Reducing Indoor Air Pollution through Personalized Ventilation for Occupants in Office Environments and Confined Spaces

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Abstract. With the increasing focus on indoor environmental quality, driven by the growing amount of time people spend in enclosed spaces, this study presents an approach to enhancing air distribution in office environments and confined spaces. A novel low-induction air diffuser is designed to deliver fresh, clean air in close proximity to occupants while maintaining their thermal comfort. Clean, unpolluted air is pivotal to healthy and productive workplaces. Yet, this paper underscores the importance of not sacrificing thermal comfort in the pursuit of improved indoor air quality. Inadequate thermal comfort may lead occupants to deactivate ventilation systems, negating the benefits of improved air quality. Inefficient temperature control can also result in discomfort, distractions, and reduced productivity. The innovative low-induction air diffuser resolves this issue, enhancing air quality near occupants without causing thermal discomfort. By directing air gently and efficiently, this solution is prepared to transform personalized ventilation systems, mitigating the discomfort associated with traditional jet flows while delivering high-quality breathable air. This research serves as a bridge between improved indoor air quality and thermal comfort, for office environments. It introduces a practical, energy-efficient solution that satisfies the core requirements of a healthy workspace—clean air and comfortable conditions.

1 Introduction

Indoor air quality (IAQ) in buildings is a major concern that demands immediate attention when evaluating the well-being and productivity of individuals in the workplace. The fundamental concept underpinning mixing ventilation, which is the most popular ventilation method in buildings, is the blending of supplied air with the pre-existing air within an enclosed space. This approach involves delivering clean air from diffusers situated at a distance from occupants. IAQ it can be profoundly influenced by passive contaminants, such

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as gases and airborne particulate matter including both indoor-generated particles (PM2.5, PM10) and outdoor-generated traffic-related particles [1-3]. These pollutants present a substantial risk to human health as they can affect occupants and lead to respiratory problems like asthma [4] or respiratory allergies [5], or can lead to cardiovascular diseases [6], or eyes, nose and throat irritations [7], thereby contributing to serios health problems for the occupants. Moreover, in office spaces, as opposed to other indoor environments, the vulnerability of occupants to contamination is exceedingly high, both through direct inhalation and indirectly via the deposition of particles on surfaces, followed by hand-to-mouth contact [5]. Therefore, ensuring high-quality breathable air at the same time without affecting the thermal comfort of the occupants within office spaces is of utmost importance, making the choice of a suitable air distribution system essential.

Personalized ventilation (PV) has been introduced as a solution to improve IAQ capable of satisfying both of these specific requirements [8].

Regarding air quality, personalized ventilation systems can contribute significantly to improving breathable air quality in office spaces. These systems can be equipped with advanced air filtration technologies and sensors to detect and respond to changes in air quality. By ensuring that each occupant receives a fresh and purified air supply, the risk of exposure to pollutants and allergens is greatly reduced. This, in turn, mitigates the potential health issues associated with poor indoor air quality, including respiratory problems and allergies.

In the context of thermal comfort, traditional HVAC systems often provide uniform temperature control for entire spaces, which might not align with the individual preferences of occupants. Personalized ventilation, on the other hand, allows for customized control, tailoring the thermal environment to each person's needs. By providing adjustable airflow and temperature settings at the individual level, it offers the promise of a more comfortable working environment, thus enhancing the overall well-being and productivity of office occupants.

PV presents an advanced capability to supply occupants in office environments and confined spaces with clean, fresh air precisely within their breathing zone [9-12]. Simultaneously, it tailors the microclimate to harmonize with individual thermal preferences. This approach enhances the overall quality of the indoor environment by delivering personalized comfort and air quality to occupants. Extensive research has been conducted to explore various configurations of PV systems, including ceiling and desk air terminal diffusers, with the objective of achieving thermal comfort and optimal air quality at varying levels of efficacy.

For example, in [12], the researchers conducted experiments in which they assessed the air quality of inhaled air by utilizing tracer gas. Their study investigated various types of air terminal devices and yielded intriguing results. Specifically, it was observed that a vertical desk grill demonstrated the highest air quality throughout the room space, whereas a round movable panel achieved the highest air quality within the occupant's breathing zone [13, 14].

In a related study, as detailed in [15], researchers conducted a comprehensive field study that focused on assessing IAQ in office environments where both displacement ventilation and personalized ventilation systems with optional window operation were employed. Their investigation uncovered noteworthy insights into the IAQ dynamics. Specifically, it was observed that under warmer conditions, opting for a higher PV flow rate operation led to the attainment of acceptable IAQ levels, highlighting the adaptability and efficacy of PV systems in creating comfortable working environments.

Furthermore, in a separate field study in an office space, as referenced in [11] the authors evaluated the impact of five different PV air terminal designs on the perceived air quality at individual workstations. Their findings revealed a notable improvement in perceived air quality across all workstations with the implementation of these PV systems. This

underscores the capacity of PV solutions to enhance occupant comfort and underscores their potential as a viable strategy for optimizing IAQ in office spaces.

Personalized ventilation systems aim to position supply air in close proximity to the occupant. In contrast to traditional ventilation systems, where as little as 5% of supplied air reaches the occupant, PV systems are capable of delivering a substantial 50% or more of the supply air directly to individuals in the space [16]. The objective of this paper is to develop a novel air diffuser with low induction using numerical simulation, capable of delivering fresh and clean air to the proximity of the occupant face, improving the IAQ nearby occupant, in a way to not affect his thermal comfort.

2 Materials and methods

2.1 Analysed geometry

The chosen solution resulted from the work carried out in the frame of scientific research grants [17-19] and aims to provide fresh and clean air as close as possible to the occupants, yet without affecting in a negative way the thermal comfort of the users. The solution consists of a steerable diffuser which will deliver fresh air in the proximity to the occupant's face.

Characteristic of this type of spherical diffuser with low induction lobed orifice for personalized ventilation **Fig. 1**a is the fact that the jet of air instilled through the diffuser will entrain a much smaller amount of air than in the case of a classic circular jet due to the specific shape of the orifices geometry [10, 20, 21].

In our setup, a low-induction spherical diffuser was incorporated into a virtual environment **Fig. 1**b. Within this virtual environment, a seated virtual manikin was positioned in front of a desk with a notebook [22, 23]. The shape of the humanoid manikin is similar with the real human with a few simplifications which will not affect the results [24, 25]. Two air diffusers were employed and positioned at the top of the notebook screen as depicted in **Fig. 1**b.

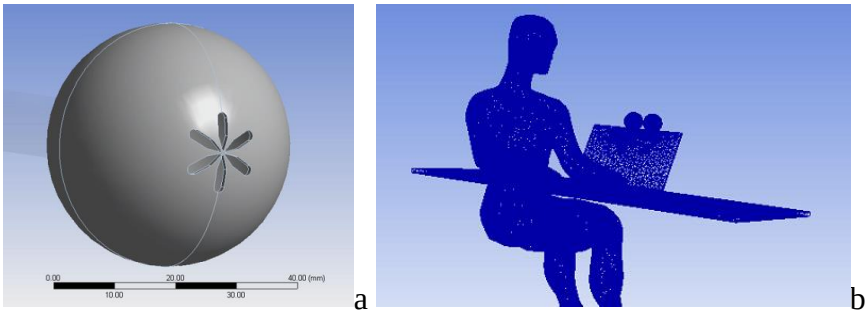

Fig. 1. a. Considered air diffuser geometry b. Entire geometry setup

2.2 Numerical grid

The numerical grids setup was performed based on our previous experience. A study of solution independence was conducted depending on the number of grid elements used (0.16 million, 0.85 million, 2 million, 5 million, 8 million). The numerical grid chosen for the numerical study was that with 5 million elements (**Fig. 2**) because of the small differences in numerical results between the 5 and 8 million element mesh.

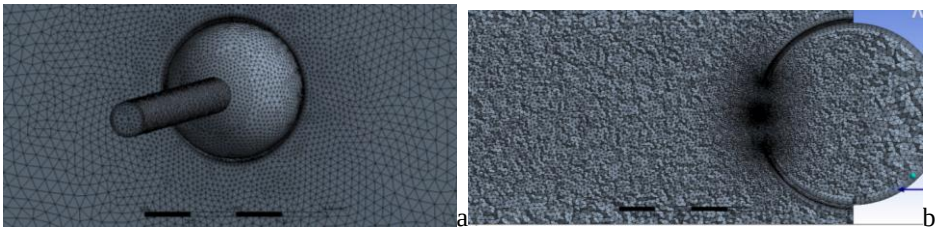

Fig. 2. Details with the 5 million element numerical grid

The mesh consisted of tetrahedral elements which play a crucial role in Computational Fluid Dynamics (CFD). These elements, characterized by their pyramidal shape, offer several advantages in mesh generation for CFD analyses. First and foremost, tetrahedral elements are highly versatile and can be effectively employed in complex geometries and their ability to adapt to irregular shapes and refine mesh in regions of interest contributes to enhanced accuracy and resolution in capturing flow phenomena. Tetrahedral elements are particularly valuable when dealing with unstructured meshing, allowing for greater flexibility in defining mesh densities where they are needed most [26]. This adaptability is especially beneficial when simulating complex and dynamic fluid behaviours making them essential for modelling the airflow through the lobed shape of the air diffuser or the natural convection in the proximity of the human shaped virtual manikin.

2.3 Numerical configuration

The flow rate was imposed considering the recommendations from [16]. The total airflow rate was 10 l/s (36m^3/h). This was the main reason why the proposed solution consists of two novel air diffusers with low induction.

The numerical simulation CFD study was conducted on this proposed geometry. Previous experience related to the study of jets was used to perform the numerical simulations. The turbulence model used was SST k-ω.

Utilizing the Shear-Stress Transport (SST) k-ω turbulence model for simulations in the context of moderate Reynolds numbers within the personalized ventilation zone offers several distinct advantages. The SST k-ω model combines the capabilities of the k-ε and k-ω models, making it well-suited for capturing a wide range of turbulent flow behaviors with precision. Here, we'll delve into the specific benefits of employing this model for personalized ventilation simulations.

One of the primary advantages of the SST k-ω model is its reliability in predicting turbulence in moderate Reynolds number flows. In personalized ventilation, where the airflow is often characterized by lower velocities and shear, this model excels at capturing the intricacies of turbulence, ensuring that the simulation results are both accurate and trustworthy.

Moreover, the SST k-ω model is known for its robustness and ability to handle adverse pressure gradients, a common occurrence in personalized ventilation scenarios where the airflow can be quite complex [26]. This robustness ensures that the simulations remain stable and converge effectively, even in regions with rapidly changing flow characteristics like in the case of our setup.

The model's effectiveness in resolving near-wall flows is particularly advantageous in personalized ventilation simulations. In the vicinity of walls or surfaces where occupants are situated, the flow patterns are critical for understanding exposure to contaminants or improving thermal comfort. The SST k-ω model excels in these scenarios, offering insights into the near-wall turbulence behavior that other models may struggle to provide.

Additionally, the SST k-ω model's compatibility with unstructured grids facilitates meshing in intricate geometries, which is often the case in personalized ventilation scenarios where the airflow paths can be irregular and highly localized. This flexibility is essential for capturing the precise flow patterns around individuals in various configurations.

3 Results and discussions

The airflow behaviour through the innovative air diffuser is depicted in the following figure (**Fig. 3**). It's evident that, owing to the diffuser's unique geometry, the airflow is characterized by convergence rather than dispersion (**Fig. 3**a,b,c). Furthermore, even beyond the converging zone, the flow maintains limited spreading (**Fig. 3**a). This observation indicates that the air diffuser exhibits low induction, aligning with the current objectives. Additionally, the turbulent kinetic energy is observed to dissipate rapidly in the vicinity of the air diffuser, signifying that the air will not transport turbulence toward the occupant, thus reducing the potential for a draft sensation (**Fig. 3**d). This favourable performance underscores the diffuser's effectiveness in maintaining occupant comfort.

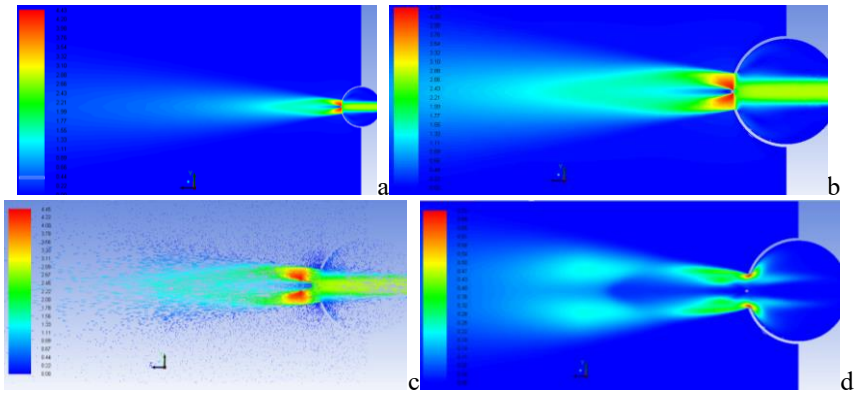

Fig. 3. Flow through the novel air diffuser a. Velocity field, b. Velocity field (close-up), c. Velocity vectors, d. Turbulent kinetic energy

An isosurface of 0.3 m/s is visible in **Fig. 4**, providing a clear depiction of how fresh air is directed toward the occupant's face.

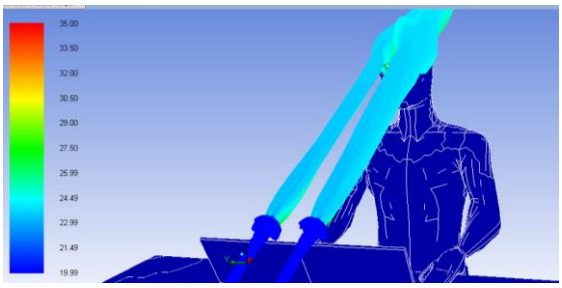

Fig. 4. Isosurface of 0.3m/s coloured by temperature

This visualization not only demonstrates the effective airflow pattern but also highlights its role in protecting the occupant from potential pollutants present within the space. This proactive approach contributes significantly to maintaining a healthier indoor environment

for the occupant and underscores its capacity to enhance occupant comfort due to low air velocity.

As Professor Fanger's work [27] explains, the air movement within enclosed spaces and its contribution to the sensation draught, it represents an undesired cooling effect on the human body caused by the air motion [27, 28]. The most widely employed quantitative model for estimating thermal comfort was proposed by Fanger [29]. In his study, subjects dressed in "standardized" clothing and engaged in "standardized" activities were exposed to various thermal conditions. In alignment with their perceived comfort, the subjects assessed this state using the ASHRAE scale [30], which comprises seven values, from very hot to cold (very hot, hot, slightly warm, comfortable, lightly cool, cool cold).

Temperature distributions in the room for the personalized ventilation system in the sagittal plane of the virtual sitting manikin (**Fig. 5**a) and in a plane passing through a lobe diffuser (**Fig. 5**b) revealed that the air provided in the proximity of the occupant face is very minimally mixed with the surrounding air.

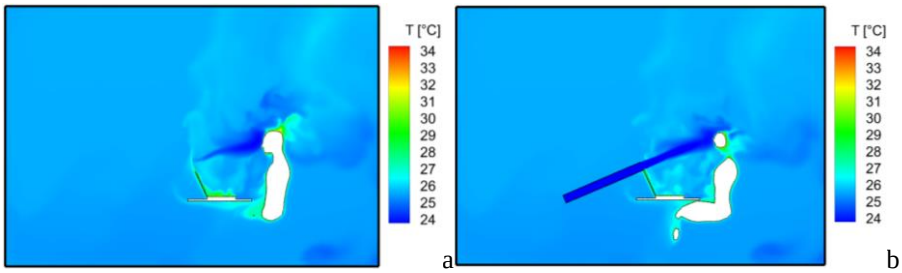

Fig. 5. Temperature distributions in the room for the personalized ventilation system a) sagittal plane, b) plane passing through an air diffuser

The same observation emerges from **Fig. 6** where it can be seen that the airflow issued from the personalized ventilation air diffuser travels almost unaffected through the breathing zone of the occupant.

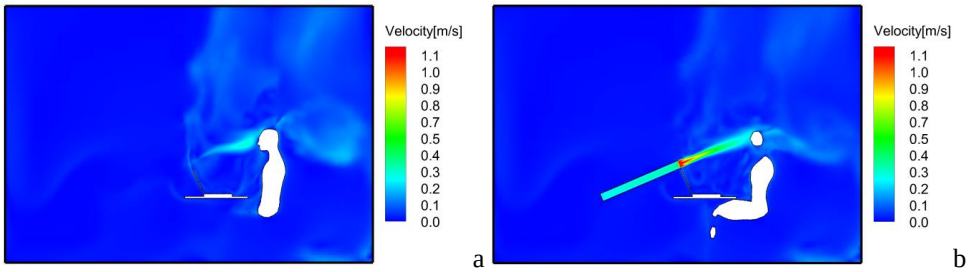

Fig. 6. Velocity distributions in the room for the personalized ventilation system a) sagittal plane, b) plane passing through an air diffuser

The velocity it's rather uniform in the proximity of the occupant face. Also, we can see that it has the capability to interact with the complex flow behaviour generated by the human body like the thermal plume of the occupant because it reaches the face of the manikin despite the above mentioned natural flow [31-33].

Regarding the draught sensation that the occupant will feel, it can be seen in **Fig. 7** that the draught rate, reaches values less than 15% in the immediate vicinity of the occupant, and aligns with the comfort sensation thresholds commonly documented in the specialized literature [34].

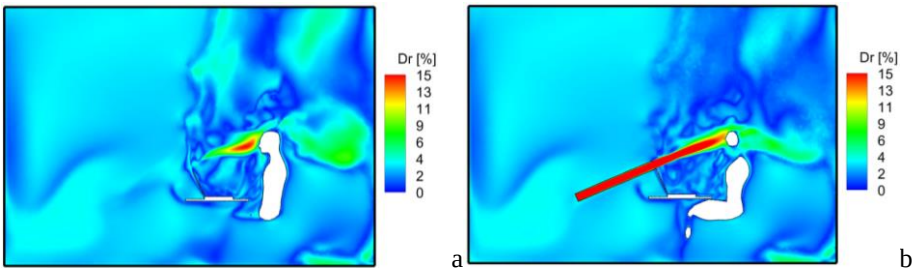

Fig. 7. Draught rate distributions in the room for the personalized ventilation system a) sagittal plane, b) plane passing through an air diffuser

Thermal comfort sensation can be estimated using Predicted Mean Vote parameter (PMV). It is a parameter used in the field of thermal comfort and indoor environmental quality. PMV is a numerical index that predicts the mean value of the thermal sensation votes of a group of people exposed to a specific thermal environment. It is used to assess and quantify how individuals are likely to perceive the thermal conditions in a given space. PMV takes into account various factors, including air temperature, mean radiant temperature, air velocity, humidity, and clothing insulation. The PMV scale typically ranges from -3 (feeling very cold) to +3 (feeling very hot), with 0 representing the point of thermal neutrality, where people are neither too cold nor too hot. PMV values above or below 0 indicate a degree of thermal discomfort [29].

In the case studied in this research it can be seen that the thermal comfort of the occupant is in the proximity of the thermal neutrality (**Fig. 8**).

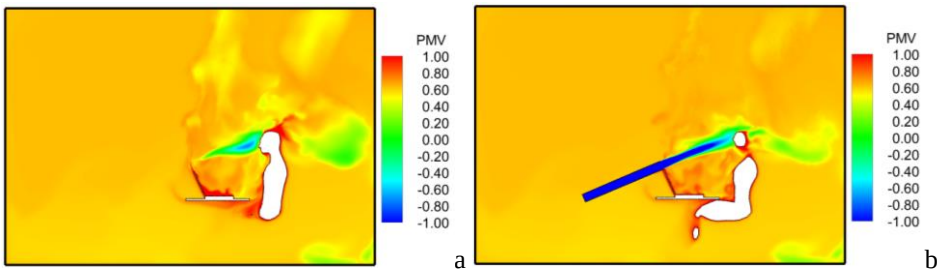

Fig. 8. PMV distributions in the room for the personalized ventilation system a) sagittal plane, b) plane passing through an air diffuser

We can see that the subject finds themselves enveloped in an environment where the Predicted Mean Vote (PMV) hovers between -1 and 1, indicative of a high level of overall thermal comfort. This range underscores that, on the whole, occupants within this setting experience conditions where they neither feel excessively cold nor uncomfortably warm. However, it's not just thermal comfort that characterizes this space; it's the simultaneous presence of fresh, clean, unpolluted air in the breathing zone that truly sets it apart.

4 Conclusions

The demand for clean, unpolluted air in office work activities cannot be overstated. It plays a pivotal role in ensuring a healthy and productive working environment. However, it's crucial not to overlook a critical aspect of this equation. While bringing cleaner air closer to the user's face is undoubtedly valuable, it alone is insufficient. For the entire concept to function effectively, the user's thermal comfort must also be satisfied.

Addressing indoor air quality is indeed a fundamental step towards creating a healthier workspace. Clean air free from contaminants, such as particulate matter and volatile organic compounds, is essential to reduce health risks, enhance cognitive performance, and ensure overall well-being. Yet, this is just one piece of the puzzle.

Thermal comfort is equally important because if a user doesn't feel comfortable, they are likely to turn off the ventilation system that brings them fresh air, negating all the benefits it offers. In other cases, employees who are too cold or too hot, those who experience draft sensation or uneven temperatures, are likely to be distracted and uncomfortable. This can hinder their concentration, reduce productivity, and even lead to health issues. Therefore, when designing systems for personalized ventilation or any indoor environmental quality improvement, achieving the right balance between clean air and thermal comfort is essential. It's not merely about purifying the air but also about creating an environment where the temperature and airflow are conducive to sustained work efficiency and occupant satisfaction. In essence, true workplace well-being is achieved when both the air we breathe and the thermal conditions we experience are harmoniously optimized.

The steerable diffuser with reduced induction by passive flow control, for use in custom ventilation systems, will deliver fresh air in proximity to the occupant's face and at the same time has been designed to solve the main problem related to this type of applications, namely the feeling of thermal discomfort of the users.

In the case of personalized ventilation systems that use a jet flow directed to the upper body, the velocity of the discharged air reaches the proximity of the face with values that exceed the accepted limits in terms of comfort. On the other hand, compared to customised ventilation systems using "laminar" air diffusers similar to displacement discharge grilles, the type of flow used also ensures an improvement in the quality of the air breathed by the user.

The proposed air diffuser delivers fresh and clean air in the proximity of the occupant but in the same time the draught rate is kept in the comfort zone, along with the PMV index.

This type of diffuser can be used in areas where it is desired to increase the quality of the air brought near the user's face and alter it with the air in the room to a lesser extent.

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