Abstract

Infectious diseases, such as COVID-19, can be transmitted by the virus-laden respiratory droplets exhaled by an infected person. People spend most of their time in indoor environments. The indoor ventilation systems can dilute or remove such respiratory droplets making the knowledge of respiratory droplet transmission in these scenarios essential to control the infection.

Respiratory droplet transmission is a complex problem, characterized by multiphase flow, polydisperse droplet population, multi-component mass transfer, and evaporation. In the numerical methods, the dispersed droplets can be treated in an Eulerian or Lagrangian manner. The Eulerian approach treats the dispersed droplets as a continuum rather than tracing the movement of individual droplets as in the Lagrangian approach. Therefore, the Eulerian approach generally has lower computational costs, which makes it attractive. However, it has difficulty in dealing with the polydispersity and evaporation of the respiratory droplets.

In this dissertation, to exploit the cost-effectiveness and simplicity of the Eulerian approach, the population balance equation (PBE) is coupled with the Eulerian-Eulerian (E-E) approach to trace the transmission of the polydispersed evaporating respiratory droplets. Two PBE-solving methods, the sectional method (SM) and the quadrature method of moments (QMOM) are adopted and compared. Codes for the EE-PBE approach are developed based on the open-source software OpenFOAM and verified and validated using experimental and numerical data in the literature. Then, different Eulerian approaches, including the pseudo-single-phase model (PSPM), the two-fluid model (TFM), and the EE-PBE approach, are adopted to investigate respiratory droplet transmission in ventilated indoor environments.

The developed EE-PBE approach is systematically verified and validated with experimental and numerical data in the literature. This is performed by first assessing the different aspects of the transmission process, including evaporation, movement of the respiratory jet (or puff), and particle transmission in ventilated environments. Finally, all features are collectively considered through the examination of the transmission of polydispersed evaporating cough droplets. Good agreements are obtained for all cases, indicating that the developed EE-PBE approach can tackle the key nature of respiratory droplets, especially evaporation and polydispersity. The two PBE-solving methods, SM and QBMM are compared and discussed. Furthermore, the results confirm the suspending trend of small droplets and the falling trend of large droplets.

The different Eulerian approaches are adopted to trace respiratory droplet transmission in ventilated indoor environments. Good agreements with experimental data in the literature are found. For the Eulerian approaches, the PSPM is suitable for the transmission of small-size droplets but a suitable diffusion coefficient is required. The TFM can provide accurate predictions for the transmission of monodispersed droplets. Meanwhile, the EE-PBE approach can trace the transmission and evaporation of polydispersed droplets. For ventilation systems, the stratum ventilation (SV) supplies fresh air to the breath zone directly may be a good choice to control indoor infection. The displacement ventilation (DV), transporting the droplets upwards and providing a stratified environment, can provide protection to some areas within the environment. The mixing ventilation (MV), distributing the droplets uniformly and providing a uniform environment, may not be suitable to control indoor infection.

In conclusion, the Eulerian approach provides reliable and efficient tools to deepen the understanding of respiratory droplet transmission and assess the performances of different ventilation systems.