Abstract

Maintaining high indoor environmental quality, including air quality, is a major challenge in densely occupied spaces such as classrooms—a challenge that gained particular importance during the COVID-19 pandemic. This dissertation presents a comprehensive study of advanced ventilation and airborne infection control strategies. The research encompasses a range of approaches, from smart natural ventilation to hybrid systems, as well as localized and integrated personal ventilation systems combined with physical barriers.

In the initial phase, an automated window-opening controller was developed and simulated to manage natural ventilation in a classroom. This strategy significantly improved indoor air quality and thermal comfort; however, without additional measures—such as air purifiers or face masks—the infection risk remained high. In the next phase, a multi-objective optimization approach was proposed to simultaneously regulate window openings and thermostat settings. The model aimed to minimize energy use, average indoor CO_2 concentration, and occupant discomfort. This solution was analyzed under two distinct climate conditions. Subsequently, a novel hybrid ventilation strategy was developed to synchronize the use of natural and mechanical ventilation based on outdoor air pollution levels and the risk of pollutant infiltration. Optimization of this strategy ensured compliance with indoor environmental quality standards while minimizing energy consumption in three cities characterized by varying outdoor air quality and climate conditions.

Experimental studies began with evaluating the role of physical barriers in aerosol transmission under mechanical ventilation. Tests were carried out in a laboratory test chamber equipped with two types of mixing ventilation systems. Nebulized aerosols and bioaerosols were used to simulate airborne infection transmission. The results indicated that physical barriers with a height of 65 cm reduced aerosol transmission when effective air mixing was present. However, in cases of insufficient airflow, the use of barriers could lead to local accumulation of contaminants. In the following stage, physical barriers were combined with a local exhaust system providing 9 L/s per person. This configuration resulted in a significant local reduction of pollutant concentration across all tested air distribution systems. Moreover, numerical studies using Computational Fluid Dynamics (CFD) showed that reducing the barrier height to 45 cm and the exhaust airflow to 6 L/s per person resulted in only a ~5% decrease in aerosol removal efficiency, while significantly reducing energy and material demand.

The final part of the dissertation provides a comparative analysis of various infection control strategies, combining infection risk assessment with Life Cycle Assessment (LCA). The results demonstrated that although some hybrid strategies—such as masks and air purifiers—offered the lowest infection risk, they also imposed substantial environmental burdens. The most balanced solution, considering both infection control effectiveness and environmental impact, was the integrated system of physical barriers and localized exhaust ventilation.

Keywords: indoor air pollution reduction; spread of air pollutants; ventilation strategies; physical barriers; life cycle assessment.