21st International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
27-30 September 2022, Aveiro, Portugal

PROPOSAL FOR MODELLING THE INFLUENCE OF ROOF SLOPE ON URBAN FLOW WITH A DIAGNOSTIC MODEL

Bruno Ribstein[1], Maxime NIBART[1], Daniel Loeb[1], Patrick Armand[2] and Christophe Duchenne[2]

[1]ARIA Technologies, France
[2]CEA, DAM, DIF, F-91297 Arpajon, France

Abstract: The dispersion of pollutants in the urban environment involves the interaction of plumes with the flow disturbed by buildings. The phenomenon includes both the meteorological conditions and the aerodynamic effects of the buildings. ARIA/ARIANET in collaboration with CEA has developed the PSWIFT model in the Parallel-Micro-SWIFT-SPRAY (PMSS) system. The PSWIFT model is a mass-conserving diagnostic atmospheric model.

The buildings are described geometrically so as not to lose resolution when projecting onto the mesh. Each building is cut into several straight triangular-based prisms from polygons stored in ESRI shapefile GIS format. In the PSWIFT model, the influence of buildings on flow is established analytically from prisms and depends on the dimensions of the building projected according to the direction of the prevailing wind.

The building cutting preprocessor was initially limited to converting flat-roofed buildings (2D polygon shapefile format and vertical extrusion using the height attribute). We here present the improvement of the preprocessor in order to treat the slope of roofs or buildings with a more complex level of detail. Simulations with the PSWIFT model were carried out using the obstacle files generated by this new version preprocessor.

The impact of the slope of roofs on the flow is studied. An isolated obstacle is considered in the presented work. The isolated obstacle allows the study of all the zones of influence of obstacles on the flow. PSWIFT results are compared against measurements in wind tunnels and/or reference numerical results of CFD models in the same configurations. The influence of buildings with slanted rools on the flow zones (cavity, displacement, skimming, wake zones) are characterized using the results of the simulations and compared with the effect of flat-roofed buildings of similar dimensions. The height of the flat-roofed buildings equals the lower, or higher, part of the sloped roofs. In the paper, it is shown that the dimensions of the zones around the buildings with sloped roofs are intermediate between those of the flat-roofed buildings considered.

Key words: *aerodynamic effects of buildings in a mass-conserving diagnostic atmospheric model***.**

INTRODUCTION

In the urban environment, exposure to air pollution is a major environmental problem. Pollutants are emitted from various sources and dispersed (advection and diffusion) over a wide range of horizontal length scales. Microscale dispersion refers to processes acting on horizontal length scales smaller than about 5 km. These dispersion processes are referred to as near-field pollutant dispersion, which has different properties from far-field dispersion. Since near-field pollutant dispersion involves the interaction of plumes with the flow disturbed by buildings, the phenomenon has both meteorological and building aerodynamics aspects.

Despite the diversity of existing CFD (Computational Fluid Dynamics) approaches, these models often remain long, expensive, and difficult to implement in a suitable time frame. PMSS (Tinarelli et al., 2007) is a flow and dispersion modelling system constituted by the microscale versions of SWIFT and SPRAY (Tinarelli et al., 1994, 2012) models. It has been developed with the aim to provide a simplified, but rigorous solution of the flow and dispersion in industrial or urban environments in a short amount of time. The semi-empirical model PSWIFT is used to diagnose the flow between buildings and to evaluate the aerodynamic influence of buildings. In this work, we are interested in the impact of architectural details on the flow, and in the consideration of non-flat roof shapes. For an isolated building, the impact of a pyramid-roofed building is evaluated by comparison to a flat-roofed building of similar dimensions. After this introduction, the numerical setup is presented, followed by a sensitivity study. The method used to model the aerodynamic effects of buildings is presented, followed by the results for the isolated building. A summary of the obtained results completes the paper.

DESCRIPTION OF THE NUMERICAL EXPERIENCES

This section presents the numerical setup. The PSWIFT model is compared to Tominaga *et al* (2015) experimental and numerical work. These authors consider pyramid-roofed buildings with three different slopes (3:10, 5:10 and 7.5:10). The results of the wind tunnel modelling (mean velocity and turbulent kinetic energy) are compared to RANS modelling and four types of turbulent closures. In our study, the flow is analyzed around a pyramid-roofed building with a roof slope of 7.5:10, the one with the greatest difference with a flat-roofed building. The building has a square base with side W=1.1He. The flow around this building is compared to flat-roofed buildings of similar dimensions. The height of the flat-roofed buildings equals the lower (He), or higher ($\mathrm{He} + \mathrm{W}/2 \cdot \tan(\theta)$ with $\tan(\theta) = 7.5/10$), part of the sloped roofs. A total of three buildings are considered during our study, listed in Table 1.

Table 1: Modelled buildings

Building	**b1**	**b2**	**b3**
Roof configuration	Flat	Flat	Pyramid
Maximum height	He	He + Wx7.5/20	He + Wx7.5/20

The direction of the wind is perpendicular to the edge of the roof. The wind profile follows a power law $u(z) = U_{He} \cdot (z/He)^{\alpha}$ with α=0.25. For the wind tunnel experiement, the reference speed equals $U_{He} = 2.6\, m/s$, the Reynolds number approximately 3500 and the roughness 10^{-4}m. The quantities are represented in PSWIFT on a scale of 1:1 (He=6m). The horizontal extent of the domain is 15He = 90m in the wind axis (X axis) by 9He = 54m in the transverse axis (Y axis). The vertical extent of the domain is 10He = 60m. The buildings are centered along the transverse axis and placed at the first third of the leeward extent.

SENSITIVITY ANALYSIS

The influence of the resolution of the flow is analyzed by comparing three different meshes: low (151x91x32), medium (226x136x43) and high resolution (451x271x78). The horizontal resolution is, respectively, 0.6m, 0.4m and 0.2m. According to Rafailidis (1997), the vertical influence of the shape of the building is limited to a thickness of 3He, where PSWIFT vertical grid is refined gradually. The following vertical grid is chosen:

[0, 0.25, 0.50, ... dz = He/K ... , 3He, 20, 25, 30, 40, 60]

with respectively dz=He/8=0.75m (32 points), dz=He/12=0.5m (43 points) and dz=He/24=0.25m (78 points). The first three levels are identical to guarantee an identical estimate of surface turbulence.

- If the wind field is best described with a high-resolution mesh, its amplitude changes little. The projected velocities U, V, W increase with the vertical grid resolution because they reach extrema values on edges of the isolated building whose representation in the PSWIFT model depends on the resolution of the mesh.
- Turbulent velocities (U* and W*) and Monin-Obukhov length (L) characterize the flow turbulence apart from the obstacle, and do not change with the grid resolution. Obstacle turbulence is essentially located at the interface between the open-air flow and the zones of influence of the obstacle. By its dependence on the vertical gradient of the projected velocities, the turbulence related to the obstacle increases with the resolution.
- Once non-dimensionalized, the flow in calm wind (with U_{He} = 0.09m/s) shows identical results for wind amplitude and turbulent kinetic energy to those obtained with U_{He} = 1m/s. This is shown in **Figure 1**. Thus, in this flow regimethe aerodynamic influence of the building does not depend on the inlet wind profile.

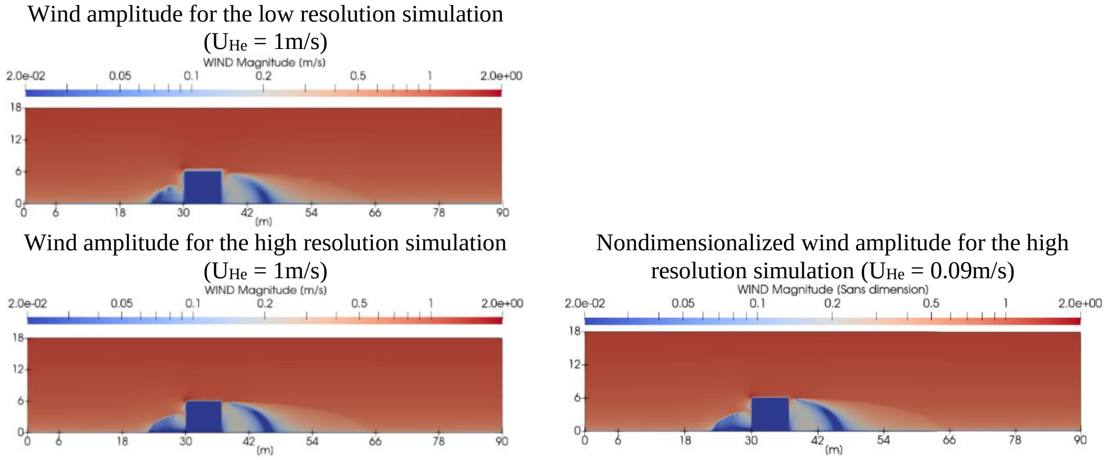
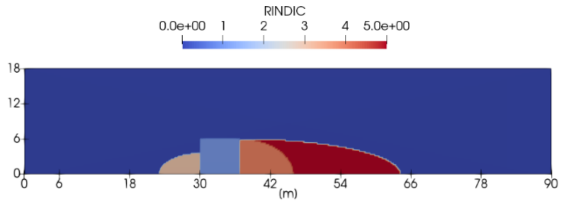


Figure 1: Sensitivity analysis on the wind amplitude

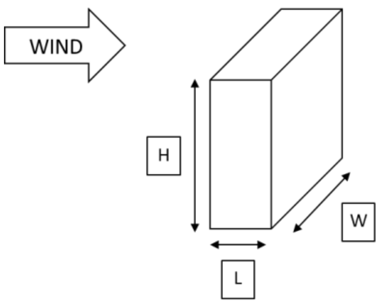
INFLUENCE OF THE BUILDING ON THE FLOW



Type	RINDIC
Open-air	0
Building	1
Canyon cavity	2
Displacement zone	3
Cavity area	4
Wake	5

Figure 2: Possible influences of buildings on flow (left) and its legend (right)

The PSWIFT model is a diagnostic and mass consistent model. By principle, the flow zones under the influence of buildings are taken into account owing to analytical formulae. **Figure 2** shows the RINDIC field, which characterizes the type of each zone: open-air, building, canyon zone, displacement zone, cavity zone, and wake zone. The length L_d of the displacement zone, the length L_r of the cavity zone and the length of the wake L_s are evaluated according to the wind and the dimensions of the building. **Figure 3** illustrates the method implemented in PSWIFT to account for the influence of a building on the flow.



$$L_d = \frac{2W}{1 + 0.8\frac{W}{H}}$$

$$L_r = \frac{1.8W}{\left(\frac{L}{H}\right)^{0.3}\left(1 + 0.24\frac{W}{H}\right)}$$

$$L_s = 3L_d$$

Figure 3: Sketch of the dimensions of a building (left) and definition of the characteristic lengths of influence of the building on the flow (right)

Some buildings are decomposed into several triangular prism to describe their complexity. The implementation of the previous formulation in the PSWIFT model is completed by the following points.

- Sloped roofs are broken down into stripes to represent the slopes by a series of flat steps, like a pyramid or staircase. The pyramid-roofed building is described by juxtaposing the "steps" one behind the other, not by stacking or nesting the "steps" on top of each other.
- Each building is described by a set of triangular prisms. The zones of influence of a building on the flow are described from this set to overcome the specific influence of each individual prism.

- The cavity and wake zones start from the highest and most leeward point of all the prisms describing a building. The displacement zone starts from $0.6H$, which is an empirical approximation of the point of stagnation on the façade.
- For the displacement zone, the bell curve in **Figure 2** is given by the following law in $z(x)$, with x_{FACADE} being the position of the façade:

$$z(x) = 0.6H\left(1 - \sqrt{\left|\frac{x - x_{FACADE}}{L_d}\right|}\right)$$

- The curves delimiting the cavity zone and the wake zone are determined in a similar way.
- **Figure 4** illustrates the importance of setting priorities to resolve ambiguities between different areas of influence.

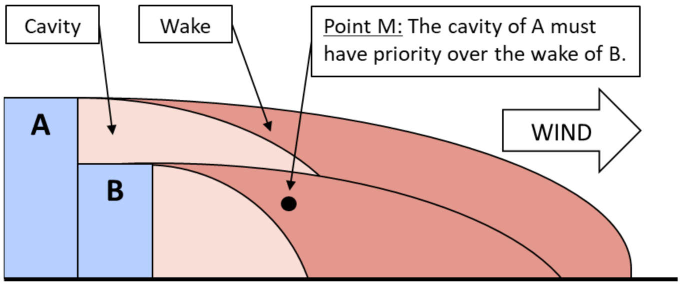


Figure 4: Diagram illustrating a practical priority problem between cavity and wake zones

RESULTS

In Y. Tominaga *et al* (2015), the roof slope appears to have little influence on the cavity length. For the three buildings described in **Table 1**, **Figure 5** shows the RINDIC field that indicates the aerodynamic effects of the buildings.

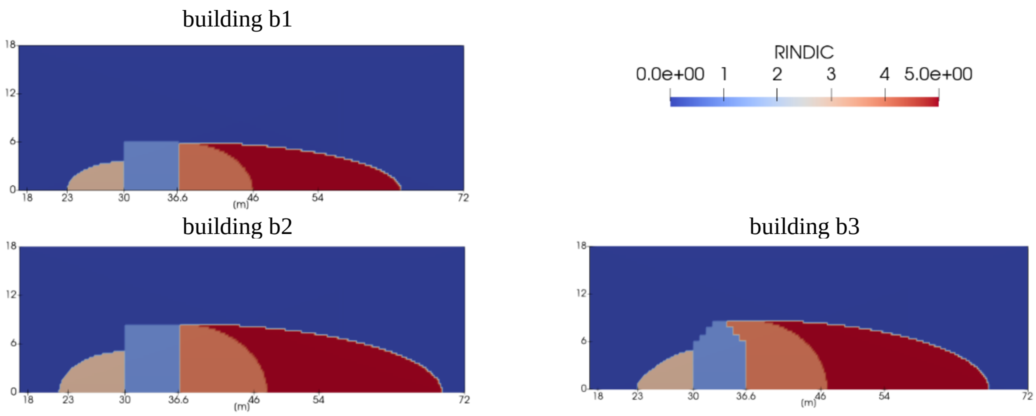


Figure 5: Possible influences of buildings on flow (RINDIC) for different buildings

The building b1 (respectively b2) has dimensions L=W=1.1He and H=He (respectively $\mathrm{H} = \mathrm{He}\,(1 + 1.1 \cdot 7.5/20)$). The numerical application of the previous formulae indicates $L_d \approx 1.17H_e$ and $L_r \approx 1.52H_e$ for building b1 and $L_d \approx 1.36H_e$ and $L_r \approx 1.80H_e$ for building b2. The figure below shows that the displacement and cavity lengths are compatible with the previous formulae.

For the pyramid-roofed building b3, the cavity and wake zones start from the highest and leeward point. The cavity length is in between those of the two flat-roofed configurations. The displacement length equals that of building b1, i.e. characteristic of the upwind façade. The stagnation point is however higher than for building b1, and corresponds to that of building b2.

Figure 6 is an application for the same pyramid-roofed building, but for a different wind direction. The wind has an angle of 45° angle with respect to the roof edge. Horizontal and vertical sections illustrate that the recirculation and wake zones orient themselves according to the wind direction. The dimensions of these characteristic zones are those of the building projected in the wind direction. They are therefore longer than in the case of wind perpendicular to the roof edge.

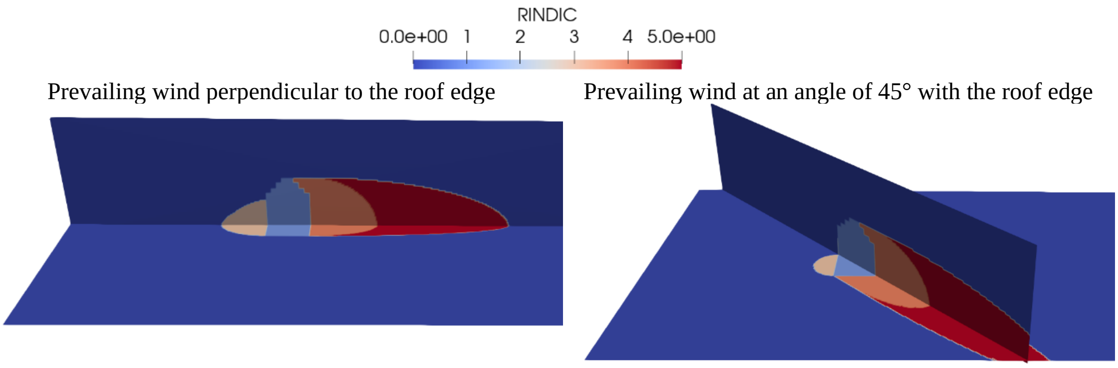


Figure 6: Zones flow characteristics (RINDIC) for the pyramid-roofed building b3

CONCLUSION

PSWIFT's pre-processor allows for a numerical description of buildings with a more complex level of detail than a flat roof representation. Buildings with sloped roofs are sliced to describe roofs with staircase steps. The work presents numerical experiments to verify the consistency of the flow for a pyramid-roofed building compared to flat-roofed buildings of similar dimensions.

In the present work, the impact of an isolated building with sloped roof is studied, and so without having to take into account the street canyons. They are likely to play an important role in a dense urban environment. Wind tunnel modelling (Rafailidis, 1997), 2D RANS simulations (Huang et al, 2009 and Takano et al, 2013), and LES simulations (Kluková et al, 2021) all suggest that street canyons and pyramidal roofs play an important role on the flow.

REFERENCES

Tinarelli G., Anfossi D., Brusasca G., Ferrero E., Giostra U., Morselli M.G., Moussafir J., Tampieri F., Trombetti F., 1994. Lagrangian particle simulation of tracer dispersion in the lee of a schematic two-dimensional hill. *J. Appl. Meteorol*. 33 (N. 6), 744–756.

Tinarelli G., Brusasca G., Oldrini O., Anfossi D., Trini Castelli S., Moussafir J., 2007. Micro-SWIFT-SPRAY (MSS): a new modelling system for the simulation of dispersion at microscale. General description and validation. In: *Air Pollution Modeling and its Application XVII. Springer International Publishing*, pp. 449-458.

Tinarelli G., Mortarini L., Trini Castelli S., Carlino G., Moussafir J., Olry C., Armand P., Anfossi D., 2012. Review and validation of Micro-Spray, a Lagrangian particle model of turbulent dispersion. In: Lin, J., Brunner, D., Gerbig, C., Stohl, A., Luhar, A., Webley, P. (Eds.), Lagrangian Modeling of the Atmosphere. vol 200. *Geophysical Monograph, American Geophysical Union*, Washington DC, pp. 311–327

Tominaga Y., Akabayashi S.-I., Kitahara T., Arinami Y., Air flow around isolated gable-roof buildings with different roof pitches: Wind tunnel experiments and CFD simulations, *Building and Environment*, Volume 84, 2015, Pages 204-213, https://doi.org/10.1016/j.buildenv.2014.11.012

Rafailidis S. Influence of Building Areal Density and Roof Shape on the Wind Characteristics Above a Town. *Boundary-Layer Meteorology* 85, 255–271 (1997). https://doi.org/10.1023/A:1000426316328

Y. Huang, X. Hu, N. Zeng, Impact of wedge-shaped roofs on airflow and pollutant dispersion inside urban street canyons, *Building and Environment*, Volume 44, Issue 12, 2009, Pages 2335-2347, https://doi.org/10.1016/j.buildenv.2009.03.024

Y. Takano, P. Moonen, On the influence of roof shape on flow and dispersion in an urban street canyon, *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 123A, 2013, Pages 107-120, https://doi.org/10.1016/j.jweia.2013.10.006

Z. Kluková, Š. Nosek, V. Fuka, Z. Jaňour, H. Chaloupecká, J. Ďoubalová, The combining effect of the roof shape, roof-height non-uniformity and source position on the pollutant transport between a street canyon and 3D urban array, *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 208, 2021, 104468, https://doi.org/10.1016/j.jweia.2020.104468