A cloud-based platform to predict wind pressure coefficients on buildings

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Abstract

Natural ventilation (NV) is a key passive strategy to design energy-efficient buildings and improve indoor air quality. Therefore, accurate modeling of the NV effects is a basic requirement to include this technique during the building design process. However, there is an important lack of wind pressure coefficients (C_p) data, essential input parameters for NV models. Besides this, there are no simple but still reliable tools to predict C_p data on buildings with arbitrary shapes and surrounding conditions, which means a significant limitation to NV modeling in real applications. For this reason, the present contribution proposes a novel cloud-based platform to predict wind pressure coefficients on buildings. The platform comprises a set of tools for performing fully unattended computational fluid dynamics (CFD) simulations of the atmospheric boundary layer and getting reliable C_p data for actual scenarios. CFD-expert decisions throughout the entire workflow are implemented to automatize the generation of the computational domain, the meshing procedure, the solution stage, and the post-processing of the results. To evaluate the performance of the platform, an exhaustive validation against wind tunnel experimental data is carried out for a wide range of case studies. These include buildings with openings, balconies, irregular floor-plans, and surrounding urban environments. The C_p results are in close agreement with experimental data, reducing 60%–77% the prediction error on the openings regarding the EnergyPlus software. The platform introduced shows being a reliable and practical C_p data source for NV modeling in real building design scenarios.

Keywords

natural ventilation;
building simulation;
airflow network model;
EnergyPlus;
wind pressure coefficient;
computational fluid dynamics

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1 Introduction

In the last years, natural ventilation (NV) has gained increased attention in the seek for achieving energy-efficient building designs. This tendency is driven by the urgent need to decrease the emissions of gases that provoke the greenhouse effect and climate change. In particular, the building stock, including commercial, residential and public edifices, consumes 30% to 40% of the energy demanded worldwide, which means between 25% and 35% of the global CO₂ emission (IEA 2016).

The naturally ventilated buildings can reduce the cooling energy consumption as much as 40%–75%, concerning the air-conditioned buildings (Liu et al. 2014; Tong et al. 2016). Although the potential of the NV effects for several regions around the world has been validated (Sorgato et al. 2016; Tong et al. 2016; Chen et al. 2017), this phenomenon has

been exploited mainly for residential buildings (Carrilho da Graça and Linden 2016). In the commercial sector, artificial air-conditioning keeps dominant through the use of heating, ventilation, and air-conditioning (HVAC) equipment, which represents about 51% of the energy used (Jung and Jazizadeh 2019). So, office buildings remain to be a great potential area to leverage the NV benefits. Especially in high-rise buildings, where wind-driven forces are less influenced by their surroundings as takes place in the low-rise ones (Tong et al. 2017).

Natural ventilation occurs when a pressure difference generated by natural forces, wind (wind-driven NV) and/or buoyancy forces (stack-driven NV), acts on one or more openings of the building envelope to induce airflows between the indoor and outdoor spaces. This exchange serves to supply and remove air mass through the building openings, and if the outdoor conditions are appropriate (e.g., the outside

List of symbols

ABL	atmospheric boundary layer	CSV	comma-separated values format
ACH	air changes per hour	DOE	U.S. Department of Energy
AFN	airflow network model	HVAC	heating, ventilation, and air-conditioning
BIM	building information modeling	IDF	EnergyPlus input data file
BPS	building performance simulation	LES	large eddy simulation
BR	blockage ratio	NRMSE	normalized-root-mean-square error
CFD	computational fluid dynamics	NV	natural ventilation
CityGML	3D city model file based on the international open data standard	RANS	Reynolds averaged Navier-Stokes
C_p	wind pressure coefficients	RMSE	root-mean-square error
$\overline{C_p}$	surface-averaged wind pressure coefficient	STL	standard triangle language file
		VTK	visualization toolkit file

temperature is lower than the inside one), a drastic cooling load reduction can be reached.

Because of the complex nature of wind-driven forces, designing naturally ventilated buildings and quantifying the actual effect of the NV for the typical local climate are challenging and difficult tasks (Ding and Lam 2019). This supposes a great limitation for the use of NV in real applications and discourages its implementation, since it represents a potential risk for building designers. To overcome this issue, the primary tool accepted for designing naturally ventilated buildings is the computational simulation (Sakiyama et al. 2020). In particular, computational fluid dynamics (CFD) is preferred when a high resolution of temporal and spatial indoor environment information is required. This tool has been used to simulate NV under a variety of conditions, including wind- and/or stack-driven flows (Zhai 2014). However, if measuring the NV impact along a typical climatic year is desired, CFD-based simulations are still unaffordable because of the computing time needed. This high computational effort is even greater whether alternative designs are being studied (e.g., varying the size and location of windows) or more complex optimization tasks involving additional architectural elements such as balconies, overhangs, are required.

Several reduced-order airflow models have been developed to quickly predict airflows through an entire building. Among these, the airflow network model (AFN) is the most reliable option for representing the NV phenomenon in complex geometries and general multi-zone buildings with several openings (Zhai et al. 2015). The AFN model proposed by Gu (2007) is widely used since it is implemented in the EnergyPlus software (Crawley et al. 2001), the most established software for building performance simulation (BPS).

Essential input data for AFN models and highly influential in the NV results are the wind-induced pressures on the building openings. This information is commonly

characterized by the wind pressure coefficients (C_p) (Cóstola et al. 2010). In BPS and AFN software, these data are incorporated in a simplified way through the surface-averaged value ($\overline{C_p}$) per wind direction (Cóstola et al. 2009). To determine $\overline{C_p}$, most BPS-AFN programs make use of secondary data sources like databases (Orme and Leksmono 2002; ASHRAE 2009) or analytical models calibrated with experimental measurements (Swami and Chandra 1988; Grosso 1992; Muehleisen and Patrizi 2013; Bre et al. 2018). For instance, EnergyPlus uses by default the analytical equation proposed by Swami and Chandra (1988) to predict $\overline{C_p}$ on wall surfaces of low-rise buildings. However, the major drawback of secondary data sources is their low applicability to actual case studies, since they are mostly limited to isolated rectangular floor-plan buildings.

Given the high relevance of C_p values as input data for AFN-BPS programs, a few attempts to develop specific tools to predict them have been made. The first effort was CpCalc, a parametric model developed by Grosso (1992) as an integrated module of the multi-zone airflow and contaminant transport model (COMIS) (Feustel 1999). CpCalc supposes an improvement regarding the Swami and Chandra model, since it predicts C_p values at different surface locations and can consider the sheltering effects. Although the method was novel, its applicability is limited because of the lack of complete and high-quality experimental data to use in its development. This is a shortcoming recognized by the author himself (Grosso 1992). Another work with the same aim was performed in the C_p Generator program. The last version (Knoll et al. 1997) also includes the prediction of the C_p values at different surface locations, sheltering effects, and incorporates sloped roofs. However, its results show large deviations compared to the corresponding experimental data (same building, points locations, and wind directions) (Cóstola et al. 2009). Besides the aforementioned limitations, the usage of these two developments is constrained

to only rectangular floor-plan buildings and cases studies within the spectrum of the database sources used to generate them. So, they cannot predict C_p values for new building shapes, which seriously limits their use in real designs.

To overcome the drawback when the building has an arbitrary topology, a primary data source has to be used to get the C_p values. A first option is to perform a wind tunnel experiment. However, this alternative is rarely employed by building design offices because of the economic cost and high know-how required. The second option comprises using a CFD-based approach, which has been recognized as a reliable tool (Cóstola et al. 2009; Ntinis et al. 2018; Zhang et al. 2020). Among the latest CFD contributions found in bibliography, Tominaga et al. (2015) used steady Reynolds-averaged Navier-Stokes (RANS) simulations to investigate the airflow and mean wind pressures on isolated gable-roof buildings with different roof pitches. Gimenez et al. (2018) studied the performance of several RANS turbulence models to predict the C_p data on isolated low-rise buildings. Then, they used the best configuration to compute the C_p data and analyzed the natural ventilation in a non-rectangular floor-plan building. Recently, Zheng et al. (2020) used steady RANS and large eddy simulation (LES) modeling to study the wind flow and mean surface pressure on buildings with balconies. Despite the advantages and reliable results of CFD, it is hardly ever employed as an everyday design tool in technical offices to get C_p data. This is because the CFD technique requires users of advanced expertise and access to high-performance computing resources.

To address the pinpointed limitations, this work introduces a new cloud-based platform to predict wind pressure coefficients on buildings. The core of the platform comprises a set of tools for performing unattended atmospheric boundary layer (ABL) simulations using CFD and getting C_p data on buildings. This work aims to reach a dedicated and easy-to-use tool, where non-trained users can attain the results within an acceptable time frame. The novel platform offers reliable C_p data for arbitrary building shapes and surrounding conditions. Advantages of not requiring either specialized hardware, with huge computational power and storage, or expensive software are gained thanks to the cloud-based approach.

Contributions throughout the entire CFD workflow are made. In pre-processing stage, a toolkit to construct the computational domain is developed. Here, the geometry of the target building and its surrounding, supplied through different input formats, is processed, reconstructed, and placed in a computational wind tunnel domain. Then, the resulting computational domain is automatically discretized. Regarding the processing stage, a series of ABL profiles for distinct terrain conditions are available, while 3D steady Reynolds-averaged Navier-Stokes (RANS) simulations,

including different RANS turbulence models, are used to compute the flow around buildings for a set of wind incidences. The post-processing stage comprises ad hoc tools for calculating detailed C_p information (C_p on building surfaces, C_p data on openings, point C_p data, among others), and flow field information (pressure and velocities), which are exported in several output formats. Finally, to evaluate the robustness and accuracy of the developed tools, an exhaustive validation for a wide range of case studies is performed. The results attained are compared with wind tunnel experimental data and contrasted with C_p estimations employed by the EnergyPlus software.

2 Methodology

2.1 Platform overview

The cloud-based platform aims to predict C_p data on buildings, spanning from isolated structures to complex case studies that involve several buildings in an urban environment. The paradigm adopted, which comprises hosting a software service in a remote location that can be accessed and used from anywhere via Internet, strives to offer a powerful but easy-to-use tool. This approach enables users to access a dedicated computational tool, without requiring either specialized hardware (with huge computational power and storage space) or expensive software.

Figure 1 shows the working scheme of the proposed tools. The strengths of the platform are based on a set of tools for performing the entire CFD-based workflow for ABL simulations and getting C_p data on buildings. These tools can be grouped into three main modules according to their application stage: pre-processing, processing and post-processing.

To request a set of desired C_p data, the platform holds a web-based user interface¹, which is implemented through modern web technologies (html5 + CSS + js) using responsive styles (i.e., design adaptable to different devices) to allow convenient, practical and cross-platform access from any type of device with an Internet connection. The request process only needs a few inputs, where the geometry of the target building and its surrounding is the main one. The geometry can be provided in different formats. Standard triangle language files (STL) are allowed because of their wide compatibility with most CAD software. EnergyPlus input data files (IDF) are supported to have compatibility with the most established software for BPS. The 3D city model files based on the international open data standard (CityGML), or its equivalent (CityJSON), can be also employed. This latter enables managing actual urban environments.

¹ <https://cpsimulator.cimec.org.ar/>

Fig. 1 Workflow and key components of the platform

Once executed the automatic procedure to attain the CFD results, the platform returns detailed C_p data. This includes $\bar{C}_p$ on building surfaces, C_p data on openings, and point C_p data. Also, flow field results as pressure and velocities are provided. The results are stored in a repository and accessed through a downloadable link. The main formats for the results are comma-separated values (CSV), Visualization Toolkit file (VTK), or EnergyPlus input data file (IDF). The latter is the same IDF file uploaded as input, which is updated with C_p data in the associated AirflowNetwork model objects.

The features and operation of the developed cloud-based tools are detailed in the following section.

2.2 Pre-processing

The pre-processing stage involves a sequence of steps to reconstruct the target building and its environment and to generate the computational wind tunnel domain. Regarding the geometry model, it should accomplish a few basic requirements: (a) the building and its environment should be oriented such that the $+z$ coordinate determines the height direction and the $+y$ coordinate is aligned with the true North, (b) length units should be in meters, and (c) the building geometry should be split into different surfaces according to their usage (e.g., walls, roofs, floors, windows, etc.). Figure 2 shows an example of the geometry references.

To provide a straightforward way for most of the BPS community, the platform supports as input geometry format

Fig. 2 Example of the geometry references for a prototype building model (Secondary School) developed by DOE (2021)

the same IDF file employed for BPS through EnergyPlus (Crawley et al. 2001). Therefore, all the buildings described in the IDF, which can have one or multiple thermal zones, are considered in the pre-processing stage. Figure 3 summarizes the pre-processing workflow for the IDF format.

The pre-processing module has other particular features for this input format. For instance, if there are openings described in the IDF, these are processed as separated surfaces to compute the C_p on each one. C_p in openings is the most detailed information that can be provided in the airflow network model. Also, shading objects are interpreted as surfaces without thickness for the CFD simulations. This feature easily allows including several architectural elements of interest like balconies, overhangs, shadings, among others.

The first action of the pre-processing stage is reading

Fig. 3 Pre-processing workflow for IDF files. An iterative procedure detects the components of the geometry, reconstructs and places them in the CFD computational domain

the input geometry from one of the input formats introduced before, and computing its extreme coordinates $EC = [(x_{min}, y_{min}, z_{min}), (x_{max}, y_{max}, z_{max})]$. Then, the original geometry is moved by the translation operation $[-(x_{max} - x_{min})/2, -(y_{max} - y_{min})/2]$ such that the center of coordinates is placed at the centroid of the buildings at ground level. Therefore, the geometry is introduced in a computational wind tunnel domain with a coincident center of coordinates, whose shape, dimensions, and meshing strategy are discussed below.

2.2.1 Computational domain definition

To perform the ABL simulations for different wind incidence angles reusing the same mesh, the platform employs a particular geometry shape for the computational wind tunnel domain (see Figure 4). A regular polygon of P sides represents the external limit of the domain, being $P = 24$, the default configuration. This feature gives the possibility of setting inflow or outflow boundary conditions for any wind incidence direction while reduces the total size of the computational domain. This kind of wind tunnel shape has several advantages, which are even more noticeable in problems where at least eight wind directions have to be studied, as was recently shown by Kastner and Dogan (2020). The platform simulates and predicts C_p data for at least 12 wind directions, exploiting enough such advantages.

Regarding the dimensions of the computational domain, the ones advised by the European best practice guidelines of COST Action 732 are met (Franke et al. 2007). These guidelines suggest the minimum distances between the building or urban model and the boundaries of the domain, and also the maximum allowed blockage ratio for typical box-shape wind tunnels. Being $H_{building}$ the height of the tallest building of the model, the inlet, the lateral and top boundary should be at least $5H_{building}$ away from the target geometry (building or set of buildings). Besides, the outflow boundary should be at least $15H_{building}$ away from the target geometry to guarantee a full development of the wake flow. The blockage ratio (BR), which is defined as the ratio of the

projected frontal (windward) area of the obstacles ($A_{building}$) and the cross-section of the computational domain (A_{domain}) (Barlow et al. 1999), should be less than 3%. This is,

$$BR = 100\% \frac{A_{building}}{A_{domain}} \leq 3\% \quad (1)$$

Given the particular shape of the computational wind tunnel domain proposed to reuse the same mesh for different wind incidence directions, these limits for the domain size have to be adapted. Figure 4 shows the reference dimensions considered. As mentioned before, the geometry of the target building or urban environment is centered in the wind tunnel domain, resulting in similar extensions for the windward, leeward, and lateral flow spaces, see Figure 4(a). Therefore, to accomplish the COST requirements for any wind incidence direction, the minimal distance between the building (or urban) and any side of the boundary has to satisfy the most critical one, which is the outflow distance ($W_{outflow}$) of at least $15H_{building}$.

In some particular cases like urban low-rise buildings (see Figure 4(a)), depending on the value of H_{domain} , the BR cannot be guaranteed. So, a new directional blockage ratio for wind tunnels with cylindrical or similar shapes is derived. This is based on the recommendation of Blocken (2015) for box-shape wind tunnel domains that define the BR for the vertical and horizontal dimensions respectively, as:

$$BR_v = 100\% \frac{H_{building}}{H_{domain}} \leq 17\% \quad (2)$$

$$BR_h = 100\% \frac{W_{building}}{W_{domain}} \leq 17\% \quad (3)$$

where W_{domain} is the width of the domain and $W_{building}$ is the maximum projected frontal width of the building (or urban envelope), herein for any wind incidence, see Figure 4(a).

Using these criteria simultaneously, a $BR \leq 3\%$ is guaranteed and a negligible virtual acceleration is achieved in both top and lateral regions of the modeled building. Finally, combining these conditions with the minimal outflow distance, the domain dimensions are defined as,

$$\frac{H_{domain}}{H_{building}} = 6 \quad (4)$$

where Eq. (4) guarantees the vertical blockage ratio of Eq. (2), and

$$W_{outflow} = \max(15H_{building}, 2.5W_{building}) \quad (5)$$

where the first term, $15H_{building}$, guarantees the minimal distance to get full development of wake flow, and the second term, $2.5W_{building}$, ensures the horizontal blockage ratio of Eq. (3).

Fig. 4 Computational domain for the CFD-based simulations: (a) the 3D perspective of the resulting computational domain for a case study of a generic urban area; (b) reference dimensions

2.2.2 Discretization

Once the computational domain is determined, the meshing module generates the mesh. Because this module is based on the *snappyHexMesh* tool (Fabritius and Tabor 2016; OpenFOAM 2021), the procedure comprises three stages. First, the surfaces that define the buildings and the boundaries of the computational domain are shaped by recursive refinements of a background hexahedral mesh. Second, a morphing stage fits the mesh to the surfaces, getting split-hex cells around the objects. The final stage shrinks back the mesh and inserts prismatic cell layers over the building surfaces. The entire process is an automated strategy suitable even for complex buildings and urban environments regardless of their alignment, but is controlled by several parameters set in advance.

A key stage on the platform is to define the meshing specification automatically. This includes setting the reference cell size of the background mesh, the refinement levels at the surfaces and inside predetermined volumetric regions, and the mesh quality requirements. For this purpose, automated analysis of the envelope of the target building and its surroundings to get the geometry reference lengths is performed. The reference cell size and the refinement level at the building surfaces are chosen to guarantee at least 20 cells per direction (Tominaga et al. 2008) on the shortest building side. With non-convex floor-plane shapes as C-shape and L-shape buildings, the refinement level is increased based on the characteristic length of the concavity detected. To guarantee that grid lines are perpendicular to the wall and correctly reproduce the flow separation, four prismatic cells layers are placed on every surface of the target building, increasing the thickness of each successive layer with an expansion ratio of two, see Figure 5(a).

Also, volumetric refinement levels according to the distance to the buildings are defined. This setting allows the

Fig. 5 Details of automatic mesh refinements: (a) detail of the cell layers next to the building surfaces; (b) detail of the volume and the surface refinements for multi-building configurations with a target building; (c) detail of the refinements on baffles surfaces.

grid to capture physical phenomena like shear layers and vortical structures. With urban environments, a one-lower-level of refinement of surrounding buildings and the ground among them is applied. Because of the aforementioned refinements, a proper number of cells is guaranteed between buildings (canyons) (Franke et al. 2004), see Figure 5(b), as well as between opposite surfaces belonging to the same building.

Thinner elements over surfaces, such as balconies and shadings, are considered *baffles*. This is, the internal faces that represent these thin walls are treated as boundary faces. Extra refinement levels can be set on these kinds of elements to depict their geometric features properly, see Figure 5(c). Finally, to avoid high grown ratios at any location of the mesh, eight cells are required as buffer layers between successive refinement levels.

The quality of the computational cells is controlled through the maximum skewness (4 on internal faces and 20 on boundary faces), the maximum non-orthogonality (70 degrees), and the minimum volume ratio between each tetrahedron and its circumscribed sphere (0.01) parameters.

The meshing procedure prioritizes these requirements over a strict conforming of any detail of the geometry. The resulting high-quality hex-dominant mesh is well suited for the finite volume method because of the low truncation errors and the fast iterative convergence (Blocken 2015).

The meshes obtained by this automatic configuration, which fulfill the state-of-art guidelines, were analyzed against successive refinements varying the reference size of the background grid, see Appendix A, which is available in the Electronic Supplementary Material of the online version of this paper.

2.3 Processing

Regarding the use of CFD simulations in ABL applications, there are two main numerical approaches to solve the turbulent flow governed by the Navier-Stokes equations: large eddy simulation (LES) modeling and Reynolds-averaged Navier-Stokes (RANS) modeling (Blocken 2018).

It is well known that the LES approach is intrinsically superior in terms of physical modeling to the RANS one. However, the RANS approach has been shown as a reliable option in several industrial and research applications (Blocken 2015; Toparlar et al. 2017; Blocken 2018). This virtuous performance led it to be a standard for simulation of flows in urban environments (Franke et al. 2007; Tominaga et al. 2008).

The computational cost of LES-based simulations is at least an order of magnitude larger than for steady RANS. Additionally, this effort grows proportionally with the number of wind directions to be analyzed. So, given the aim of providing reliable C_p data results within an acceptable time frame for building designers, the RANS approach is adopted and implemented in this work, as described below.

2.3.1 RANS modeling approach

The ABL flow is considered as an incompressible homogeneous viscous fluid flow with constant density ρ and kinematic viscosity ν . RANS modeling approach comprises the Reynolds decomposition of the fields of the Navier-Stokes equations. This is, the velocity $\mathbf{u}$ and pressure p are split into its mean value (time-averaged or ensemble-averaged) and fluctuating parts. For instance, $\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'$, where $\bar{\mathbf{u}}$ is the mean value and $\mathbf{u}'$ the fluctuating part. Hence, by applying this decomposition to variables of the Navier-Stokes equations ($\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'$, $p = \bar{p} + p'$) and averaging, leads to the Reynolds averaged Navier-Stokes (RANS) equations (Ferziger and Peric 2002), which are described as:

$$\nabla \cdot \bar{\mathbf{u}} = 0 \quad (6)$$

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + (\bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}}) = -\frac{1}{\rho} \nabla \bar{p} + \nu \Delta \bar{\mathbf{u}} - \nabla \cdot (\overline{\mathbf{u}' \mathbf{u}'}) \quad (7)$$

where the unknowns are the mean velocity field $\bar{\mathbf{u}}$ and the mean pressure field $\bar{p}$.

RANS turbulence modeling Most of RANS models assume that the fluctuating part $\mathbf{u}'$ obey the Boussinesq hypothesis, such that,

$$\overline{\mathbf{u}' \mathbf{u}'} = \nu_t \nabla^s \bar{\mathbf{u}} \quad (8)$$

where ν_t is the eddy viscosity and ∇^s is the symmetric gradient operator.

Several RANS models have been developed over years for general applications (Jones and Launder 1972; Spalart and Allmaras 1992; Yakhot et al. 1992; Menter 1994; Shih et al. 1995). Most of them are based on solving transport equations for turbulent variables to determine the value of ν_t . The standard k - ϵ model cannot reproduce the separation and reverse flow on the rooftop of a building because of its overestimation of turbulence energy in the impinging region of the building wall. Given these well-known problems, the best practice guidelines conclude it should not be used in wind engineering simulations (Franke et al. 2004, 2007; Tominaga et al. 2008). Some alternative models to improve this particular aspect have been developed (Kato and Launder 1993; Tsuchiya et al. 1997). However, its application did not become extensive since the improvements were not significant or other desired features of the original model were lost.

From the revised versions of k - ϵ model, the platform employs by default the renormalization group (RNG) k - ϵ model (Yakhot et al. 1992) for low-rise buildings and the k - ω SST model (Menter 1994) for high-rise buildings. Based on our experience and other research references (Tominaga et al. 2015; Tominaga 2015; Toparlar et al. 2017), the employed models are the options with the best agreement with experimental wind tunnel data for ABL applications. Alternatively, there are also available the realizable k - ϵ model (Shih et al. 1995), and optimized RANS models. These latter were recalibrated for ABL simulations aiming to improve the C_p prediction on specific buildings typologies and surrounding conditions (Gimenez and Bre 2019).

2.3.2 Boundary conditions

Given the particular shape of the computational domain used, the boundary conditions at the planes of the external bounds are changed according to the wind incidence analyzed. This is made by comparing the orientation of the normal vector to the surface, say $\mathbf{n}$, with the current wind velocity $\mathbf{u}_{in}$. Hence, if $\mathbf{u}_{in} \cdot \mathbf{n} > 0$, the boundary is an outflow patch (zero static pressure). The boundary is prescribed as a symmetry plane, i.e., zero normal velocity and zero normal gradients of all variables if $\mathbf{u}_{in} \cdot \mathbf{n} = 0$ (i.e., $\mathbf{u}_{in}$ perpendicular to $\mathbf{n}$). An inlet boundary condition is imposed if $\mathbf{u}_{in} \cdot \mathbf{n} < 0$.

The wind incidence angle is defined as

$\theta = \arccos(-\mathbf{j} \cdot \mathbf{u}_{\text{in}} / |\mathbf{u}_{\text{in}}|)$, where $\mathbf{j}$ is the y -coordinate versor. This means that zero angle $\theta = 0^\circ$ is defined when the wind flow is coming from the $+y$ direction, which is the north direction under our guidelines to provide the geometry. Incidence angles are then altered following a clockwise rotation.

For the inlet boundary conditions, the approaching wind profile for a neutral ABL is modeled using boundary conditions suggested by Richards and Hoxey (1993), being the inflow velocity defined as:

$$|\mathbf{u}_{\text{in}}| = \frac{U_{\text{ABL}}^*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \quad (9)$$

where U_{ABL}^* is the friction velocity, $\kappa = 0.41$ is the von Karman's constant, z is the vertical coordinate (m), and z_0 is the aerodynamic roughness height (m).

The kinetic energy, k , and turbulence dissipation rate, ε , inlet profiles are defined as:

$$k = \frac{U_{\text{ABL}}^{*2}}{\sqrt{C_\mu}} \quad (10)$$

$$\varepsilon = \frac{U_{\text{ABL}}^{*3}}{\kappa(z + z_0)}$$

where $C_\mu = 0.09$ is the turbulent viscosity coefficient.

The friction velocity is estimated as:

$$U_{\text{ABL}}^* = \kappa \frac{U_{\text{ref}}}{\ln((z_{\text{ref}} + z_0) / z_0)} \quad (11)$$

where U_{ref} is the reference velocity (m/s) at the reference height given z_{ref} (m).

Therefore, to model an inlet velocity profile based on the log-law through Eqs. (9) and (11), the values of U_{ref} , z_{ref} , and z_0 have to be defined. So, the platform offers four optional modules: (1) *Log-law*, (2) *Terrain classification*, (3) *Auto-fitting*, and (4) *Power-law*.

Using the first option, *Log-law*, the users should supply the three values for U_{ref} , z_{ref} , and z_0 to customize the wind speed profile for their particular analysis. Values of U_{ref} ranging 10–50 m/s at $z_{\text{ref}} = 200$ to 600 m (velocity at gradient height) are satisfactory, while to select the z_0 value is recommended to follow the roughness classification proposed by Wieringa (1992). The second alternative, *Terrain classification*, provides four discrete options to configure the ABL profile in practical applications. Table 1 reports the parameter values used for each choice.

Sometimes the users can desire to employ a power-law or measured data at different heights that cannot be easily related to a log-law within the options of the parameter values given above. So, to overcome this, the *Auto-fitting* and the *Power-law* options are also available.

Table 1 Discrete terrain classification

Case	z_0 [m]	z_{ref} [m]	U_{ref} [m/s]
1. Very flat terrain	0.0025	250	40
2. Open country	0.025	350	40
3. Suburban	0.25	450	40
4. Urban	2.5	550	40

In the first one, the users should provide a set of velocity values at different heights through a two-column CSV file. Using these values, an automatic fitting procedure based on numerical optimization is performed to determinate the configuration of the U_{ref} , z_{ref} , and z_0 which best agrees with the input data.

In the *Power-law* module, the users should provide the three-parameter values, U_s , z_s , and α , which define the ABL profile as:

$$|\mathbf{u}_{\text{in}}| = U_s \left(\frac{z}{z_s}\right)^\alpha \quad (12)$$

Then, an automatic fitting procedure is employed to determinate the configuration of U_{ref} , z_{ref} , and z_0 of Eqs. (9) and (11) that best agree with the desired power-law within the limits of the domain, i.e. $0 \leq z_{\text{ref}} \leq H_{\text{domain}}$.

A critical requirement is to guarantee that the inflow ABL profile imposed preserves its shape throughout the upstream domain despite the distance from the inlet to the building, i.e. maintains the horizontal homogeneity. Therefore, a compatible wall function on the ground is applied along with a fixed shear stress condition on the top (τ_{top}) boundary of the domain (Heargraves and Wright 2007). This latter is defined as:

$$\tau_{\text{top}} = \rho U_{\text{ABL}}^{*2} \quad (13)$$

and the wall function at the ground, which also considers its roughness, estimates the wall shear stress τ_{ground} as:

$$\tau_{\text{ground}} = \frac{\rho \kappa C_\mu^{1/4} k_c^{1/2} |\mathbf{u}_c|}{\ln((z_c + z_0) / z_0)} \quad (14)$$

where the subscript c refers to the cell next to the ground, and z_c is the normal distance from the ground to this cell center.

Regarding building surfaces, these are modeled as smooth surfaces and a non-slip condition for the velocity is imposed on them. Hybrid wall functions are used for turbulent variables. These models provide boundary conditions that adapt to the location of the first cell center. The particular implementation used in this work is described in Liu (2016).

In conclusion, Table 2 summarizes the boundary conditions employed by the platform.

Table 2 Summary of the boundary conditions employed

Location	Velocity	Pressure	Turbulent variables
Inlet	ABL profile – Eq. (9)	Zero-gradient	ABL profiles – Eqs. (10)
Outlet	Outflow	Outflow	Outflow
Ground	No-slip	Zero-gradient	ABL wall functions – Eq. (14)
Top	Shear stress – Eq. (13)	Zero-gradient	Zero-gradient
Building walls	No-slip	Zero-gradient	Hybrid wall functions (Liu et al. 2016)

2.3.3 Solver settings

The time-averaged RANS equations are solved using an implicit, segregated, three-dimensional finite volume method (FVM). Pressure-velocity coupling is solved with the SIMPLE algorithm (Ferziger and Peric 2002) by using the implementation available in the open-source software OpenFOAM. The running procedure starts the simulation with velocity and turbulent fields initialized everywhere to the free-stream conditions. At the beginning, first-order schemes for the convective and viscous terms of the RANS equations along with under relaxation are employed to guarantee stability. After the initial 500 iterations, the relaxation is gradually deactivated. Then, the spatial and time discretization schemes are switched to second-order to avoid numerical/artificial diffusion (Blocken 2015). The iterative solving process continues until the normalized residuals for continuity, velocity components, and turbulent fields have decreased by five orders of magnitude each one.

2.3.4 Parallelization

To achieve a reliable description of the C_p behavior regarding the incoming flow direction, the default configuration evaluates 12 wind incidence angles (every 30 degrees). This means solving 12 steady-state CFD simulations. The computing time per simulation is about five core hours per million elements, leading to a total requirement of about 40 core hours for typical isolated buildings, and at least 200 core hours in typical urban environments. Therefore, to respond within a reasonable window time of design, the automated processing of a request for C_p data is executed in an HPC cluster (Seshat 2020) employing a two-level parallelization scheme. First, a task parallelization level is implemented, where an internal queuing system distributes the individual simulations to available idle nodes. Second, each simulation runs in parallel using the computing cores available in the assigned node. This latter requires the partition of the computational domain, which is also an unattended process implemented on the platform. Finally, the global queuing system of the cluster manages the execution of the simultaneous requests.

2.4 Post-processing

Once the numerical solutions for each wind direction requested are reached, automated post-processing is carried out to calculate detailed C_p data.

The C_p at any point of the façade is defined as the dimensionless ratio between the dynamic pressure at that point and the dynamic pressure of the airflow (wind) in the freestream. Mathematically, it is expressed as,

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho U_H^2} \quad (15)$$

where p is the static pressure (Pa) at a point of façade and p_∞ is the static reference pressure (Pa) at freestream (i.e., far away from any disturbance), which is taken as 0 Pa by default.

The term $\frac{1}{2} \rho U_H^2$ is the dynamic pressure (Pa), where ρ is the air density and U_H is the freestream wind speed, which is taken at the building mean roof height H in the upstream undisturbed flow, see Figure 6.

Once the C_p field is calculated, the averaged pressure coefficient ($\overline{C_p}$) on each building surface i (wall, roof, opening) can be derived. When using FVM, C_p are discrete values associated with the centroid of each internal element (cell) or boundary element (face). So, the $\overline{C_p}$ for a building surface i is calculated as,

$$\overline{C_p}(i) = \frac{1}{A_i} \sum_{j=1}^{N_i} C_{p_j} A_j \quad (16)$$

where C_{p_j} is the pressure coefficient computed in j -th face, with area A_j , on the target surface i , being N_i the number of surface faces on the target surface i , and $A_i = \sum_{j=1}^{N_i} A_j$, the area of the target surface i .

After automatically carry out this post-processing stage for each wind incidence simulated, the output results are returned to the user.

Fig. 6 Reference values employed to calculate the C_p and $\overline{C_p}$ data

3 Case studies

This section aims to present a comprehensive validation of the tools and the capabilities for a wide range of case

studies. To achieve this, the numerical solutions obtained via the automatic procedure described above are compared with experimental wind tunnel data.

Most of the experimental data are taken from the wind-tunnel measurements performed by the Wind Engineering Information Center of Tokyo Polytechnic University (TPU 2021), but also there are results got from other experimental studies. Simultaneously, the C_p data commonly employed by most building designers through EnergyPlus are also computed and compared to show the hidden inaccuracies when using these models, even for simple building shapes.

The input geometries and the output results derived from the case studies analyzed are provided in Bre and Gimenez (2021) for a closer analysis or its reproduction.

3.1 $\overline{C_p}$ in openings

The first validation case aims to evaluate the capabilities of the automatic cloud-based tools to predict the $\overline{C_p}$ on the building openings.

A set of wind tunnel results for an isolated low-rise building² available in the TPU database (TPU 2021) is chosen. The building has a depth-to-breadth ratio $D/B = 3/2$ and a height-to-breadth ratio $H/B = 1/4$, being $B = 16$ m, $D = 24$ m, and $H = 4$ m. The length scale for the TPU database experiments was set at 1:100. The 384 wind pressure measurement taps were disposed uniformly over the surfaces of the tested models. Basic spaces among the taps were 20 mm, corresponding to 2 m at full scale. In every case presented in this work, breadth is measured on the surface that is orthogonal to the wind direction when the incidence angle $\theta = 0^\circ$. Figure 7(a) shows the geometry of the case study generated in an IDF file, including the dimension references. The mesh generated this case study has almost 650 K polyhedral cells, where 97% of them are hexahedra, see Figure 7(b).

Three rectangular windows (Win-1, Win-2, and Win-3) of height = 2 m and breadth = 5 m are placed on Surf-2. They are centered at both height and width, with a horizontal separation of 8 m between their vertical axes. As exposed in the method section, these three windows are recognized by the platform-tools since they are defined as *fenestration* surfaces in the IDF. So, separated boundary surfaces are generated to compute $\overline{C_p}$ on each one of them. The latter enables generating the corresponding AirflowNetwork objects during the post-processing process.

The wind profile used in the TPU experiment emulates an ABL power-law that represents a terrain category III

according to the AIJ recommendations (Tamura et al. 2004). The mean speed measured at 10 cm of height was about 7.4 m/s which corresponds to about 22 m/s at a height of 10 m on the full scale. Therefore, at the real scale, this wind profile can be defined by parameter values: $U_s = 23.8$ m/s, $z_s = 10$ m and $\alpha = 0.2$. Using these values in the *Power-law* module, the configuration $U_{ref} = 22.41$ m/s, $z_{ref} = 9.82$ m and $z_0 = 0.0615$ m achieves the best fitting of the log-law to the experimental power-law. To compute C_p values, $U_H = 18.49$ m/s is used, while an undisturbed pressure $p_\infty = 0$ Pa is taken in agreement with the value employed in the TPU experiment.

Figure 7(c) shows the comparison of $\overline{C_p}$ results obtained for each window against the experimental ones derived from the pressure taps on the corresponding window area. Note that for each wind incidence angle, the TPU database presents the entire time series of point C_p data. So, each C_p series is first averaged in time, and then the surface-averaged ($\overline{C_p}$) on the window is calculated as an area-weighted average. Also, values of $\overline{C_p}$ on Surf-2 obtained using Swami and Chandra (S&C) equation (Swami and Chandra 1988), available by default in EnergyPlus for low-rise buildings, are plotted. This serves to analyze the common assumption of using the C_p value of the entire surface (wall) for all the openings (Win-1, Win-2, and Win-3) on it.

Fig. 7 Case study of a low-rise building with openings (windows): (a) the geometry model generated in the IDF file; (b) details of the resulting mesh; (c) results of $\overline{C_p}$ on three windows of a low-rise building, the experimental ones derived from TPU database and the computed using the analytical S&C equation (EnergyPlus); (d) RMSEs regarding experimental data of, both, the estimations of EnergyPlus and the results of this work

² http://www.wind.arch.t-kougei.ac.jp/info_center/windpressure/lowrise/g120200.html

Regarding the accuracy of $\overline{C_p}$ values predicted by the platform, the results show a proper agreement with the experimental data on the three windows for almost all the wind incidence angles in comparison. The largest differences, but actually small in error magnitude, are found for $\theta = 0^\circ$ and for the wind angles where $\overline{C_p}(\theta)$ presents local extrema (minimum or maximum), e.g., $\theta = 75^\circ$ for Win-1.

For a given wind incidence angle, the $\overline{C_p}$ value computed on any window highly depends on its location on the surface. In particular, when lateral windows (Win-1 and Win-3) are placed in the wake just behind a separation zone ($\theta = 0^\circ$ and $\theta = 180^\circ$ respectively) significant differences regarding $\overline{C_p}$ on the central window are observed. These variances are expected to be even wider for non-rectangular floor-plan buildings or comparing between windows with different areas. Even for a rectangular floor-plan building, EnergyPlus has considerable discrepancies on the windows located at left- or right-side of the wall (Win-1 and Win-3). An acceptable $\overline{C_p}$ prediction is only achieved when the window is centered (Win-2). These differences are quantitatively analyzed through the root-mean-square error (RMSE) obtained for $\overline{C_p}$ values on the three windows with both methods, see Figure 7(d). The results of the platform decrease four times the RMSE error regarding EnergyPlus prediction on lateral windows, while for the central window the reduction is about 2.5 times.

Finally, using the post-processing module for IDF files, the updated file is obtained, including the objects *EXTERNALNODE* and *WINDPRESSURECOEFFICIENTVALUES* (one of them for each window), and *WINDPRESSURECOEFFICIENTARRAY* of the AirflowNetwork model. This updated IDF file is provided in Bre and Gimenez (2021).

3.2 Buildings with balconies

This case study aims to evaluate the capability of the platform to generate the model and accurately predict the C_p values on the surfaces of a complex building with balconies. The case under consideration was originally studied by Chand et al. (1998) through a wind-tunnel experimental analysis. Later, it was replicated by Montazeri and Blocken (2013) using a dedicated CFD approach, from now on referred to as “M&B”.

The building model at experimental scale (1:30) has a breadth $B = 0.6$ m, depth $D = 0.25$ m, and height $H = 0.5$ m, resulting in the aspect ratios $D/B = 0.4167$ and $H/B = 0.8333$. Three balconies with breadth = 0.15 m, depth = 0.05 m and height = 0.03 m are positioned at every one of the five floors except the ground floor. Wind pressures were measured along three vertical lines on the windward and leeward facade positioned in the middle of the balconies. Forty-five holes were drilled at equidistant points along

each measurement line.

The geometry of the experimental scale model is generated using EnergyPlus objects through an IDF file, see Figure 8(a). The geometry of the balconies is easily reproduced using *Shading* objects. For this model, the resulting mesh has around 2.4 M polyhedral cells, where the 97% are hexahedrons. Figure 8(b) shows the grid on the building and the ground, where one extra level of refinement is employed around the surfaces without thickness representing the balconies.

In the experiment, the ABL speed profile was generated by a combination of three devices, vortex generators, a grid of horizontal rods, and a set of roughness elements on the floor of the test section, resulting in a vertical profile that obeys a log-law. Speed values of this profile were measured

Fig. 8 Case study of a medium-rise building with balconies: (a) geometry model generated in the IDF file; (b) details of resulting mesh; (c) ABL profile obtained by fitting the experimental measurements taken from Chand et al. (1998)

at different heights, which are used to calibrate the ABL profile through the Auto-fitting module, see Figure 8(c). The parameter values that represent the best fitting are: $U_{ref} = 8.7811$ m/s, $z_{ref} = 1.1158$ m, and $z_0 = 0.0123$ m. To compute C_p values, the freestream velocity measured at the height of the building, $U_H = 7.264$ m/s is employed, while a reference pressure $p_\infty = 4$ Pa is taken, which is measured at the height of the building and 0.9 m upstream in concordance with the experimental study.

Figure 9 shows the C_p results for a wind incidence angle $\theta = 0^\circ$ compared to the experimental ones (Chand et al. 1998), the ones achieved by M&B (Montazeri and Blocken 2013) using CFD simulation with the RNG turbulence model, and the ones estimated by EnergyPlus. Regarding C_p values obtained in this work along the vertical centerlines, a satisfactory agreement with the experimental data is observed on both windward and leeward sides, where the best fitting is achieved between the 2nd and 4th floors, see Figure 9(a). A similar pattern and level of accuracy is observed for the vertical lines centered on the balconies at left- and right-sides,

for both windward and leeward sides, see Figure 9(b). In comparison with CFD results obtained by M&B, as expected, the accuracy is similar. The results of the platform present a slightly lower performance on the windward side, but obtain better results on the leeward side, which are particularly noticeable between the 2nd and 4th floors. The C_p estimations of EnergyPlus show a poor quality on the windward side where the C_p 's have a complex behavior because of the presence of balconies. This limitation is slightly overcome on the leeward side, however, it still has low accuracy. This comparison is quantitatively summarized in Figure 9(c) through the RMSEs. In terms of RMSE, the results from this work and the achieved by a dedicated CFD study (M&B) have a similar and acceptable performance to predict the complex behavior of the flow on a building with balconies. Both CFD studies show RMSEs around 2.5–3 times lower than EnergyPlus for windward and leeward sides, respectively.

Figure 10 shows a similar comparison of C_p results, but for a wind incidence angle $\theta = 45^\circ$. Regarding C_p values obtained on the vertical centerlines, a proper agreement is

Fig. 9 Comparison of C_p results for a wind incidence angle $\theta = 0^\circ$ against the experimental ones (Exp.) reported by Chand et al. (1998), the results obtained by M&B (Montazeri and Blocken 2013) using a dedicated CFD study, and the results estimated by EnergyPlus: (a) vertical centerlines; (b) vertical lines centered on the balconies located at left- and right-sides; (c) RMSEs of the results obtained by using the different approaches regarding the experimental reference

Fig. 10 Comparison of C_p results for a wind incidence angle $\theta = 45^\circ$ against the experimental ones (Exp.) reported by Chand et al. (1998), the results obtained by M&B (Montazeri and Blocken 2013) using a dedicated CFD study, and the results estimated by EnergyPlus: (a) vertical centerlines; (b) vertical lines centered on the balconies located at left- and right-sides; (c) RMSEs of the results obtained by using the different approaches regarding the experimental reference

observed with the experimental data on both windward and leeward sides. The best agreement is, as in the $\theta = 0^\circ$ case, achieved between the 2nd and 4th floors. In comparison with CFD results attained by M&B, on the windward side, the results present slightly better fitting over the entire height except between 1st and 2nd floors. As to the leeward side, the results in this work are also slightly better at the entire height except under the 1st floor, where both have similar accuracy, but are overestimated by the platform and underestimated by M&B. The results achieved in this work on the lines centered in the balconies at the left-side presents a good agreement with the experimental data on the leeward side, but some considerable differences are observed on the windward side, especially between 1st and 2nd floors. As compared to CFD results obtained by M&B, on the windward side the results present a lower accuracy, but on the leeward side, the results are considerably more accurate, achieving a reliable prediction of the effects produced by the leeward balconies. Regarding the EnergyPlus estimations, despite their constant value throughout the walls, these get an enhanced fitting in terms of magnitude on the leeward side, achieving similar performance to the CFD-based ones. However, on the windward side, apart from not reproducing the behavior of C_p 's over the potential openings behind balconies, the discrepancies are considerable in magnitude regarding the experimental values reaching RMSEs about 4 times larger than the CFD-based approaches.

Overall, the C_p results achieved by the platform for this complex case study with balconies are accurate enough compared with the experimental ones (Chand et al. 1998). In contrast with the detailed and dedicated CFD-based analysis carried out by Montazeri and Blocken (2013), the results have a similar level of accuracy. The differences between both can be because of minor variations in the mesh, ABL speed configuration, and the value of the reference pressure (p_∞). However, remarkably, the herein results are obtained using an unattended procedure.

3.3 Generic urban environment

Urban building modeling is a rising field aiming to analyze the performance of a group of buildings, considering the correlated effects among them and attempting to close the gap between the predicted and actual performance of current buildings. Natural ventilation is a problem that spans different scales, from an urban context down to the neighborhood and the building itself. So, the behavior of natural ventilation in buildings is directly related to the actual environments that surround them.

Towards integrating actual urban environments, this section presents a detailed validation of the prediction of C_p values on a non-isolated low-rise building in a generic urban

area. This case study³ and its experimental results are taken from TPU (2021) database. The target study is a gable-roofed building with a depth-to-breadth ratio $D/B = 3/2$, a height-to-breadth ratio $H_0/B = 1/2$, and pitch roof angle $\beta = 26.7^\circ$, see Figure 11(a). Real-scale sizes are $B = 16$ m, $D = 24$ m, and $H_0 = 12$ m, with an experimental scale of 1:100. To measure the wind pressure, over 350 taps were placed uniformly over the surfaces of the target building. The same geometry configuration is employed for the surrounding buildings, which are willing in a regular arrangement with an area density of $C_A = 0.3$, see Figures 11(b) and (c). This area density C_A is defined as,

$$C_A = \frac{\text{area occupied by buildings}}{\text{area of site}} = \frac{BD}{B'D'} \quad (17)$$

where, B and D are the breadth and depth of the buildings, respectively, B' and D' are the average distances between corresponding points on adjacent buildings in the two coordinate directions, as shown in Figure 11(c). Note that despite the regular building topologies and the “well-organized” arrangement, this is a challenging case study because of the complexity of the flow generated along the multiple canyons.

Fig. 11 Gable-roofed low-rise building in a generic urban area: (a) target building; (b) building arrangement of the case study; (c) reference of area density definition

³ http://www.wind.arch.t-kougei.ac.jp/info_center/windpressure/grouplowrise/216616.html

The wind profile used in the TPU experiment emulates an ABL power-law that represents a terrain category III according to the AIJ recommendations (Tamura et al. 2004). The mean speed measured at 10 cm of height was about 7.8 m/s, which corresponds to about 23.4 m/s at a height of 10 m at full scale with an exponent $\alpha = 0.2$. Using these in the *Power-law* module, $U_{\text{ref}} = 23.78$ m/s, $z_{\text{ref}} = 9.86$ m, and $z_0 = 0.1208$ m are the configuration to achieve the best agreement between the log-law and the experimental power-law. To compute C_p values, $U_H = 25.65$ m/s is obtained, while an undisturbed pressure $p_\infty = 0$ Pa is taken in concordance with the one employed in the TPU experiment.

The mesh generated by the platform has almost 3M polyhedral cells, where 96% of them are hexahedrons. This mesh is presented in Figure 12(a), including the details of the different levels of refinement explained in the method section.

Regarding the pressure coefficients, Figures 12(b)–(d) show the C_p values obtained for two walls and one roof of the target building. As can be observed from the experimental results, most of C_p values on the target building surfaces are negative. This is because the target building is in the

Fig. 12 Comparison results for the gable-roofed low-rise building in a generic urban area: (a) details of the resulting mesh; (b) Surf-1b; (c) Surf-2; (d) Surf-5; (e) RMSEs

wake zone of other surrounding buildings for every wind incidence angle. These negative pressure regions with multiple separations of the flow resulting from the sheltered condition are well known to be the most difficult to predict using a RANS modeling approach. Despite this, the C_p results achieved using the standard RNG turbulence model show an acceptable agreement with the experimental ones derived from the TPU database. The results properly capture the tendencies of C_p regarding the wind incidence angles. The latter is an accomplished requirement to get useful data to feed natural ventilation models. Regarding EnergyPlus, except for few wind incidence angles, the estimations present large discrepancies with the experimental results. Moreover, for some surfaces (e.g. Surf-5) and wind angles ($0^\circ < \theta < 180^\circ$), EnergyPlus predicts unphysical results, i.e. positive C_p values instead of negative ones.

Figure 12(e) shows the RMSEs of EnergyPlus and the results achieved by the platform for this complex case study. Besides the results properly reflect the complex physics of the flow in the generic urban arrangement, also presents an RMSE 3–4 times lower than the EnergyPlus estimations.

3.4 High-rise building with S-shape floor-plan

This case study aims to evaluate the capability of the platform to generate the model and accurately predict the C_p values on the surfaces of a high-rise building with an irregular (S-shape) floor-plan. The model and the experimental results are taken from Medvecká et al. (2018), see Figure 13. The

Fig. 13 High-rise model with S-shape floor-plan: (a) model and measurement levels; (b) details of the resulting mesh; (c) details of the measurement locations per level and the floor-plan dimensions

scale of the model was 1:350. At experimental scale, the model has a breadth $B = 0.15$ m, a depth $D = 0.15$ m, and a height $H = 0.3$ m, resulting in the aspect ratios $D/B = 1$ and $H/B = 2$. The experimental measurements are made at four height levels using 24 probes around the building per level, see Figure 13(c).

The wind profile employed in the experiment corresponds to a terrain between categories III and IV. So, this is modeled using the *Power-law* module with the configuration $U_{\text{ref}} = 1$ m/s, $z_{\text{ref}} = 0.3$ m and $z_0 = 0.00233$ m.

To compute C_p values, $U_H = 1$ m/s is used, while an undisturbed pressure $p_\infty = 0$ Pa is employed in agreement with the value employed in the experiment. For this case study, the mesh has around 565 K polyhedral cells, where 97% are hexahedrons, see Figure 13(b). The results for wind incidence angles of $\theta = 0^\circ$ and $\theta = 45^\circ$ are considered for the analysis.

Figure 14 shows the C_p results for a wind incidence angle $\theta = 0^\circ$ compared to the experimental ones at the four measurement levels. The predicted C_p values properly agree with the experimental data. The largest differences are

Fig. 14 Comparison of C_p results obtained for a wind incidence angle $\theta = 0^\circ$ against the experimental ones reported by Medvečka et al. (2018)

observed in probes 1 and 2, where the highest negative values are because of the flow separation, being more noticeable at the lower levels (C and D). These deviations are related to the limited accuracy of RANS turbulence models to predict the flow in the separation region. Overall, the results show the best and the worst performance at levels B and C, with RMSEs of 0.1117 and 0.1325, respectively.

Figure 15 shows the C_p results predicted for a wind incidence angle of $\theta = 45^\circ$ compared to the experimental ones. A good agreement with the experimental data is observed at the four measurement levels. As for the case of $\theta = 0^\circ$, the largest differences are observed in probes where the highest negative values are presented after the flow separation. For this oblique wind direction, such values are in probes 13 and 14 and probes 2–4. Overall, the results show similar performance at the four levels, with an RMSE value around 0.1318.

4 Discussion

The platform provides a rich set of fully automatic tools

Fig. 15 Comparison of C_p results obtained for a wind incidence angle $\theta = 45^\circ$ against the experimental ones reported by Medvečka et al. (2018)

and capabilities to predict wind pressure coefficients on buildings in a wide range of actual scenarios. The steady RANS modeling approach could be pointed out as a limitation to perform accurate simulations of turbulent ABL flows. However, the results obtained have shown being reliable enough for the primary aim of predicting time-averaged C_p data to feed NV models. In fact, reliable results in relation to experimental ones for case studies with increasing complexity were shown through the exhaustive validation presented in this work. For these case studies, EnergyPlus showed serious limitations for predicting C_p data, even for the simplest one which fits well within its application spectrum. It is well known that deviations on C_p values highly influence the prediction of the air changes per hour (ACH) driven by natural ventilation (Cóstola et al. 2010; Gimenez et al. 2018) and infiltrations (Charisi et al. 2017). Then, these large inaccuracies for the calculation of the ACH mean a poor prediction of the potential of energy conservation and indoor air quality. This latter application has currently a central role because its proper evaluation is mandatory to achieve the requirements demanded by the present COVID-19 global pandemic.

Regarding more complex case studies as multi-building configurations and real urban environments, the results are expected to be much closer than those achieved by parametric equations like the employed by EnergyPlus, as shown for the related case study. Users must know that RANS modeling limitations are more noticeable in these kinds of scenarios, since buildings downstream from other ones is a standard situation (Blocken et al. 2011). Despite this, even for academic and research proposes, the employment of RANS models keeps dominant, being used by 96% of the researchers (Toparlar et al. 2017) because of their outstanding balance between accuracy and computational effort.

It is worth mentioning the short computation times are required by the platform to complete a C_p study because of its parallelized execution environment. For instance, evaluating twenty-four wind incidence angles led to a total requirement of about four hours for the isolated building studied in Section 3.1, where the simulation was carried out in a small group of five computing nodes of four cores each. This requirement was increased to only twelve hours when the sixteen wind incidence angles were analyzed in the generic urban case in Section 3.3.

The platform is growing continuously and hosts the recent advances in high-performance computing and turbulence modeling. Regarding this latter, the authors are developing and evaluating two major research lines. The first one is based on the recalibration of RANS models for particular ABL applications (Gimenez and Bre 2019), which has shown significant improvements regarding the standard ones. The second one is the very promising pseudo-DNS

method based on a multi-scale approach for the full simulation of the turbulence instabilities at their different scales (Idelsohn et al. 2020, 2021). This latter methodology aims to offer the accuracy and transient behavior of LES models but the computational cost of RANS models.

5 Limitations and future works

Although the current status of the platform already represents a significant advance for the BPS community, it still has room for improvements and potential development areas, as is following summarized:

- Regarding input geometry formats, while the compatibility with EnergyPlus files (IDF) is fully developed, the compatibility with STL and CityGML formats should be completed. In particular, for this latter, more utilities to manage other types of sheltering objects, included in the standard, should be developed and tested. Future works also plan to incorporate the gbXML format, which is widely supported by building programs like most commercial building information modeling (BIM) software (Bracht et al. 2021)..
- The module for automatic pre-processing is in continuous evolution to manage increasingly complex case studies. In particular, new features are being developed to process and mesh geometries, where surfaces with very different length scales are simultaneously present.
- Regarding ABL modeling, the alternatives provided to configure the wind velocity profile give great versatility to meet the different levels of user needs. However, some extra features should be implemented to pursue approaching real-world applications. Among others, the incorporation and validation of the capacity to envisage topography heights as streets with sloppiness, hills, etc., as well as incorporating porous media models to better represent the sheltering effects of the vegetation, would be valuable contributions. Taking advantage of the current developments, coupling with transport models to simulate pollutants would be of interest in investigating their effect on reducing the natural ventilation potential in urban environments.
- Besides the current tools offered to predict C_p data of a building design, the platform is also thought to host C_p databases. These can be experimental-based or developed using the current CFD-based tools, particularly for parametric shape buildings that are commonly employed in the industry like H-, U-, L-shape, among others.
- Last, the web-based interface is a working prototype aiming to give an access point to the tools, as is shown in the method section. However, the interface developed as well as other features will be improved following the professional feedbacks received.

6 Conclusions

A new cloud-based platform to predict wind pressure coefficients (C_p) on buildings was introduced. The core of the platform comprises a set of fully automatic CFD-based tools for performing atmospheric boundary layer (ABL) simulations and obtaining detailed C_p data. The tools can achieve results for arbitrary building shapes and surrounding environments. To reach the aim and get reliable results within the building designers' time window, a broad spectrum of novel tools was devised and developed.

The first contribution is related to the capability of processing the geometric information of the target building and its surrounding environment from different input formats (IDF, STL, and CityGML) and reconstruct this information properly in a computational wind tunnel domain. Regarding this latter, a novel shape based on a regular polygon of P sides is proposed to reuse the same mesh for the several simulations required due to varying the wind incidence angle. Further, a new directional blockage ratio is derived, aiming to avoid the virtual acceleration simultaneously in horizontal and vertical directions.

Regarding the meshing procedure, a module to auto-mesh the resulting computational tunnel domain was developed. This module addresses the proper level of grid refinement and guarantees the mesh requirements recommended in the international guidelines for the best practices for the CFD simulation of flows in urban environments. The module has shown great robustness since, mostly and despite the complexity of the analyzed case, the automatic procedure achieves meshes with a large percentage of hexahedral cells. This aspect favors the quality of the numerical solution attained.

Four easy-to-configure modules to establish the horizontally homogeneous ABL wind profile were developed to address the different expertise levels and requirements of users. The first one is a straightforward module to set a wind profile based on the log-law by selecting from four types of terrains. Two modules are based on customizable log- and power-law, respectively. The latest one is to fit automatically a set of measured values using the log-law wind profile.

To achieve reliable results but within an acceptable time frame for building designers, a scheme of two-level parallelization was developed and implemented on the platform. The simulation-level addresses the partition of the computational domain and parallel simulation of a wind incidence angle, and the task-level parallelizes the required simulations over the computational resources. This feature, besides the use of a RANS modeling approach, allows users to have quick responses and dispose of several potential options during the design stage.

Above all the aforementioned contributions, remarkably, the entire workflow and the expert-CFD decisions taken in each stage are fully automatic. Within this unattended pipeline, particular and useful features to assist many building designers were developed by achieving full compatibility of the inputs and outputs with the EnergyPlus software. This means that the input geometry can be provided from the same IDF file generated to perform a building performance simulation (BPS) in EnergyPlus. Here, a valuable procedure is the auto-recognition of the openings (windows and doors) to compute the averaged pressure coefficients ($\bar{C}_p$) on them. Then, the associated airflow network objects are set as outputs in an updated IDF file. Shading objects defined in the IDF to represent architectural elements of interest, such as balconies, overhangs, shadings, are considered and included in the CFD simulations.

Finally, the strengths and capabilities of the platform were tested through an exhaustive validation against wind tunnel experimental data. The case studies include buildings with openings, balconies, an irregular floor-plan, and a surrounding urban environment. The results have shown a suitable agreement with the experimental data. In the simplest case of an isolated low-rise building, the RMSE of C_p data predicted by EnergyPlus is reduced using our platform from 60% to 77% on central and side windows, respectively. For a more complex case study of a target building surrounded by a generic arrangement of other buildings, the results can reduce the RMSE up to 85% in comparison with the EnergyPlus estimations.

Therefore, the novel platform introduced in this work has shown being a reliable C_p data source and its development represents a significant contribution to the BPS community. We invite readers, researchers, and practitioners to test the platform in their research and projects.

Data availability

For a closer analysis or its reproduction, the results and the input geometry data used to generate them can be found at <http://dx.doi.org/10.5281/zenodo.5796295>.

Electronic Supplementary Material (ESM): the appendix is available in the online version of this article at <https://10.1007/s12273-021-0881-9>.

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