) provided that the latest are able to predict the mean speed, the turbulent intensity and a hydrodynamic time scale.

Key words: *Deterministic model, LES, Wind tunnel experiment, Natural ventilation, Maximum wind speed***.**

INTRODUCTION

Scientific interest on indoor air pollution increases, since modern people spend most of their time within enclosed spaces (Klepeis et al., 2001). Concentration values of several pollutants may be higher indoors than outdoors, due to building construction materials, paints, furniture, equipment, smoking, cleaning products and other sources (Zhang and Smith, 2003). Furthermore, this period, it is of utmost importance to study indoor air quality due to the appearance of new hazardous viruses such as COVID-19 (Diaz-Calderon et al., 2021).

The introduction of outdoor air in an indoor environment is one important factor in promoting good air quality. Air may enter in several different ways such as through windows and doors. One method of natural ventilation is the wind induced cross-ventilation which has been utilized in traditional and modern buildings for air quality improvement (e.g. Heracleous and Michael, 2019). While there are several cross-ventilation studies that examine both the indoor and outdoor part of the flow (e.g. Ramponi and Blocken, 2012), most detailed investigations of flow and pollutant dispersion at confined spaces usually consider only the indoor part.

Furthermore, it is well known that the lowest individual exposure to hazardous substances is caused by the maximum wind speed and as a result its reliable prediction by a numerical model becomes of utmost importance. In case of complex models (e.g. LES) the prediction of the maximum value can be achieved by the wind speed time series. However, in case of simple models (e.g. RANS) the incorporation of a deterministic model could be a possible solution. For this reason, in the present study, a deterministic model that was developed for the outdoor environment (Efthimiou et al., 2017) is tested without any change in its parameters, in order to check its suitability to be used in the indoor environment.

METHODOLOGY

In this study we use the theoretical approach proposed by Efthimiou et al. (2017) in order to approximate the maximum time-averaged wind speed in the interval $\Delta\tau$, $V_{max}(\Delta\tau)$, which is modelled by:

$$V_{max}(\Delta\tau) = \bar{V}\left[1 + b\left(\frac{\Delta\tau}{T_V}\right)^{-\nu} I\right] \tag{1}$$

where $\bar{V}$ is the mean wind speed and I is the wind-speed fluctuation intensity given by:

$$I = \frac{\overline{V'^2}}{\overline{V}^2} \tag{2}$$

T_V is the wind-speed integral time scale derived from the wind-speed autocorrelation function $R_V(\tau)$ via:

$$T_V = \int_0^\infty R_V(\tau)d\tau \tag{3}$$

and $R_V(\tau)$ is defined as:

$$R_V(\tau) = \frac{\overline{V'(t)V'(t+\tau)}}{\overline{V'^2}} \tag{4}$$

It should be noted that Eq. 1 was developed initially for the estimation of maximum concentrations of airborne pollutants released from point sources. The parameters b and ν in Eq. 1 can be derived empirically and typically exhibit a wide range of values as demonstrated in previous studies. This is a result of the combination of limitations of the model, experimental errors, insufficient stationarity of the time series and the finite duration of the analyzed signal used to derive these values. Previous studies on the dispersion of airborne material in atmospheric flows suggested indicative values of b = 1.5 and ν = 0.3. For the wind speed in the Atmospheric Surface Layer (Efthimiou et al., 2017) the values for these parameters were set equal to b = 6.0 and ν = 0.3 and the same values are used also in this study for the indoor environment.

THE WIND TUNNEL EXPERIMENT

The experimental measurements were conducted in the atmospheric boundary layer wind tunnel at Niigata Institute of Technology (e.g. Shirzadi et al., 2020). The target building was a cuboid with dimensions of 0.2 m × 0.2 m × 0.16 m for the building width, depth, and height, with two openings of dimensions 0.036 m × 0.092 m over the windward and leeward facades as shown in Figure 1. The target building was surrounded by eight similar buildings without openings, which were arranged in a regular configuration with a planar area ratio of 25%. According to Scopus the specific experiment has been cited 28 times until 13 March 2022.

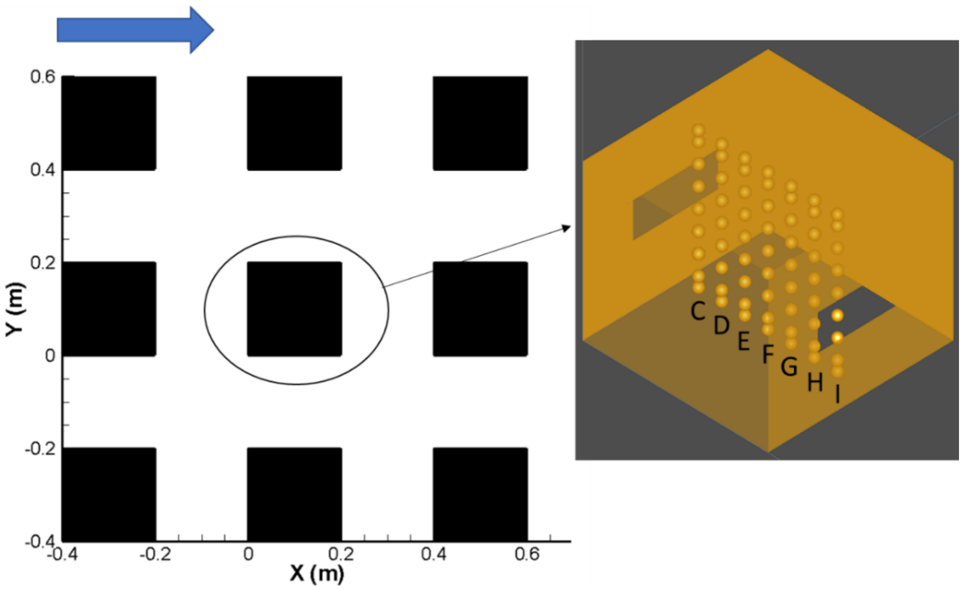

Figure 1. Urban model of idealized complexity mounted in the boundary-layer wind tunnel and close-up view of the interior of the target building. The 63 sensors inside the target building are presented also (yellow circles).

THE NUMERICAL SIMULATIONS

The wind flow computations were performed with the CFD code ADREA-HF (http://www2.ipta.demokritos.gr/pages/ADREA-HF.html). The Eulerian version of the model, solving the LES equations has been used in this study. The code uses finite volumes with rectangular parallelepiped cells for the discretization of the transport equations. To describe the complex geometry, the volume porosity concept is used with solid surfaces of any orientation allowed to cross the computational cells.

In the present simulation, the domain extends horizontally by 0.8 m upwind of the first and lateral buildings and by 2.4 m downwind of the last buildings. The vertical dimension of the domain is 0.96 m. The above dimensions conform to the recommendations of COST Action 732.

The grid is Cartesian. Cubic cells have been selected inside the urban area in order to decrease the discretization errors. Outside the urban area, the grid increases logarithmically by a factor of 1.1. It is well known by CFD practices for microscale modeling that the building height should be described by at least ten cells. Thus, a minimum cell size should be equal to $dx_{min} = dy_{min} = dz_{min} = 0.008$ m. The total number of cells of the present simulation is 1,464,750.

Concerning the boundary conditions, similar strategy has been folowed with Tolias et al., 2018 using the values of the present experiment.

RESULTS AND DISCUSSION

Estimation of the b parameter

Initially the estimation of the b parameter is performed. The autocorrelation time T_V is calculated from the autocorrelation function $R_V(\tau)$ (Eq. 3) on the interval from 1.0 to zero. The wind-speed time series are considered to be characterized by a sufficiently high temporal resolution. At each sensor location, a numerical peak $V_{max}(\Delta\tau)$ is identified and a b value is estimated from Eq. 1 using $V_{max}(\Delta\tau)$; the values of b range from 1.9 to 9.1 (Fig. 2). The value of 6, is exceeded five times out of 63 (i.e. 7.9%) and seems to point more to 'outlier' behaviour. This dataset clearly indicates that a value of b = 6.0 is appropriate for this flow scenario. This is an important finding as the value of 6.0 was estimated also in Efthimiou et al., 2017 for the outdoor environment.

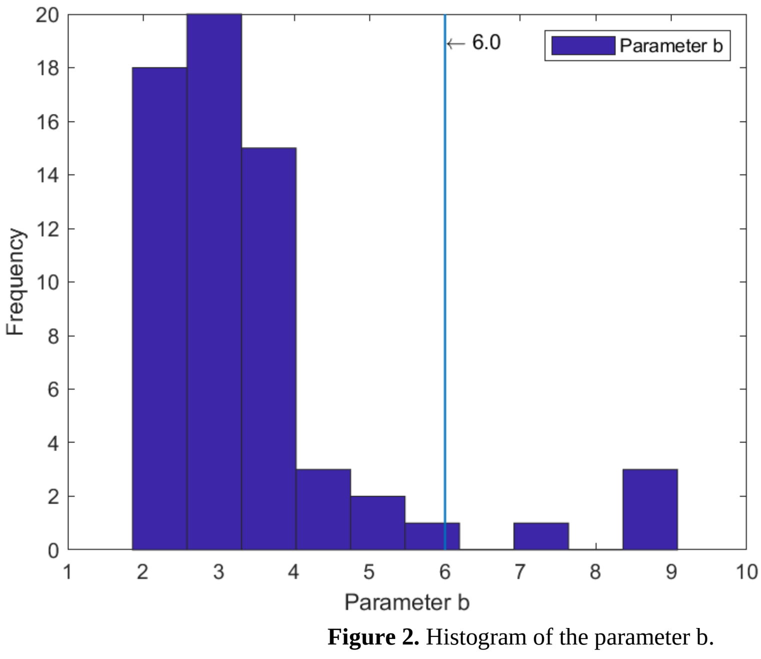

Figure 2. Histogram of the parameter b.

Performance of the deterministic model

Fig. 3 shows a scatter plot comparing $V_{max}(\Delta\tau)$ as obtained from the deterministic model (Eq. 1) fed by LES results and the equivalents predicted by the LES simulation. More specifically, horizontal axis x is the maximum wind speeds predicted from the LES wind speed time series. The deterministic model provides a success rate of 92.1% (only five values are below the 1:1 line), which supports the hypothesis that, similar to the outdoor environment, the proposed theoretical $V_{max}(\Delta\tau)$ serves as an upper bound of the corresponding predicted $V_{max}(\Delta\tau)$.

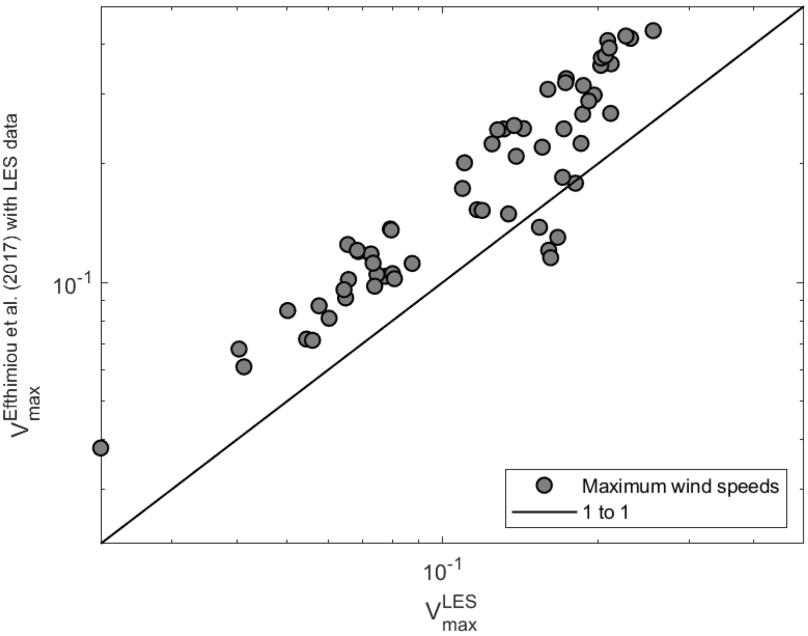

Figure 3. Performance of the deterministic model (Eq. 1).

CONCLUSIONS

By using an existing deterministic model for estimating the maximum wind speed in the Atmospheric Surface Layer based on readily available turbulence statistics (Efthimiou et al., 2017), we demonstrated that this modelling approach can be succesfully implemented also in the indoor environment without any change in its parameters.

The problem itself is quite complex and adequate validation studies require extensive experimental datasets that will include wind speed time series. Such comprehensive validation efforts exceed the scope of a single study, but the work presented here represents a significant first step towards a thorough testing of the proposed methodology.

The deterministic model broadens the capability of ensemble-averaged computational models such as Reynolds–averaged Navier Stokes–CFD models to estimate the maximum wind speed provided that reliable predictions of mean wind speeds, wind-speed fluctuations and integral time scales are available from these computations. This is a work that will be performed in the future.

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