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The role of numerical modeling in improving indoor air quality

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The COVID-19 pandemic significantly contributed to deepen our understanding of respiratory virus transmission, emphasizing the critical role of indoor environments and the necessity of effective ventilation. Historically, public health guidelines primarily addressed large droplet as transmission routes. It was not until the spring of 2021, due to the increasing scientific evidence, that major health organizations like the US CDC and WHO recognized airborne transmission as the predominant pathway for SARS-CoV-2. Environmental measures to disinfect and clean surfaces in public and semi-public places did not significantly reduce the spread of COVID-19. In contrast, the cancellation of small gatherings and the closure of educational institutions, i.e., activities characterized by high crowding in poorly ventilated indoor environments, had a significant impact on reducing the spread of the virus.
This shift underscored the importance of managing indoor air quality through improved ventilation and air cleaning strategies. Numerical modelling, from zero-dimensional (0D) to complex three dimensional (3D) Computational Fluid Dynamics (CFD) techniques, have proven essential in optimizing HVAC systems and designing effective airflow patterns to ensure safety and comfort in confined spaces. This work presents mathematical and numerical modelling activities conducted in various indoor environments, contributing to a better understanding of pollutant and viral aerosol transmission, with a particular emphasis on validating the results obtained.
The transmission of respiratory viruses occurs through three routes: large respiratory particles (spray) transmission, inhalation of airborne respiratory particles, and touch transmission. Historically, public health guidelines underestimated airborne transmission, but the pandemic highlighted its significance. Enhanced ventilation and air cleaning strategies, supported by numerical modeling, particularly CFD, are crucial for mitigating airborne transmission. In fact, CFD provides detailed insights into velocity, pressure, and temperature fields, as well as particle distribution, enabling the optimization of HVAC systems and airflow patterns in confined spaces.
This study employs a Eulerian-Lagrangian approach to model the dispersion of virus-laden respiratory particles in indoor environments. The model tracks individual particles using a force balance equation, considering forces such as drag, gravity, and virtual mass. The particle number emission rate (ERN) and volume distributions were estimated based on experimental data, focusing on airborne respiratory particles (<90 μm). The model was validated through experimental measurements, including Particle Image Velocimetry (PIV), and applied to various indoor settings, such as close-contact interactions, car cabins, and university lecture rooms. CFD simulations demonstrated that large respiratory particles (>100 μm) significantly contribute to infection risk at distances less than 0.6 meters, while airborne respiratory particles dominate at greater distances. In car cabins, airflow patterns significantly influenced the spatial distribution of virus-laden particles, with higher exposure risks for passengers sitting behind an infected driver. In lecture rooms, the air change rate (ACH) alone was insufficient to assess exposure risk; local airflow patterns and the asymmetric disposition of seats relative to diffusers and exhaust grilles played crucial roles.

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