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Authors

Schiavon, Stefano

Melikov, Arsen

Cermak, Radim

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An Index for Evaluation of Air Quality Improvement in Rooms with Personalized Ventilation Based on Occupied Density and Normalized Concentration

Stefano Schiavon^{1,2,3}, Arsen Melikov², Radim Cermak⁴, Michele De Carli¹ and Xianting Li³

¹University of Padova, Department of Applied Physics, V. Venezia,1 IT-35131, Padova, Italy, www.dft.unipd.it

²Technical University of Denmark, International Centre for Indoor Environment and Energy, Department of Mechanical Engineering, Building 402, DK-2800 Lyngby, Denmark, www.ie.dtu.dk

³Tsinghua University, Department of Building Science, 100084, Beijing, China, <http://dbs.arch.tsinghua.edu.cn>

⁴Ingersoll Rand Climate Control Technologies, R&D Center Prague, CZ-25301 Hostivice, Czech Republic, www.irco.com

Corresponding email: stefanoschiavon@gmail.com

SUMMARY

The personal ventilation (PV) system decreases the pollutant concentration mostly in the microenvironment at the workstation, but it can also increase the contaminant in other zone of the room. Therefore, occupant's exposure to pollutant depends on the ratio of time occupant stays at the workstation over total time he/she stays in the room. This ratio is named occupied density (OD).

An index, using a modified definition of OD, is developed to compare and quantify the variation in terms of inhaled pollution by occupant in a room with PV in conjunction with a total-volume ventilation system. The index is applied to data collected during full-scale room measurements.

The results show that the index can be used at the design stage for assessment the benefit of PV when applied in practice for office buildings with different OD. It is for example demonstrated that if the occupied density is lower than 0.5 the use of displacement ventilation alone will be advantageous with regard to human-produced contaminants in comparison when it is combined with PV system.

INTRODUCTION

The Personalized Ventilation (PV) system aims for supplying clean and cool air at low velocity and turbulence directly at workplaces. PV provides user with control of his/her personal microenvironment. Several studies had shown the capacity of a PV system to decrease the pollution in inhaled air [1] and to reduce the transport of contaminants between occupants [2], to improve the perceived air quality and thermal comfort [3]. PV system has the potential to save energy due to the possibility to reduce the ventilation airflow thanks to its high ventilation efficiency and to the possibility of raising the ambient air temperature [4, 5].

Occupants, depending on their activities during working time, may spend only a part of time in the office and even a smaller time at the desk [6, 7, 8]. Most of the studies focused on the

measurement of the time an occupant stay in a room over the working time. To the knowledge of the authors only one study reported on the time occupants in office buildings spend at the workstation over the time they stay in the office [9].

To describe the probability distribution of occupants in the room Zhao et al [10] develop the concept of occupied density. The occupied density for the i th occupant is the ratio of time that occupant stays in a certain region over the time that occupant stays in the room, e.g. if the occupant stays at the desk for 3 hours and the total time he stays in the room is 4 hours, then the occupied density of the desk of that occupant is 0.75. Computational Fluid Dynamic (CFD) was used to apply this concept for studying the contaminant exposure of occupant when PV is used in combination with a total-volume ventilation system [11]. The results showed that the effect of desk mounted personalized ventilation depends significantly on the type of occupant activity patterns, and so on occupied density, therefore the application of PV should be restricted to certain types of space and human activities. The capacity of PV to decrease the pollutant intake depends on, among other parameters, the time the occupant stays at the desk. The longer the occupant stays at the workstation, the higher he/she will benefit the advantages of PV. In order to apply the occupied density index to full-scale measurement of PV is needed to discretized it and to clearly define which are the zones that influences the human contaminant exposure.

In this paper, a new index combining a normalized concentration and a tailored definition of occupied density is proposed for assessment of benefit in regard to inhaled air quality from use of PV in practice is presented. Data from full-scale measurements are used to demonstrate the applicability of the index. The benefit of this new index is that it can be applied to real measurement and not only to Computational Fluid Dynamic, as the one proposed by Yang et al [11]. It can help to evaluate and quantify the contaminant occupant exposure, therefore the applicability of a PV system in practice.

METHOD

Occupant normalized concentration index

In order to describe the different location an occupant can stays in a room ventilated with PV and, at the same time, do not increase too much the number of measurements needed to quantify the assumed locations a modified definition of the occupied density index suggested by Zhao et al [10] is developed. The occupied zone of the room is divided in two regions:

1. Workstation region, e.g. occupant working at the desk, characterized by the average values of physical parameters measured at the workstation at the height of 1.1 m above the floor.
2. Background region, characterized by the average values of physical parameters measured at the height of 1.7 m above the floor. It is supposed that the occupant is standing in the office when he/she is not at the workstation.

Thus the ratio of time the occupant is at the workstation over the total time he/she stays in the ventilated room, defines the workstation occupied density index ODW:

$$ODW = \frac{\tau_W}{\tau_{TOT}} \quad (1)$$

Where τ_{TOT} is the total time the occupant stays in the ventilated room, τ_W is the time the occupant spends at the workstation and τ_S is the time the occupant spends standing in the remaining (background) area of the room, e.g. $\tau_{TOT} = \tau_W + \tau_S$. Similarly, the ratio of time that the occupant spends in the background area of the room over the total time he/she stays in the ventilated room is defined as, the background occupied density index, ODB. It is clear that the sum of ODB and ODW will be equal to 1.

The normalized concentration of contaminant c is defined by the following equation:

$$c = \frac{\bar{c} - \bar{c}_S}{\bar{c}_E - \bar{c}_S} \quad (2)$$

where \bar{c} is the contaminant concentration in a point, \bar{c}_S is the contaminant concentration in the supply air, \bar{c}_E is the contaminant concentration in the exhaust air.

The normalized concentration is equal to 1 if there is complete mixing of air and contaminants. If the air quality is better than in the exhaust, the normalized concentration is lower than 1 and vice versa. The supply air has a normalized concentration of 0. The reciprocal value of the normalized concentration is known as ventilation effectiveness [12] or as pollutant removal efficiency [13].

The occupant normalized concentration (C) is the normalized concentration weighed by the workstation occupied density, ODW. i.e. it is the weighed normalized concentration to which the occupant is exposed in average if he/she stays for τ_W at the workstation and for τ_S in the background area. This index is mathematically described by the following equation:

$$C = c_W \cdot ODW + c_S \cdot (1 - ODW) \quad (3)$$

c_W is the normalized concentration of pollution inhaled by the occupant at the workstation; c_S is the normalized concentration inhaled by the occupant standing in the background area of the room. The occupant normalized concentration (C) is a linear function of ODW. The occupant normalized concentration is an index which determines the quantity of pollutant in air inhaled by the occupant. The occupant normalized concentration can be used to calculate the average pollutant exposure as function of the pollutant distribution in a space and of the occupant activity. It can be applied to total-ventilation system and to personal ventilation system. The lower the normalized concentration is, the better the inhaled air quality is.

The index can be used for comparison of different air distribution systems in regard to quality of the air inhaled by occupants performing office work with different type of occupancy. In the following the index is applied in the case of PV in conjunction with total volume ventilation. Three scenarios are considered: first, the performance of only the total-volume ventilation system in operation is characterized by the normalized concentration defined at the workstation (c_{TVW}) and in the background of the room (c_{TVS}); second, the performance of the total-volume ventilation operating in conjunction with PV which efficiently protects the occupant and provides clean air in inhalation is characterized by the normalized concentration at the workstation (c_{PVW}), and by the normalized concentration in the background (c_{PVS}); third,

the performance of the total-volume ventilation operating in conjunction with PV which does not provide clean air to inhalation (or may be turned off) and does not protect the occupant from air pollution present in the room air is characterized by the normalized concentration at the workstation (C_{PVnpW}), and by the normalized concentration in the background (C_{PVS}). The defined normalized concentrations are used to calculate the occupant normalized concentration, in the case of total volume ventilation alone (C_{TV}), total volume ventilation in conjunction with personalized ventilation protecting the occupant (C_{PVp}), and total volume ventilation in conjunction with PV which does not protect the occupant efficiently or is turned off (C_{PVnp}). The normalized concentrations, C_{TVW} , C_{TVS} , C_{PVpW} , C_{PVnpW} and C_{PVS} are function of the type of the total-volume and the personalized ventilation systems adopted and of the pollution source considered; the occupant normalized concentrations C_{TV} , C_{PVp} and C_{PVnp} are also function of the ODW. The lower the occupant normalized concentration is the better the inhaled air quality will be because the amount of inhaled pollution will be lower.

In order to quantify the difference in performance of two air distribution solutions the Variation of Occupant Normalized Concentration is define by Equation 4:

$$VONC_j = \left(\frac{C_{TV}}{C_{PVj}} - 1 \right) \cdot 100 \quad (4)$$

$j = p, np$

The evaluation is made in case of occupant protected by PV (p) and unprotected occupant (np).

A positive value for $VONC_j$ means that the PV system decreases the pollution concentration in inhalation, e.g. improves the quality of the inhaled air, while negative values mean that the total-ventilation system alone can provide occupant with better inhaled air quality. The index $VONC_j$ can be used by designers for justification of the use of a PV system in practice from inhaled air quality point of view.

Validation of the index

The usefulness of the developed index is demonstrated with data collected during full-scale measurements of personalised ventilation in conjunction with total volume ventilation system (mixing and displacement) and total volume ventilation performing alone as reported in [2,14].

A typical two-person office arrangement was simulated in a full-scale test room (4.8 x 5.4 x 2.6 m³) as shown in Figure 1. Each workstation consisted of a desk with a personalized air terminal device, a breathing thermal manikin simulating a seated occupant, typical office furniture, a PC, and a desk lamp. The total heat load in the office, including six fluorescent light fixtures evenly distributed over the ceiling, was 22.5 W/m². A PV system with round movable panel as air terminal devices was used. This air terminal device is designed to supply airflow at low turbulence intensity. Detail description of the device is given in [15].

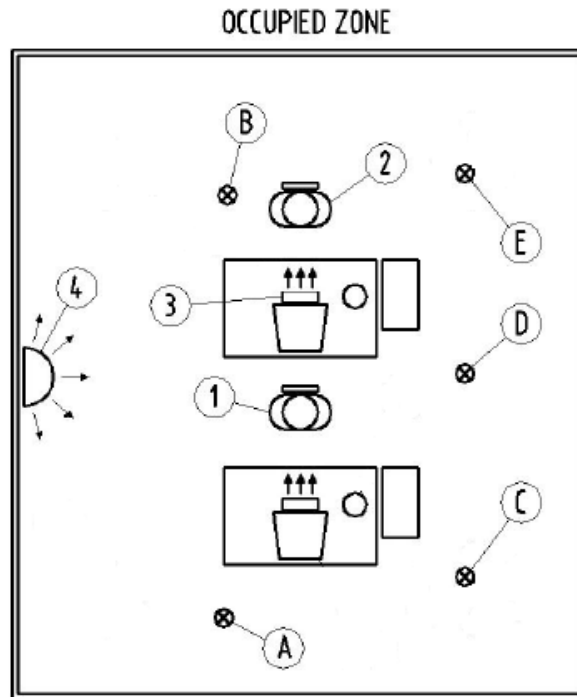


Figure 1 Office plan: (1) Front or polluting thermal breathing manikin, (2) Back or exposed thermal breathing manikin, (3) Personalized ventilation –round movable panel, (4) Displacement ventilation supply, (A)-(D) measuring points at 1.7m above the floor. At ceiling are placed the ceiling light fixture, in the centre of the ceiling is placed the mixing ventilation supply. The total heat of the room is 22W/m^2 (Computers, desk lamps, thermal manikins, ceiling light fixtures)

Two types of total-volume ventilation system were used: mixing and displacement. A swirl diffuser situated in the centre of the ceiling was used for the mixing ventilation and a semicircular unit placed on the floor in the middle of the longer wall was used for the displacement ventilation. Air was exhausted at the ceiling level. Clean air at 20°C with a total flow rate of 80 l/s ($= 4.3$ air changes per hour) was supplied to the room, ensuring a maximum room air temperature of 26°C . The 80 l/s was supplied either entirely through the total volume ventilation system or partly through the PV system. When combined, the PV of the front manikin (position 1, Figure 1) was used at 0 or 15 l/s and the PV of the back manikin (position 2) at 15 or 0 l/s .

The breathing thermal manikins' surface temperature was controlled so as to correspond to the skin temperature of an "average" person in thermal comfort. An artificial lung placed outside the manikins simulated the human breathing during light physical work. It consisted of 2.5 s inhalation, 2.5 s exhalation, and pause; exhalation through the nose/inhalation through the mouth; pulmonary ventilation 6 l/min . The exhaled air was heated at 36°C to achieve density similar to the density of air exhaled by people (1.144 kg/m^3 : 3.6% CO_2 , 95% RH, 34°C at room temperature $20\text{-}26^\circ\text{C}$). The pause was set at 0.9 and 1.1 s respectively for the two manikins to prevent synchronization. Airborne pollution was simulated by means of tracer-gas. A concentrate and active pollution source was simulated. A constant dose of sulphur hexafluoride (SF_6) was used to mark the air exhaled from the front manikin (here named polluting manikin), representing virulent agents or tobacco smoke.

The concentration of the tracer gas was measured at several points and in the air inhaled by the thermal manikins. A tracer-gas monitor based on a photo-acoustic principle of

measurement was used. The characteristics of the instruments and the analysis of uncertainty are detailed presented by Cermak [2]. The conditions and the locations of the measurements of normalized concentrations (C_{TVW} , C_{TVS} , C_{PVpW} , C_{PVnpW} , C_{PVS}) are listed in Table 1.

Table 1 Locations and conditions of the normalized concentration measurements for the human-produced contaminant

Normalized Concentration	TV air flow *	PV Front air flow *	PV Back air flow *	Pollution source	Where is measured
C_{TVW}	80	0	0	Front	Inhaled by Back**
C_{TVS}	80	0	0	Front	Average of A B C D E***
C_{PVpW}	65	0	15	Front	Inhaled by Back
C_{PVnpW}	65	15	0	Front	Inhaled by Back
C_{PVS}	65	15	0	Front	Average of A B C D E

* The air flow is expressed in l/s

** The concentration was measure in the air inhaled by the back manikin.

*** The average value measured at 1.7 m above the floor at points A, B, C, D, E (see Figure 1).

RESULTS

Data from two types of total-volume systems (mixing and displacement), an active and concentrate pollution sources, and a PV system using round movable panel as air terminal device were taken from an higher number of experiments in order to show the potential of the new index. The measured normalized concentrations, listed in Table 2, were used in Equation 3 to calculate the occupant normalized concentrations C_{TV} , C_{PVp} , C_{PVnp} as function of ODW.

Table 2 Normalized concentration of human-produced contaminant (SF_6) for mixing ventilation and displacement ventilation. Round movable panel was used as air terminal device

Normalized Concentration	Mixing	Displacement
C_{TVW}	0.93	0.15
C_{TVS}	1.06	0.76
C_{PVpW}	0.13	0.03
C_{PVnpW}	0.98	0.85
C_{PVS}	1.07	0.9

An example is shown in Figure 2, when the total-volume system used was mixing ventilation. Previous analyses of this experimental data compared the normalized concentration for $ODW=1$, i.e. when occupants are steady exposed to the personal ventilation flow[16]. With the occupant normalized concentration is possible to quantify the occupant exposure for the whole range of ODW values, from 0 till 1. In Figure 2, can be seen that the introduction of PV does not influence significantly the contaminant distribution in the room and the inhaled air quality of the un protected occupant does not change appreciably. The PV is able to reduce the contaminant concentration of the occupants protected by PV. Thanks to the occupant normalized concentration index is possible to show and quantify that, due to the higher concentration of pollutant outside the personal airflow, the occupant exposure to contaminant increase with the reduction of ODW.

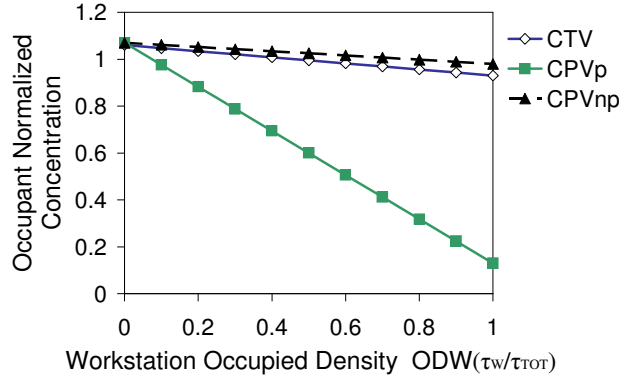


Figure 2 Occupant normalized concentration (C_{TV} , C_{PVp} , C_{PVnp}) versus workstation occupied density (ODW) when the total-volume system used was mixing ventilation.

In Figure 3 is shown the occupant normalized concentrations versus the ODW when total-volume system used was displacement ventilation. The comparison of the results in the figure show that the occupant normalized concentration for displacement ventilation alone at ODW=0.5 is three times higher than at ODW=1, and four time higher than at ODW=0.3. This means that the benefits of a displacement ventilation will be lower for minor values of ODW.

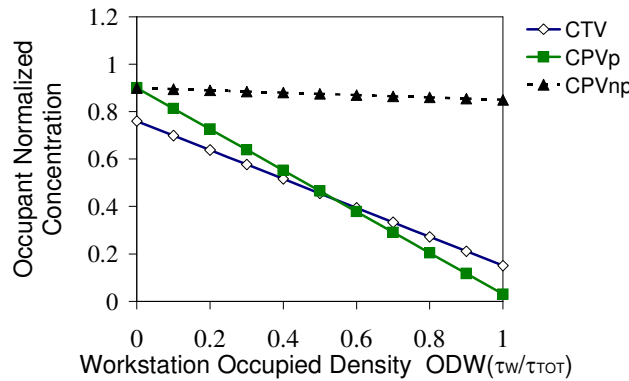


Figure 3 Occupant normalized concentration (C_{TV} , C_{PVp} , C_{PVnp}) versus workstation occupied density (ODW) when the total-volume system used was displacement ventilation.

When ODW=1, the normalized concentration (c_{TVW}) to which a sitting occupant is exposed if only displacement ventilation is used is 0.15 and in the case of combined PV and displacement systems the normalized concentration (c_{PVpW}) of a protected occupant is 0.03. The PV has a ventilation effectiveness that is 5 times higher than the ventilation effectiveness of displacement ventilation and therefore PV is able to provide a better inhaled air quality than displacement ventilation alone. For ODW=0.5 the occupant normalized concentration is the same for the two systems, but the normalized concentration will be almost 2 times higher if the occupant does not use it PV system, i.e. unprotected occupant. For lower values of ODW, displacement ventilation appears to be more effective in providing the occupant better inhaled air quality.

Using the normalized concentrations measured in the experiments, and ODW=0.3 and ODW=0.5 VONC_j was calculated for j=p and np, i.e. for the protected and unprotected occupant. The results are summarized in Table 3.

Table 3 Variation of Occupant Normalized Concentration ($VONC_j$) calculated for protected and unprotected occupant, when the $ODW=0.3$ or 0.5 , e.g. occupied density as identified in office buildings [9]. The results listed in the table are expressed in percent.

TV system	ODW=0.3*		ODW=0.5*	
	p**	np	p	np
Mixing	30	-2	66	-3
Displacement	-10	-35	-2	-48

* to $ODW=0.3$ correspond clerical work and to $ODW=0.5$ correspond business work [9]

** p is the protected occupant, np is the unprotected occupant

DISCUSSION

Nobe et al [9] have measured the average seat occupancy rate in a large scale office in Japan. 240 workstations were monitored, during weekday office hours for the attendant occupants only (the outing persons were removed). The results were classified in a function of the type of occupants' activity. It was obtained that for clerical work the average value of ODW was equal to 0.47, for technical work ODW was equal to 0.37, for business work ODW was equal to 0.31. This indicates that occupants stay at the workstation less often than away from it. Moreover the time an occupant spent at the desk was found to depend on the type of job, e.g. the ODW could be related to the type of human activity.

Figure 2 and Figure 3 show that the occupant exposure to pollutant depends also on the occupied density. Comparing only the performance of a total-volume and PV for $ODW=1$ is not enough. In order to accurately assess the performance of PV the concentration of pollution at the workstation (typically in inhaled air) as well as in the rest of the room should be reported, This will make it possible to accurately assess the occupant's exposure to contaminants considering also ODW .

Values of ODW lower than 0.5 indicate a strong influence of the pollution concentration in the room away from the workstation on the occupant's exposure. Therefore the performance of PV with regard to inhaled air quality should be evaluated based on at least two criteria: first its ability to provide 100% clean air in inhalation ($ODW=1$) and second, on its ability to avoid an increase of pollutant concentration in the background region, measured at 1.7 m, compared to the total-volume system alone. It means that the occupant normalized concentration have to be evaluated also for $ODW<0.5$. For example, in the case of Figure 3, Melikov et al [16] underlined that PV generate an higher concentration of pollutant at 1.7 m than displacement ventilation alone because it promotes mixing of contaminants located in its vicinity. When ODW is lower than 0.5, the occupant exposure will be lower for displacement ventilation alone than with the personal ventilation system. For $ODW=0.3$, corresponding to business work according to Nobe et al [9], the occupant normalized concentration of displacement ventilation alone is 0.54 while for the PV system is 0.64. The introduced in this paper index makes it possible to assess more realistically occupants' exposure in a room based on non-uniformity in pollution distribution in the room and occupant activity.

$VONC_j$ is used to quantify how much the occupant normalized concentration would vary if PV is used in conjunction with total-volume ventilation system, compared to a total-volume system alone. When mixing ventilation is used in conjunction with PV system, as reported in Table 3, $VONC_p$ would be equal to 30% for occupants performing business work ($ODW\approx 0.3$). If the occupants perform a clerical work ($ODW\approx 0.5$), $VONC_p$ would increase to 66%. The

occupant normalized concentration for unprotected occupant will not change (-2%). In rooms with PV in conjunction with displacement ventilation an occupant performing business type of work ($ODW \approx 0.3$) will be exposed to a high pollution concentration $VONC_p = -10\%$ while protected with PV system and much higher pollution concentration ($VONC_p = -35\%$ when he/she is not protected by PV system. In this way is possible to quantify the improvement or worsening in terms of occupant exposure or total intake contaminant by the $VONC_j$ index and thus to estimate applicability of a PV system.

The main limitations of the developed index are: 1) The database providing occupant density as a function of occupant activity is so far limited; 2) The index considers only two possible position of the occupants, standing in the background area of the room or sitting at the desk.

CONCLUSIONS

- An index which makes it possible to assess more realistically occupant's exposure in a room characterized by a non-uniform pollution distribution is introduced.
- The performance and applicability of personalized ventilation in practice should be evaluated on its ability to provide clean air in inhalation and to avoid an increase of pollutant concentration in the background region, measured at 1.7 m, compared to one generated by the total-volume system alone, therefore they depend also on occupied density.
- It is demonstrated that displacement ventilation alone was able to provide to the occupant with better inhaled air quality than displacement ventilation in conjunction with PV with round movable panel as an air supply device when occupied density is lower than 0.5.

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