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From Flow Instability to Airborne Transmission of Respiratory Diseases: A Computational Fluid Dynamics Approach

Mathematical modeling and computational fluid dynamics (CFD) play an essential role in advancing our understanding of complex flow phenomena such as shear-layer instability, vortex dynamics, and the emergence of chaotic flow behaviour. Among a wide range of engineering and environmental systems, these phenomena often arise in the airborne transmission of respiratory pathogens, governing their spatio-temporal dispersion. Because they frequently occur at high Reynolds numbers and involve strong nonlinear interactions between exhaled droplets, fluid inertia, viscosity, and turbulence, analytical solutions are rarely possible. Mathematical modelling, therefore, provides the theoretical framework needed to describe these instabilities, while CFD simulations offer a powerful tool for resolving the detailed spatial and temporal evolution of the flowfield. From exhalation jets to the wakes formed behind walking individuals, shear layer instabilities (e.g., Kelvin–Helmholtz instability) are responsible for the formation, growth, and breakdown of coherent vortical structures, consequently governing the pathogen dispersion. Integrating mathematical modelling with modern CFD techniques—such as large eddy simulation (LES), direct numerical simulation (DNS) enables us to sufficiently resolve the length/time-scales emerging in the turbulence energy cascade and ultimately extract the vortex dynamics and chaotic flow structures critical to the dispersion of infectious pathogens.