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Multi-scale fluid dynamic analysis of indoor infection transmission risk by respiratory droplets

Objectives. Indoor transmission of pathogens between hosts primarily occurs through exhaled respiratory droplets. Transmission mechanisms include direct or indirect contact with contaminated surfaces, and direct or indirect inhalation of droplet nuclei. Droplet trajectory depends primarily on their size among other factors such as ambient thermohygrometric conditions and transport charactersitics within the exhaled breath cloud. Large droplets are dominated by inertia and follow quasi-parabolic trajectories reaching the ground before their evaporation completes. On the contrary, small droplets are dominated by drag forces and are carried around indefinitely by local air streams. Inertia and drag compete over intermediate size droplets that change behaviour as they evaporate. Large droplets are among the prime responsible of fomite transmission, intermediate size droplets of direct inhalation transmission, and small droplet nuclei of airborne transmission. Droplet dispersion has been investigated in the literature by several numerical means including CFD simulations and analytical models. Objective of the present work is to present a novel multi-scale model combining the wide modelling capabilities of CFD analyses with the accuracy and reduced computational effort of analytical models. Assumptions on the saliva viral load and on the quantity of exhaled droplets allow spatial risk maps to be built able to discriminate between the various transmission routes for different types of respiratory events.

Methods. The authors recently developed an analytical model solving the equations of droplet transport, evaporation, energy, and chemical composition. The model also accounts for droplet turbulent dispersion using a random walk approach and implements a randomised droplet injection mechanism making it suitable for statistical analyses on the trajectories of large sets of droplet. The governing equations of the model depend on the varying local ambient conditions encountered by the droplet during its flight such as air velocity, temperature and relative humidity. This calls for detailed exhaled breath cloud models that cannot be simply obtained from jet theory empirical formulas. To overcome this limit, the analytical model is coupled to 3D U-RANS CFD simulations of the exhaled jet providing accurate representations of the buoyant breath cloud for various types of respiratory events. The analytical model is coupled one-way with CFD simulations: at each time step, the model queries the CFD results to get the local ambient conditions and use this information to update the droplet position and diameter. Droplet are simulated up to when they either settle to the ground or evaporation terminates and their solid nucleus is transported by local air flows with negligible terminal velocity. The multi-scale model thus built is used to analyse the droplet trajectories from different respiratory events. The scenarios investigated include mouth breathing, speaking, nose breathing, coughing, and sneezing. A SARS-CoV-2 infected individual not wearing a face mask is assumed, and the domain of the analysis is a large non-ventilated empty confined space.

Results. Droplet trajectories visualization provides an immediate qualitative representation of the infection risk area around the infected individual. With assumptions on the virus concentration in the saliva, the infectious dose likely to cause the disease if inhaled, and the quantity and size distribution of the droplets exhaled for each respiratory event, trajectory data is further processed to obtain practical quantitative spatial virus concentration maps. These maps are derived for the room volume and, by considering the droplets settling to the ground, for the floor surface in front of the individual thus providing means for quantifying the risks associated to both direct inhalation and fomite transmission routes. By assuming well-mixed airborne droplet nuclei after the simulation stops tracking them, Wells-Riley model further provides numerical evaluations for the background virus concentration responsible for airborne transmission. By estimating the breathing rate and the exposure time of a susceptible individual, information on the virus concentration is translated into virus inhalability spatial maps and, lastly, into infection transmission risk maps.

Conclusions. The multi-scale model proposed exploits the advantages of both CFD and analytical modelling

providing accurate predictions of exhaled droplet trajectories. It also allows large sets of droplets to be evaluated with limited computational effort. The model was used to simulate different scenarios handling more than 40 thousand droplets each. This data allowed to investigate the main physical phenomena influencing the droplet motion. Above all, it allowed useful spatial risk maps to be derived that can quantify the risk of contagion in specific situations, helping in better calibrating prevention needs.

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