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CFD optimization of a personal air cleaner to protect from airborne particles in transport microenvironments

Transport microenvironments are critical indoor settings where exposure to environmental pollutants and respiratory particles poses significant health risks. Commuters in cars, buses and other means of transportation are particularly vulnerable due to the high concentration of pollutants on roads and highways, combined with inefficient filtration systems in vehicle. These factors result in high concentrations of toxic gases and particles entering transport microenvironments through windows, HVAC systems, or cabin leakages. An additional health concern is the increased risk of infection from airborne transmission of virus-laden respiratory particles, due to crowding and poor ventilation. Mitigating exposure in transport environments is challenging, as conventional HVAC systems often fail to provide adequate protection. Consequently, research has focused on personal ventilation solutions such as air curtains, directional jets, and portable air purifiers. Their design, however, requires careful optimization to prevent thermal discomfort and unintended particle recirculation.
In response to these challenges, we have developed and patented a portable personal air cleaner (patent n. 102022000010346) designed to reduce airborne particle exposure. When placed on desks or tables in front of users, this device creates a protective fluid-dynamic shield by supplying filtered air in a controlled flow pattern, effectively lowering airborne particle concentrations in the breathing zone of a seated individual. Its effectiveness was demonstrated through 3D Computational Fluid Dynamics (CFD) simulations validated by experimental measurements, showing protection rates exceeding 92% in close-proximity settings and 99% in shared indoor environments.
Building on this fluid-dynamic approach, this study introduces a validated CFD methodology for designing a personal air cleaner optimized for transport environments. The proposed device, intended for installation above the users'head (e.g., for bus and truck drivers), operates on a dual airflow system: an outer high-velocity annular jet forming a protective shield around the users' head and a central low-velocity swirl flow minimizing particle exposure while maintaining comfort. The development process consisted of three stages: (i) CFD-based diffuser design; (ii) experimental air velocity characterization and numerical model validation; (iii) particle number and mass (PM10) concentrations measurements, in both the protected area generated by the personal ventilation and in ambient air to determine the reduction in airborne particle concentration.
Advanced 3D CFD simulations allowed optimize the internal geometry of the diffuser to achieve a uniform conical jet structure, thereby enhancing the protective shield's effectiveness. The device was then prototyped and tested using a 3D-printed model equipped with a commercially available fan filter unit, which imposed specific geometric constraints influencing design choices. Validation was performed through velocity fields measurements using a multi-hole pressure probe, confirming the reliability of the CFD model in predicting flow behavior.
Particle number and PM10 concentrations measurements further demonstrated the air cleaner effectiveness in reducing airborne particle concentrations within the protected area. A reduction of up to 60% was observed at 15 cm from the airflow injection, then decreasing with the distance. Notably, an excessive increase in the annular flow rate was found to reduce the effectiveness of the device, underscoring the importance of precise flow balancing. Despite the geometric constraints imposed by the commercial fan filter unit, the achieved reduction in exposure highlights the feasibility of using targeted airflow patterns to protect individuals in transport microenvironments. The validated CFD tool is currently being used to refine the air cleaner's configuration, free from the limitations of the commercial fan filter unit, to enhance overall efficiency. Specifically, ongoing numerical simulations focus on increasing the annular section diameter to extend the distance between jets,

thereby mitigating interference between the annular jet and the central swirling jet –an identified limiting factor in the device's efficiency. By optimizing these dimensions, the protective shield's effectiveness is expected to improve.

Additional simulations will assess real-life interactions, including the impact of the user's thermal plume on airflow patterns and protection efficiency. These efforts aim to optimize airflow dynamics in practical applications, ensuring the device's effectiveness under varying environmental conditions. Ultimately, this research paves the way for the commercialization of a portable, high-efficiency personal air cleaner designed specifically for transport applications, addressing the urgent need for improved air quality in enclosed commuting environments.

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