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A Novel CFD-Experimental Analysis for Enhancing Air Distribution and Indoor Air Quality in Existing Buildings Using High Induction Diffusers

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Abstract— Between 2000 and 2021, Canada's energy use rose by 10%, though efficiency gains prevented a 21% increase. Space heating and cooling dominate consumption, making up 63% in homes and 61% in commercial buildings. Ceiling-based ventilation worsens thermal stratification, raising energy use and lowering indoor air quality. This study explores high-induction diffusers for better ventilation without increasing heating and cooling loads. A combined computational fluid dynamic (CFD) and experimental approach was employed to evaluate the ventilation effectiveness of high-induction diffusers in comparison to conventional diffuser designs. The study utilized ASHRAE Standards 62.1 and 129 to quantify ventilation effectiveness (E_z), while evaluating the local mean age of air. Experimental measurements were conducted at the Indoor Environment Research Facility (IERF), assessing air distribution performance under controlled conditions using tracer gas decay methods with sulfur hexafluoride (SF_6). Results indicate that high-induction diffusers significantly improve air mixing, reducing thermal stratification and localized discomfort. Enhanced entrainment leads to a higher E_z value, thereby optimizing airflow distribution and mitigating the necessity for supplementary heating or cooling devices. In retrofitted systems, increased E_z improves IAQ without increasing ventilation rates, whereas in new HVAC designs, it enables reductions in outdoor air requirements, minimizing system oversizing and reducing energy consumption. Findings suggest that integrating high-induction diffusers in ventilation systems can enhance occupant comfort, lower HVAC operational costs, and support energy conservation efforts up to 25%. This study contributes to advancing HVAC design by demonstrating that optimizing air diffusion strategies can achieve both energy efficiency and improved thermal comfort in commercial and residential buildings.

Keywords-component; High-induction diffusers; Ventilation effectiveness; Indoor air quality (IAQ); Energy-efficient HVAC systems; Age of Air.

I. INTRODUCTION

Between 2000 and 2021, Canada's total energy consumption increased by 10%. However, in the absence of energy efficiency advancements, this growth trajectory would have reached 21%, underscoring the pivotal role of efficiency improvements in mitigating energy demand escalation. Over the same period, energy efficiency in Canada improved by 13% [1], contributing significantly to energy conservation efforts and serving as a fundamental strategy in national decarbonization initiatives.

A sectoral analysis reveals that space heating and cooling accounted for 63% of the total energy consumption in residential buildings, while commercial and institutional buildings allocated 61% of their energy utilized to similar end-uses [1]. These findings highlight the critical need for optimizing heating, ventilation, and air conditioning (HVAC) systems and integrating advanced energy-efficient technologies to enhance thermal performance and reduce overall energy demand in the built environment.

Inefficient air distribution, particularly in ceiling-based ventilation systems responsible for both heating and cooling, significantly contributes to thermal stratification. This phenomenon results in a greater occurrence of high-throw regions and stagnant zones, which significantly deteriorate indoor air quality (IAQ). A practical example of this issue is the necessity of using localized heating, such as a heater under a desk, even when the central heating system operates continuously and maintains the room temperature within the designated comfort range. This indicates insufficient air mixing and low ventilation effectiveness, compelling HVAC systems to be oversized to mitigate these deficiencies. As a result, the waste of the thermal load and overall energy consumption of the system increase, reducing its efficiency and sustainability.

Optimizing air supply strategies can mitigate these challenges by enhancing IAQ and reducing the dependency on supplementary ventilation systems. Previous research has approached this issue through various methodologies, primarily focusing on either modification to the geometry of air diffusers or reconfigurations of airflow delivery patterns. For instance, Raphe et al. [2] demonstrated that optimizing the perforation patterns of duct diffusers could halve the age of air discrepancy within a room, thereby improving ventilation efficiency. Similarly, An et al. [3] introduced an innovative displacement ventilation system incorporating a four-way cassette fan coil unit (FCU) in conjunction with air purifiers (APs). Their study showed that this hybrid approach effectively delivered clean air while reducing the local mean age of air in office environments operating in heating mode. Generally speaking, hybrid ventilation approaches that incorporate localized ventilation systems necessitate additional components, such as specialized accessories and extended ductwork, which are not always applicable. Consequently, these systems incur higher implementation and operational costs compared to optimized single ventilation designs that minimize the overall layout complexity while maintaining efficiency.

This study addresses the challenge of inadequate ventilation in existing buildings by employing high-induction diffusers while maintaining the original heating and cooling loads. Although previous research has explored solutions involving variable mass flow rate systems [4] and alternative methodologies [5-8], this work focuses on two key objectives that were not covered completely in the literature. First, it aims to enhance ventilation performance by increasing the induction ratio of the supply diffusers without imposing additional thermal loads on the HVAC system. Second, it quantifies potential energy savings by evaluating the ventilation effectiveness of high-induction diffusers in comparison to conventional diffuser designs, using a novel CFD-experimental analysis.

II. Methodology

A. Thermal Comfort Criteria

Thermal comfort assessment has historically relied on models and indices such as the Air Diffusion Performance Index (ADPI), Predicted Mean Vote (PMV), and Predicted Percentage of Dissatisfied (PPD), all of which aim to maintain an occupant satisfaction rate exceeding 80% within indoor environments. However, the thermal comfort ranges in these models are primarily based on empirical datasets from the 1970s and 1980s, reflecting the thermal preferences of occupants from that period and the ventilation system performance available at the time. Consequently, their applicability to modern buildings and diverse occupant profiles is increasingly questioned. It is therefore recommended to integrate tenant feedback with these predictive models to ensure optimal indoor comfort in buildings.

A large-scale survey by Parkinson et al. [9] involving over 38,800 office workers revealed a significant discrepancy between predicted and actual occupant satisfaction. Despite the application of the ADPI method, which theoretically limits dissatisfaction to below 20%, empirical findings indicated that 64% of women and 49% of men reported discomfort with office temperatures. This disparity is largely attributed to heterogeneous thermal preferences, particularly among recent immigrants, as well as spatial temperature variations leading to localized hot and cold zones, because of the low ventilation effectiveness of the ventilation system.

Incidentally, the PMV model is known to systematically overestimate thermal discomfort in warm conditions, often resulting in the oversizing of HVAC systems. This miscalculation leads to excessive cooling, increased energy demand, and higher operational costs. Interestingly enough, overcooling in commercial buildings across the United States and Canada accounts for approximately 8% of total electricity consumption within the commercial sector [10]. Comparable deviations in computational accuracy are also observed in heating mode, where the modeling assumptions and numerical methods can introduce systematic biases.

A more effective approach to enhancing thermal comfort while optimizing energy use involves improving ventilation effectiveness through changing the diffusers' design. Increased uniformity in air velocity distribution mitigates thermal stratification, thereby reducing localized discomfort and improving overall occupant satisfaction. Addressing these limitations in traditional models is crucial for developing more adaptive and energy-efficient HVAC control strategies in modern buildings.

B. Ventilation Effectiveness Calculation

ASHRAE Standard 62.1 [11] establishes the minimum ventilation requirements for indoor air quality by defining the minimum required zone outdoor airflow (V_{oz}) and the minimum required breathing zone airflow (V_{bz}). These parameters are determined based on the type of application, occupant density, and the zone's floor area, as expressed in Equations (1) and (2):

$$V_{oz} = \left(\frac{V_{bz}}{E_z}\right) \tag{1}$$

$$V_{bz} = (R_p \times P_z) + (R_a \times A_z) \tag{2}$$

Where:

R_p = Required outdoor airflow rate per person, [CFM. person^{-1}] or [l. s^{-1}. person^{-1}].

P_z = Design zone population.

R_a = Required outdoor airflow rate per unit area, [CFM. ft^{-2}] or [l. s^{-1}. m^{-2}].

A_z = Zone floor area, [ft^2] or [m^2].

E_z = Zone air distribution effectiveness.

The parameter E_z is the sole factor in Equations (1) that quantifies the effectiveness of air distribution and, consequently, the performance of ventilation systems. This parameter plays a crucial role in optimizing energy efficiency by influencing the required outdoor airflow (V_{oz}). Two distinct design scenarios can be considered:

1. *Retrofitting an Existing Building*: In this case, the zone outdoor airflow (V_{oz}) is fixed based on the existing HVAC system capacity. Enhancing E_z during system refurbishment leads to improved air distribution, reducing stagnation zones and excessive throw distances. This, in turn, enhances occupant comfort and indoor air quality without modifying the ventilation system's total airflow rate.

2. *New System Design*: When designing a ventilation system from the ground up, increasing E_z directly reduces the minimum required zone outdoor airflow (V_{oz}). This prevents unnecessary oversizing of HVAC components, thereby lowering initial capital costs and long-term operational energy consumption. A higher E_z minimizes thermal load waste by optimizing air mixing and reducing ventilation inefficiencies.

In both cases, maximizing E_z is critical for achieving energy-efficient ventilation while ensuring compliance with ASHRAE Standard 62.1 [11]. In this study, the E_z value was evaluated following ASHRAE Standard 129 [12] as suggested as an alternative method by ASHRAE Standard 62.1 [11]. Additionally, numerical simulations were conducted using the authors' validated computational models, extending from their prior research [13-14], to assess the impact of E_z improvements on ventilation system performance.

III. Experimental measurements

The induction ratio quantifies the mixing performance of a diffuser by defining the ratio of secondary air volume (entrained from the surrounding space) to the primary air volume (supplied directly by the diffuser). Mathematically, it is expressed as a dimensionless ratio (e.g., 4:1), where higher values indicate enhanced mixing efficiency between the supplied and ambient air. This study investigates the influence of different induction ratios on overall ventilation effectiveness by analyzing two distinct diffuser types:

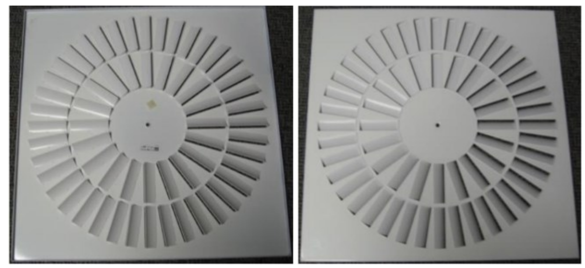
1. A 6" Square Cone diffuser, which represents a conventional air distribution approach, Figure 1-a.

2. A high-induction NAD-DAL359 diffuser, designed with curved blades and 600 [mm] x 600 [mm] frame to maximize entrainment and air mixing, Figure 1-b.

Experimental measurements were conducted at the Indoor Environment Research Facility (IERF) located in the National Research Council Canada (Ottawa campus) to assess the total ventilation effectiveness of the system when using these diffusers, installed in the suspended ceiling of the test room, Figure 2.

The outdoor airflow rate for occupants was established at 47 [l. s^{-1}] (100 [CFM]) to align with the minimum requirement of 8.5 [l. s^{-1}. $person^{-1}$] (17 [CFM. $person^{-1}$]) as specified in ASHRAE Standard 62.1 [11]. To ensure adequate ventilation, the total outdoor airflow rate for the room was set at 547 [l. s^{-1}] (1160 [CFM]), corresponding to an air circulation rate of 6.11 [l. s^{-1}. m^{-2}] (1.2 [CFM. ft^{-2}]). This configuration was selected to maintain compliance with ventilation standards while optimizing indoor air quality and occupant comfort.

(a)



(b)

Figure 1: Front and back face plate of (a) square cone diffuser. (b) High induction DAL 359 diffuser.

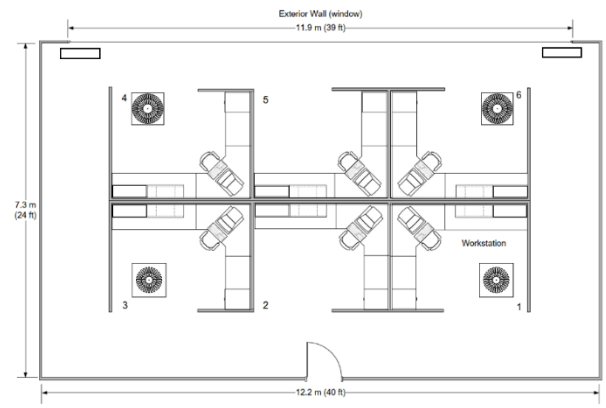


Figure 2: The IERF test room layout.

The dry-bulb temperature and air velocity were systematically measured at four distinct elevations above the floor: 0.1 [m], 1.1 [m], 1.7 [m], and 2.7 [m] (respectively equivalent to 0.3 [ft], 3.6 [ft], 5.6 [ft], and 8.85 [ft]). To assess the ventilation effectiveness and determine the local age of air a tracer gas decay method was employed using sulfur hexafluoride (SF_6), which exhibits similar transport properties to air. Per the ASHRAE Standard 129 [12], the step-up and step-down techniques were applied to track SF_6 concentration variations over time. Measurement instrumentation included resistance temperature detectors (RTD, Model 500M), relative humidity and temperature (RH&T) sensors, omnidirectional hot-sphere anemometers (Model Thermo Air 6/64), a gas chromatograph equipped with an electron capture detector (GC-ECD), and tracer gas sampling tubes. This comprehensive approach ensured high accuracy in characterizing airflow patterns and evaluating indoor air distribution.

IV. Numerical Simulations

A 3D computational model of the test room was developed using ANSYS Design Modeler 2024-R2, incorporating necessary simplifications to optimize computational efficiency. For instance, suspended lights were excluded from the model, as their influence on airflow distribution was deemed negligible.

Prior to conducting numerical simulations, a mesh sensitivity analysis was performed to ensure the accuracy and reliability of the computational results. The final discretized domain consisted of approximately 67 million computational cells, demonstrating satisfactory convergence and predictive accuracy. Figure 3 presents the geometric configuration of the test room along with its detailed dimensions.

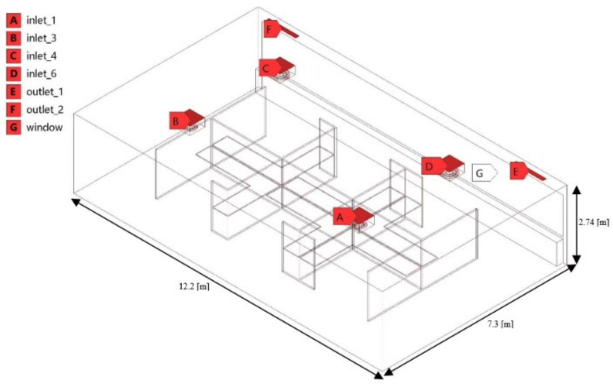


Figure 3: A 3D model of the IERF test room.

Following the authors' previous research [13], a computational model utilizing the Realizable k-ε turbulence model has been developed within ANSYS Fluent 2024-R2. This model is designed to solve the Reynolds-Averaged Navier-Stokes (RANS) equations, the conservation equations, and the convection-diffusion equation governing the Age of Air (AoA) as a passive scalar. The AoA transport equation is integrated into the primary governing equations via a user-defined function (UDF), ensuring accurate coupling with the flow field.

For spatial discretization, second-order upwind schemes are employed to enhance solution accuracy, while the SIMPLE algorithm is implemented to address the pressure-velocity coupling. Convergence is achieved when the residuals drop below 10^{-8} for the AoA scalar and 10^{-5} for the remaining governing equations. Model validation (not included here) indicates at least 95% prediction accuracy for airflow velocity, confirming the reliability of the numerical framework.

V. Results and Discussions

As stated earlier, ensuring optimal indoor air quality (IAQ) while minimizing energy consumption is a fundamental requirement in retrofitting existing buildings and designing new ventilation systems. This section presents a comprehensive analysis of air distribution uniformity achieved through different diffuser configurations. The investigation begins with an assessment of airflow uniformity, followed by a detailed comparison of the ventilation effectiveness parameter, E_z. The E_z value, which is equal to air change effectiveness according to the alternative methods of the ASHRAE Standards 62.1 [11] and 129 [12], is determined based on both experimental measurements and computational predictions of the mean age of air. This comparative analysis provides insights into the efficiency of various air distribution strategies in enhancing IAQ and energy performance.

A. Air Velocity

Figure 4 shows the air velocity contours at three elevations, 0.1 [m], 1.1 [m], and 1.7 [m], within the test room for both diffuser configurations. Comparative analysis indicates that the local air velocity variations are more pronounced in the case of the square cone diffuser, with velocity fluctuations ranging from 0 to 0.5 [m. s^{-1}]. In contrast, the NAD DAL359 high-induction diffuser exhibits a lower velocity variation, between 0 and 0.3 [m. s^{-1}], demonstrating a more uniform air distribution. The enhanced uniformity associated with high-induction diffusers is a key factor in achieving better thermal comfort and ventilation efficiency.

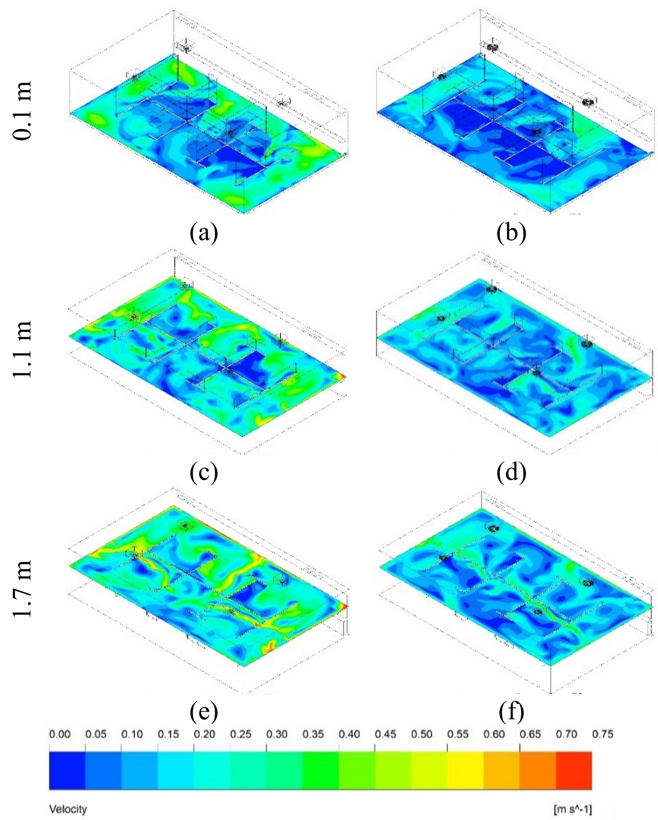


Figure 4: Air velocity contours at XZ Plane for square cone (a), (c), and (e), and NAD DAL359 high-induction diffuser (b), (d), and (f).

Furthermore, Figure 5 illustrates the air velocity contours along vertical planes for both diffusers. The results reveal significant stagnation zones beneath the table at lower elevations when using the square cone diffuser, along with a high-throw region near the head for both sedentary and standing occupants at 6 cubicles. This airflow pattern leads to the cold feet–warm head situation, a common cause of thermal discomfort, which typically necessitates the use of localized ventilation solutions to mitigate uneven air distribution.

Conversely, the high-induction diffuser ensures a more consistent airflow pattern without requiring supplementary ventilation systems. It maintains air velocities within the range of 0 to 0.25 [m. s^{-1}] from ceiling to floor, effectively reducing thermal stratification and mitigating localized thermal discomfort. This performance emphasizes the potential of high-induction diffusers in optimizing indoor air distribution while enhancing occupant comfort.

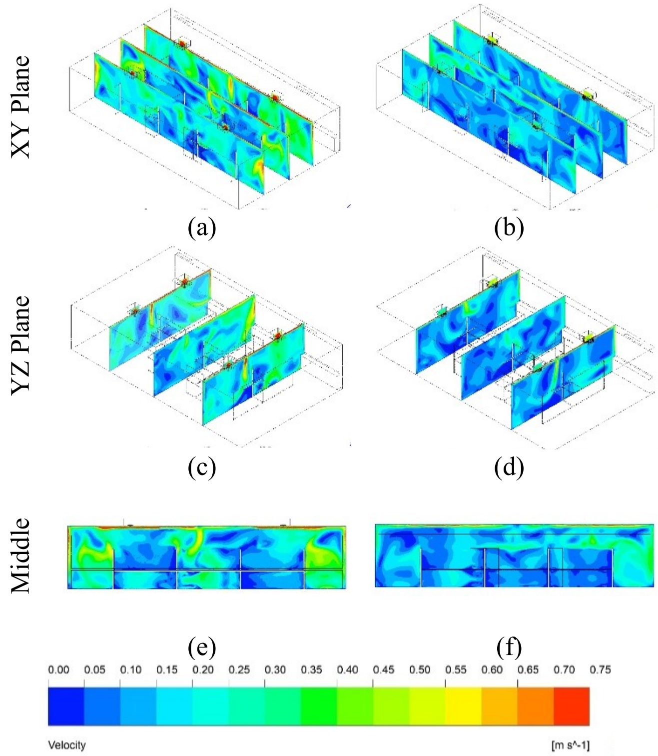


Figure 5: Air velocity contours for square cone (a), (c), and (e), and NAD DAL359 high-induction diffuser (b), (d), and (f).

B. Age of Air

Alongside the previously discussed local air velocity distribution, this section focuses on the local age of air at various elevations, as illustrated in Figure 6. The age of air is a critical parameter in assessing indoor air quality (IAQ), as it directly correlates with occupant exposure to recirculated or aged air. Prolonged exposure to older air is associated with reduced cognitive performance and an increased risk of airborne disease transmission.

The contour plots in Figure 6-(b), (d), and (e) indicate that the implementation of high-induction diffusers results in a uniformly lower AoA throughout the room. This suggests that fresh air is effectively distributed across all occupant positions, ensuring enhanced ventilation efficiency. Conversely, ventilation using square cone diffusers exhibits a highly non-uniform air distribution, where fresh air is predominantly supplied to cubicles 1, 4, and 5, while the remaining workspaces experience significantly aged air exceeding 500 seconds, particularly at the head level for seated occupants.

Quantitatively, high-induction diffusers reduce the mean age of air by approximately 50 to 80 seconds at all measured elevations compared to square cone diffusers. This substantial reduction demonstrates their superior capability in enhancing IAQ and pollutant removal efficiency, further reinforcing their effectiveness in minimizing airborne contaminant exposure in enclosed environments.

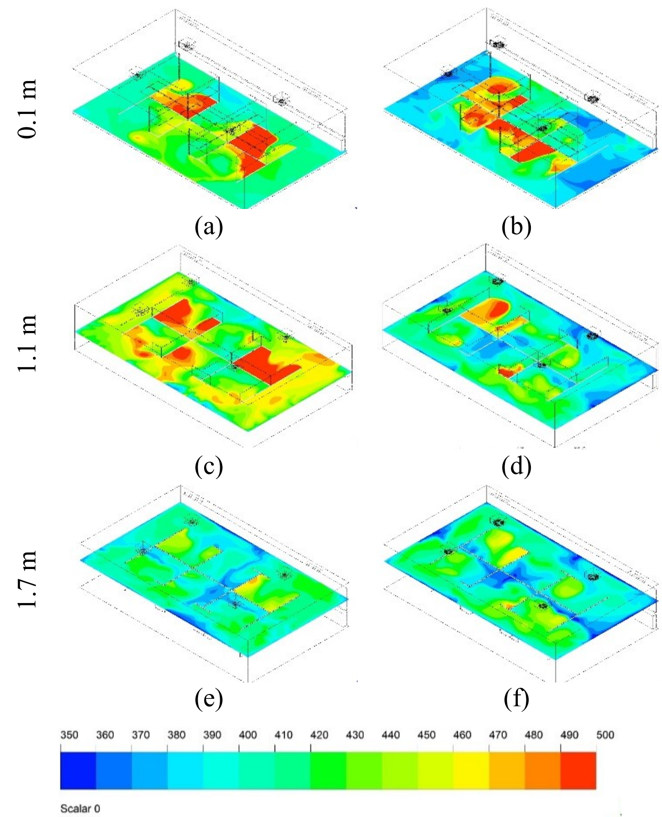


Figure 6: Age of Air contours at XZ Plane for square cone (a), (c), and (e), and NAD DAL359 high-induction diffuser (b), (d), and (f).

C. Zone Air Distribution Effectiveness

Table 1 represents the Air Change Effectiveness (ACE) values, which are equivalent to the E_z parameter, obtained from experimental measurements, CFD simulations, and a hybrid approach integrating both experimental data and CFD based on the age of air calculations for the two diffuser types under investigation. A comparison of these results with the recommended E_z values specified in ASHRAE Standard 62.1 [11] for ceiling-mounted warm air supply systems, where the supply air temperature is at least 8°C (15°F) above the ambient space temperature with a ceiling return in heating mode, reveals a significant improvement with the high-induction diffusers. Specifically, the required minimum outdoor airflow can be reduced by approximately 20% to 25%, directly enhancing energy efficiency. This reduction translates into substantial energy savings for the ventilation system, enabling the downsizing of HVAC components, and thereby further optimizing operational costs.

Table 1: Mean values of Air Change Effectiveness in the room.

Diffuser type	Measurement	CFD	Combined
Square Cone	0.77	0.81	0.79
NAD DAL359 High Induction	1.03	0.98	1.01

VI. CONCLUSION

This study highlights the critical role of high-induction diffusers in enhancing ventilation effectiveness and optimizing HVAC performance in indoor environments. The findings demonstrate that increasing the induction ratio of supply diffusers significantly improves air mixing, reduces thermal stratification, and enhances indoor air quality (IAQ) without imposing additional thermal loads on the HVAC system. Through a comprehensive CFD-experimental analysis, this research quantitatively assesses the performance benefits of high-induction diffusers over conventional designs, providing valuable insights into energy-efficient ventilation strategies.

The results underline the limitations of conventional ceiling-based ventilation systems, which often exhibit inefficient air distribution, leading to localized thermal discomfort and unnecessary energy consumption. By improving the entrainment and mixing efficiency of supplied air, the NAD DAL358 high-induction diffuser contributes to a more uniform thermal environment, reducing the need for supplementary heating or cooling devices. This, in turn, enhances occupant comfort while simultaneously decreasing the overall energy demand of HVAC systems.

From an energy conservation perspective, the study aligns with national decarbonization goals by demonstrating how optimized air distribution can lead to substantial reductions in ventilation-related energy consumption. The findings confirm that retrofitting existing buildings with high-induction diffusers benefits from the higher zone air distribution effectiveness (E_z), allowing for more efficient utilization of ventilation airflow and minimizing system oversizing. For new HVAC system designs, integrating high-induction diffusers enables a reduction in the required outdoor airflow rate (V_{oz}), decreasing capital investment and operational costs while maintaining compliance with ASHRAE Standard 62.1 [11].

Furthermore, the research highlights the shortcomings of traditional thermal comfort models, such as PMV and ADPI, which often misrepresent actual occupant satisfaction levels due to their reliance on outdated empirical datasets. By incorporating advanced ventilation strategies that improve air distribution uniformity, this study offers a pathway toward refining thermal comfort models and establishing more adaptive HVAC control strategies tailored to modern buildings and diverse occupant preferences.

In conclusion, high-induction ventilation systems present a viable and energy-efficient alternative to conventional air distribution methods, with demonstrated benefits in both thermal comfort and energy conservation. Future research should explore the long-term impact of these diffusers on HVAC system longevity and operational sustainability, as well as investigate their effectiveness across various building typologies and climatic conditions. By integrating advanced airflow management techniques, the built environment can achieve enhanced IAQ, reduced energy expenditure, and improved occupant well-being, aligning with broader sustainability objectives in the field of building energy efficiency.

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