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Developing a respiring manikin setup to simulate face-to-face conversations in an indoor setting

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Abstract. While the worst COVID-19 pandemic is past us and everything has almost returned to normal, we should act on the lessons learned and prepare for a future pandemic. Public places of large social gatherings like cafes, bars, and restaurants might be the most vulnerable indoor environments because the occupants face each other in combination with poor ventilation. However, little research has been done to study such a social setting. As an initial experimental study, a respiring manikin setup is developed to mimic face-to-face conversations between two occupants. This setup can mimic and visualize speech-like particle-laden flow in different environmental conditions. It has the potential to quantify the illuminated flow field for correlation with numerical simulations and be used with infectious viruses for virology studies in the context of airborne transmission.

1. Introduction

The unpreparedness of our healthcare systems was exposed during the recent pandemic, and numerous lives were lost because of that [1]. Strict public health measures have been proven effective in mitigating the spread of infectious diseases [2], but they are not practical to implement when there is a relatively low risk of infection. Normally, humans are social creatures without these restrictions and tend to interact in social settings like event spaces, restaurants, and bars. In these settings, it is increasingly common for the occupants to face each other a short distance apart and converse. Combining this occupant configuration with sub-par ventilation strategies can result in widespread airborne transmission in case of an outbreak [3, 4]. In preparation for a future pathogen that spreads through respiratory droplets in the air, it is important to look at a scenario where society is the most vulnerable [5].

Previously, studies have looked at hospitals and classrooms due to recency bias fresh from the pandemic [6, 7]. Occupant configurations in these settings include patients in bed with or without a healthcare worker or a classroom with all students facing in one direction with or without an instructor. Compared to face-to-face occupant configurations, the airflow regimes in these settings can vary in their potential to spread infectious respiratory particles (IRPs) through the air. Recently, studies have started looking at social settings with face-to-face occupant configurations [8, 9, 10]. More research is required to answer questions like how IRPs propagate from an infectious person to a susceptible person, how long it takes to infect them, how the indoor space should be ventilated to protect them, etc.

To address this knowledge gap, a respiring manikin setup has been developed in one of the controlled climate chambers in the SenseLab at TU Delft [11] that aims to study different aspects

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of airborne transmission in indoor environments where two occupants engage in respiratory activities. The setup can be used with optical methods like particle image velocimetry to validate numerical models simulating exposure risk in such scenarios. These numerical models will be able to look at the flow patterns at a room scale with large occupancy and potentially look at effective ventilation strategies to minimize exposure risk. In this paper, a simplified two-occupant face-to-face configuration is experimentally studied by developing a respiring manikin head that can mimic speech-like pulsatile and particle-laden flow. The manikin head setup is tested for generating turbulent puffs observed while talking, simulating the thermal plume for different temperature differences, and visualizing the interaction of emanated particle-laden flow.

2. Experimental setup

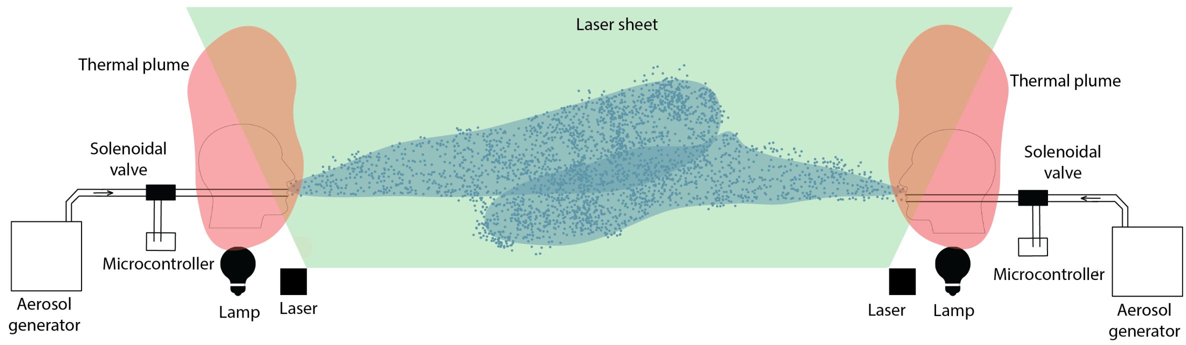

Figure 1: A simplified schematic of the experimental setup.

2.1. Particle-laden flow generation

Two portable aerosol generators are used to simulate the exhaled respiratory flow. The devices aerosolize Di-Ethyl-Hexyl-Sebacat (DEHS) and release it vertically up, creating particle sizes ranging from 0.02μm to 6μm, which is a subset of the particle size spectrum observed in normal speech, which is from 1μm to 10μm [12, 13]. Typically, smaller particle sizes ($< 5\mu$m) carry pathogens through the air, transmitting infectious diseases between an infected individual and a susceptible one [14]. The flow rate of the generated aerosol stream is around 5L/min, which is slightly lower than the respiratory flow rate during speech but is quite realistic and close within reason to simulate speech, with less vocalization and frequent pauses [15].

2.2. Manikin head details

The aerosol generator used in this study releases the particle stream in the upward direction. To mimic respiratory flow emanating from an occupant, it was modified using 0.75-inch diameter pipe fittings with an elbow bend to direct the aerosol stream horizontally (see Figure 1). The pipe fittings also accommodate the solenoidal valve for flow pulsation before the elbow bend. A 3D-printed manikin head with a hollowed-out channel simulating the buccal cavity is used at the other end of the elbow bend, as shown in Figure 2. While the flow rate is pulsated, the speech flow aerodynamics is highly dependent on the shape of the mouth, which is highly dynamic. When making speech sounds, the mouth changes from circular, elliptical, slit-like, partially closed, and fully closed. Since the 3D-printed manikin head is rigid and focuses here on the aerodynamics and airflow behaviour in speech production, the mouth of the manikin head is chosen to be elliptical with teeth-like projections as illustrated in Figure 3. The elliptical orifice has semi-major and minor axis lengths of 0.015 m and 0.01 m, respectively.

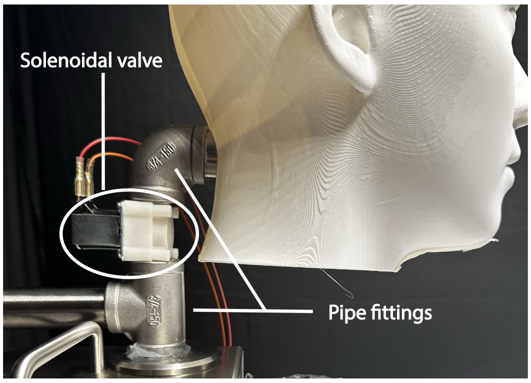

Figure 2: Placement of the solenoidal valve ahead of the manikin head.

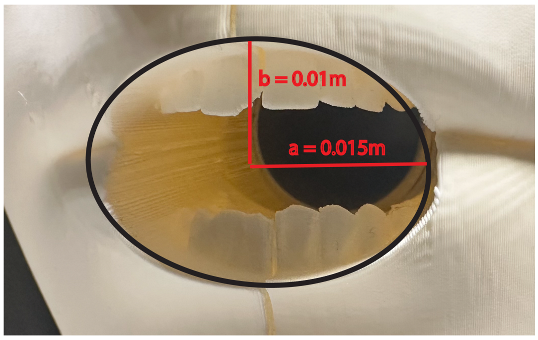

Figure 3: Design of the mouth opening with dimensions and teeth-like obstructions.

2.3. Implementing speech-like pulsatile characteristics

Respiratory activities like speaking or breathing result in pulsatile flows. The flow rate during speech fluctuates more when compared to breathing, attributed to tongue, lips, and teeth movement. In this setup, the primary fluctuation in the flow rate is brought about by a 12 V-no minimum pressure-solenoidal valve controlled by an Arduino Uno. The Arduino is programmed with two phases of a conversation: speech and pause. In the first phase, the valve is in its "open" state for short windows of 500 ms, followed by short windows of 500 ms, where the valve is in its "closed" state, which lasts for about 8 seconds. In the second phase, the valve stays in its "closed" state for 8 seconds. The resulting flow because of this pulsation pattern is shown in Figure 4. To simulate a realistic conversation, one person speaks while the other listens, and then the other person speaks, and the first one listens. The speech signals of each manikin head are assigned with a phase difference of 4 seconds to account for some overlap in speech, as illustrated in Figure 5.

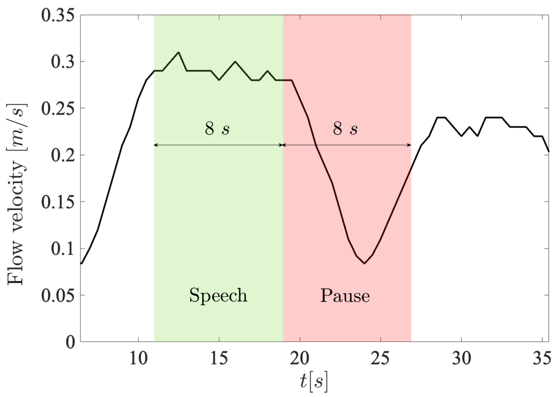

Figure 4: The measured flow velocity with the pulsation mechanism with indicated speech and pause phases for an occupant.

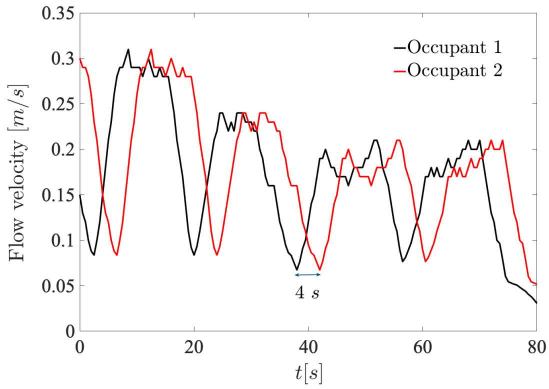

Figure 5: The measured flow velocity of the pulsated respiratory signals from the two manikin heads with a phase difference of 4 seconds.

2.4. Test chamber ambient conditions

The experiments are performed in a controlled test chamber with temperature and relative humidity controlled through ventilation flow from an air handling unit. During the experiment, the ventilation is turned off so that there is no background flow, and the room temperature stays constant at 21°C and relative humidity is 25%. A thermal lamp placed under the manikin head simulates temperature differences between the occupant's skin and the air inside the test chamber. A strong thermal plume is generated when the thermal lamp is turned on, simulating an occupant (skin temperature ∼ 32-35°C) in an ideal indoor space (air temperature ∼ 21-24°C), creating an ∼ 8-14°C temperature difference between skin and air. When the thermal lamp is turned off, no thermal plume is generated, simulating an occupant in a poorly ventilated room during summer (air temperature ∼ 30-32°C) creating a ∼ 0-5°C temperature difference between skin and air.

2.5. Layout of the test chamber and illumination

The respiring manikin setup is housed in a 2.1 m x 2.3 m x 2.1 m test chamber according to the layout shown in Figure 6. The table where the aerosol generators and the rest of the setup are placed is close to the centre of the room. The aerosol stream from the setup is illuminated with the help of levelling lasers shown in Figure 1. The illuminated tracer particles are captured from within the test chamber using a camera and tripod. The camera and tripod setup are accommodated at the side with a greater distance between the table and the wall and capture a side view of the respiring manikin setup as shown in Figure 7. This is also the plane of visualisation used in the next section of this paper.

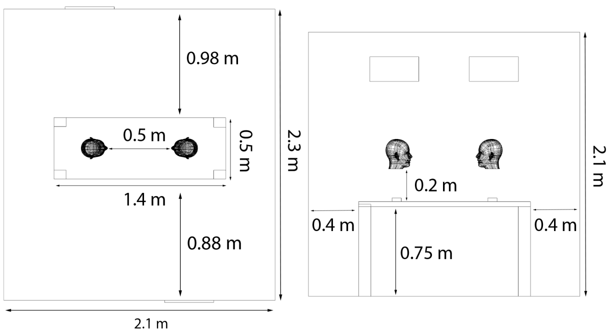

Figure 6: Top view (left) and side view (right) of the test chamber with the layout of the experimental setup.

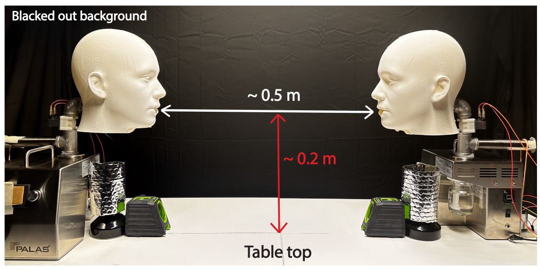

Figure 7: The experimental setup in the test chamber.

3. Results

The DEHS tracers, when illuminated by the laser sheet, visualise the pulsatile respiratory flow emanating from the mouth and propagating axially. The frequent opening and closing of the valve lead to the formation of turbulent puffs that aid the propagation of the flow. For a single occupant in an ideal indoor space, when the temperature difference between the skin and the air is ∼ 8-14°C, the flow visualisations in Figure 8a represent the respiratory flow while speaking. The four images are taken 1, 3, 5 and 7 seconds after the first speech phase starts.

When an occupant is in a poorly ventilated and uncooled indoor space during summer, with negligible temperature difference between the skin and the air, the flow visualizations in Figure 8b show the evolution of respiratory flow during speech. Comparing Figures 8a and 8b, the respiratory jet's axial extent is visibly enhanced when the occupant speaks in the second indoor

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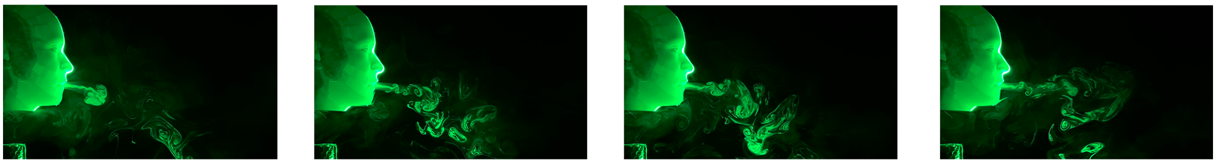
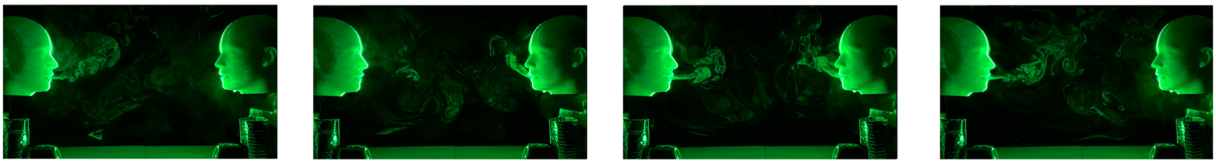
(a) Flow visualisation of a single occupant speaking in an ideal indoor environment.



(b) Flow visualisation of a single occupant speaking in a poorly ventilated space during summer



(c) Flow visualisation of two occupants speaking in an ideal indoor environment.

(d) Flow visualisation of two occupants speaking in a poorly ventilated space during summer.

Figure 8: Time-varying flow visualization of (a-b) Single occupant (c-d) Two occupants.

space. Typically, the respiratory jet cannot penetrate the buoyant thermal plume, thus limiting its propagation. The higher the temperature difference between the skin and the air, the stronger the upward thermal flow and the lesser the speech flow penetration.

Now, looking at two occupants facing each other while talking, the respiratory flows are out of phase during a conversation, with short overlap periods. The images are taken 3, 8, and 10 seconds after the first image. When two occupants speak face-to-face in an ideal indoor space, the respiratory jets cannot penetrate the buoyant upward flow from the lamps; hence, they do not collide at the same horizontal level but interact vertically higher than the original jet centreline. In the visualisations in Figure 8c, there is a time-varying asymmetric flow in the axial direction and a net upward flow. The flowfield is more chaotic than in previous cases because of the four flow sources (two manikin heads and two thermal lamps), making no evident axial evolution but is more like turbulent mixing.

If the two occupants are conversing in a poorly ventilated indoor space during summer, the respiratory jets propagate towards each other and collide head-on, as seen in Figure 8d. There is an asymmetry in the resulting airflow patterns of the jet because of the phase difference. Since the respiratory jets interact head-on, the respiratory plume's evolution is limited in the axial direction and enhanced in the lateral direction.

4. Discussion and Conclusions

A respiring manikin was developed to simulate speech-like particle-laden pulsatile flow in different environmental conditions. The assigned volume flow signals had speech and pause intervals to model a real conversation. The manikin head was designed to create an exhaled flow closer to reality. Two such respiring manikins were set up in a controlled test chamber facing each other to simulate face-to-face conversations. The aerosol flow was visualized using a laser sheet.

The flow visualizations show the strong dependency of respiratory flow behaviour on environmental factors. In an indoor environment with standard air temperature, it was observed that the axial extent of the respiratory plume is limited due to interference from the buoyant thermal plume. Conversely, in a poorly ventilated space during summer with high air temperature, the thermal plume is very weak, and due to the absence of any interaction with the buoyant flow, the axial extent of the respiratory plume is enhanced. In the context of a conversation between two occupants, assuming one is infected and the other is susceptible, In an ideal indoor environment, the turbulent mixing and limited propagation could possibly protect the susceptible occupant, while in the poorly ventilated space, entrainment and lateral spread can increase the global infection risk in the room.

The advantage of this respiring manikin setup is its modularity. The setup here is explicitly used for face-to-face conversations, but the manikin heads could be placed facing the same direction, either behind another or side by side. They could be placed as if sitting in a lecture hall, one behind another but at a higher level. Apart from the occupant configuration flexibility, the flow rate signal for speech is programmable through an Arduino, making any speech or breathing signals possible to simulate in this setup as long as it is within 5L/min. Another aspect that can be changed in this setup is the aerosolized medium in this paper. DEHS was used to generate fine particle tracers that follow the flow patterns and are safe to use in a test chamber. In a Biosafety level 3 lab environment, the aerosolizing medium could be changed from DEHS to a virus-containing saline solution, and this setup will be able to simulate the airflow from an infected individual shedding virus as the person is talking. Making it very suitable for studying the viability of viruses transmitted through the air and their potential for airborne transmission.

The developed respiring manikin setup is not limited to visualisation purposes but can also be used as a Particle Image Velocimetry (PIV) setup, where instead of a regular camera, a high-speed camera is used to capture the motion of individual tracer particles and quantify the flow field visualised in this study. This opens avenues for Proper Orthogonal Decomposition (POD)/Dynamic Mode Decomposition (DMD) for large-scale flow structures, unsteady flow analysis, or validating high-fidelity numerical simulations that expand upon this occupant configuration but for a large social space like a restaurant or a café. The latter can help quantify the risk of exposure to infectious respiratory particles (IRPs) in such spaces and design better ventilation strategies accordingly. These custom ventilation strategies will keep IRPs away from the occupants or remove them from the space, making the masses less vulnerable to a future outbreak.

CRediT authorship contribution statement
Arghyanir Giri: Writing – original draft, Methodology, Investigation, Conceptualization. **Clara García-Sánchez**: Writing – review & editing, Supervision, Methodology, Conceptualization. **Philomena M. Bluyssen**: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

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