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09 Qualitative and comparative assessment of natural ventilation flow patterns through the use of physical models in a Water Table and CFD simulations

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Qualitative and comparative assessment of natural ventilation flow patterns through the use of physical models in a Water Table and CFD simulations

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ABSTRACT (ENG): *Natural ventilation is essential for air renewal, building cooling, and promoting thermal comfort for users. However, its analysis requires complex software. Water tables present an accessible and easy-to-handle alternative to overcome this limitation. The objective is to qualitatively assess whether the results generated by the water table accurately represent natural ventilation flow patterns in more complex physical models. Experimental tests are conducted on a water table and compared with Computational Fluid Dynamics (CFD) simulations to achieve this. The methodology consists of four stages: 1) determining the model; 2) characterizing the water table; 3) describing the configurations used in the computational simulations; and 4) analyzing the results. The results were satisfactory, showing similarities in air flow behavior in both the internal and external areas of the building, although discrepancies emerged in zones with low air circulation.*

Keywords: *natural ventilation, water table, CFD.*

RESUMO (PT): A ventilação natural é essencial para renovação do ar ambiente, resfriamento da edificação e promoção do conforto térmico dos usuários, porém sua análise requer softwares complexos. O uso de mesas d'água surge como uma alternativa acessível e de fácil manuseio para superar essa limitação. Objetiva-se avaliar qualitativamente se os resultados gerados pela mesa d'água representam com precisão os padrões de fluxo de ventilação natural em modelos físicos mais complexos. Para tanto, são realizados testes experimentais em uma mesa d'água, e comparados com simulações de Dinâmica dos Fluidos Computacional. A metodologia é composta por quatro etapas: 1) determinação do modelo; 2) caracterização da mesa d'água; 3) descrição das configurações utilizadas nas simulações computacionais; e 4) análise dos resultados. Os resultados foram satisfatórios, com semelhanças no comportamento do fluxo de ar nas áreas internas e externas da edificação, embora tenham surgido divergências nas zonas de baixa circulação de ar.

Palavras-chave: ventilação natural, mesa d'água, CFD.

1. Introduction

Integrating sustainability in architecture is a growing concern, especially considering the building's significant impact on global energy consumption and greenhouse gas emissions (United Nations Environment Programme, 2021). In this context, the search for passive strategies, such as natural ventilation, stands out as a sustainable approach to reducing energy consumption in buildings.

When considering sustainability in architecture, it is essential to prioritize techniques that promote human thermal comfort and energy efficiency, such as natural ventilation. In addition to helping reduce internal thermal loads, natural ventilation can also be an environmentally friendly solution, reducing the reliance on high-energy-consuming HVAC systems. For efficient implementation of this technique, the importance of studying the internal and external flow patterns in buildings and understanding this phenomenon in the early stages of design is emphasized (Frota; Shiffer, 1999; Lamberts; Dutra; Pereira, 2014; Subhashini; Thirumaran, 2019).

Beyond the aspects related to thermal comfort and thermal load, it is also crucial to consider issues related to air quality. In winter, it is common to reduce air exchange with the external environment to avoid cold air from entering. Similarly, sealing off a space in summer may be prioritized to reduce thermal exchange with the warmer exterior. In both cases, it is important to emphasize the need for air renewal, carried out through ventilation, to ensure hygiene (Rivero, 1986).

A greater number of hygiene-related issues are observed in Social Housing (HIS). In general, in these projects, aspects related to construction costs, both in terms of materials and construction systems, are prioritized (Triana; Lamberts; Sassi, 2015). As a result, problems are commonly observed in these environments, and concerning ventilation, mold, and fungi can develop due to moisture resulting from inadequate ventilation (Bach; Veiga, 2020).

In addition to the issues above, there is also a lack of attention to the north-south orientation of the housing units. Projects from the *Minha Casa Minha Vida* program, another social housing implementation policy, often do not receive proper attention regarding the orientation of the units. Therefore, conducting studies evaluating how ventilation occurs within the dwellings is essential. In this regard, computational fluid dynamics (CFD) simulations conducted in a case study in Campinas showed that diagonal orientation presented better results (Morais; Labaki, 2017).

CFD assessments and on-site measurements have shown that changes in openings contribute to user comfort and highlight how the lack of air circulation can cause thermal discomfort, depending on the climatic situation (Elshafei et al., 2017). Evidence shows the configuration of openings influences users' thermal comfort (Tiburcio; Bittencourt, 2017). Thus, the configuration of openings is crucial for user comfort and the overall ventilation of the space (Gao; Lee, 2011).

Consequently, CFD analysis presents significant potential for the qualitative and quantitative evaluation of flow patterns in environments that must be analyzed (Chen, 2003). Despite its accuracy in evaluating physical parameters related to natural ventilation in architectural design, this tool requires complex software, high costs, licensing, difficulties in defining boundary conditions, and challenges related to fluid obstacles, limiting its incorporation in the early design stages (Shirzadi; Mirzaei; Naghashzadegan, 2018; Sacht; Lukiantchuki, 2017).

Besides CFD analysis, the wind tunnel is a reliable tool for qualitative and quantitative verifications (Sach; Lukiantchuki, 2017). However, its use requires ample physical space, specific equipment installation, and specialized personnel operation, limiting its accessibility (Bittencourt; Cândido, 2010).

To address these challenges, using water tables to visualize the phenomenon has been suggested as an efficient alternative (Xavier et al., 2020; Mundhe; Damle, 2020; Rossi et al., 2019). The water table is a qualitative analysis tool for natural ventilation, visually reproducing physical properties similar to the real phenomenon (Toledo; Pereira, 2003). Thus, it is a tool that can reliably provide information to guide decisions in the early stages of project development (Royan; Vaidya, 2020).

Water table experiments allow the visualization of fluid movement in reduced-scale models, enabling the analysis of their behavior. This tool can verify and quantify flow patterns generated inside and around buildings (Mundhe; Damle, 2020). In this context, the analysis can be expanded to include entire floors, covering all internal spaces of apartment buildings, using physical models applied in a water table (Toledo; Pereira, 2005).

Furthermore, when analyzing the internal environments of commercial buildings specifically designed for office use, the water table verifies the impacts of facade devices on flow patterns within the interior spaces (Lima et al., 2021). Regarding air movement in indoor spaces, it is important to highlight the role of ventilation in mitigating the spread of airborne pathogens, emphasizing how the water table can be a valuable tool for these analyses (Mattia; Chvatal, 2021).

However, this approach still has limitations, such as the two-dimensional visualization, the lack of quantitative measurements, and the influences caused by specific environmental factors (Custódio et al., 2021). Therefore, further studies are needed to explore alternative approaches with specific analysis parameters and compare them with more complex and reliable methods, such as CFD, to address the limitations of the water table's efficiency (Custódio et al., 2023).

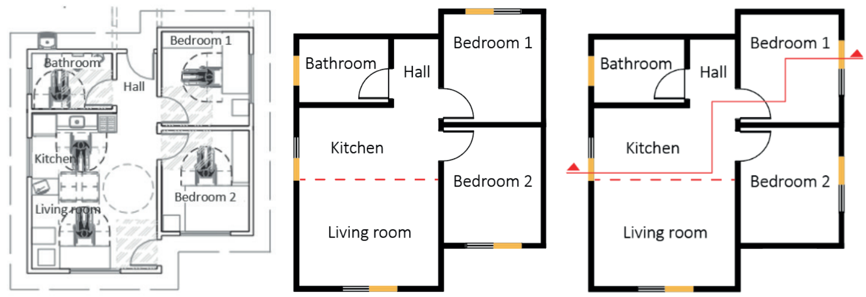
Thus, this article aims to qualitatively assess whether the results generated by the water table accurately represent the flow patterns of natural ventilation in more complex physical models. Experimental tests are conducted in a water table to achieve this, and the results are compared to CFD simulations.

2. Method

This study follows a structured methodology comprising the following stages: 1) model determination; 2) characterization of the water table and its input parameters for experiment development; 3) description of the configurations used in the computational simulations employing CFD; and 4) analysis of the results.

2.1. Determination of the model

The defined analysis model is a representative Social Interest Housing (HIS) of the Brazilian Federal Government's *Minha Casa Minha Vida* program (Triana; Lamberts; Sassi, 2015). The floor plan (Figure 1a) is divided into two bedrooms, a bathroom, and a living space that integrates the kitchen, living room and circulation to the bathroom. The same HIS model served as the basis in the research of Ribeiro (2022), which derived the floor plan in figure 1b, used for the water table experiments.



(a) (b) (c)

50% of the free span of the opening is designated for natural ventilation

The imaginary line is the boundary between the kitchen and the living room.

Section

Figure 1 – (a) Model of the floor plan of a representative HIS. Source: adapted from Triana, Lamberts, and Sassi (2015). (b) The floor plan model has room openings on the opposite walls. (c) The floor plan model has room openings on the adjacent walls. Source: adapted from Ribeiro (2022).

For the tests, fixed opening configuration parameters were defined as follows: the location of the external openings of the bedrooms is on the wall opposite the door (Figure 1b) and adjacent to the door (Figure 1c); the positioning of the external openings of the bedrooms is centralized on the wall for both models (Figures 1b and 1c); external doors were considered closed; internal doors are closed but with the upper flag open (opening above the door that allows the passage of air); the other openings maintained the same configuration as the representative HIS model. The wind incidence angle was adopted as the analysis factor regarding the variable parameter.

For this purpose, 45°, 90°, and 135° angles were adopted (Figure 2), corresponding to Brazil's predominant wind orientations. 45° represents the Northeast, 90° the East, and 135° the Southeast, with the North considered zero degrees (Ribeiro, 2022).

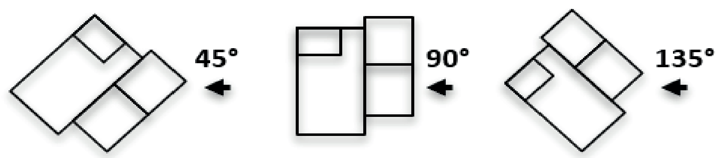


Figure 2 - Indication of wind incidence angles. Source: adapted from Ribeiro (2022).

A permanent ventilation system was considered to visualize the fluid flow inside the environments in both the model on the water table and the CFD model. Additionally, two planes of natural ventilation visualization were used in the model: horizontal (6 tests in floor plan) and vertical (1 test in section), so that the analyses were complementary, considering the two-dimensional verification. The models for analysis were made of laser-cut 2-millimeter-thick acrylic sheets at a 1:25 scale. Further information about the model production can be found in the work of Ribeiro (2022).

2.2. Characterization of the water table and the tests performed

The water table used in this study has a test area of 1.20 m x 0.71 m, as shown in figure 3. The equipment consists of two vertically shaped reservoirs at the ends (upstream and downstream), connected at the top by a level horizontal plane, forming a wide channel for the flow of a fluid sheet with a constant height of 1 cm. At the bottom, a set of hydraulic connections installed in an electrical pumping system and controlled by a frequency inverter maintains a controlled and cyclical water flow between the tanks, ensuring the fluid flow is constant (Figure 4).

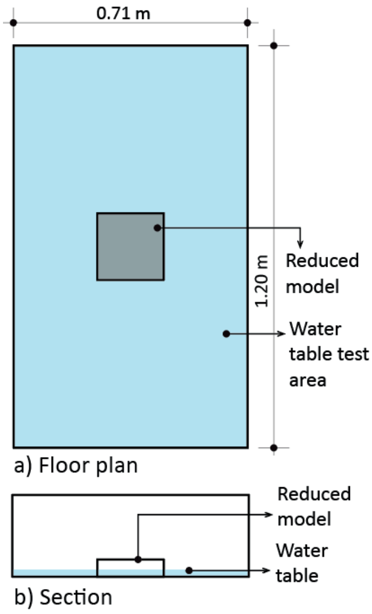


Figure 3 - Dimension of the water table test area. Source: the authors.

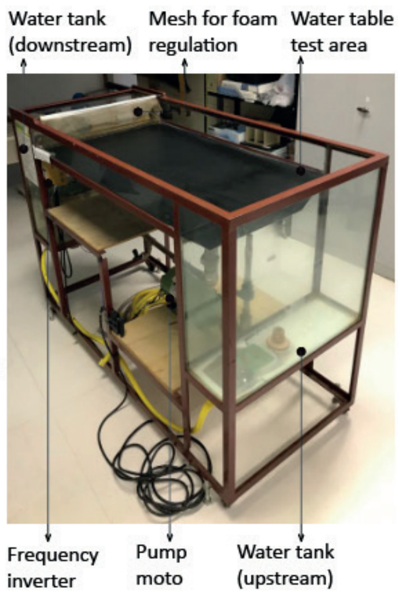


Figure 4 - Water table. Source: the authors.

The tracer method and the direct injection technique of the indicator (detergent) were adopted, which generates contrast with the test plane and the model since they are suitable for low speed and allow quick visualization of the flow patterns, as indicated by Rossi et al. (2019), Toledo and Pereira (2003) and Toledo and Pereira (2005). For this purpose, the liquid contained a solution of water and detergent in the proportion of 150 milliliters of detergent dissolved in 100 liters of water.

After filling the water table and adding the detergent, the equipment activation instructions were followed, establishing a frequency value of 40 Hz for approximately 5 minutes until foam formation. After forming the foam, the frequency value was reduced to 25 Hz, considering the laminar flow and steady-state direction characteristic of low-speed water flow (Ribeiro, 2022).

For the experiments on the water table, the reduced physical model was analyzed in isolation, meaning that the influences of the built and natural environment were disregarded, and all tests had the same test conditions.

The model was placed in the central part of the test plan to reduce edge effects in the experiments. Photographic records and videos were taken for each experiment using a smartphone mounted on a support positioned 60 cm above the water table's test plan. Ribeiro's (2023) work provides more information about the experimental procedures.

2.3. Description of the configurations used in the computer simulations

This study conducted simulations using the ANSYS CFX software (2023) student version, while modeling was done in AutoCAD software (2023), and later exported to CFD in *.igs* format. The domain modeling was based on the dimensions of the water table test area (width = 0.71 m; height = 0.30 m; and length = 1.20 m). The evaluation models were constructed following the dimensions of the physical models and positioned in the center of the domain to avoid edge effects (Custódio et al., 2021).

With that said, the input data entered into the Workbench suite of the CFX software for conducting simulations include the following steps:

(1) Geometry: import the model generated in AutoCAD;

(2) Mesh (computational mesh generation):

> **(2.1)** tetrahedral structure;
>
> **(2.2)** refinement of surfaces in the domain and building of 3x10-2 m and 1.5x10-2 m, respectively (Figure 5). The combination of these parameters determines the number of elements and, consequently, the simulation processing time.

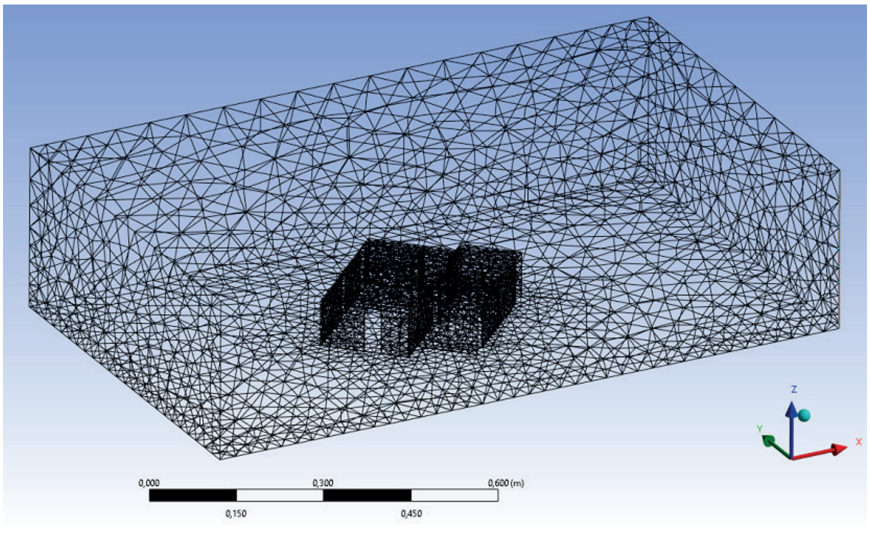


Figure 5 - Computational mesh generation. Source: the authors.

(3) Setup (definition of boundary conditions):

> **(3.1)** Domain conditions - Input: INLET, output: OUTLET, sides, and roof: WALL free slip (no friction), floor and building surfaces: WALL no slip (with friction) (Widiastuti et al., 2020). These conditions were set to resemble those established in the water table test.;
>
> **(3.2)** regimen — permanent;
>
> **(3.4)** heat transfer model - Isothermal (25 °C) (Custódio et al., 2023);
>
> **(3.5)** air velocity - 0.20 m/s: representative of the frequency used in the water table tests (Xavier et al., 2020);
>
> **(3.6)** turbulence model - K-epsilon (commonly used in various studies on natural ventilation), the input parameters for turbulence were: average intensity of 5% (default software value).

(4) Solution (processing of solutions):

> **(4.1)** Convergence level - maximum 10-4 (Shirzadi; Mirzaei; Naghashzadegan, 2018);
>
> **(4.2)** number of iterations - Minimum 100 and maximum 1000.

(5) Results (visualization of results):

> **(5.1)** Visualization: 2D dimension in a plane 1 cm above the floor;
>
> **(5.2)** symbol: vectors, with a dimension of 0.8 m.

2.4. Analysis of the results

The assessment of congruence between the water table experiments and CFD simulations was conducted through a qualitative analysis of the air distribution in the selected models. The qualitative comparative analyses of air distribution were performed by overlaying the results obtained from the experimental tests on the water table and the results found in the CFD simulations (Custódio et al., 2021; Almeida et al., 2020).

For this purpose, the results were optimized through schematic drawings, which assessed the representation of flow patterns in the water table in line with the CFD. The drawings were generated using Adobe® Illustrator software and later exported in PNG format.

3. Results and discussion

Figures 6 and 7 show the tests conducted on the ground floor of the model derived from the representative HIS. They present the results of the water table experiments, CFD simulations, and graphical overlay schemes of the airflow, considering the three analyzed wind incidences (45°, 90°, and 135°).

In general, the fluid distribution observed in the water table experiments showed significant similarity to the results obtained in the computer simulations, both internally and externally. The most evident similarities in the internal fluid behavior at the three analyzed incidence angles are noted where the fluid flow manifests most expressively, in the main wind flow, referring to areas where the fluid in motion finds the shortest path between the inlet and outlet openings.

This aspect can be observed more clearly in figure 6c, which presents a graphical overlay of the fluid flow in the tools used. It refers to the tests in which the room openings are on opposite walls. The mentioned paths are marked in a solid line and have the following opening directions: W1 to D1, W2 to D2, D2 to W4 and W3, D1 to D3, and subsequently W5.

Regarding the external congruences of the air movement, the windward face coincides since it is the side of wind incidence (Figure 6c). The leeward face also showed similarities in the expressive fluid flow and the air recirculation near the W4 outlet in the study of the 135° angle. This air recirculation is due to the fluid volume encountered by the flow patterns from W5 and W4 and the fluid's acceleration caused by the building's lower edge.

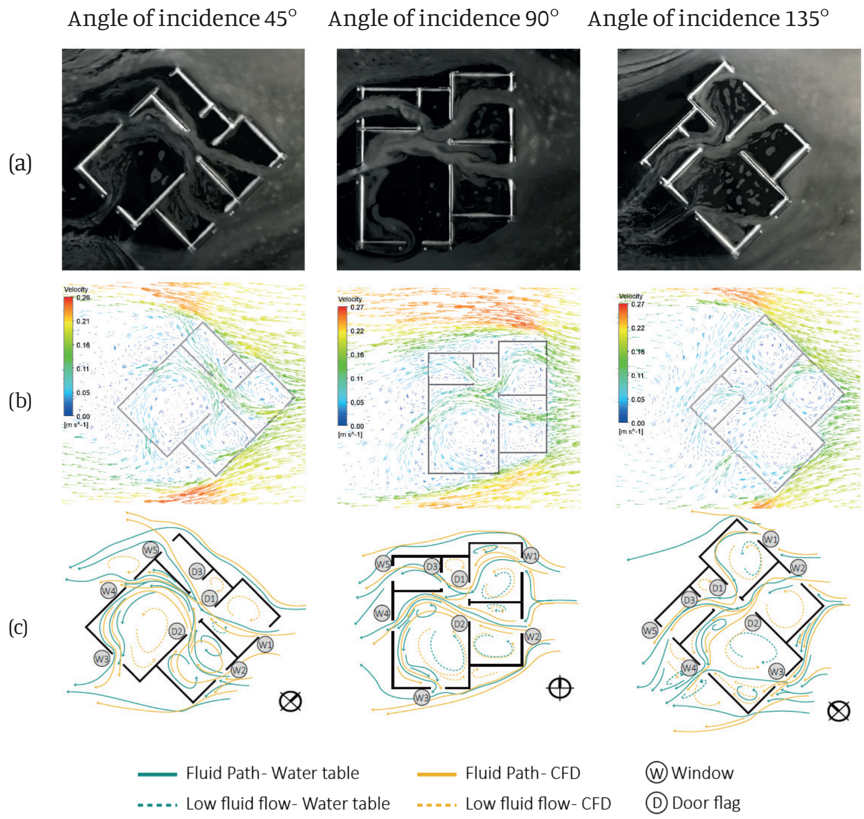


Figure 6 – (a) fluid flow for CFD simulations, (b) experiments in the water table, and (c) graphical schemes of the CFD and water table overlay - Floor Plan model with room openings on the opposite walls. Source: the authors.

Despite the results between the water table tests and CFD simulations being corresponding in most cases, some divergences were noted, particularly in areas with low air circulation or stagnant air, which can be identified by areas with a lack of foam (water table tests) and by vectors expressing lower air velocities (computer simulations). Regarding the observed external divergences, it was noted that at angles of 45° and 135°, the upper zones near the corners showed different air paths, as they experienced deviations due to the built obstacle.

Concerning the analyses of the inconsistency of the internal air distribution, for the wind incidence angle of 45° (Figure 6c), it is noticeable that in the living room and bedroom 1, there is a wind shadow in the water table tests, while in the simulations, there were undulatory movements that generated air recirculation, even at low speed (approximately 0.03 m/s). The same aspect can be observed in the 135° angle study, in bedroom 2, and the area between D1 and D3 for all three analyzed incidence angles.

Regarding fluid distribution in the model with room openings on adjacent walls (Figure 7), a notable similarity was observed between the experiments conducted in the water table and the computational simulations, especially in the external zones for the three angles analyzed in the case study, both on the windward and leeward sides. Some similarities and variations in fluid behavior were identified in the analysis of the internal zones.

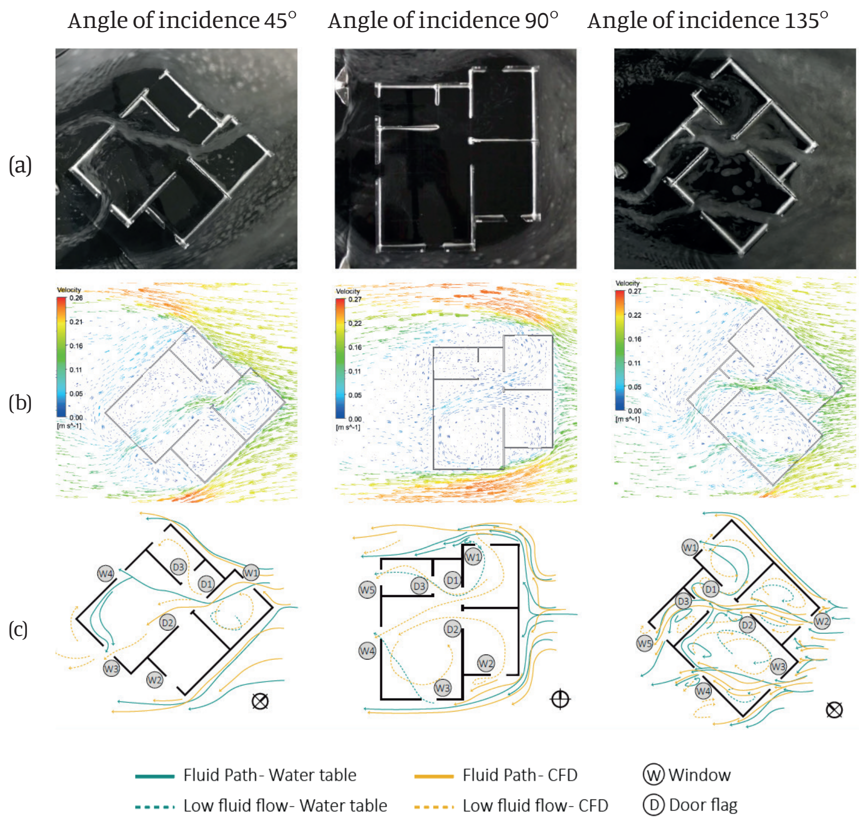


Figure 7 – (a) fluid flow for CFD simulations, (b) experiments in the water table and (c) graphical schemes of the CFD and water table overlay - Floor Plan model with room openings on the adjacent walls. Source: the authors.

For the 45º angle (Figure 7c), stagnant air areas were observed in room 2 and the bathroom and limited recirculation in room 1, with the air inlet opening W1 coinciding in both methods. However, the fluid entering through W1 followed different paths when exiting through D1. In the water table tests, two air outlets, W4 and W3, were identified with no significant loss of speed. In contrast, in the computational simulations, the fluid experienced a reduction in speed until it reached the W3 outlet.

In the tests conducted for the 90º angle, greater similarities were observed, both in the external zones, where the airflow is more intense and deflects around the edges of the building, and in the internal areas, which showed low airflow circulation in all rooms. For the 135º angle, significant similarities were noted, both in the more prominent airflow and in areas of low circulation. The only discrepancy was found in room 1, where the water table tests showed a significant flow, while the computational simulations revealed low air recirculation.

Figure 8 shows the section of the studied HIS (see the cutting line in figure 2b). The opening configuration is characterized as follows: external openings are open (W1 and W4), the bedroom door is closed, and the upper flap of the bedroom door is open (D1).

(a)

(b)

(c)

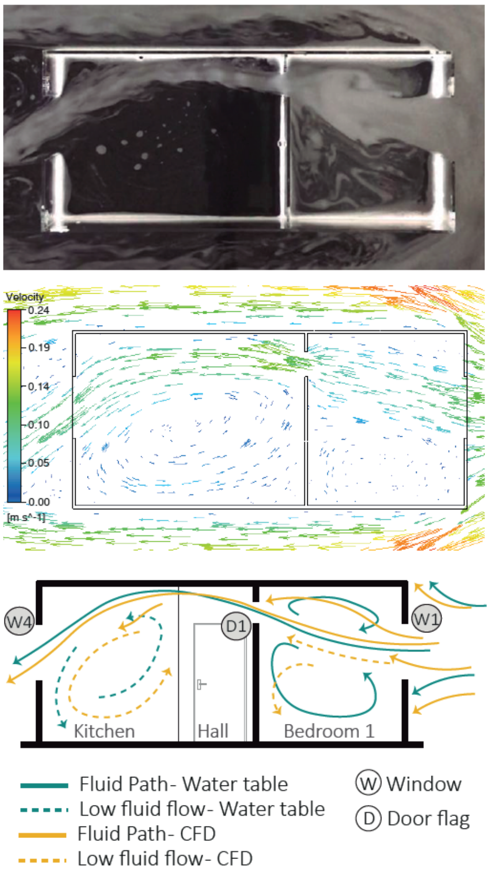


Figure 8 – (a) fluid flow for CFD simulations, (b) experiments in the water table, and (c) graphical schemes of the CFD and water table overlay – Section. Source: the authors.

In this case, it is noticed that the fluid flow in the internal spaces shows great similarity in the overlay of CFD simulations with the experiments conducted on the water table, which confirms the reliability of the physical equipment used. The more closely the results match those in CFD, the more representative the tested model. It is observed that the most expressive air path occurs from the height of the windowsill of W1 (located on the windward side) towards the upper part of the environment and the opposite of W1, i.e., towards the D1 opening. Then, the fluid flows into the other room, where it encounters the W4 air outlet.

The internal fluid flow in the two tools used conforms in the areas of more expressive air passage and the zones of air recirculation, mostly located in the lower part of the space (Figure 8).

Complementary to these analyses, through the section, it is possible to verify the relationship between the dimensions of the air inlet and outlet openings, which influence the quality and quantity of fluid flow in the environment. According to Olgyay (2016), when the air inlet opening is larger than the outlet, lower speeds and more uniform air distribution in the space are observed, which can be seen in the first section of the analysis (from the windward side — right side), where bedroom 1 has W1 with a larger dimension than D1. It is noticeable that the fluid distribution is more homogeneous in the environment.

On the other hand, when the air inlet opening is smaller than the outlet, higher speeds and more irregular air distribution are observed, as seen in the second section of the study, where D1 is smaller than W4, and it is noticeable that the lower zone of the space lacks air.

It is important to note that the speed cannot be perceived through the images of the water table tests; however, it is evident that the air distribution in the observed environments is similar to that described by Olgyay (2016).

Another aspect to highlight is that the test with the bedroom door closed but with the upper flap of the door open, in addition to allowing cross ventilation and air renewal in the environment, also contributes to the privacy of the space, which becomes an encouraging factor in adopting this element in dwellings.

4. Conclusion

The qualitative evaluation of natural ventilation by comparing the water table and computational CFD simulation tools proved satisfactory. The fluid flow characteristics in the internal and external areas of the study object, which is a more complex model characterized by a compartmentalized layout, were significantly similar.

The main similarity in fluid behavior revealed by both tools is related to the path of the main wind flow in the spaces, observed in the three incidence angles analyzed in the horizontal plane (floor plan) for openings on both opposite and adjacent walls, as well as in the test conducted in the vertical plane (section). However, the notable divergence pertains to certain areas of air recirculation that did not converge despite showing low velocity in the simulation, especially in the tests with a 45° angle in the floor plan with openings on opposite walls.

The experiments conducted in the water table were validated through computational CFD simulations, which highlighted the compatibility of the tools in their experimental results, considering, in this case, the adopted parameters: the housing model used, the configuration of openings, and the angles of incidence of the winds. Therefore, reliability in using the water table as equipment for qualitative evaluation of natural ventilation can be attributed to similar results found in the literature (Xavier et al., 2020; Royan; Vaidya, 2020; Custódio et al., 2023).

In addition, the tool is easy to handle compared to computational simulations that require more in-depth knowledge. However, the water table has limitations in evaluating the phenomenon, as its visualization is two-dimensional; in this context, the tool should be used responsibly.

The comparative qualitative analysis presented in this article can significantly enrich the theoretical foundation and the applied practices in architecture and urban planning. It can advance the understanding of natural ventilation in buildings and contribute to the evolution of standards and practices in the field. The study offers substantial contributions in the academic realm by fostering discussions on natural ventilation behavior based on experimental and computational simulation methods.

For architecture and urban planning professionals, validating methods such as the water table and CFD simulations provide practical and reliable tools for evaluating and proposing strategies to optimize natural ventilation in indoor environments. Furthermore, the research results have the potential to influence the formulation and updating of building codes and regulations by demonstrating the effectiveness of different approaches in analyzing natural ventilation in buildings.

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