Optimization of airflow rate in a displacement-ventilated room to minimize particle inhalation risk and control energy consumption

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SUMMARY

Indoor inhalation exposure can be minimized through mechanical ventilation. On the other hand, building and mechanical ventilation design remain as the main sources of energy consumption. The present study focuses on the optimization of a displacement-ventilated room by applying computational fluid dynamics, virtual manikins and a genetic algorithm in order to minimize airborne viral density while reducing the energy consumption level.

KEYWORDS

Mechanical ventilation design; Genetic algorithm; Multi-objective optimization; Computational fluid dynamics

1 INTRODUCTION

In the built environment, ventilation systems are essential to maintain air quality but their performance is highly influenced by temperature, wind speed, supply-exhaust vents layout and size and airflow rate. Particles released by human activities greatly contribute to personal inhalation and must therefore be studied in conjunction with these building factors. Computational fluid dynamics (CFD) has been used to predict indoor airflow and distribution of pollutants, especially large eddy simulation, which precisely predicts particle movement (Murga et al., 2022). However, when considering ventilation design and its best outcome, study of multiple CFD-based cases can increase computational burden. This research applies a genetic algorithm to optimize the performance of a displacement system in a room with a speaking virtual manikin in terms of inhalation risk and energy consumption by adjusting the layout and size of the supply-exhaust vents and ventilation airflow rate. The objective was to enhance the built environment by integrating human-building flows and CFD-optimization algorithms.

2 METHODOLOGY

2.1 Built environment and virtual manikin

The target room had dimensions of 3 × 3 × 3 meters and the ventilation rate corresponded to the outdoor air requirement of 10 L/s per person. A displacement ventilation system was added, where the air was supplied at a low height and exhausted at ceiling level, creating a stratified distribution to carry pollutants above occupant-level. Room design as well as supply-exhaust layout is shown in Figure 1 a) and b). A virtual manikin was standing in the middle of the room, constantly talking based on a 1-to-10 enumeration model, scaled 50% to simulate "loud" speaking [3]. Particles were released from its mouth at peak velocities during speech. The flow in the room was validated with previously reported simulation and experimental data of a similarly ventilated room by Yoo and Ito (2022) and Nielsen et al. (2003) (Figure 1 c)).

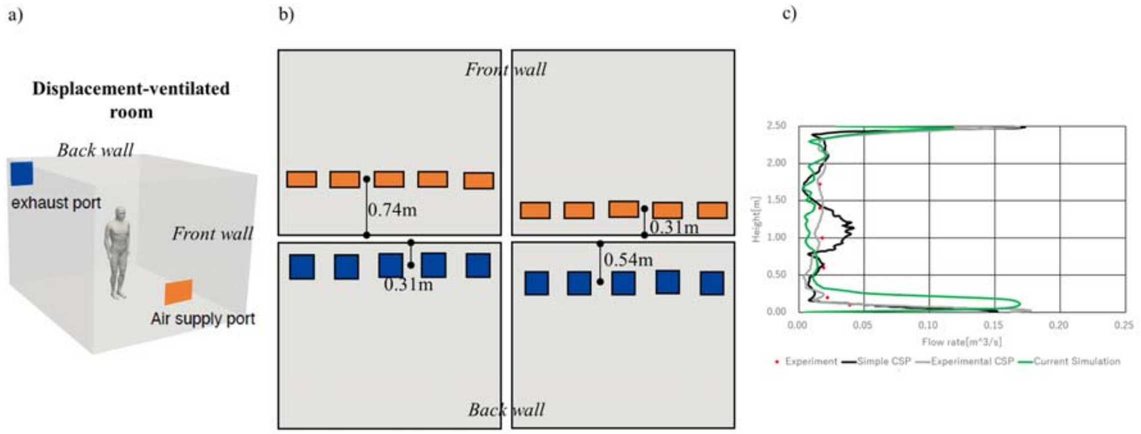

Figure 1: a) Room design, b) Layout of supply-exhaust vents and c) Indoor flow validation

2.2 Numerical methods

The current study uses a discrete particle model along with a fully compressible Navier-Stokes solver. The solver uses a Lagrangian-Eulerian method in which the carrier/background fluid equations of motion are resolved in an Eulerian reference frame. Concurrently, the particles are modelled as discrete Lagrangian particles. Governing equations and further details have already been published by Li et al. (2016).

2.3 Building optimization

Building parameters considered for optimization were: a) inlet size (0.2×0.4 m2 or 0.3×0.5 m2), b) outlet size (0.3×0.3 m2 or 0.45×0.45 m2), c) inlet/outlet location (Figure 1 b)) and d) airflow rate (0.01 to 0.06 m3/s). The first objective function of the genetic algorith was the infection risk, measured through the time-averaged viral density in the inhalation zone (between 1.5 and 1.8 m). The second objective function was the energy consumption, measured through a normalized value obtained by dividing the airflow rate used by the minimum airflow rate in this study (0.01 m3/s). The Pareto solution was generated by advancing the calculation through six generations and was considered converged when the resulting hypervolume remained unchanged after two consecutive generations.

3 RESULTS

The dynamic interactions between indoor airflow and the flow around the human envelope were studied. results in terms of viral density and power are presented in Figure 2 a). Following the Pareto solution, particle number decreased by 50% when the worst case (P1) and the optimized solution that maintains the same power consumption (P2) are compared. On the other hand, power level can be lowered to 1 for energy reduction while slightly lowering virus density (P3) when compared to P1. Particle distribution inside the room for the worst- (P1) and best-case

(P3) scenarios in power level 6 are presented in Figure 2 b). Particles remained at breathing-level when building parameters were not optimized but were successfully removed after optimization. Then, optimization algorithms can be joined to virtual manikins to improve building design and minimize airborne transmission while managing energy consumption.

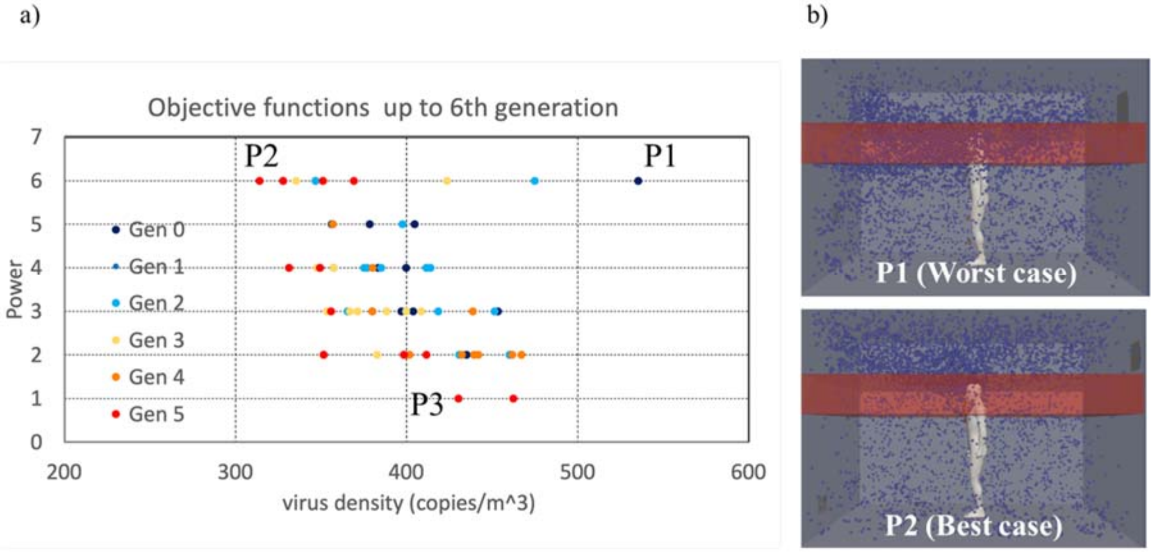

Figure 2: a) Pareto solution and b) Comparison of P1 and P2

4 CONCLUSIONS

This research introduced the application of virtual manikins and optimization algorithms to evaluate airborne transmission inside the indoor environment. The main objective of this study was to develop a framework for evaluation and design of a sustainable environment.

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