Individual control of the frequency of intermittent personalized ventilation and its effect on cross-contamination in an office space

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Abstract. The transmission of respiratory diseases is influenced to a great extent by the ventilation in the space, mainly localized ventilation near the infection source (i.e. the infected person): One of the strategies that has been proven efficient in providing occupants with protection indoor are source control strategies. Personalized Ventilation (PV) is such strategy that delivers conditioned clean air towards the breathing zone of the user, thus providing protection while procuring acceptable levels of thermal comfort. In recent studies, PV applications varied the supplied cool clean air intermittently, mimicking natural outdoor conditions in order to enhance occupants' thermal comfort and improve energy efficiency. Such system operation is referred to as Intermittent PV (I-PV). The highly turbulent oscillatory jet may however promote the dispersion of contaminants, especially when the user is infected. Furthermore, the individual preferences of IPV frequency also affects the contaminants' transport. To the authors' knowledge, such effect has not been tackled in literature. Therefore, this work investigates the impact of individually controlling the frequency of an I-PV system on cross-contamination between occupants in an office space. An infected person is considered seated in a tandem (i.e. back-to-face) position with respect to a healthy person, located at a distance of 1.5 m. This seating configuration is usually the most critical when using PV. The contamination source is the breathing of the infected person. The IPV is considered to operate at an average flowrate of 10 l/s, with a minimum of 4 l/s. The IPV users are free to control the frequency of flow delivery in a range of [0.3 Hz – 1 Hz]. A validated computational fluid dynamics (CFD) model of an office space equipped with IPV and background mixing ventilation is used to assess the cross-contamination between the occupants. A comparison between IPV frequencies is conducted to highlight the influence of IPV frequency control on contaminants dispersion and the resulting exposure level of the healthy occupant.

Keywords. Intermittent Personalized Ventilation, Individual Control, Cross Contamination, Breathing, Indoor Air Quality.
DOI: https://doi.org/10.34641/clima.2022.192

1. Introduction

The transmission of airborne infectious diseases is a critical threat to human health, and needs to be thoroughly mitigated. One of the main sources of such transmissions in indoor spaces is the dispersion of infectious expelled airborne particles due to the respiratory activities of an infected person such as breathing (1). The transmission of such airborne contaminants is mainly influenced by room ventilation (2). Total volume ventilation strategies like mixing ventilation (MV) provide a uniform environment in the space – thus, they do not guarantee the simultaneous provision of high ventilation efficiency for each individual, nor do they provide people with their favoured thermal comfort level, failing thereby to meet the different preferences of all occupants. Therefore, many researchers have shed light on the concept of localized air-conditioning: personalized ventilation (PV). This system usually assists the traditional air conditioning systems, providing cool clean air to the breathing zone (BZ) of the occupant, which enhances the inhaled air quality and provides the desired thermal comfort levels (3). Recently, different studies considered a PV system supplying a dynamic airflow fluctuating between a minimum and a maximum at a characteristic frequency. This system is known as intermittent PV (I-PV). Such operation provides the user with enhanced thermal comfort states while ensuring good levels of breathable air quality (4, 5).

However, the I-PV system creates a non-uniform environment in the microclimate of occupants, resulting in an undesirable transport of exhaled contaminants when an infected person is using the I-PV, hence enhancing cross contamination between occupants. Furthermore, considering the individual preferences of I-PV users, the control of the frequency of the flow delivery and the resulting turbulence levels may affect the level of contaminants transport. The effect of the individual control of the I-PV frequency on the dispersion of exhaled contaminants, and resulting exposure of the healthy occupant has not been tackled yet in literature to the authors' knowledge. Thus, it is of value to investigate it thoroughly.

In this work, a desk-mounted I-PV system is assisting a MV system in conditioning a typical office space. The objective is to study the effect of frequency fluctuation of I-PV on the transport of particles generated by an infected user due to breathing. The infected person is considered seated in a tandem (i.e. back-to-face) position with respect to a healthy person, located at a distance of 1.5 m. The I-PV is operating at an average flowrate of 10 l/s, with a minimum of 4 l/s. The users are free to change the frequency of the I-PV flow in the range of 0.3-1 Hz. Note that such range is proven in literature to provide acceptable levels of thermal comfort for PV users (5). A 3-D computational fluid dynamics (CFD) model is used to simulate the potential contaminants' transport and assess the resulting exposure levels.

2. Research Methods

This work considered a two-workstation office space of dimensions 4.8 m (length) × 3.4 m (width) × 2.6 m (height), conditioned by a MV+I-PV system (**Fig. 1**). The MV system consisted of two supply diffusers at ceiling level and an exhaust diffuser at mid-upper part of the wall. The PV system consisted of computer-mounted panel supplying conditioned clean air horizontally towards the face of the occupants. The PV inlet was of diameter of 10 cm, located at a typical horizontal distance of 40 cm from the face (3, 6). Each ventilation system was served by its own air-handling unit. An infected person was located 1.5 m (7) in front of a healthy occupant, in a back-to-face seating configuration (i.e. tandem seating) (see **Fig. 1**). Both occupants were considered using I-PV that supplied a sinusoidal air flowrate $\dot{m}_{I-PV}$ with a minimum of 4 l/s and an average of 10 l/s at a specific frequency f_{I-PV}. The users had the freedom to change this frequency between 0.3 and 1 Hz. These limits consisted of the typical minimum and maximum operating frequency values that ensure thermal comfort as reported by previous I-PV studies (4, 5). Thus, nine simulations were considered as presented in **Tab. 1** where f_{I-PV_i} is the frequency adopted by the infected person and f_{I-PV_h} is the frequency preferred by the healthy person. Note that the delivered air temperature of the PV system was fixed at 23 °C (8). The contamination source was considered the nose-exhaled breath of the infected person. The periodic breathing pattern followed a sine curve consisting of 3 s of inhalation and 3 s of exhalation, with a maximum velocity of 1.33 m/s (9). The pulmonary ventilation was 8.4 l/min with a 10 times per minute breathing cycle, representing a normal person at low activity level (10). The nostrils were round openings with diameter of 12 mm, similar to those of healthy adults (11). The exhaled flow contained passive contaminants (i.e. species) (12). The temperature of the exhaled air was reported in literature to be around 32 °C (13).

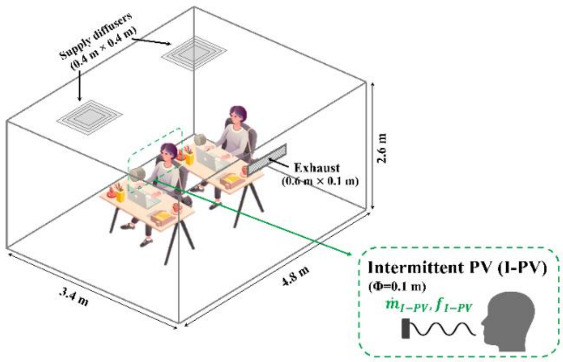

Fig. 1 - Schematic of the office space layout with the intermittent personalized ventilation.

Tab. 1 - Different considered operation scenarios.

f_{I-PV_i} (Hz)	f_{I-PV_h} (Hz)
	0.3
0.3	0.5
	1
	0.3
0.5	0.5
	1
	0.3
1	0.5
	1

3. Numerical Methods

A 3-D CFD model was developed in the study of Katramiz et al. (8) for the considered office space using the commercial software ANSYS Fluent (version 19.2) (14). The model was used to simulate the transport of the expelled contaminants produced by breathing upon the use of I-PV. **Fig. 2** presents the computational domain used in Fluent, with the proper mesh configuration that was selected to capture the flow physics, especially in front of the face of each occupant where a sphere of influence was created. After performing a grid independence test, the adopted mesh consisted of 1.5/2 cm face sizing on the manikin and walls respectively, resulting in 3,713,769 elements (8). Note that the developed model was experimentally validated by Katramiz et al. (8), where good agreement was reported between the experimental and numerical results, with a maximum relative error of 7.5 % in terms of exposure level of the healthy occupant.

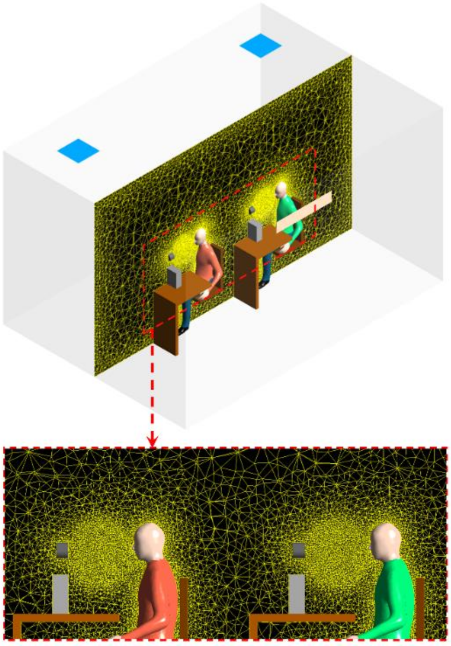

Fig. 2 - Illustration of the computational domain used in the CFD model and the mesh at the cross-sectional mid-plane (x = 0 m).

3.1 Airflow model

High turbulence levels were present in the space due to the I-PV flow and breathing flow nature; thus, the renormalization group (RNG) k-ε turbulence model with enhanced wall treatment and full buoyancy effects was used to solve for the turbulent kinetic energy k and its rate of dissipation ε in the continuum phase (i.e. room airflow). This model was employed in similar studies due to its relatively low computational cost, and robustness when describing indoor airflows with contaminant distribution (15). The Boussinesq approximation was used to account for the buoyancy effects. For the pressure equation, the "PRESTO!" scheme was used as it considers pressure gradients near boundaries (4, 5). The Pressure-Implicit with Splitting of Operators (PISO) algorithm was employed to couple the velocity and pressure fields due to its suitability for transient flows (4). The exhaled passive contaminants were considered as species, following the airstream and were thus simulated using the tracer gas "Nitrous oxide N_2O" - typically used in literature for exhaled infectious contaminants' representation (16, 17). The species' transport equation was therefore employed to solve for the tracer gas concentration in the space. The second order upwind scheme was employed to discretize the mass, momentum, energy, k, ε and turbulence equations. The solver was set to transient as the conditions in the space were time dependent; and a second order implicit time stepping was adopted with a time step of 0.05 s. It is noteworthy to mention that a solution is considered convergent when the scaled residuals reach 10^{-5} for all parameters except energy that should be less than 10^{-7}, with the mass and heat balance ensured in the space.

3.2 Boundary conditions

Adequate selection of the boundary conditions in the CFD model is crucial to obtain accurate results from the numerical simulations concerning airflow and concentration fields. The adopted boundary conditions for the different domain boundaries in the CFD model are presented in **Tab. 2**. Both supply diffusers of the MV system were set to a constant velocity inlet and the MV exhaust was assigned as a pressure outlet. Both PV inlet and nose of the infected person were set to a velocity inlet: the I-PV flow and the exhaled jet were each properly defined by a user-defined function (UDF). The rate of N_2O generation during exhalation was defined by a mass fraction of 5% (18, 19).

Tab. 2 - Boundary conditions of the CFD model.

Boundary condition	CFD boundary conditions
MV inlet	Velocity inlet - V = 0.3 m/s - T = 20 ^{0}C
MV exhaust	Pressure outlet - Zero-gauge pressure
I-PV inlet	Velocity inlet - UDF of I-PV air velocity - T = 23 ^{0}C
Nose opening	Velocity inlet - UDF of breathing velocity - T = 32 ^{0}C
Walls, Ceiling, thermal manikin, PC	Wall, constant heat flux: - Walls: 15 W/m^2 - Ceiling (lights): 10 W/m^2 - Thermal manikin: 39 W/m^2 - PC: 100 W

3.3 Cross-contamination assessment

The airflow field near the occupants resulting mainly from the I-PV flow may cause the transport of the exhaled contaminants by the infected person towards the healthy occupant sitting in the back, causing cross-contamination. The effect of the I-PV on cross-contamination between occupants is measured by the inhalation intake fraction (*iF*) index presented in equation (1): $\overline{C_{BZ}}$ is the average contaminants concentration at the BZ of the exposed (healthy) person when steady periodic conditions are reached (after around 20 mins from the initiation of the breathing, i.e. after 200 breathing cycles of the infected person), and $\overline{C_S}$ is the average concentration of exhaled contaminants at the source (i.e. at the nose of the infected person). Note that the BZ is defined as a spherical control volume having a diameter of 2 cm, located 2.5 cm away from the nose of the occupant (4).

$$iF = \frac{\overline{C_{BZ}}}{\overline{C_S}} \quad (1)$$

4. Results and discussion

This work investigates the effect of using I-PV at different frequencies on the dispersion of exhaled contaminants in the space and resulting cross-contamination towards a healthy person sitting at 1.5 m distance from the infected person in a tandem position. Thus, nine simulations considering the entire f_{I-PV} range were conducted (as presented in **Tab. 1**) in the aim of assessing the exposure level of the healthy occupant for all possible individual f_{I-PV} control scenarios. When accounting for the personal preferences of I-PV users, the efficiency of the I-PV in protecting the users from potential cross-contamination might differ with respect to the adopted frequency. This was assessed by obtaining the *iF* for all the possible operation scenarios as presented in **Tab. 3**.

With the increase in the frequency adopted by the infected person (f_{I-PV_i}), the turbulence level of the I-PV flow increases, aggravating thereby the transport of contaminants towards the back. This results in an increase in the exposure of the healthy person: for example, for a fixed f_{I-PV_h} of 0.5 Hz, the *iF* increased by 62.6 % when f_{I-PV_i} increased from 0.3 to 1 Hz (**Tab. 3**). On the other hand, when the frequency adopted by the healthy person (f_{I-PV_h}) increases from 0.3 Hz to 0.5 Hz, the concentration of contaminants at the BZ decreases due to the increased rate of clean air supply overcoming the increased turbulence and mixing effects as presented in **Fig. 3**: for a fixed f_{I-PV_i} of 1 Hz, the increase in f_{I-PV_h} from 0.3 to 0.5 Hz provided more clean air towards the BZ which increased the protection effect. However, further increasing f_{I-PV_h} from 0.5 to 1 Hz at a fixed f_{I-PV_i} caused a pronounced entrainment of contaminants into the supplied I-PV jet to the healthy person, which jeopardized the air quality at the BZ. This is seen in **Fig. 3 (b)** and **(c)** for a f_{I-PV_i} of 1 Hz. As a result, the *iF* increased from 11.97×10^{-4} at $f_{I-PV_h} = 0.5\ Hz$ to 20.08×10^{-4} at $f_{I-PV_h} = 1\ Hz$ (**Tab. 3**).

From the above-mentioned observations, and keeping in mind that one cannot know a priori who is infected and who is healthy in the space, it is clear that the increase in the frequency of I-PV for both all users is in general unfavourable, as it amplifies the cross-contamination between them due to the increased turbulence and entrainment of contaminants into the delivered PV jet. Thus, it is recommended to operate the I-PV in the lower range of [0.3 - 0.5] Hz for enhanced protection level.

It is noteworthy to mention that for the same space configuration (seating position, breathing pattern, PV system etc.), a **steady PV supply of 10 l/s** for both users resulted in an *iF* of approximately 11.5×10^{-4} (8). Comparing this value with the obtained results in **Tab. 3** for different I-PV frequencies, it is clear that the operation of PV at the recommended low frequency range of [0.3 - 0.5] Hz ensures lower exposure levels (i.e. lower iF values). Thus, operating the PV system in an intermittent way at low frequency range provides better protection against cross-contamination than operating it in a steady way.

Tab. 3 - Summary of *iF* for all the considered cases.

	iF **($\times 10^{-4}$)**		
$f_{I-PV_i} \setminus f_{I-PV_h}$	**0.3 Hz**	**0.5 Hz**	**1 Hz**
0.3 Hz	7.55	7.36	8.21
0.5 Hz	8.72	8.44	11.65
1 Hz	12.21	11.97	20.08

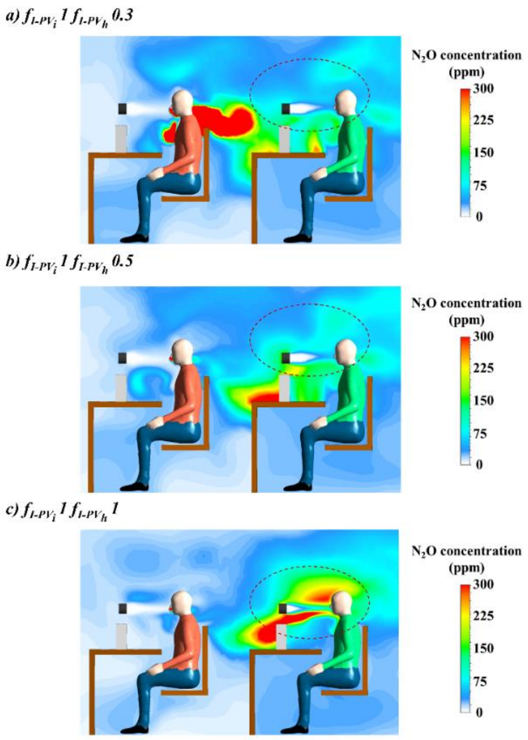

Fig. 3 - N_2O concentration contours at the cross-sectional mid-plane during highest exposure levels for the cases of: a) $f_{I-PV_i}1\ f_{I-PV_h}0.3$, b) $f_{I-PV_i}1\ f_{I-PV_h}0.5$ and c) $f_{I-PV_i}1\ f_{I-PV_h}1$.

5. Conclusions

This work studied the effect of individually controlling the frequency of the I-PV flow on the dispersion of exhaled contaminants in the space and the resulting cross-contamination. A two-workstation office space was considered to be occupied by one healthy occupant and another infected occupant contaminating the space via nose breathing. A validated 3-D CFD model was thus used to simulate the different f_{I-PV} operation scenarios. Results showed that when considering cross-contamination, the increase in the frequency of I-PV for users is generally undesirable, as it increases the turbulence and entrainment of contaminants into the delivered jet, which puts the healthy occupant at increased risk of exposure. It is thus recommended to operate the I-PV in the lower range of [0.3 - 0.5] Hz for enhanced protection level.

6. Limitations and Future Work

This work highlighted the effect of fluctuation the frequency of the I-PV flow on the potential cross-contamination in a two-workstation office where one of the occupants was infected. The latter was considered breathing from the nose. Furthermore, typical office settings were considered: a MV background ventilation, a common PV air terminal device (computer-mounted panel of 10 cm diameter (4)), a tandem seating layout, a typical distance of 1.5 m between occupants (7), and occupants' head always facing the PV air terminal device outlet. Such configurations are not fixed in real-life scenarios, and changing any of these settings may affect the dispersion of contaminants and the resultant cross-contamination. This will be a topic of future investigations.

7. Acknowledgement

The authors would like to acknowledge the financial support of the Munib and Angela Masri Institute of Energy and Natural Resources at the American University of Beirut grant award. In addition, the American University of Beirut PhD scholarship to Ms. Katramiz is highly acknowledged.

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Data Statement

The datasets generated during and/or analysed during the current study are not available because they are contained within the article.