Qualitative analysis of natural ventilation: comparison between experimental tests on the water table and computational simulations in CFD

Análise qualitativa da ventilação natural: comparação entre testes experimentais na mesa d'água e simulações computacionais em CFD

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Abstract

The optimization of natural ventilation in buildings contributes to the reduction of energy consumption. However, to precisely analyze the physical parameters involving natural ventilation, the use of complex software is required. Nevertheless, to address this limitation, the use of water tables is an accessible and easy-to-handle strategy that allows the visualization of the phenomenon, especially in the early stages of project. Therefore, the objective is to avaluate qualitatively assess whether the results generated on the water table accurately represent the natural ventilation flow in physical models. For this purpose, simplified physical experiments are compared with Computational Fluid Dynamics (CFD) simulations. The methodology consists of four stages: 1) Determination of the model; 2) Characterization of the water table and its input parameters for experiment development; 3) Description of the configurations adopted in computational simulations; and 4) Analysis of the results. The results were satisfactory, and the qualitative assessment of natural ventilation through the comparison of the water table and CFD simulation tools demonstrated compatibility, with significant similarities in fluid flow characteristics in both the internal and external areas of the dwelling.

Keywords: *Natural ventilation; Water table; Computational simulation; CFD; Indoor air.*

Resumo

A otimização da ventilação natural em edificações contribui para a redução do consumo de energia. No entanto, para analisar precisamente os parâmetros físicos que envolvem a ventilação natural, é necessário o uso de softwares complexos. Contudo, para enfrentar essa limitação, o uso de mesas d'água é uma estratégia acessível e fácil de manusear, permitindo a visualização do fenômeno, especialmente nas fases iniciais de projeto. Portanto, objetiva-se avaliar qualitativamente se os resultados gerados na mesa d'água representam com precisão o fluxo de ventilação natural em modelos físicos. Para isso, experimentos físicos simplificados são comparados com simulações de Dinâmica dos Fluidos Computacional (CFD). A metodologia consiste em quatro etapas: 1) Determinação do modelo; 2) Caracterização da mesa d'água e seus parâmetros de entrada para o desenvolvimento do experimento; 3) Descrição das configurações adotadas nas simulações computacionais; e 4) Análise dos resultados. Os resultados foram satisfatórios, e a avaliação qualitativa da ventilação natural por meio da comparação das ferramentas de mesa d'água e simulação CFD demonstrou compatibilidade, com semelhanças significativas nas características do fluxo de fluido tanto nas áreas internas quanto externas da habitação.

Palavras-chave: Ventilação natural; Mesa d’água; Simulação computacional; CFD; Ar interno.

1. Introduction

The integration of sustainability into architecture is a growing concern, especially given the significant impact buildings have on global energy consumption and greenhouse gas emissions [1]. In this context, the pursuit of 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 contributing to the reduction of internal thermal loads, natural ventilation can also be an environmentally friendly solution, reducing dependence on energy-intensive HVAC systems. For an efficient implementation of this technique, the importance of studying the internal and external airflow in buildings is highlighted and understanding this phenomenon in the early stages of project design [2], [3], [4].

However, the most appropriate and precise analysis of the physical parameters related to natural ventilation in architectural design requires the use of complex software, including that employing Computational Fluid Dynamics (CFD). These tools have high computational costs, licensing requirements, difficulty in establishing boundary conditions, and obstacles to be incorporated in the early stages of the project [5], [6].

To address these challenges, the use of water tables for visualizing the phenomenon has been suggested as an efficient alternative [7], [8], [9]. The water table serves as a qualitative analysis tool for natural ventilation, visually reproducing physical properties akin to the real phenomenon [10]. Thus, it is an analysis tool that can reliably contribute information to guide decisions in the early stages of project development [11].

However, there are still limitations to this approach, such as visualization in only two dimensions, lack of quantitative measurements, and influences caused by specific environmental factors [12]. Therefore, conducting further studies to explore alternative approaches with specific analysis parameters and comparing them with more complex and reliable methods, such as CFD, is necessary to address the limitations of water table efficiency [13].

Therefore, this paper aims to qualitatively assess whether the results generated on the water table accurately represent the natural ventilation airflow in more complex physical models. For this purpose, simplified physical experiments are compared with Computational Fluid Dynamics (CFD) simulations.

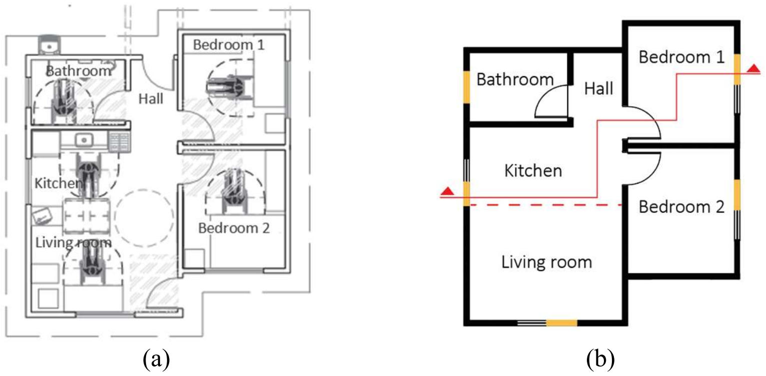
2. Method

This study adopts a structured work method in the following steps: 1) Determination of the model; 2) Characterization of the water table and its input parameters for the development of experiments; 3) Description of the configurations adopted in computational simulations using 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 [14]. 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 [15], which derived the floor plan in figure 1b that was used for the experiments on the water table.

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); the positioning of the external openings of the bedrooms is centralized on the wall (Figure 1b); 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. Regarding the variable parameter, the wind incidence angle was adopted as the analysis factor.



(a) (b)

50% of the free span of the opening is designated for natural ventilation
Imaginary line serves as the boundary between the kitchen and the living room
Section

Figure 1: (a) Model of the floor plan of a representative HIS [14], and (b) Model of the floor plan [15].

Source: Adapted from [14].

For this purpose, angles of 45, 90, and 135° were adopted (Figure 2), which correspond to predominant wind orientations in Brazil, with 45° representing the Northeast, 90° the East, and 135° the Southeast, considering the North as zero degrees [15].

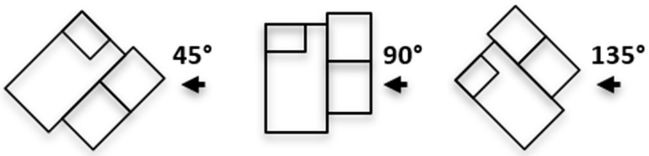


Figure 2: Indication of wind incidence angles. Source: Adapted from [15].

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 (3 tests in floor plan) and vertical (1 test in section, see Figure 1b), 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 [15].

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 that the fluid flow is constant (Figure 4).

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 a quick visualization of the airflow, as indicated by various authors [9], [10], [16]. 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.

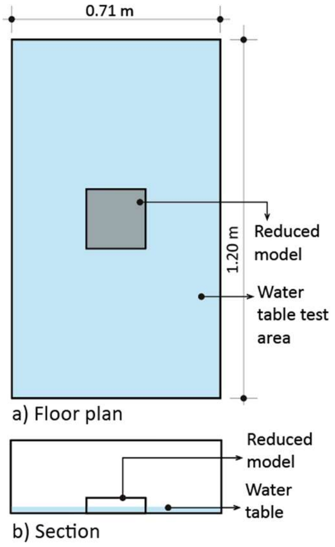


Figure 3: Dimension of the water table test área.

Source: Prepared by the authors.

Figure 4: Water table.

Source: Prepared by the authors.

After filling the water table and adding the detergent, the equipment activation instructions were followed, which consisted of establishing a frequency value of 40 Hz for approximately 5 minutes until foam formation. After the foam was formed, the frequency value was reduced to 25Hz, considering the laminar flow and steady-state direction characteristic of low-speed water flow [15].

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. More information about the experimental procedures can be found in the work of [15].

2.3 Description of the configurations used in the computer simulations

For this study, simulations were conducted 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 [12].

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; **(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) [17]; (3.2) regimen – permanent; (3.4) heat transfer model - Isothermal (25 °C) [13]; (3.5) air velocity - 0.20 m/s: representative of the frequency used in the water table tests [7]; and (3.6) turbulence model - K-epsilon [18]; **(4) Solution** (processing of solutions): (4.1) Convergence level - maximum 10-4 [5]; and (4.2) number of iterations - Minimum 100 and maximum 1000; and **(5) Results** (visualization of results): (5.1) Visualization: 2D dimension in a plane 1 cm above the floor; and (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 [12], [19]. For this purpose, the results were optimized through schematic drawings to assess the representation of air flow 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

3.1 Qualitative analysis of air distribution

The tests conducted on the ground floor of the model derived from the representative HIS can be observed in Figure 5, where the results related to the experiments on the water table, CFD simulations, and graphical overlay schemes are shown for the three considered 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, that is, 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 5c, where the graphical overlay of the fluid flow in the tools used is presented. The mentioned paths are marked in a solid line and have the following directions of openings: 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, it is evident that the windward face coincides since it is the side of wind incidence. The leeward face also showed similarities both in the expressive fluid flow and in the air recirculation near the W4 outlet in the study of the 135° angle. This air recirculation is due to the encounter of the fluid volume provided by the air flow from W5, W4, and the acceleration of the fluid caused by the lower edge of the building.

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 5c), 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 also in the area between D1 and D3 for all three analyzed incidence angles.

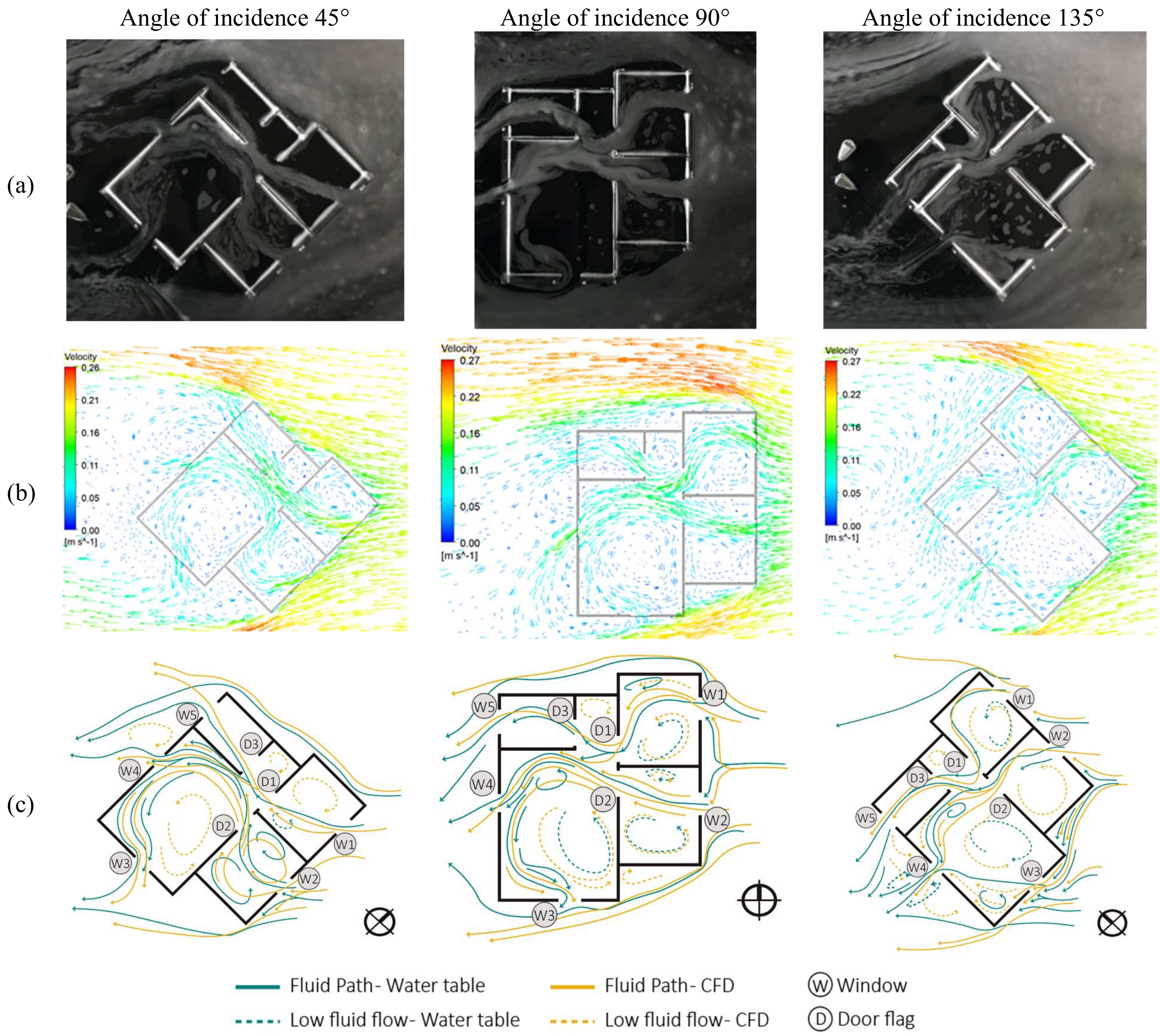


Figure 5: Fluid flow for CFD simulations (a), experiments in the water table (b), and graphical schemes of the CFD and water table overlay (c) - Floor Plan. Source: (a) [15]; (b) e (c) prepared by the authors.

Regarding the section of the studied HIS (see the cutting line in Figure 2b), it can be observed in Figure 6, where 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).

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 conformity between the internal fluid flow in the two tools used occurs both in the areas of more expressive air passage and in the zones of air recirculation, mostly located in the lower part of the space (Figure 6).

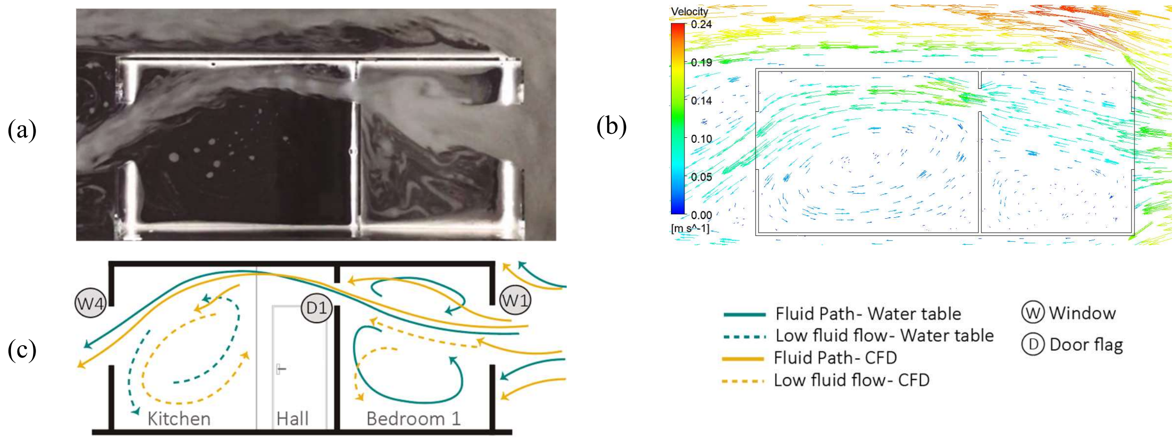


Figure 6: Fluid flow for CFD simulations (a), experiments in the water table (b), and graphical schemes of the CFD and water table overlay (c) – Section. Source: (a) [15]; (b) e (c) prepared by the authors.

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 [20], 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, and 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 [20].

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 through the comparison of the water table and computational CFD simulation tools proved to be satisfactory, as there were significant similarities in 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.

The main similarity in fluid behavior revealed in both tools is related to the path of the main wind flow in the spaces, being correlated in the three analyzed angles of incidence in the horizontal plane (floor plan), as well as in the test carried out in the vertical plane (section). However, the divergence to be noted is regarding some areas of air recirculation that did not converge, despite showing low speed in the simulation, especially in the tests with a 45°angle.

The validation of the experiments conducted in the water table was produced through computational CFD simulations, which allowed highlighting 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. Thus, reliability in the use of the water table as equipment for qualitative evaluation of natural ventilation can be attributed, with similar results found in the literature [7], [11], [13].

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

References

[1] IEA (2021), Global Status Report for Buildings and Construction 2021. International Energy Agency, Paris, 2021. [Online], Available: https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction. [15 January 2023].

[2] Frota, A. B. and Shiffer, S. R. (1999). Manual do Conforto Térmico. p.243.

[3] Lamberts, R. et al. (2014). Eficiência Energética na Arquitetura. p.382.

[4] Subhashini, S. and Thirumaran, K. (2019). CFD simulations for examining natural ventilation in the learning spaces of an educational building with courtyards in Madurai. Building Services Engineering Research And Technology, 4: p. 466-479.

[5] Shirzadi, M. et al. (2018). Development of an adaptive discharge coefficient to improve the accuracy of cross-ventilation airflow calculation in building energy simulation tools. Building And Environment, 127: p. 277-290.

[6] Sacht, H. and Lukiantchuki, M. A. (2017). Windows Size and the Performance of Natural Ventilation. Procedia Engineering, 196: p.972-979.

[7] Xavier, A. C. de A. et al. (2020). Visualização da ventilação natural em ensaios na mesa d´’água comparado a simulações computacionais. PARC Pesquisa em Arquitetura e Construção, 11: p: e020020.

[8] Mundhe, P. and Damle, R. M. (2020). A methodology for quantifying flow patterns in a water-table apparatus for naturally ventilated buildings. Architectural Science Review, 64: p. 98-108.

[9] Rossi, M. M. et al. (2019). A mesa d’água como ferramenta de apoio para a caracterização de um modelo genérico a ser ensaiado em túnel de vento. Revista IPT: Tecnologia e Inovação, 3: p. 70-80.

[10] Toledo, A. and Pereira, F. (2003). Potencial da Mesa D'água para a visualização Analógica da Ventilação Natural em Edifícios. In: Encontro latino-americano de conforto no ambiente construído, 7: p. 1383-1390.

[11] Royan, M. and Vaidya, P. (2020) Construction, validation and testing of a water table for natural ventilation analysis. Energy And Buildings, 226: p. 110356-110356.

[12] Custódio, M. I. et. al. (2021). Estudo Qualitativo da Ventilação Natural em Ambientes Internos: Uma Análise Comparativa Do Aplicativo De Smartphone Windtunnel CFD e CFD. In: Encontro latino-americano de conforto no ambiente construído, 7: p. 958-967.

[13] Custódio, M. I. et. al. (2023). A. Avaliação da taxa de obstrução do modelo físico reduzido na área de ensaio na mesa d'água. Ambiente Construído, 23: p. 105-120.

[14] Triana, M. A. et al (2015). Characterisation of representative building typologies for social housing projects in Brazil and its energy performance. Energy Policy, 8: p. 524–541.

[15] Ribeiro, R. M. (2022). Análise do desempenho da ventilação natural de acordo com as diretrizes referentes às aberturas na ABNT NBR 15.575 e em Códigos de Obras e Edificações no Brasil. Dissertação (Mestrado em Arquitetura e Urbanismo) – Universidade Federal de Santa Catarina, Florianópolis, 2022. Available: https://repositorio.ufsc.br/handle/123456789/235416. [05 January 2023].

[16] Toledo A. M. and Pereira F. O. R. Natural ventilation due to wind action: practice knowledge against experimental airflow visualisation. In: International Conference Passive and Low Energy Cooling for the Built Environment, 2: p. 1009-1014.

[17] Widiastuti R. et al. (2020). CFD Simulation on the Natural Ventilation and Building Thermal Performance. Iop Conference Series: Earth and Environmental Science, 448: p. 012004.

[18] YI, Y. K. et al. (2023). Application of machine learning (ML) and genetic algorithm (GA) to optimize window wing wall design for natural ventilation. Journal Of Building Engineering, 68, p: 106218.

[19] Almeida, F. S. et al. (2020). Análise do uso de aplicativo virtual para estudo da ventilação natural em ambientes internos. In: Encontro nacional de tecnologia do ambiente construído, 18: p. 1-10.

[20] Olgyay, V. Arquitectura y Clima (2016). p. 2003.