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Local control of near-field diffusion of infected respiratory cloud in a room by air-blades

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Abstract. The respiratory cloud of an infective subject contains droplets of mucosalivary fluid carrying pathogens. As this cloud spreads at a certain distance from the emission point, the droplets accumulate and their volume concentration increases in the room unless dilution, adequate ventilation, or filtration reduce it. A susceptible subject, standing a short distance away can be exposed more easily to the infected respiratory cloud, thus inhaling a higher dose of pathogens than someone breathing the mixed air in the room. A local airflow pattern can be employed to reduce this short-distance risk of inhalation and potential contagion. We present experimental and numerical investigations of a novel device acting as a barrier to airborne pathogen diffusion at a short distance. This portable device generates V-shaped air blades in front of the subjects, shifting the respiratory clouds. The air blades are generated by 12 small fans, three on each side of the cube. The air is sucked into the small plenum inside the device body through the bases. By being positioned obliquely on a meeting table, the device acts as a direct barrier to virus-laden aerosols without any filtration. The experimental tests show that the system can reduce the local concentration of aerosol by 63 to 84% at the respiratory position of a subject sitting at a table in front of an infective person. CFD simulation outputs using the Multiphase Eulerian-Lagrangian model show a good agreement with the experimental results. The validated model will be used to extend the range of investigation to different settings and to perform a parametrical analysis of the main design conditions.

1. Introduction

In the last few years, the highly infectious Severe Acute Respiratory Syndrome COVID-19 virus has forced humanity to adapt rapidly. Recent research has proven that respiratory droplets which either directly expose another person or evaporate and create droplet nuclei that may remain suspended as an airborne particle for a long time can spread the virus. In an indoor environment, people are more susceptible to respiratory disease outbreaks. In fact, people can be exposed directly to an infective subject`s respiratory cloud, and indirectly by being immersed in a volume where virus-laden aerosols accumulate[1]. Under some circumstances, ventilation systems and indoor airflow topology can

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effectively mitigate the spreading of viruses [2]. In general, besides source control, avoiding exposure to mucosalivary fluid is the most effective strategy to help stop the transmission of respiratory viruses, and this can be achieved by a number of measures.

When the respiratory aerosol emitted by an infective person is dispersed in a closed environment, it will tend to accumulate and occupy the entire volume, by advection and diffusion. Advection is strictly related to the indoor airflow topology, in turn depending on the ventilation systems, the effect of thermal sources, people's activity, and the operation of any openings (doors and windows). Aerosol might persist in an indoor environment for many days [3]. The resulting concentration of aerosol in the volume can be reduced by dilution through ventilation or filtration of the indoor air. Ventilation and filtration will create new airflow patterns in the indoor setting, thus also influencing the advection of infective aerosol and potentially introducing local non-homogenous distribution of infected aerosol in the volume [4]. There are two primary methods for obtaining adequate dilution through ventilation: either striving for efficient air mixing in the space or attempting to create two layers of air, with cool fresh air in the occupied lower zone and warm waste air in the vacated top zone of the room [5]. For the former approach, once the well-mixed limitation of the environment is achieved, exposure is subsequently diminished [6]. Within populated enclosed areas, the well-mixed threshold would be difficult to attain, thus caution must be applied to make sure there are not any high-risk regions of concentration or airflow recirculation. The latter approach, displacement ventilation, in which fresh air is provided at a relatively moderate velocity close to the ground and withdrawn towards the ceilings, is proven to have energy-saving advantages in addition to producing favorable circumstances for a fresh respiratory area. However, despite ventilation's effectivity in controlling indirect routes and reducing the accumulated viral load in the occupied zone of an indoor volume, its efficacy for direct exposure is poor.

On the other hand, infection risk is highly increased by direct exposure, which is characterized as being immersed in an infected respiratory cloud. Direct exposure definition corresponds largely to what has been called more frequently short distance route [7]. To control the local airflow field and to counteract direct transmission, making barriers might intercept the flow of droplets in order to mitigate the infection risk of the susceptible occupants. In this respect, researchers have examined effective preventative measures of various systems, including individual ventilation[8] and air purifiers[9]. There is abundant research on the effectiveness of air purifiers demonstrating that their use is quite cheap compared to replacing an HVAC system and that numerous portable purifiers can be used in one area [10]. These devices can dramatically lower particle concentrations in a room, at direct or indirect exposure. Air purifier use has been associated with a wide range of infection risk reduction, from less than 10% to almost 90% on average in various indoor settings [11]. On the other hand, Personalized Ventilation is frequently used in vehicles to increase travellers' comfort levels. Recent epidemics of respiratory disorders have drawn researchers' attention to this effective ventilation approach to the management of the viral risk of transmission. The examination of the impact of various PV air terminal devices on direct respiratory exposure has revealed that PV (10 L/s) could significantly improve the breathing quality of air, with a maximum exposure reduction of pollutants of 97% [12]. However, each of these solutions has drawbacks of its own. PV, for instance, requires specific ducting, which restricts its use to locations with particular conditions. In addition, even though portable purifiers are ductless, they still require filter management, and due to the high-pressure drop of the filters, this necessitates a high capturing flow rate and, as a result, high electrical power.

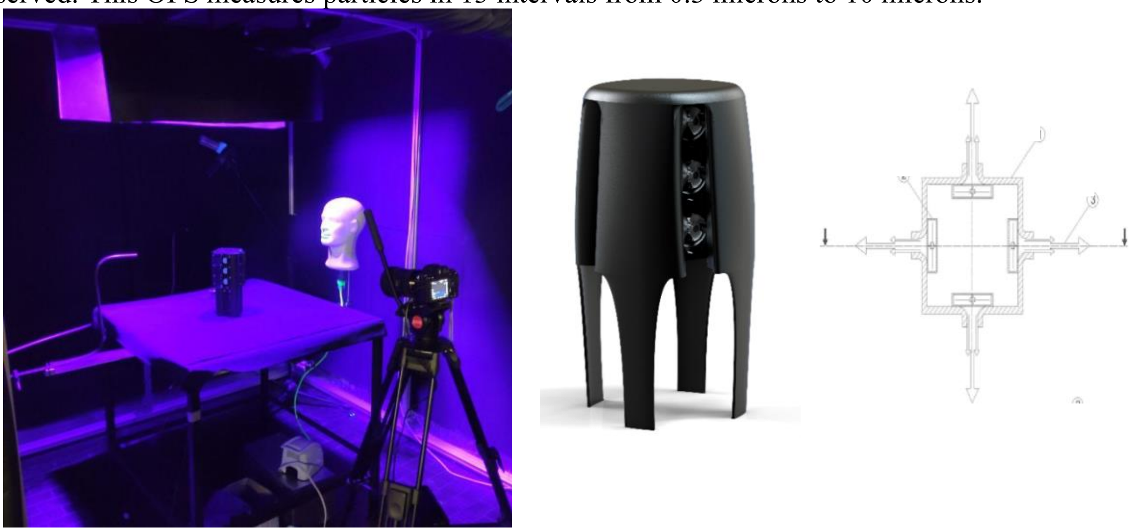
In this study, a novel device that works on the direct exposure range is presented. This V-shaped air blade device, called Bio-stopper, acts as a short-range barrier for virus-laden bioaerosols, eliminating the shortcomings of similar devices, as well as being simple to use, cheap and with readily available components. In terms of its structure, Bio-stopper is stand-alone and portable, and also without the need for filter management, making it very user-friendly. In the current study, the authors provide an integrated strategy to evaluate the close proximity effectiveness of a novel solution based on the aforementioned technique that permits the evaluation of the pathogens discharged. An experimental test setup has been employed to quantify the number of droplets passing the Bio-stopper. In addition, a numerical method has been adopted to simulate the test settings and assess the number of viral loads a susceptible individual would receive while seated at a table 80cm away from an infective person. In this simulation, the Bio-stopper airflow is characterized by velocity vectors in various planes of the enclosed space examined.

2. Experimental methodology

After discovering and comprehending how the Covid-19 virus spreads during the peak of the pandemic, the mindsets began to shift toward establishing personal safe zones in close spaces, particularly unique locations for group gatherings. To accomplish this, a 90° V-shaped air blade named Bio-stopper has been suggested by this research. The final form of Bio-stopper (see figure 1) after many trials and errors is composed of two components, the main body, and the bases. The main cube-shaped body is made up of 12 miniature, low-consumption fans, three of which are mounted on each side of the cube. The air enters the main body through the bases, where it is sucked up and blown out by the fans. Bio-stopper functions as a direct barrier to virus-laden aerosols by being positioned obliquely on a meeting table. This device operates without any filtration over a short distance. The benefits of this gadget include being simple, affordable, minimal maintenance, lightweight, portable, and ductless.

The test equipment is installed in a sealed, dark chamber (3x3x3m) in order to accurately visualize the test. To vividly track the particles, here, fluorescent aerosols generated by an aerosol generator are utilized, and two 80-watt UVA LEDs are used to observe them during the test. Additionally, a professional camera is also employed to capture the particle transmission (see figure 1a). In the chamber, there is a table on which, a TSI 3330 optical particle sizer and a mannequin head connected to the aerosol generator are attached to each side. The median of the particles generated by the generator is 3 microns. Prior to the test, Testo 405i and Testo 440 dp instruments were used to measuring Bio-stopper's velocity and turbulence intensity parameters, respectively.

The tests were carried out in two ways with and without Bio-stopper. Each experiment is carried out for 300 seconds and runs five times. The generator device is then turned on at the beginning of the test, and the mannequin's head, which serves as a proxy for the infective individual placed at one side of the table, releases fluorescent aerosol particles into the air through two nasal and oral outlets. On the other side of the table, there is a tube connected to the Optical Particle Sizer (OPS) as a representative of the susceptible subject to count the number of particles. The OPS device is set in 30-second spans so that the changes and fluctuation of the aerosol generator production can be better observed. This OPS measures particles in 13 intervals from 0.3 microns to 10 microns.



a) b) c)

Figure 1. a) Experimental set-up, b) manufactured Bio-stopper, c)2-D schematic of Bio-stopper

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3. CFD

For the numerical characterization of the fields of velocity, pressure, and temperature as well as the aerosol dynamics, the Computational Fluid Dynamics (CFD) technique has been utilized. The Star CCM+ software, which is based on finite volumes, has been used. The requirement for a versatile tool with total control over the boundary conditions of the solved PDEs led to this decision. The significant complexity of the proposed technique has paid off by enabling a full description of thermo-fluid dynamic fields and associated aerosol dynamics in both space and time. The Lagrangian multi-phase model has been used to mathematically simulate the travel of the particles through the airflow. The Eulerian-Lagrangian method, in which the continuum equations for the airflow (continuous phase) are solved and Newton's equation of motion is solved for each particle, is particularly justified since the spacing between particles in the expelled air plume is sufficiently large and the volume percentage of the particle is sufficiently low ($<10^3$)[13]. Having an affordable simulation, the particle distributions were considered through normal distribution [14]. The particle's shape was supposedly spherical, and the size was taken into account in the range of 0.5 to 10 microns with a mean size of 1 micron and a standard deviation of 1. The solution time step is considered 0.05s. In this study, the effect of droplet evaporation on the physic was neglected. For the boundary condition values, Bio-stopper outlet velocity, airborne particle initial velocity, and inlet pressure of the device were considered 3, 3.9 m/s, and 0 Pa, respectively. To model the physics of the problem, implicit unsteady, segregated, turbulent k-omega, two-way coupling, and Schiller-Naumann models were employed for a time, flow, viscous regime, particle and airflow interaction, and drag force coefficient, respectively.
As shown in figure 2, the geometry taken into consideration for this investigation consists of two identically sized individuals seated 80 cm apart on a table. One individual is an emitter who exhales through the nasal and oral outlets of the respiratory tracks, which are modeled by two cone-shaped injectors. The other individual is a vulnerable participant who is seated on the other side of the table and is invaded by airborne particles through inhalation. The Bio-stopper is placed at the center of the table. The layout of the computational mesh was carefully considered: the simulations were carried out using polyhedral-based unstructured computing grids, and a prism layer mesh model is employed in conjunction with a central volume mesh.

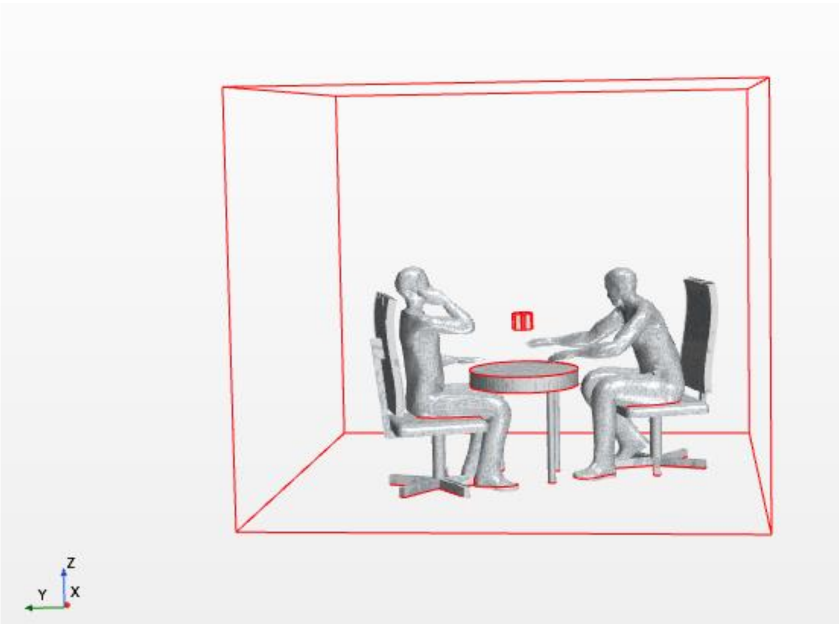


Figure 2. Geometry adopted in the simulation

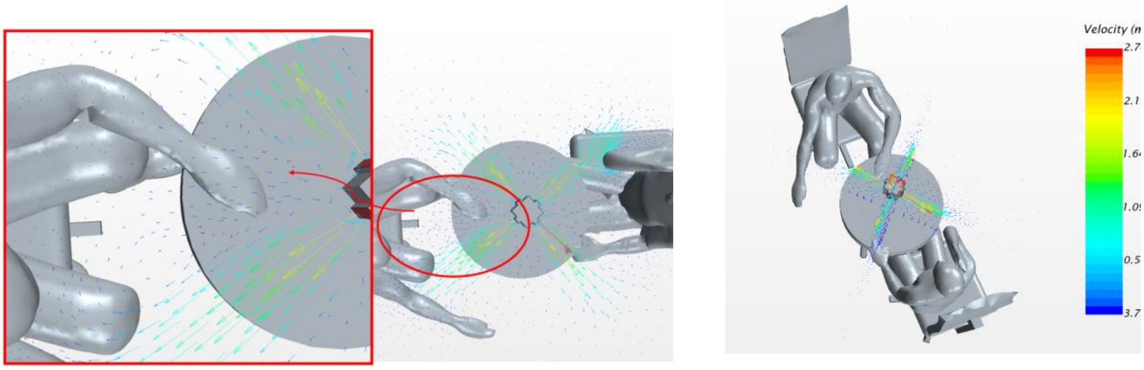
4. Results and discussion

4.1. Experimental results

To assess the efficiency of Bio-stopper, tests were conducted with and without the device. Investigations have been done on the parameters of particle volume and particle number as a function of mean diameter. The geometric mean of five tests determines both the quantity and volume of particles. The particles were counted for 300 seconds at 30-second intervals, as was previously described. Figure 4a in this regard demonstrates, accordingly, the quantity before and after the Bio-stopper is turned on. By comparing the data obtained with and without Bio-stopper, it was found that there was an average 63-84% reduction in the number of particles that an infective individual may transmit to a susceptible subject. For instance, the highest reduction of the transferred particles was 84%, which is equivalent to a diameter range of 2.2 to 3 microns, when comparing the geometric mean of particles in the time range of 120 to 150 seconds. When the entire number of carried particles is taken into account without considering the diameter interval, the average value decreases to 78%.

4.2. CFD results

To check the efficiency of Bio-stopper by numerical simulation in Star CCM+ software, firstly, the way of creating the velocity field has been investigated as a vector in figure 3. This figure shows that this device creates 4 zones by 4 blades, as 4 fan outputs, on a table. As it is clear, due to the suction and blowing created by the Bio-stopper, turbulent flow is created in these four zones and a reversal flow is formed there. According to the magnification shown in the respiratory area of the susceptible person, two eddies are formed, and these eddies would have the ability to change direction and return particles with low momentum. In order to reduce the visual interference between people sitting at the table the device is placed at a lower height with respect to the respiratory outlet.

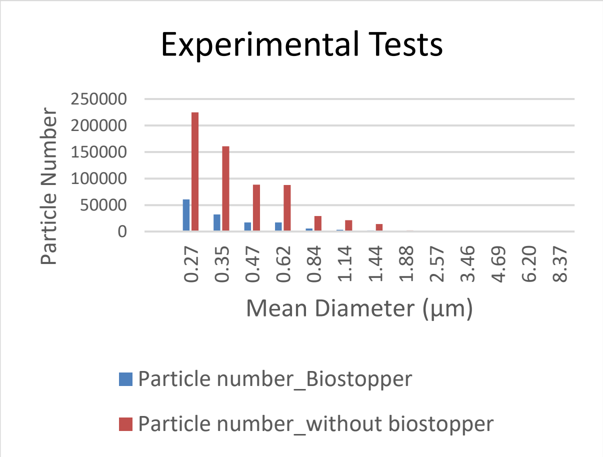


a) b)

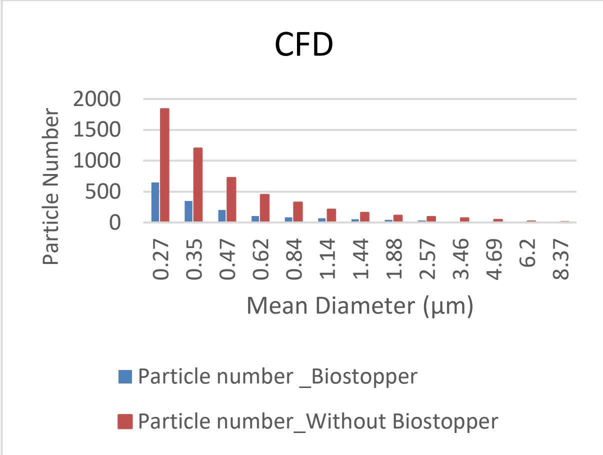
Figure 3. Velocity vectors a) on the horizontal plane, b) on two vertical planes intersected with Bio-stopper outlets

To confirm the methodology, this study compared experimental data and CFD results to analyze the effectiveness of Bio-stopper in minimizing the quantity of airborne transported from an infected person to a susceptible person. In this way, the test conditions were considered as stated in section 2, while for CFD, the conditions for the speaking mode were considered in normal mode. The particle production speed was 3.9 m/s[7], the number of parcels produced at one time was 100, and the flow rate of the particles produced from two 60-degree conical injectors was considered to be 1000/s and the rest of the environmental conditions are considered the same for both states. In the experimental mode, the number of particles measured by OPS was at a distance of 80 cm from the head of the mannequin, while for the CFD mode, the number of particles attached to the surface of the mouth and nose of the susceptible person was. As it is clear from the graphs (figure 4), the comparison of the results has shown an acceptable agreement. The experimental data revealed a reduction in the number of passing particles of 63 to 84%, while the CFD results indicate a reduction of 61 to 77%. It must be noted that the experimental source was emitting a vastly higher number of particles compared to the

CFD, which simulated a real number of particles emitted by a person. In the experiment, this was needed to clearly differentiate the emitted particles from the background particles and achieve meaningful readings.



a)



b)

Figure 4. Comparison of particle counting in two modes of with- and without Bio-stopper operation for a) experimental tests b) CFD results

5. Conclusion

Due to the high death rate during the Covid-19 pandemic, the importance of preventing or reducing the high transmission rate of virus-laden aerosols in closed environments has become more vital than ever. The droplets caused by the respiratory plume are spread in a closed environment and their concentration increases, which puts susceptible people at risk of infection in two ways, either by direct or indirect exposure. This study has proposed a cheap, portable device without the need for a filter in order to reduce the risk of infection, undertaking a numerical and experimental investigation of its performance. This device acts as a 90° V-air blade forming a barrier to the spread of direct exposure to airborne pathogens. In the experimental part of this research, considering a completely closed environment, the efficiency of the novel Bio-stopper device was studied by using a mannequin head connected to a liquid aerosol generator and screwing it to a table to represent the respiratory droplet generator, while placing an OPS device to represent a target susceptible person for particle counting. In the CFD part of this study, the experimental geometry was simulated using the Eulerian-Lagrangian model. Comparing the results obtained by the experimental data and the numerical output shows a good agreement. The validated model will be used to extend the range of investigation and to perform a parametrical analysis of the main design conditions. By analyzing the results obtained in this study in detail, the key findings of this study are:

- According to the experimental data, Bio-stopper reduced by up to 84% the airborne particle transmission carried by mucosalivary fluid
- According to the CFD results, Bio-stopper decreased by up to 77% the airborne particles transmitted by mucosalivary fluid
- Bio-stopper creates a reversal flow in the respiratory zone of the susceptible subject which may change the direction of particles and return them with low momentum.

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