Experimental and numerical analysis of a new wind tunnel for building and mechanical ventilation components performance assessment

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Abstract. Aeraulic, air movement, and wind effects studies are of high importance when assessing building performances. Indeed, several studies have been conducted using wind tunnels to better understand aerodynamics inside and around buildings. The objective of this study is to accurately characterize the air velocity field inside the test chamber of a wind tunnel at different locations using the Hot-Wire-Anemometry technique and propose an experimental protocol to extend the use of wind tunnels to study mechanical ventilation systems’ performances. To this end, a first intercomparing protocol involving six hot-wire anemometers was carried out to verify the accuracy of measurements. In addition, we have developed a CFD numerical model of the wind tunnel under the Ansys Fluent environment. Several turbulence models, numerical schemes, and mesh types were studied to analyze the air velocity distribution and identify the appropriate model fitting experimental results. As a result, the CFD model uses the Quadrilateral Structured Fine Mapped mesh, Standard k−ε as a turbulence model, and MUSCL as a discretization scheme with a relative error of 5.21% to experiment values. Both wind tunnel and its numerical model are designated to establish on-demand building and ventilation components performance assessment using a hybrid approach, numerical and experimental.

1 Introduction

The rapid acceleration of global growth has led to an increase in urban density, which strains architecture and infrastructure [1]. Most structures in the past few decades mimicked foreign architectural designs and lacked significant scientific conception [2]. The lack of appropriate technology, including test tools such as wind tunnels, was the main contributing factor behind that shortage. As a result, only reverse or empirical design could be used; the scientific design was therefore not always a possibility. This implies that architects were only able to construct the same design or reject alternative designs. Windy conditions’ impact on building designs can now be examined at higher levels thanks to the broad availability of wind tunnels [3]. The expansion of the use of wind tunnels responded to a need for the development of aerodynamic research and analysis, particularly in the field of wind engineering. The building-specific wind tunnel technology has been improved to replicate airflow and other environmental factors inside and outside building models [4]. It enables the design of buildings while considering how they respond to wind loads to increase the building’s performance [5]. The city’s unfavorable wind conditions heighten the need for air conditioning in the summer, obstructing the flow of internal and outdoor ventilation, and increasing the amount of energy needed for heating in the winter [6]. Building energy consumption can be significantly decreased by using modern technology such as wind tunnel testing in the analysis of its design efficiency [3]. It simulates wind conditions for use in the city conception phase, enabling urban planners and designers to make informed decisions about how to best use the available natural resources for building and energy efficiency. Wind tunnels are among the most important tools used in aerodynamics research [7]. They are used to examine how air moving across solid objects affects their surfaces. Even though computational models have recently made great strides, wind tunnel testing is still necessary to provide the full range of data required to guide accurate design decisions for multiple real-world engineering problems [8]. Several types of wind tunnels exist, which can generally be classified according to two main criteria. The first criteria depend on the speed range. Low-Speed wind tunnels are characterized by excellent flow quality and a low level of turbulence [4], while High-Speed wind tunnels are those operating at speeds where compressibility effects are significant [9]. Based on the second criteria of shape, wind tunnels are classified into two types, the Open-Circuit wind tunnel where the air follows a straight path from the entrance through a contraction zone to the test section, followed by a diffuser, a fan section, and an outlet, and the Closed-Circuit wind tunnel which has small to no interactions with the outside world, the air is continuously recirculated from the test section's exit back to the fan through a series of turning vanes [10]. There are two types of airflow measurement in wind...
tunnel testing. The first is the “point measurement” which is done point by point using an instrument such as Hot Wire Anemometry (HWA), Pulse Wire Anemometry (PWA), Laser Dropper Anemometry (LDA), Irwin Prob, etc. In order to obtain a complete image of the airflow field using this method, there must be a sufficient amount and density of measurement points. Most of the point measurement instruments are intrusive and vulnerable to perturbations, making it challenging to gather precise and detailed data. The second type is the “Area measurement” which provides spatially continuous information on the flow conditions across a significant portion or the entire area under examination, such as Particle Image Velocimetry (PIV), Infrared Thermography (IR), and Scour techniques [11]. This paper reports on work carried out to extend the use of a new wind tunnel facility for the buildings and the ventilation components assessment. For this, the aim of this work is (i) to present a new intercomparing protocol for ensuring the reliability and verifying the accuracy of sensors intended to be used in the experiment (ii) to perform airflow measurements at different positions within the test chamber of the wind tunnel and (iii) to develop a first CFD model of the facility based on the experimental results. This paper presents a detailed methodology for intercomparing protocol and developing a numerical model that is not available in the literature, especially for a building wind tunnel. It can serve as a reference and recommendation for reliability tests on sensors and measuring instruments, and as a methodology to be followed for future numerical model development of wind tunnels.

2 Study methodology

This work is part of a larger study investigating various parameters related to the wind tunnel: turbulence level, flow uniformity, and wind speed. The focus of this paper is on wind speed. We conducted this study on the wind tunnel through various wind tests using wind speed sensors and multiple numerical simulations. This is to verify the reliability of sensors and the accuracy of the data they provide and then to identify the CFD model that fits the experimental results. We performed the wind tests for 6 minutes at each wind speed range and recorded the measured wind speed values every 0.2 seconds. Since the values measured by the sensors are instantaneous, we used statistical functions such as the standard deviation and the mean values to represent and compare them.

2.1 Facility presentation

In 2018, a new wind tunnel was built in the Laboratory of Tribology and Systems Dynamics (LTDS) at the School of Civil Environmental and Urban Engineering (ENTPE, University of Lyon) in collaboration with the Center for Studies on Risks, the Environment, Mobility and Urban Planning (CEREMA) within the framework of the thesis of Doctor Adeline Mélois to assess the impact of the wind during building air leakage measurement for a single zone building at a reduced scale [12]. The LTDS wind tunnel presented in Fig. 1 is an open-circuit facility. It has been sized to provide a steady wind from 0 to at least 7 m. s⁻¹ [13]. With this range of wind speed, the facility is classified as a Low-Speed wind tunnel.

![LTDS wind tunnel](image)

The wind tunnel has been designed according to the methodology explained by Stefano et al [14]. It includes the following five components: 1) a settling chamber with a honeycomb and 2 screens, 2) a contraction component; 3) a test chamber, 4) a diffuser, and 5) a fan. Fig. 2 shows the key components of the wind tunnel which is 4.11 m long with a maximal cross-sectional area of 4.0 m² for the settling chamber and 1 m² for the test chamber [12].

![Dimensions of the wind tunnel (in mm)](image)

2.2 Wind speed sensors

For this study, we employed six hot wire anemometers (HWA), three directional and three omnidirectional HWAs. The dimensions and the shape of the HWAs probes are presented in Fig. 3 and Fig. 4. In the case of unidirectional HWA, the wire is protected by a mesh screening due to its fragility and sensitivity [15]. The unidirectional probe should be directly facing the wind to provide an accurate reading.

![Unidirectional probe dimensions](image)

For omnidirectional HWA, the wire detects airflow in a 360-degree circle around it, but not in a circular plane.
around the probe. In addition, because of the round needle shape wire, it is unrequired to keep the probe perpendicular to the wind direction [15].

![Fig. 4. Omnidirectional probe dimensions](image)

### 2.3 Intercomparing protocol

The sensors have been used in numerous experiments. The immediate use of the sensors without a verification of their reliability can give rise to a concern about the uncertainty of the results they provide. The intercomparing protocol's purpose is to identify a low-cost method for regular reliability verification of the sensors. By characterizing the deviations between the sensors to correct the values obtained during the airflow measurement inside the wind tunnel. During the intercomparing protocol tests, we have placed the probes of the Unidirectional and Omnidirectional HWAs in a way to place the wires at the same height level.

#### 2.3.1 Repeatability and reproducibility tests

The repeatability and reproducibility tests serve as the first step of our intercomparing protocol. We performed the repeatability tests to identify whether the wind tunnel provides identical wind distribution and to verify the sensor’s readings for repeated tests. For the reproducibility tests, we placed the sensors at the same positions to identify whether the differences in measurements are caused by the change in position or the sensor readings error. Fig. 5 shows the positions of the anemometers in the wind tunnel test chamber during the repeatability and reproducibility tests.

![Fig. 5. Arrangement of sensors inside the wind tunnel during repeatability and reproducibility tests](image)

#### 2.3.2 Comparison tests

The second step of the intercomparing protocol is comparing each anemometer with a reference sensor. For this purpose, we added a seventh anemometer classified as a unidirectional probe as a reference sensor. This comparison aims to use linear regression to adjust each sensor reading. The reference sensor is not calibrated, it is an arbitrary decision. Hence the adjustments only allow homogenizing the sensors readings instead of getting the real value. To ensure the same test conditions on the two sensors (the sensor to adjust and the reference sensor), we placed the sensors in the middle of the test chamber and then arranged the wires of the probes at the same height as shown in Fig. 6. Although this method does not obviate the need for calibration, it does allow for the monitoring of the sensors' relative deviation from each other.

![Fig. 6. Arrangement of sensors during the comparison test](image)

### 2.4 Airflow characterization

We adopted both experimental and numerical approaches for airflow characterization. The experimental approach aim is to build the first dataset of the airflow measurements at distinct locations of the wind tunnel. The use of the hot wire anemometry technique allows for obtaining the information only at the measured point, while the numerical approach aims at the development of the first numerical model using experimental data. This is to obtain continuous wind speed information and determine other information at all positions within the wind tunnel.

#### 2.4.1 Experimental characterization

To achieve maximum measurement positions, we designed a coarser mesh on the horizontal plane at different heights. According to the coarser mesh we designed, we conducted the measurements at 36 positions per height plane, at 100 mm, 200 mm, 500 mm, and 800 mm, a sum of 144 measurement positions. Fig. 7 presents the coarse mesh and the measurement positions on the horizontal plane. While Fig. 8 presents the coarse mesh on the vertical plane and the height plans of measurement.

![Fig. 7. The coarse mesh of measurement positions on the horizontal plane](image)
Since we planned the measurements at different heights, without a mounting bracket, it would be difficult to assemble the sensors and hold them at the measurement positions. In response to this situation, for preventing the sensors from moving upwind, we made a bracket out of a metal bar on which we welded metal collars.

Fig. 9 presents the anemometer’s final setup we deployed for the characterization assessment.

2.4.2 Numerical model

Using Ansys fluent environment, we conducted the numerical study to identify the appropriate wind tunnel CFD model that treats near walls and displays airflow symmetry and homogeneity in the velocity profiles. This is through three comparisons analysis of discretization schemes, turbulence models, and meshes types.

2.4.2.1 Model description

In the present work, we considered the wind tunnel’s two-dimensional geometry presented in Fig. 10. It combines the test chamber and diffuser in one rectangle with dimensions of 2.217 m in length (x-axis) and 1 m in height (y-axis). The wind enters through the inlet and leaves through the outlet on the opposite side.

2.4.2.2 Boundary conditions

For simplifying the problem, instead of using time-dependent governing equations, we solved time-average Navier stokes differential equations for steady state. The description of airflow development using high Reynolds numbers and incompressible flows is based on the conservative law of mass and momentum using cartesian coordinates as follows:

\[
\frac{\partial (U_j)}{\partial x_j} = 0
\]  
(1)

Momentum conservation

\[
\frac{\partial (U_j U_j)}{\partial x_i} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial (U_j)}{\partial x_j} (v \frac{\partial U_j}{\partial x_j} - \bar{u}_i \bar{u}_j)
\]  
(2)

Energy conservation

\[
\frac{\partial (U_j T)}{\partial x_j} = \frac{\partial }{\partial x_j} (v \frac{\partial T}{\partial x_j}) - \bar{w}_i \bar{T}
\]  
(3)

Where the quantity \(\bar{u}_i \bar{u}_j\) is the unknown Reynolds stresses and the quantity \(\bar{w}_i \bar{T}\) are heat fluxes.

We considered the inlet and the outlet as inlet flow and outlet flow. The boundary conditions we applied in this model are symmetry and the solid wall. The pressure at the outflow is assumed to be uniform on the y-axis, and the transport variables are treated as having a gradient of zero. The velocity component, Kinetic energy of turbulence (k₀) and energy dissipation rate (\(\varepsilon_0\)) are considered to have a uniform distribution at the inlet on the y-axis.

2.4.2.3 Discretization schemes

We applied the pressure-based solver and PISO algorithm to examine the performance of four discretization schemes: First Order Upwind, Second Order Upwind, Quadratic Upwind Interpolation (QUICK), and Monotone Upstream Centered Schemes for Conservation Laws (MUSCL).

2.4.2.4 Turbulence models

For the identification of the adequate turbulence model, we evaluated two levels of turbulence modeling closure. On the first level we applied the two equations models, the Standard k – \(\varepsilon\) model, the RNG k – \(\varepsilon\) model, the Realizable k – \(\varepsilon\) model, the Standard k – \(\omega\) model, and the SST k – \(\omega\) model. On the second one with a second-moment closure, we launched the simulation by various options: the linear pressure strain, quadratic pressure strain, stress BSL, and stress omega RSM models. We used The Fluent Enhanced Wall Treatment option for k – \(\varepsilon\) models to achieve near-wall modeling with the accuracy of the standard two-layer approach for fine meshes without degrading the results for the wall function meshes [16]. For k – \(\omega\) models the wall boundary conditions are applied by default in the same way as the turbulent kinetic energy k equation is treated when enhanced wall treatments are used for k – \(\varepsilon\) models[17]. In the case of RSM models, we applied the standard wall function.
2.4.2.5 Mesh types

The selection of the mesh is a crucial step in a numerical simulation. To select the mesh that offers the best precision, and to compare the effect of meshing on the results, we created four different mesh types presented in Fig. 11(a,b,c, and d) Triangular mesh with inflation, Quadrilateral mapped mesh, Triangular mapped mesh, and a Multizone (Quadrilaterals/Triangles) mesh with inflation on which we conduct the first comparative studies of discretization schemes and turbulence models. To accurately represent locations where the flow encounters a quick velocity change, the models mesh in fine elements. We used the inflating layer meshes in mesh 1 and mesh 2 to reflect the boundary layer region more accurately. This choice aids in precisely resolving the boundary layer and predicting any separation or reattachment points. Applying structured mapped meshes for mesh 3 and mesh 4 has the advantage of producing an organized and high-quality mesh while consuming less computing time and memory.

![Fig. 11. Mesh types](image)

3 Results and discussion

3.1 Repeatability tests results

For the repeatability tests, we repeated the wind test twice for each wind speed range. After each test, the wind tunnel is turned off and restarted for the following test. We tested six different configurations with air speeds ranging from 1 m. s\(^{-1}\) to 7 m. s\(^{-1}\). We altered the sensor placements in each configuration. The results of the repeatability tests at 4 m. s\(^{-1}\) for configurations 1 and 2 are presented in Fig. 12 (a and b). A1-A6 indicates the numbers we provided to the anemometers at the beginning of the experiment. The results show agreement between the first and the second tests. Some differences were observed. To quantify these differences numerically, we calculated the average deviations of the measurements for each sensor. The maximum mean value of the measurements means deviations is 0.02 m. s\(^{-1}\), which is below the sensors’ measurement accuracy ± 0.2 m. s\(^{-1}\). This result indicates that the sensors are reliable in providing the same readings for repeated tests and that the wind tunnel provides the same distribution of wind even after being restarted.

![Fig. 12. Graphs of repeatability tests results at 4 m. s\(^{-1}\)](image)

3.2 Reproducibility tests results

We attempted through the reproducibility tests to analyze the measurement values of the sensors based on their position in the wind tunnel. All the anemometers were placed in the same positions: A, B, C, D, E and F in the middle of the test chamber. Fig. 13 (a and b) presents the results of reproducibility test results at positions B and C at 4 m. s\(^{-1}\).

![Fig. 13. Graphs of reproducibility tests results at 4 m. s\(^{-1}\)](image)

The results show a significant mismatch between the mean wind speed readings of the sensors. The maximum value of mean velocity deviation for sensors readings is
0.44 m.s\(^{-1}\). This demonstrates that even if the sensors are placed in the same position and exposed to the same wind speed, they would not provide the same measurement readings. These differences were not caused by the wind tunnel, because it is already justified by the results of the repeatability tests that it produces the same wind distribution after its restart. This analysis leads us to conclude that the measurements values disparities were caused by sensors measurement errors, which need to be adjusted.

### 3.3 Comparison tests results

The comparison test results of the six sensors presented revealed strongly correlated measurement values, from which we were able to obtain linear regression equations. Fig. 14 (a and b) presents the linear regression graphs of anemometer 1 (A1) and anemometer 3 (A3), the reference anemometer is indicated as (A7). R-squared values are close to 1, this result guarantees that we can accurately predict the sensors correct readings by the application of the linear regression equations to correct future measurements.

By analyzing the data shown on the maps, we find that the mean velocity values on \(x_5\), \(x_6\), and \(x_7\) at positions B and C, where the chamber is positioned and close to the boundary layers at the heights of 100 mm and at 800 mm, are close to those of the control. High-speed values are remarked, between \(x_1\) and \(x_2\) in the 200 mm and 500 mm planes, at A, B, and C. Since these positions are so close to the fan, we presumed that the turbulence created by the fan is the reason for higher readings.

### 3.4 Characterization measurements results

The results of the experimental wind velocity characterization after correction using the linear regression equations at the height planes 500 mm and 800 mm are presented in Fig. 15 (a and b). Dark colors on the results maps have higher mean velocity values, while lighter colors present lower values.

### 3.5 Numerical model results

In the discretization scheme comparison, we applied the Standard \(k - \varepsilon\) model as a turbulence model. The calculation of the mean relative error of the simulation to experimental results allowed us to identify that MUSCL is the appropriate discretization scheme for our model. Then we used MUSCL in the turbulence models comparison study, where we analyzed the velocity outlines simulation results of each turbulence model. Each model generated a distinct set of air velocity profiles and outlines. While the Standard \(k - \omega\) failed to depict the homogeneity of flow in the test chamber, it provided better flow symmetry in the longitudinal velocity profiles. The \(k - \varepsilon\) models, and SST \(k - \omega\) model successfully solved and simulated the values of wind speeds near the walls. Flow symmetry and homogeneity are proved by the RSM models, but the near walls weren't well represented. The evaluation of the results with the consideration of the relative error led us to select the best models for each turbulence model. As a result, we decided to simulate the Standard \(k - \varepsilon\),
RNG $k-\varepsilon$, SST $k-\omega$, and RSM Stress Omega model in the mesh study. The simulation results of the mesh types are presented in Fig. 16 (a,b,c and d), Fig. 17 (a,b,c and d), Fig. 18 (a,b,c and d), and Fig. 19 (a,b,c and d). The comparison between the experiment and numerical results of vertical profiles of longitudinal velocities at $x_5=1.1m$ and $4m.s^{-1}$ are presented in Fig. 20 (a,b,c and d).

Fig. 16. Standard $k-\varepsilon$ velocity magnitude outlines

Fig. 17. RNG $k-\varepsilon$ velocity magnitude outlines

Fig. 18. SST $k-\omega$ velocity magnitude outlines

Fig. 19. RSM stress omega velocity magnitude outlines

Fig. 20. Comparison of experiment measurement with the meshes simulation results at $4m.s^{-1}$

For the two-dimensional geometry of the wind tunnel, mesh 1 and mesh 3 provided good results for airflow symmetry and homogeneity for all turbulence models. Mesh 2 and mesh 4 on the other hand, did not resolve the flow near the walls and did not reveal a homogeneous flow for all the turbulence models. The Standard $k-\varepsilon$ turbulence model demonstrates the lowest relative error values for the four mesh types, the closest match in comparison to the experimental measurements, as well as presenting the contours of the mean velocity values.
near the wall and flow symmetry in velocity magnitude outcomes. This result brings us back to the fact that the $k-\varepsilon$ models enable the use of the enhanced wall treatment option and that Standard $k-\varepsilon$ model is recognized to capture the effects of turbulence near the wall. According to the results of the velocity magnitude outcomes, comparison to the experiment measurement, and the calculation of relative error to the experiment results the model using Quadrilateral Structured mapped mesh, the Standard $k-\varepsilon$ model and MUSCL scheme has the least error in comparison to experimental results with a value of 5.21%.

4 Conclusion

This work has been carried out by adopting experimental and numerical investigations. The first experiment investigation led us to develop a pre-experimentation methodology. Indeed, before any experiment, this methodology will be used to evaluate the accuracy of sensors and the dispersion of wind in the wind tunnel test chamber. The findings of the intercomparing tests allowed us to conclude that the disparities in measurements are related to the sensors rather than the wind tunnel. Furthermore, the results of the comparison tests revealed strongly correlated data and R-squared values close to 1, allowing us to confidently apply the adjustment to the wind tunnel characterization measurements. Secondly, the numerical investigation was devoted to developing a numerical model of the wind tunnel using the computational fluid dynamics of the Ansys Fluent environment. We performed multiple simulations of the wind tunnel's 2D model for this aim. These simulations were accomplished to compare and analyze different discretization schemes, turbulence models, and types of mesh, to define the appropriate CFD model that fits the experimental results. In each comparison, velocity outcomes analysis was performed, simulations findings were compared with the experimental results and the relative error to the experiment results was calculated. As a result, the appropriate CFD model fitting to experiment results uses Quadrilateral Structured Fine Mapped mesh, Standard $k-\varepsilon$ as a turbulence model, and MUSCL as a discretization scheme with an overall relative error of 5.21% to the experimental data.

References


