APPLICATION OF COMPUTATIONAL FLUID DYNAMICS (CFD) IN ASSESSING THE IMPACT OF SITE LAYOUT ON NATURAL VENTILATION AROUND BUILDINGS: A GLOBAL OVERVIEW AND THE CURRENT STATE IN VIETNAM

ỨNG DỤNG MÔ PHỎNG ĐỘNG LỰC HỌC CHẤT LƯU (CFD) ĐÁNH GIÁ ẢNH HƯỞNG CỦA BỐ CỤC MẶT BẰNG ĐẾN THÔNG GIÓ TỰ NHIÊN XUNG QUANH CÔNG TRÌNH: TỔNG QUAN THẾ GIỚI VÀ THỰC TRẠNG TẠI VIỆT NAM

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Abstract: This paper investigates the role of natural ventilation and the application of Computational Fluid Dynamics (CFD) as a core component in sustainable architectural design. Amidst climate change and stringent requirements for Indoor Environmental Quality (IEQ), natural ventilation serves not only to dilute indoor pollutants but also to optimize thermal comfort and energy efficiency. Utilizing the Systematic Literature Review (SLR) method, the study analyzes the transition of CFD techniques from the aerospace industry to architecture, spanning from detailed facade components to urban wind corridor planning. In Vietnam, despite challenges regarding the shortage of digitized meteorological data and high investment costs, the adoption of CFD remains an inevitable pathway under the pressure of energy efficiency standards such as National Technical Regulation QCVN 09:2017/BXD on Energy Efficiency Buildings. The paper concludes that shifting from qualitative experience-based design to evidence-based design through simulation is key to creating buildings that effectively adapt to tropical humid climates. Consequently, the author proposes the urgent establishment of digitized climate databases and the standardization of simulation validation processes within design documentation to promote sustainable architecture in Vietnam.

Keywords: Natural Ventilation, CFD Simulation, sustainable architecture, thermal comfort.

Tóm tắt: Bài báo nghiên cứu vai trò của thông gió tự nhiên và ứng dụng mô phỏng Động lực học chất lưu (CFD) như một thành tố cốt lõi trong thiết kế kiến trúc bền vững. Trong bối cảnh biến đổi khí hậu và yêu cầu khắt khe về Chất lượng Môi trường Trong nhà (IEQ), thông gió tự nhiên không chỉ giúp pha loãng nồng độ các chất gây ô nhiễm mà còn tối ưu hóa tiện nghi nhiệt và tiết kiệm năng lượng. Bằng phương pháp Tổng quan hệ thống (SLR), nghiên cứu phân tích sự dịch chuyển của kỹ thuật CFD từ lĩnh vực hàng không vũ trụ sang kiến trúc, từ quy mô chi tiết cấu tạo mặt đứng đến quy hoạch hành lang gió đô thị. Tại Việt Nam, dù đối mặt với thách thức về thiếu hụt dữ liệu khí tượng số hóa và rào cản chi phí đầu tư, việc ứng dụng CFD vẫn là lộ trình tất yếu dưới áp lực của các quy chuẩn hiệu quả năng lượng như QCVN 09:2017/BXD. Bài báo kết luận rằng, việc chuyển dịch từ kinh nghiệm cảm tính sang thiết kế dựa trên dữ liệu mô phỏng là chìa khóa để kiến tạo các công trình thích ứng tốt với khí hậu nhiệt đới ẩm. Từ đó, tác giả đề xuất cần sớm xây dựng cơ sở dữ liệu khí hậu số hóa và chuẩn hóa quy trình thẩm định mô phỏng trong hồ sơ thiết kế để thúc đẩy kiến trúc bền vững tại Việt Nam.

Từ khóa: Thông gió tự nhiên, mô phỏng CFD, kiến trúc bền vững, tiện nghi nhiệt.

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I. INTRODUCTION

Natural ventilation goes beyond mere air movement, playing a core role in sustainable architectural design strategies, directly impacting energy efficiency, physical health, and the microclimatic comfort of users. Unlike mechanical (forced) ventilation systems, natural ventilation operates based on physical dynamics: wind pressure and air density differences due to temperature variations (the buoyancy effect or chimney/thermal pressure effect). The essential goal of this solution is to optimize Indoor Environmental Quality (IEQ) by providing a flow of fresh air to dilute and eliminate endogenous pollutants, including volatile organic compounds (VOCs), impurities, and especially the accumulation of CO_2. In high-density spaces lacking effective ventilation, excessive CO_2 concentrations can lead to Sick Building Syndrome (SBS), typically characterized by headaches and impaired concentration; whereas optimal passive ventilation designs can maintain these concentrations at standard levels. Furthermore, air convection plays a crucial role in controlling humidity, inhibiting mold growth, and releasing secondary heat accumulated on building surfaces, thereby significantly improving the overall thermal comfort of the building.

Computational Fluid Dynamics (CFD) simulations rely on solving partial differential equations for mass conservation (continuity equations), momentum (Navier-Stokes equations), and energy, combined with turbulence models to predict the distribution of pressure, velocity, and temperature of air inside and outside a building.

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In architecture, this technique is widely used to analyze aerodynamic phenomena such as the Venturi effect (wind acceleration in narrow gaps), vortices, and flow separation around building edges. Compared to traditional methods such as wind tunnel experiments, CFD offers significant advantages in terms of cost-effectiveness, execution speed, and the ability to provide detailed visual data at every point in the simulation space.

The applications of CFD extend from detailed building designs, such as window and opening placement, to macro-scale planning of urban wind corridors to channel cool air from green spaces or bodies of water deep into the urban core. Integrating CFD into the design process allows for parametric studies, comparing multiple floor plan layouts to find the optimal configuration for capturing summer breezes and blocking winter cold winds, thus creating thermal comfort for the building space.

II. RESEARCH METHODOLOGY

This paper uses the Systematic Literature Review (SLR) method

Category	Inclusion Criteria	Exclusion Criteria
Document type	The original research articles and review articles have undergone peer review.	Conference proceedings, book chapters, and technical reports that have not undergone peer review.
. **Language & Time**	Written in English and Vietnamese. Published within the last 15 years (2011 - 2026).	Other languages. The studies are too old, using outdated simulation technology.
Method	The use of CFD simulation or a combination of CFD with field measurements/wind tunnel testing is mandatory.	Using only general energy analysis software (EnergyPlus) without a detailed CFD model.
Spatial scope	Assess the wind flow **around** and **outside** the building (Outdoor wind environment).	Focus entirely on indoor air quality ventilation or mechanical ventilation (HVAC).
Architectural Elements	There is an assessment of changes in the shape, spacing, or arrangement of buildings.	This research focuses purely on the technical aspects of CFD algorithms, without being tied to architectural spatial forms.

Table 1. Criteria for selecting and excluding review documents

III. EXCHANGE AND DISCUSSION

3.1. Global overview

Although initially developed primarily to solve complex problems in the defense and aerospace fields, Computational Fluid Dynamics (CFD) has expanded dramatically and penetrated almost all fields, especially architectural research and building design [1] . Today, CFD has become an indispensable analytical tool, helping architects and engineers assess environmental performance, optimize facade design and move towards the development of sustainable green buildings [2] .

One of the most important and common applications of CFD in architecture is the study and optimization of natural ventilation. Natural ventilation reduces reliance on mechanical air conditioning systems, thereby saving energy and improving indoor air quality [3], [4] . CFD allows detailed simulation of air flows interacting with building forms, thereby evaluating strategies such as cross-ventilation and single-sided ventilation [5], [6] . Researchers have used CFD to analyze the impact of facade elements such as balconies, louvers, and window configurations on ventilation performance [4], [5], [6] . For example, adding wing walls on balconies can redirect airflow, significantly increasing the speed and distribution of airflow in apartments that can only be ventilated from one side [6] . In addition, CFD is also widely applied to design specific spaces to promote the buoyancy-driven effect such as atria, wind-catchers and voids in high-rise buildings [7], [8], [9] .

On a macro scale, CFD plays a key role in high-density building planning and microclimate assessment. In dense cities like Hong Kong, explosive growth has led to urban heat island effect (UHI), negatively impacting human health [10] . By using CFD, planners can analyze the outdoor wind environment to develop design solutions such as expanding bottom overhead spaces, diversifying building height configurations, and establishing ventilation corridors [10] . This helps improve urban microclimate and increase pedestrian comfort [11] . The maturity of this method is evident in the fact that the Institute of Architects of Japan (AIJ) has issued comprehensive practice guidelines on the application of CFD in pedestrian wind environment assessment [12] .

To comprehensively assess thermal comfort and energy efficiency, current architectural studies tend to combine CFD simulations with Building Energy Simulation (BES) or multi-zone models [3], [11] . Since CFD mainly calculates airflow without directly evaluating energy consumption over long periods, this combination allows the extraction of temperature and wind velocity distribution data from CFD as input for BES [3], [11] . As a result, architects can develop hybrid ventilation control strategies, optimizing passive cooling at night before switching to mechanical air conditioning, reducing cooling load while maintaining thermal comfort [3], [11] .

In terms of architectural simulation techniques, RANS (Reynolds-Averaged Navier-Stokes) models, especially the k–ϵ variants (such as standard, RNG, realizable) and SST k–ω, remain the standard of practice due to achieving a balance between computing cost and accuracy [7], [12], [13] . Although Large Vortex Simulation (LES) provides superior accuracy for time-varying flow characteristics such as jet flapping, the computational cost of LES is tens to hundreds of times higher than RANS, making it difficult to apply widely in real-world projects with time constraints [12], [14] . To ensure the reliability of simulations, CFD results are often rigorously validated with actual measurement data or wind tunnel experiments [6], [11], [12] .

Looking to the future, the design process is witnessing seamless integration between CFD and Building Information Modeling (BIM). Detailed geometric and material data from BIM automates the process of generating computational meshes for CFD and BES, significantly enhancing the accuracy of simulations. In addition, the explosion of Artificial Intelligence (AI), Machine Learning, and Digital Twins/Reduced Order Models technology promises to overcome the computational time barrier of CFD [1] . These technologies enable real-time prediction of airflow environments (Engineering Virtual Reality) and are directly embedded into CAD/PLM software, ushering in an era where CFD becomes an intuitive and essential tool on every architect's desk [1] .

3.2. Current situation in Vietnam

Challenges and barriers to the widespread adoption of CFDs in Vietnam: Despite the enormous potential of CFDs, the widespread adoption of this technology in Vietnam's construction industry still faces inherent challenges regarding data infrastructure resources. Barriers related to input data and climate standards. A major problem is the lack of up-to-date and detailed meteorological data. The primary basis for climate observation data used in construction design calculations is QCVN 02:2022/BXD (National Technical Regulation on Natural Conditions Data Used in Construction). This is a crucial and mandatory document, but currently, the level of detail is unevenly distributed across locations. Data is often compiled from inconsistently distributed meteorological stations. For projects in remote areas or with unique terrain (valleys, islands), separate survey units are still needed during design because general data can have significant errors. The regulation also provides reliable data over a certain period. Meanwhile, climate change is occurring very rapidly. A long-term construction project needs to rely on dynamic forecasts rather than just historical data.

Data computing capacity and intersection of professional qualifications: CFD simulation is not a fast, computationally intensive process. It requires significant hardware resources, typically dedicated workstations or high-performance computing (HPC) clusters to handle large-scale models. Furthermore, a shortage of personnel with deep expertise in both architecture and fluid mechanics is a significant barrier. This leads to inappropriate boundary condition setups or inadequate grid generation experience, potentially resulting in visually appealing but worthless results that can be misleading in design decisions.

Perception and Investment Costs: Many investors in Vietnam still view CFD simulation as an additional expense rather than an investment for savings. While an optimized floor plan design through CFD can significantly reduce air conditioning system capacity and save annual energy costs, the barrier of initial consulting fees still causes many projects to skip this step.

3.3. Future research and development trends

To promote the application of CFD in assessing ventilation quality through floor plan layouts in Vietnam. It's not just a technical issue, but also a shift in project management thinking:

From the perspective of the management: Specific technical standards and regulations on thermal comfort and natural ventilation in buildings need to be issued soon. Integrating CFD simulation results as a mandatory component in the basic design review dossier (for large-scale projects) will create a solid legal framework for the development of sustainable architecture.

From the developer's perspective: CFD should be viewed as a strategic investment rather than an expense. Optimizing aerodynamics from the planning stage not only helps reduce operating costs (HVAC) but also increases the commercial value and user health of the property.

From the consulting firm's perspective: They need to proactively improve their professional capabilities and master simulation tools. Instead of using CFD as a final verification tool, architects should apply it as a design tool to shape the form and organize space from the initial sketches, ensuring maximum compatibility with Vietnam's specific microclimate conditions.

Integrating CFD into BIM and parametric design processes: The trend of digitizing construction industry data through Building Information Modeling (BIM) facilitates the design process alongside the use of CFD. Extracting geometric data directly from BIM models to simulation software minimizes errors and saves time.

Building a digitized meteorological database: The Ministry of Construction and related agencies need to update the construction climate data system in the form of digital files (such as .epw) for all provinces and cities. This will create a common input data source, ensuring consistency in simulation results from consulting firms and facilitating their verification by state management agencies.

Figure 1. Action framework for promoting the application of CFD in architectural site evaluation

IV. CONCLUSION

The integration of Computational Fluid Dynamics (CFD) simulation technology into the site layout analysis and optimization phase represents a significant paradigm shift in modern architectural thinking. For decades, architects have predominantly relied on intuitive solutions, accumulated experience, or conventional design rules. However, the sheer complexity of modern urban contexts demands a more rigorous and precise approach. This technological integration allows practitioners to make a radical transition toward data-driven design. By quantifying complex variables such as airflow, pressure, and temperature distribution, CFD provides a strict scientific foundation for verifying the effectiveness of spatial organization strategies right from the pre-design stage. This proactive approach helps minimize critical errors in building physics that, historically, could only be detected post-occupancy.

In the Vietnamese market, although the widespread implementation of this technology still faces certain barriers, the transition is fundamentally irreversible. Current challenges stem primarily from a lack of specialized technical infrastructure and a disparity in professional awareness and software proficiency within the architectural community. Nevertheless, the pressure to adapt is mounting from both domestic regulatory frameworks and international trends. The primary driving force is the progressive tightening of national energy efficiency standards, most notably the National Technical Regulation QCVN 09:2017/BXD on Energy Efficiency Buildings. This regulation mandates stringent requirements for building envelopes and natural ventilation, positioning simulation as the most viable methodology to definitively demonstrate compliance.

Simultaneously, the global momentum toward green buildings and sustainable development has profoundly reshaped investor expectations. In this contemporary context, CFD is no longer perceived merely as a supplementary luxury tool or a medium for graphic demonstration. It is steadily evolving into an essential, inseparable component in the creation of healthy living spaces that boast high adaptability to climate change. Mastering CFD empowers architects to explicitly predict and validate the performance of shading devices, wind flow patterns, and the thermal dissipation capabilities of various materials through highly visual data and color-coded contour maps.

Ultimately, the ongoing research and practical application efforts of domestic experts extend far beyond simply mastering a complex simulation tool. These endeavors represent direct, targeted actions aimed at resolving the distinct microclimatic challenges of Vietnam's hot and humid tropical environment. In such a specific climate, the optimization of natural ventilation and thermal comfort remains the absolute core of sustainable architecture. Utilizing CFD to simulate diverse microclimate scenarios enables designers to identify the optimal balance between architectural form and natural conditions. This optimization significantly reduces the building's reliance on mechanical HVAC (Heating, Ventilation, and Air Conditioning) systems, thereby directly contributing to the broader industry goal of reducing carbon emissions.

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