Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms

F.A. Berlanga[a1], I. Olmedo[a], M. Ruiz de Adana[a], J.M. Villafruela[b], J.F. San José[b], F. Castro[b]

[a]Department of Chemical Physics and Applied Thermodynamics, University of Córdoba, 14014 Córdoba, Spain

[b]Department of Energy and Fluid Mechanics, University of Valladolid, 47011 Valladolid, Spain

[1]felix.berlanga@uco.es

Nomenclature

ACH	Air changes per hour (h^{-1})
AIIR	Airborne infection isolation room
CFD	Computational fluid mechanics
CP	Patient
D	Exhaust grille placed on the lower part of the West wall
DR	Percentage of dissatisfied people as a result of draught
DV	Displacement ventilation
G	Supply grille diffuser placed on the East wall of the room
GD	Ventilation system configuration combining G supply and D exhaust
GU	Ventilation system configuration combining G supply and U exhaust
IHR	Individual hospital room
IF	Intake fraction
IF_{max}	Maximum intake fraction
$IF_{125\%}$	Peaks average intake fraction
S	Supply swirl diffuser placed on the ceiling of the room
SD	Ventilation system configuration combining S supply and D exhaust
SU	Ventilation system configuration combining S supply and U exhaust
U	Exhaust grille placed on the upper part of the West wall
$\langle\bar{c}\rangle$	Mean tracer gas concentration of contaminant of the chamber (ppm)
$\bar{c}_e$	Average tracer gas concentration of the exhaust air (ppm)
$\bar{c}_P$	Average tracer gas concentration in a determined point (ppm)
$\bar{c}_{P,125\%}$	Average peaks tracer gas concentration in a determined point (ppm)
$c_{P,max}$	Maximum tracer gas concentration in a determined pint (ppm)
$\bar{c}_{CP,exh}$	Average contaminant concentration emitted through the CP exhalation (ppm)
$\bar{c}_s$	Average tracer gas concentration in the supply air (ppm)
e_P^c	Local relative exposure coefficient
$e_{P,125\%}^c$	Local relative average peaks concentration exposure coefficient
$e_{P,max}^c$	Local relative maximum exposure coefficient
$f_{P,125\%}$	Local maximum exposure frequency (h^{-1})
H	Total height of the chamber (m)

HR_i	Average relative humidity in a determined point (%)
HW	Health worker
IAQ	Indoor air quality
IF	Intake fraction
Inh	Point located inside the inhalation airway of HW manikin
MV	Mixing ventilation
P3	Pole located far from thermal loads
PHW	Pole located near health worker location
PCP	Pole located near patient location
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied (%)
ppm	Particles per million
$Q_{b,exh}$	Exhaled volume of CP (l/min)
$Q_{b,inh}$	Inhaled volume rate of HW (l/min)
T_i	Average ambient temperature in a determined point (ºC)
T_{globe}	Globe temperature (ºC)
U	Exhaust grilles placed in the upper part of the West wall
Z	Height along the Z axis of the chamber (m)
V_i	Average absolute air velocity in a determined point (m/s)
$\Delta T_{prN\text{-}S}$	Radiant temperature asymmetry due to the South radiant wall (ºC)
$\Delta T_{h\text{-}f}$	Temperature difference between head level (1.1 m or 1.7 m height) and feet level (0.1 m height) (ºC)
ε^a	Air change efficiency index
ε_P^a	Local air change index for a determined point
ε^c	Contaminant removal effectiveness index
$\langle\tau\rangle$	Mean age of air in the room (min)
τ_n	Nominal time constant (min)
τ_P	Local mean age of air in a determined point (min)

Abstract

This study evaluates the convenience of the use of four different mixing ventilation configurations in individual hospital rooms (IHR) based on ventilation performance and health workers (HW) exposure to the contaminants released by a confined patient (CP). Two supply configurations: grilles in the upper part of a wall (G) and swirl ceiling diffusers (S), combined with two different exhaust grilles positions in the opposite wall: upper part (U) and lower part (D) are tested using typical IHR set up. Occupants are represented by thermal breathing manikins, CP lies on a bed while HW stands close to it. Three air renewal rates are tested to determine their influence in the studied variables, 6, 9 and 12 ACH covering the whole range of ventilation requirements of such spaces. The experimental conditions considering the thermal comfort of the occupants are taken into account. Different

ventilation configurations create different air distribution patterns inside the room. G configurations lead to high HW transient exposure values while S maintain low values that decrease when ACH is increased, so this second configuration is preferred for IHRs. Results are also compared with a displacement ventilation (DV) study highlighting the convenience of this strategy for IHRs.

Keywords

mixing ventilation; hospital room; personal exposure; ventilation effectiveness thermal comfort; airborne transmission of diseases.

1 Introduction

Hospitals environments are risky places for cross infections because of the close interaction of healthy and infected people [1]. Health workers successively visit different patients and, if they are infected, can become disease vector [2]. Visitors are also in contact with patients and they can spread the disease out of the hospital environment. Pathogens that spread diseases such as influenza and tuberculosis can be transported through the air [3–5] being respiratory events such breathing [6], sneezing [7] and coughing [8] the main exit route for it. Together with other bioeffluents, emitted droplets of different size transport pathogens through the air [9]. These particles suffer an evaporative effect that reduce their size until they are transformed into droplet nuclei [10–13]. Depending on the size of the resulting particle, it can precipitate quickly because of the effect of the gravity (if its diameter is greater or 10 μm) or move through the air by means of the ventilation-induced effects (in the case that its diameter is lower than 10 μm) [10]. These small particles can be spread over long distances and be the cause of cross infections between people [13]. The dispersion of these particles is influenced by ventilation flows [14]. Thus, a convenient ventilation strategy can reduce the possibility of these infections [12,15] since it has an influence on particle dynamics [16].

Different types of spaces with different ventilation requirements can be present in hospitals [17]. Focusing our attention in individual hospital rooms (IHRs), airborne infectious isolation rooms (AIIRs) as a specific configuration of IHRs, present specific ventilation requirements. While recovery rooms minimal ventilation rate is fixed in 6 ACH, the requirements for AIIRs increase this value to 12 ACH [17]. Patients considered highly contagious, or especially sensible to infections, are confined in AIIRs. These spaces maintain a negative pressure differential with respect of the rest of the building, in addition to other security measures [18] in order to maintain the patients isolated from the rest of the building. Different National Health committees have published guides about AIIRs design [5,19–22]. Regarding the prevention of airborne cross infections, these regulations focus their attention in assuring a high ventilation air renewal rate. These recommendations are based on the belief that high renewal rates could reduce cross infection risk in such spaces by diluting and removing pathogens. Nevertheless, recent research focuses attention on providing a good air distribution rather than on maintaining high renewal rates as being the most important factor in reducing cross infection risk [15,23,24]. Thus, if this requirement is met, strategies to reduce energy usage in ventilation systems by lowering airflow rates can be achieved [25]. These strategies should not compromise the thermal comfort of the occupants [26,27].

Recent studies have tested innovative ventilation strategies such displacement ventilation (DV) [28,29] and personalized ventilation [30–32] in health environments. Furthermore, more efficient ventilation methods based on source control that reduce substantially the risk of exposure have been suggested [17]. Nevertheless, nowadays, mixing ventilation (MV) is the most used indoor ventilation strategy in such spaces, especially in IHR [19,33].

The configuration of the ventilation of an indoor space system has a direct influence on ventilation effectiveness [34]. The ventilation efficiency in an AIIR like room has been registered for mixing ventilation and 12 and 24 ACH through the local air quality index [35]. This value has been also obtained numerically for different ventilation rates switching between linear and radial supply diffusers for a hospital room set-up. Another numerical study analyzed ventilation efficiency values for a number of combinations of wall and ceiling supply and exhaust cases in hospital rooms [36]. These studies highlight the influence of the relative position of the supply diffusers and exhausts on the flow dynamics and hence on the ventilation performance inside the room. An experimental research has been also carried out using a hospital room setup but using DV for a range of ventilation rates from 6 to 12 ACH [37], showing the potential of this ventilation strategy for these spaces if it is well designed, highlighting the high importance of the heat loads in air distribution for this case. Different studies have obtained different occupants exposure to the exhaled contaminants of patients in hospital rooms. The role of the ventilation rate in the exposure index of a health worker has been studied numerically for a ceiling supply mixing configuration [23]. An experimental research have been performed to evaluate the exposure the other patient in two bed hospital rooms using tracer gases for MV and DV [28]. The problem has been also studied numerically for downward ventilation [38] and for ceiling mixing ventilation [39]. The exposure in the positions where a health worker could locate inside an isolation room have been also obtained for high ventilation rates [35], finding a dependence with the negative pressure differential level in AIIRs. All these studies agree in the influence of ventilation strategy and ventilation flow dynamics on patient exhaled contaminants distribution. That distribution has a determinant effect on the exposure of the rest of the occupants of the room. However, none of these researches studies the influence of different ventilation strategies and air ventilation rates on the exposure of exhaled contaminants in a hospital room.

This paper presents an experimental analysis of the use of different mixing ventilation configurations in a representative case of study of an IHR setup. Two different supply air configurations, through grilles (G) situated at a lateral wall or through two swirl diffusers (S) placed at the ceiling. Two ways to remove the exhaust air of the room have been also tested, by using two grilles placed in the upper part of a lateral wall (U) or by using two grilles placed in the lower part of the same wall (D). The combination of these tests make four different mixing ventilation system configurations. Three different air ventilation rates have been used for each ventilation configuration. The air changes per hour (ACH) is switched from 6 ACH, recommended for recuperation rooms to 9 ACH and to 12 ACH indicated for AIIRs. The experimental setup reproduce a realistic IHR where two thermal manikins representing a lying confined patient (CP) and a health worker standing close to it (HW).

2 Methods

Two different indicators are gathered to determine the convenience of each ventilation configuration. (1) Ventilation efficiency indices and (2) HW exposure to CP exhaled contaminants and aerosols. Specific experiments are carried out to determine these indicators for each ventilation configuration and air ventilation rate. Ventilation efficiency indices are obtained to determine the ventilation performance of each case for the IHR set-up implemented following standard methods [40]. Specifically air change efficiency (ε^a) and the local air change index (ε_P^a) together with the contaminant removal effectiveness (ε^c) are obtained. HW exposure to the contaminants exhaled by CP is determined by seeding CP exhalation flow with R134A as tracer gas to surrogate them. Tracer gas exposition is registered in several points inside the experimental chamber and around HW inhalation area. This way, the average and peak HW exposure is evaluated though different exposure to contaminants (e_P^c) and intake fraction (IF) indices. To assess the transient nature of HW contaminants exposure, the average of the concentration peaks and the maximum peak concentration registered are also considered to obtain derived exposure indices, ($e_{P,max}^c$ and $e_{P,125\%}^c$) and (IF_{ma} and $IF_{125\%}$) respectively.

2.1 Test room and experimental set-up

This study is carried out in an experimental chamber with a typical IHR configuration setup [37] within the HVAC (heating, ventilation and air-conditioning systems) laboratory at the University of Cordoba. The experimental setup can be seen at Figure 1.

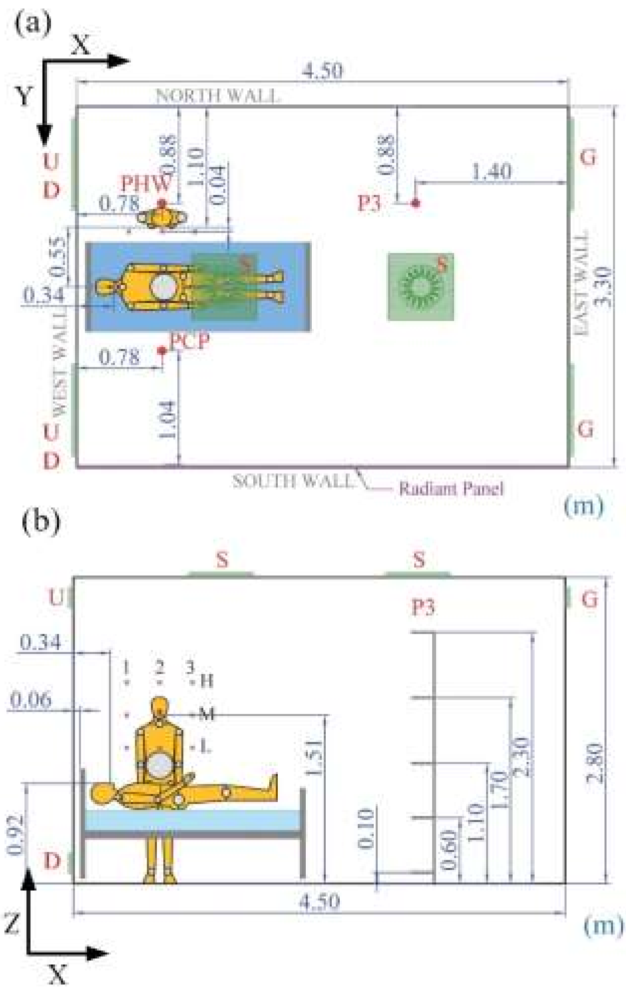

Figure 1. (a) Plan view of the test room; (b) Profile view of the test room. Ceiling swirl air diffuser (S). Wall grille air diffuser (G). Upper exhaust grilles (U). Lower exhaust grilles (D). Vertical Poles (PCP, PHW and P3). Columns of the point matrix of tracer gas measurements (1, 2 and 3). Rows of the point matrix of tracer gas measurements (H, M, L).

The nine points that register tracer gas concentration around the inhalation point of HW are distributed in three columns (1, 2 and 3) and three rows (H, M and L) in the same vertical plane. Rows and columns are spaced at 300 mm between each other, being the point M2 placed just in front of the mouth, center of HW, with a 4 cm gap between them, being it the inhalation point. Contaminant exposure in these points help to infer the distribution of contaminants around the breathing zone of HW and hence the routes followed by the contaminants from the exhalation of CP to HW inhalation.

2.2 Ventilation configurations

Clean air is supplied through two swirl diffusers, S, (VDW 400X16, Trox, Germany) or through two wall grilles, G (AEH 1008X158, Trox, Germany), depending on the test carried out. Likewise, the exhaust is realized through two grilles placed in the upper part of the West wall, U, or through two grilles placed in the lower part of the same wall, D. U and D grilles are the same model than G ones. Figure 2 shows the diagrams of the four ventilation system configurations tested in this study.

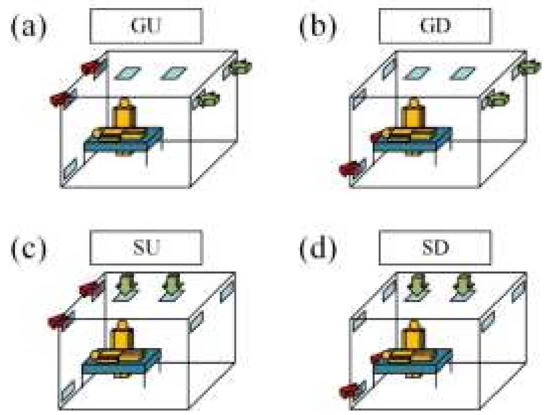

Figure 2. Ventilation system configurations tested in this study: (a) Wall grille supply combined with upper wall exhausts (GU); (b) Wall grille supply combined with lower wall exhausts (GD); (c) Ceiling swirl supply combined with upper wall exhausts (SU); (d) Ceiling swirl supply combined with lower wall exhausts.

The ventilation system has been set at three different air change rates, ACH, 6, 9 and 12 h^{-1} supplying air at a supply temperature, T_s, of 18.2 ºC, 20.6 ºC and 21.8 ºC respectively in order to maintain a mean temperature in the exhaust, T_e, of 25±1ºC. This is done to reproduce comparable and realistic IHR conditions for the tests [41]. A summary of the conditions of the three tests performed can be seen at Table 1.

Table 1. Experimental conditions of the tests performed.

Renewal Rate (ACH)	Supply air flow rate (m^3/h)	Supply air temperature (ºC)
6	250	18.2
9	375	20.6
12	500	21.8

Part of the effective area of the supply diffusers is covered when 6 and 9 ACH ventilation tests are performed, Figure 3. This is necessary in order to maintain the same supply velocity and thus the same air throw in the room for all the experimental tests.

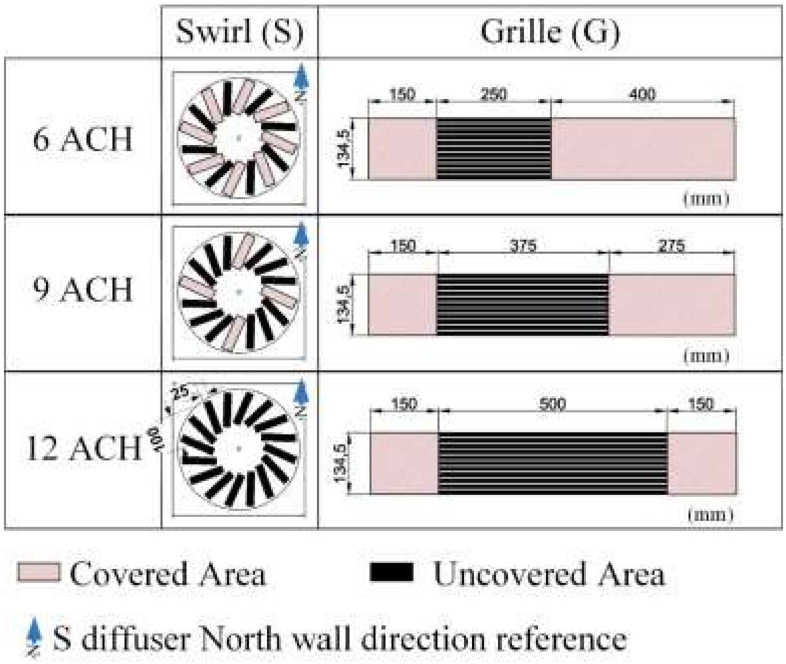

Figure 3. Supply diffuser covered area for each test performed.

2.3 Thermal loads and breathing thermal manikins

Inside the experimental chamber there are two thermal manikins representing a patient, CP, and a health worker, HW. Both manikins have the same geometry, and have been used previously in other research studies [6,37,42]. The body of the manikins is heated to achieve a homogeneous surface temperature of 34 ºC which lead to the thermal gains summarized in Table 2.

The South wall is covered by an hydronic wall radiant system to simulate an external wall heat gain of 500 W [37]. The rest of the walls of the chamber are considered adiabatic because the temperature out of the chamber is maintained at the inward set point temperature. A summary of the thermal gains inside the experimental chamber, thermal manikins and radiant wall, can be seen at Table 2.

Table 2. Thermal gains in the experimental chamber.

Source		Load (W)	
Radiant Panel		500	
HW Manikin	Head	5.6	85
	Arms	14.4	
	Torso	19.2	
	Legs	40.8	
	Breathing	5	
CP Manikin	Head	4.9	75
	Arms	12.6	
	Torso	16.8	
	Legs	35.7	
	Breathing	5	
Total			660 W

Each thermal manikin has its own independent breathing system with the capability of performing different breathing flows. The breathing functions characteristics of both thermal manikins are shown in Table 3.

Table 3. Breathing function of both thermal manikins.

Respiration frequency (min^{-1})		Minute volume (l/min)	Tidal volume (l)
In	Out		
17.90	16.43	9.46	0.55

CP exhales fresh air taken from the exterior of the experimental chamber conveniently seeded with tracer gas. In the same way HW inhales through the nose and, after analyze the tracer gas concentration of the inhaled air, it is expelled far from the experimental chamber. This way, CP manikin exhalation is the only source of contaminants present inside the experimental chamber during contaminant exposure experiments. In the same way HW can be considered the target where the contaminant exposure is evaluated.

2.4 Measuring instruments

Temperature, humidity and air velocity measurements are registered at different heights along three different poles (PHW, PCP and P3). Table 4 summarizes the height of the different measurement points, while its position on the chamber plane can be seen in Figure 1.

Table 4. Probes position along the height of each pole.

Height (m)	P3 Pole	PHW Pole	PCP Pole
2.3	T_i	T_i, V_i	T_i, V_i
1.7	T_i	T_i, V_i, HR_i	T_i, V_i, HR_i
1.1	T_i	T_i, V_i	T_i, V_i
0.6	T_i	T_i, V_i	T_i, V_i
0.1	T_i	T_i, V_i	T_i, V_i

Ambient temperature probes (T_i) consist of J-type thermocouples with an accuracy of 2% in the range $15 - 45\ ℃$. Absolute air velocity (V_i) is measured using hot-sphere anemometers (TSI Air Velocity Transducer 8475, TSI, Minnesota) with a 3% accuracy in the range of 0.02 to 2.5 m/s. Ambient relative humidity (HR_i) has been measured using air humidity sensors (HMT100, Vaisala, Finland) with a calibration accuracy of 1.7% on the full range 0-100%.

The temperature of the inner surfaces of the chamber is registered during the tests by means of 15 resistive temperature probes (PT100, TC Direct, UK). Using the inner enclosure average temperatures, radiant temperature is calculated using the method B.4.2 of EN ISO 7726 standard [43]. These probes have been calibrated in the range form 20 to 40ºC to assure an accuracy of $\pm 0.3℃$.

Tracer gas equipment is used to study the exposure of manikin HW to the contaminants exhaled by CP manikin. R134a is selected as a tracer gas as it has been done in similar previous studies [37,44,45]. To dose the tracer gas emitted through CP exhalation and register tracer gas concentration around HW manikin close environment, a multipoint sampler and doser (Innova 1303, LumaSense Technologies, California) along with a photoacoustic gas monitor (Innova 1412, LumaSense Technologies, California) are used.

Smoke has been introduced in the room completely mixed with the supply ventilation air through the diffusers in order to analyze airfow distribution inside the chamber in each case. A commercial specific fluid (Normal Power Mix, Safex, Germany) is used on the smoke generator machine (F2010Plus, Safex, Germany). Videos have been recorded using a digital video camera (DSC-H50, SONY, Japan). All the edited videos have been added as Supplementary Information.

2.5 Thermal comfort indices

The procedures detailed in ISO EN 7730 [46] are used to determine different thermal comfort indices for the position of PCP and PHW poles. A standing person performing a light activity, standing (1.4 met), is considered in PHW pole position while for the PCP pole a sitting one is considered, seated quiet (1 met). According to the usual light clothing conditions in hospitals, a clothing level index of 0.57 clo, trousers and short sleeved T-shirt, is assumed [47].

In order to determine general thermal comfort operative temperature (T_o) and the predicted mean vote (PMV) - predicted percentage of dissatisfied (PPD) values are obtained. Local thermal discomfort is also considered by means of the gathering of different indices. The radiant temperature asymmetry between the South and North the walls ($\Delta T_{pr,N-S}$), where a radiant panel simulates an external thermal gain . The draft discomfort is evaluated through the draught local discomfort (DR). Finally, the temperature difference between the head and feet (ΔT_{hf}) is gathered to assess the discomfort due to the temperature gradient along the height of the chamber.

2.6 Ventilation performance indices

In order to determine the effectiveness of the ventilation, two ventilation efficiency indices have been used, air change efficiency (ε^{a}) and the local air change index (ε_{P}^{a}). The first index evaluates the ventilation efficiency globally while and the second determines its performance in a determined point. The expressions used to define these indices are:

$$\varepsilon^a = \frac{\tau_n}{2 \cdot \langle \tau \rangle} \cdot 100 \tag{1}$$

$$\varepsilon_P^a = \frac{\tau_n}{\tau_P} \cdot 100 \tag{2}$$

Being, τ_n the nominal time constant, τ_P the local mean age of air and $\langle \tau \rangle$ is the chamber mean age of air. The step down method [40] is used to determine the times involved in the indices, being 40 ppm the initial concentration chosen. Tracer gas concentration is registered over time in the exhaust to obtain ε^a and in three different points around HW inhalation surroundings (M1, M2, and M3) to obtain ε_P^a.

The contaminant removal effectiveness index (ε^c) is obtained for the whole chamber with the purpose of determining global contaminant removal performance of the contaminants emitted through CP exhalation. Contaminants are surrogated by R134A as a tracer gas witch is seeded completely mixed with CP exhalation flow at a concentration of 7382 ppm. Contaminant removal effectiveness index has been previously obtained in recent studies [36,44,45,48]. Its value is obtained as follows:

$$\varepsilon^c = \frac{\bar{c}_e - \bar{c}_s}{\langle \bar{c} \rangle - \bar{c}_s} \tag{3}$$

Where $\langle \bar{c} \rangle$ represents the mean concentration of contaminant of the chamber and $\bar{c}_e$ and $\bar{c}_s$ represents the mean contaminant concentrations in the exhaust and in the supply respectively. The value of $\langle \bar{c} \rangle$ is obtained immediately after the stationary experiment finishes by shutting down the ventilation system and mixing the air inside the chamber using an auxiliary fan [40].

2.7 HW tracer gas exposure

In order to determine the exposure of HW to the contaminants emitted by CP, its exhalation is seeded with tracer gas as it was previously detailed in ε^c evaluation method. Tracer gas concentration is registered in 9 points around HW inhalation surroundings distributed in three columns (1, 2 and 3) and 3 rows (H, M and L) as can be seen in Figure 1. Additionally, the concentration is also recorded inside the inhalation of HW airway. Each test is performed stationary during 6 hours after steady state conditions are obtained inside the chamber. In order to be sure that the experimental exposure time is enough to obtain representative values of the tracer gas exposure, a detailed analysis have been carried out. The results are shown in a Supplementary Information section.

The concentration measurement along the time in each point (P) is used to calculate the concentration mean value, ($\bar{c}_P$), and the concentration maximum value, ($c_{P,max}$). Since it has been observed that concentration peaks arise in different points in a transitory way, the average peaks concentration ($\bar{c}_{P,125\%}$) and its frequency $\left(f_{P,125\%}\right)$ are defined to describe this circumstance. A peak is considered when its value exceed the 125% of the average value of the concentration.

Two derived exposure indices, exposure to contaminants (e_P^c) and intake fraction (IF) are obtained to evaluate the exposition of HW to the contaminants released by CP.

The exposure to contaminants (e_P^c) relates the local contaminant concentration with the difference between average one obtained in the exhaust ($\bar{c}_e^c$) and in the supply ($\bar{c}_s^c$). Contaminant concentration in the supply is always is always null because the tracer gas used can't been found naturally in the atmosphere. This index is obtained for each contaminant index $\bar{c}_P$, $\bar{c}_{P,125\%}$ and $c_{P,max}$, to obtain e_P^c, $e_{P,125\%}^c$ and $e_{P,max}^c$ as follows:

$$e_P^c = \frac{\bar{c}_P - \bar{c}_s}{\bar{c}_e - \bar{c}_s};\ e_{P,125\%}^c = \frac{\bar{c}_{P,125\%} - \bar{c}_s}{\bar{c}_e - \bar{c}_s};\ e_{P,max}^c = \frac{\bar{c}_{P,max} - \bar{c}_s}{\bar{c}_e - \bar{c}_s} \tag{4}$$

Additionally, intake fraction (IF), which is the ratio of the mass of a pollutant inhaled to the mass of the pollutant emitted seeded in CP exhalation at a certain concentration ($\bar{c}_{CP,exh}$), is evaluated for the measuring point placed inside the inhalation airway of HW (Inh). This index is obtained for each contaminant value $\bar{c}_P$, $c_{125\%}$ and $\bar{c}_{P,maxk}$, to obtain IF, $IF_{125\%}$ and IF_{max}:(Inh). The equations used are the following:

$$IF = \frac{\int Q_{b,inh} \cdot c_{inh} \, \mathrm{d}t}{\int Q_{b,exh} \cdot c_{CP,exh} \, \mathrm{d}t}; \; IF_{125\%} = \frac{\int Q_{b,inh} \cdot c_{inh,125\%} \, \mathrm{d}t}{\int Q_{b,exh} \cdot c_{CP,exh} \, \mathrm{d}t}; \; IF_{max} = \frac{\int Q_{b,inh} \cdot c_{inh,max} \, \mathrm{d}t}{\int Q_{b,exh} \cdot c_{CP,exh} \, \mathrm{d}t} \tag{5}$$

Where $Q_{b,inh}$ and $Q_{b,exh}$ are the inhaled and exhaled breathing flows of the manikins respectively. Since both manikins perform the same breathing function, the intake fraction expression can be simplified to the quotient between the average tracer gas concentration value in the inhalation airway of HW ($\bar{c}_{inh}$) and the tracer gas concentration emitted through CP exhalation ($\bar{c}_{CP,exh}$). The value of $\bar{c}_{CP,exh}$ is obtained averaging the tracer gas concentration measurements registered inside the exhalation airways of CP during a 6 h experiment. The values of $IF_{125\%}$ and IF_{max} are calculated replacing $\bar{c}_{inh}$ by $\bar{c}_{inh,125\%}$ and $\bar{c}_{inh,max}$ respectively.

3 Results and discussion

3.1 Experimental conditions

The vertical temperature gradients measured for the four experiments at the three poles of the room: PCP, PHW and P3 are shown in Figure 4.

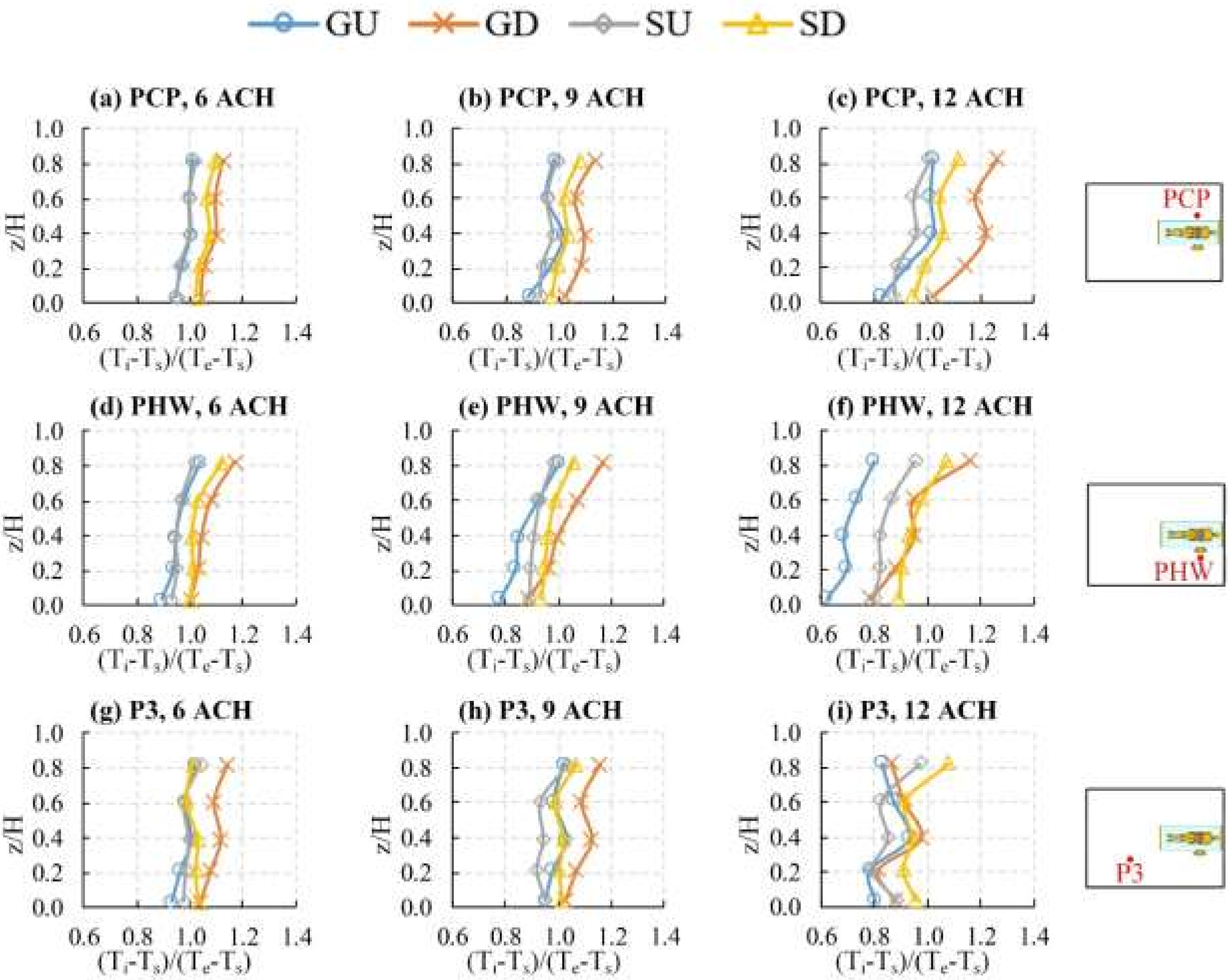

Figure 4. Non dimensional profiles of temperature along the three vertical poles of the room, PCP, PHW and P3 for different ventilation system configurations, GU, GD, SU and SD, and different air change rates, 6 9, and 12 ACH.

Results show a similar temperature distribution along the three temperature poles for each experiment. Dimensionless temperature profiles show, in general, a slight positive gradient with height in all cases, that is higher when the extraction of the air is made by the lower exhaust grilles (D). This may be due to a difficult of the warm air to find the exhaust in an area affected by the thermal convection of the manikins. According to the results, the use of the upper exhaust grilles (U) lead to lower relative temperature values. The differences between the obtained profiles are more evident when the ventilation rate is increased especially for PCP and PHW profiles. These differences could be a consequence of different airflow distributions patterns generated by each ventilation system.

Global and local comfort indices are evaluated for two positions inside the chamber, PHW and PCP, see Figure 1. Results have been summarized in Table 5.

Table 5. General and local thermal comfort indices for health worker (PHW) and patient (PCP) under different ventilation configuration and different air changes per hour, ACH.

		PHW						PCP					
		To	***PMV***	***PPD***	$\Delta T_{prN\text{-}S}$	$\Delta T_{h\text{-}f}$	***DR***	***To***	***PMV***	***PPD***	$\Delta T_{prN\text{-}S}$	$\Delta T_{h\text{-}f}$	***DR***
		℃	**-**	**%**	**K**	**K**	**%**	**℃**	**-**	**%**	**K**	**K**	**%**
GU	**6**	25.7	0.71	15.6	0.8	0.5	2.6	26.0	-0.18	5.7	2.3	0.4	1.1
	9	25.4	0.56	11.6	0.6	0.6	7.3	25.8	-0.27	6.5	2.2	0.6	3.4
	12	24.6	0.28	6.6	0.7	0.3	13.9	25.5	-0.52	10.6	2.4	0.6	7.5
GD	**6**	26.1	0.72	16	0.7	0.5	7.0	26.3	-0.07	5.1	2.1	0.4	2.0
	9	25.6	0.63	13.3	0.5	0.7	6.1	25.8	-0.31	6.9	2.2	0.3	5.5
	12	25.2	0.39	8.1	0.7	0.4	15.5	25.9	-0.2	5.8	2.1	0.5	5.5
SU	**6**	25.7	0.71	15.7	0.3	0.3	0.0	26.0	-0.2	5.8	1.9	0.3	3.5
	9	25.6	0.69	15	0.4	0.2	4.6	25.9	-0.27	6.5	1.9	0.2	5.6
	12	25.4	0.6	12.6	0.4	0.3	6.1	25.8	-0.32	7.1	2.0	0.3	5.8
SD	**6**	25.7	0.7	15.4	0.4	0.3	0.0	26.0	-0.19	5.7	2.0	0.3	0.0
	9	25.8	0.72	16	0.3	0.3	2.2	26.0	-0.22	6	1.9	0.3	6.4
	12	25.7	0.7	15.5	0.4	0.3	2.3	26.0	-0.32	7.1	1.9	0.3	7.5

Results show that T_o decreases slightly when air ventilation rate increases. That means that the increase of the air ventilation rate has an impact on the T_o at the poles positions. This effect is more evident when G supply is used, being both PCP and PHW pole positions exposed to this effect. This is due to the increase of the air velocity in the occupied zone when the air ventilation rate is increased as the increment of the DR index for G tests indicates. It does not happen in S tests presumably because of the different flow distribution originated by this diffuser. Anyway, the values obtained are situated in the comfort zone for summer clothing and sedentary activity for low relative humidity situations [46,49].

General thermal comfort indices summarized in Table 5 have been plotted in Figure 5 for better understanding, where thermal comfort categories are defined according to the standard EN ISO 7730 [46].

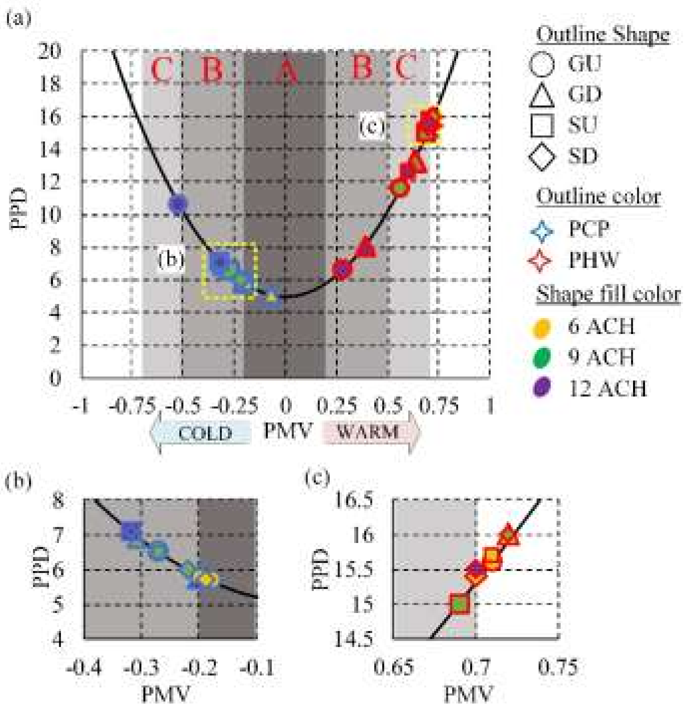

Figure 5. Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV) for different ventilation configurations and different air changes per hour; (a) Full range of results; (b) Detail view of some of PCP results; (c) Detail view of some PHW results.

According to the results, thermal comfort indices PMV for PCP and PHW positions differs in all the cases. PMV indices for PCP position reflects a slightly cold sensation, in most cases between the categories A and B. Nevertheless, for PHW position, this index reflects a warm sensation, which even overpass C category in some cases as it can be seen at Figure 5 (c). This is directly related with the different activity levels considered in each pole. Results suggest that the increase in ventilation rate lead to colder sensations in all cases.

To assess completely comfort in the room, different local discomfort indices have been obtained and presented in Table 5. Radiant temperature asymmetry due to South radiant wall, $\Delta T_{prN\text{-}S}$, is higher in PCP position due to its proximity to the South wall. The increase of the ventilation rate does not lead to different values of $\Delta T_{prN\text{-}S}$. It can be also noted that the use of the S supply reduces $\Delta T_{prN\text{-}S}$ and

$\Delta T_{h\text{-}f}$ indices. It can be due to the effect of the S diffuser on the radiant wall. The value of *DR* increases with the air ventilation rate. It is because the increase of the average air velocity generated by the increase of the air ventilation rate. The effect is more evident for G supply ventilation configurations and PHW position. The different ventilation airflow rate could modify the air distribution patterns inside the room making the air reach directly the standing person head height at PHW position, increasing local discomfort in this case.

3.2 Ventilation performance

The values of τ_n ,$\langle\bar{\tau}\rangle$ and ε^a have been obtained for each ventilation configuration. Results are shown in Figure 6.

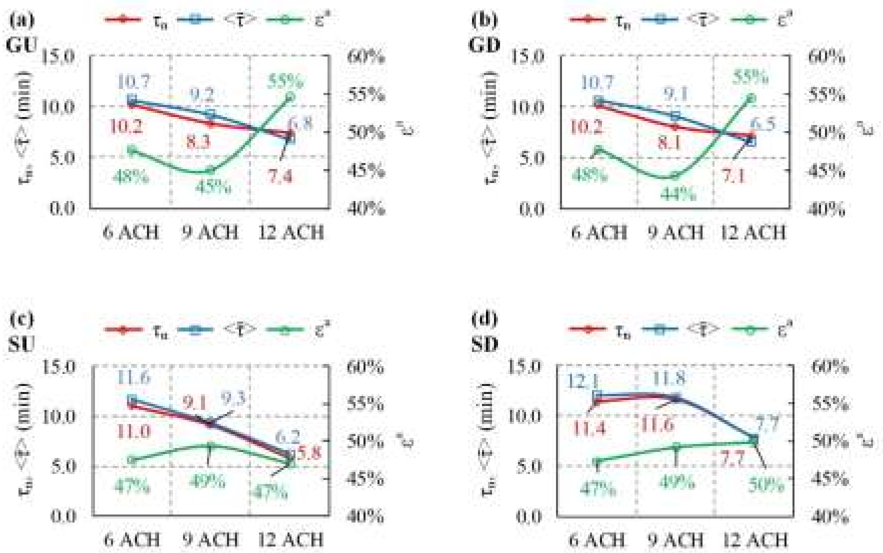

Figure 6. Air change efficiency (ε^a), nominal time constant (τ_n) and room mean age of air $\langle\bar{\tau}\rangle$ for the four ventilation configurations considered at different air change rates. (a) GU; (b) GD; (c) SU; (d) SD.

According to the results obtained, the value of ε^a is around 50% in all cases. If this value is reached, a perfect mixing situation is found [40]. The values of τ_n and $\langle\bar{\tau}\rangle$ times tend to decrease when the ventilation rate increases. This decreasing tendency is different for each ventilation configuration. The value of $\langle\bar{\tau}\rangle$ is higher than τ_n in all cases except for G supply when 12 ACH is tested, being this the only case where ε^a exceeds 50%. That means that the contaminants are evacuated quickly through the exhaust remaining short time inside the room. However, it is found that ε^a barely reach

45% when G supply is used in 9 ACH tests. That means that the contaminants take more time to leave the room, this way contaminants have the possibility of being stacked inside.

When S supply is chosen, the value of ε^a remains close but under 50% for all the air changes used. It can be noted that the increase of air ventilation rate improve ε^a value in SD cases but not in SU ones. Even so, in both configurations, the differences of ε^a for the different ACH tested are lower than in G supply cases.

The results of ε_P^a values are obtained in three points in the near surrounding of HW inhalation area, M1, M2 and M3 and are shown in Figure 7.

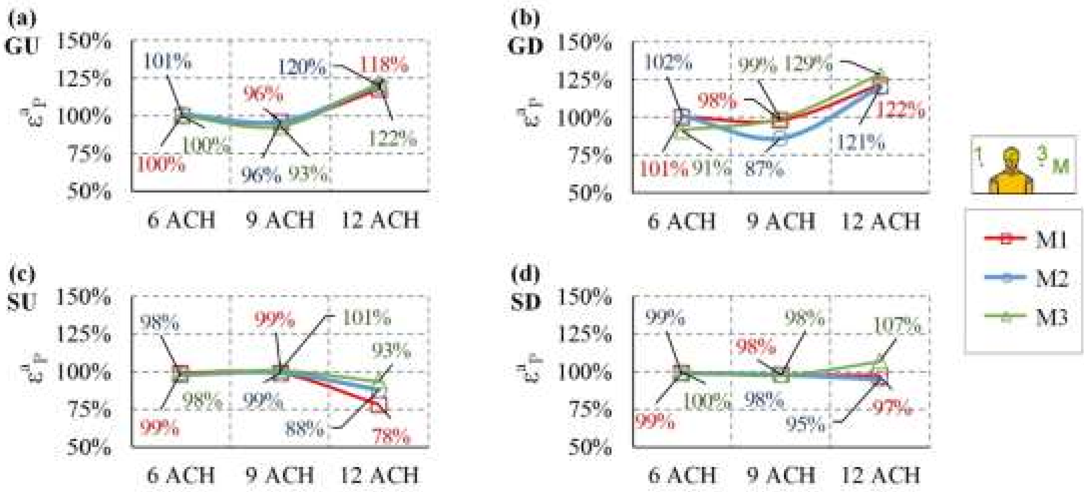

Figure 7. Local air change index (ε_P^a) for three points around HW inhalation point at different air change rates. (a) GU ventilation strategy; (b) GD ventilation strategy; (c) SU ventilation strategy; (d) SD ventilation strategy.

The values of ε_P^a remains close to 100% for all the tests performed. It means that the air is well mixed in the local area around HW inhalation area as in the whole room. Differences in ε_P^a between the configurations tested are found especially at higher ventilation rates. When G supply is used the value of ε_P^a tends to decrease for 9 ACH, especially for GD test in M2, to afterward increase to about 120% for 12 ACH one. That means that contaminants remain more time in the surroundings of HW when 9 ACH are performed than in the cases of 6 and 12 ACH. These fluctuations in ε_P^a values can be due to changes in air distribution patterns inside the room when the ACH value is modified.

In S supply cases, a higher dispersion of results is found under 12 ACH ventilation rate, in contrast with the data homogeneity of the 6 and 9 ACH tests. When the ventilation rate is high, a stronger swirl downward flow from the diffusers could be breaking the arising convective flow from CP manikin body. This way, the horizontal spreading of contaminants is promoted, leading to different contaminants concentration in the three points considered.

In both G and S supply configurations, no improvement is found in ε_P^a when the ventilation rate is increased from 6 to 9 ACH. When the ventilation rate is increased to 12 ACH the value of ε_P^a increases under G supply configuration while in S cases its value becomes dependent on the position.

In order to analyze how contaminants are globally removed by each ventilation configuration, ε^c index is obtained. To do this, the average contaminant concentration in the room ($\langle \bar{c} \rangle$) and in the exhaust ($\bar{c}_e$) have been registered for all the tests carried out. Results are shown in Figure 8.

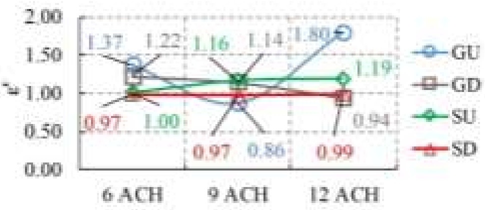

Figure 8. Contaminant removal effectiveness (ε^c) index for the four ventilation configuration tested.

According to the results, the values of ε^c remains around 1 for nearly all the tests. The values for GD and SU maintain values over the unit while SD values are slightly under the unit. This might be due to the difficult of the upward exhaled contaminants to reach the D exhaust placed in the lower part of the room. The case of GU is different to the rest, for 12 and 6 ACH it performs the highest values of ε^c. This is positive because it means that the contaminants path to the exhaust is relatively short and quick. However, for GU with 9 ACH the lowest value of ε^c is obtained. It can be due to the short circuit generated between the G supply grilles and the exhausts grilles placed at the same height in the opposite wall. In that way, the airflow from the supply grilles is not able to reach the CP exhalation area and remove efficiently the contaminants exhaled.

3.3 HW tracer gas exposure

Tracer gas exposure is evaluated in 9 points around the inhalation of HW and in the inhalation of HW (Inh), as it can be seen in Figure 1. Figure 9 shows the values of e_P^c, $e_{P,125\%}^c$, and $e_{P,max}^c$ for these points.

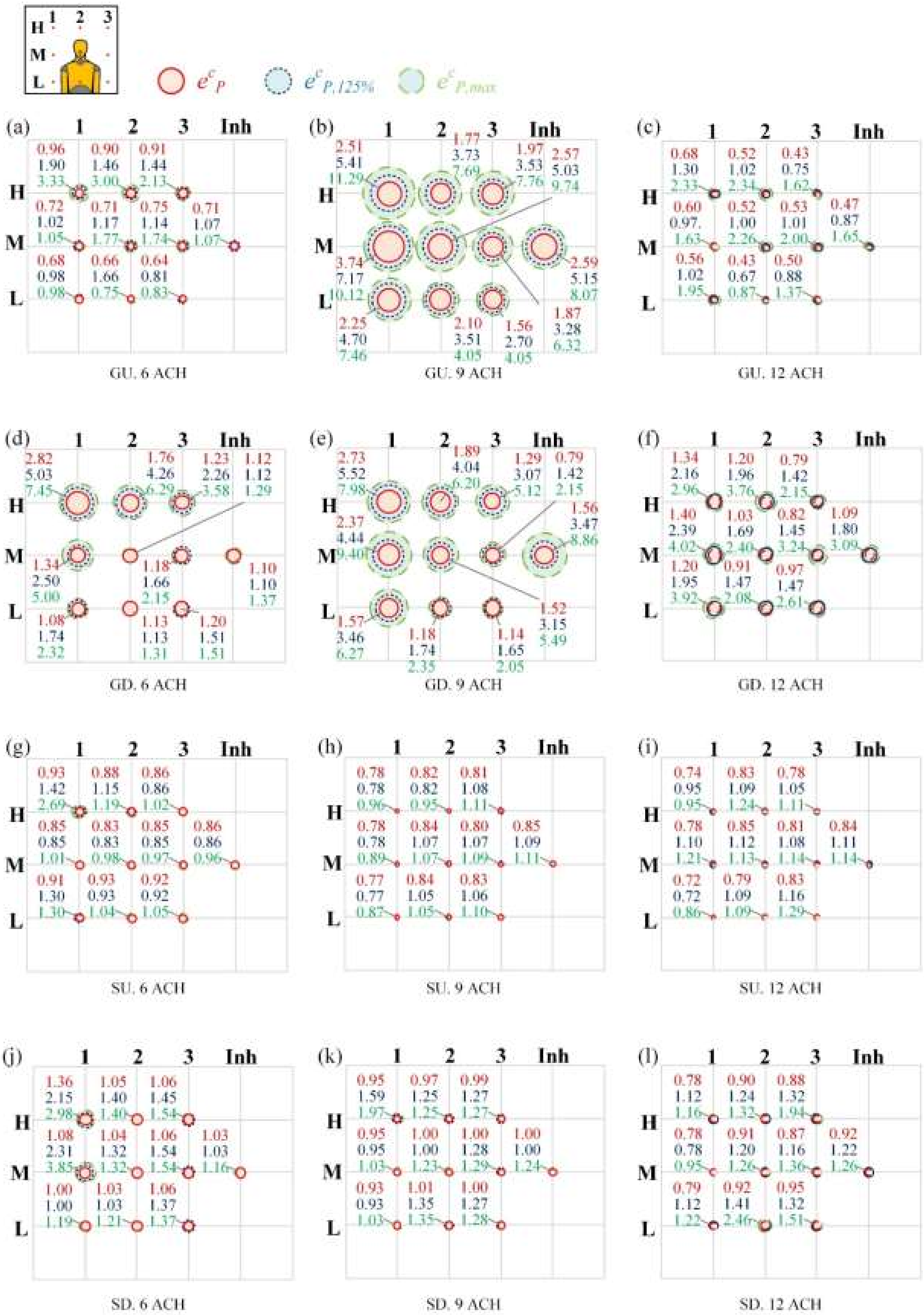

Figure 9. Local relative contaminant exposure coefficient (e^c_P), local relative average peaks concentration exposure coefficient ($e^c_{P,125\%}$) and maximum peak exposition coefficient ($e^c_{P,max}$) for the tests carried out. (a) GU 6 ACH; (b) GU 9 ACH; (c) GU 12

ACH; (d) GD 6 ACH; (e) GD 9 ACH; (f) GD 12 ACH; (g) SU 6 ACH; (h) SU 9 ACH; (i) SU 12 ACH; (j) SD 6 ACH; (k) SD 9 ACH; (l) SD 12 ACH.

According to the results, there is a notable difference between the results obtained for G supply tests and the ones obtained for S supply. In general terms, it can be noted that the exposure indices are higher in the cases where G supply is used. S supply tests maintain homogeneous e_P^c values in all the points, and in most of them the value is the same that $e_{P,125\%}^c$ and very close to 1. The values of $e_{P,max}^c$ show values not far from e_P^c in all cases, revealing a high homogeneity over time for contaminant concentration. It can be noted that exposure indices show lower values for SU in comparison with SD.

In contrast, G supply exposure values behaves in a very different way, showing in some cases high discrepancies between exposure values depending on the position, the ACH and the height of the exhaust. GU 9 ACH stands out as the case where the exposition is higher in all the points around the HW and in its inhalation. The explanation might be found in the ventilation flow distribution inside the chamber. The clean air from the grille diffusers is not able to remove the exhaled contaminants from the occupied zone maybe due to a short circuit produced between the grilles and the exhausts for that case. Figure 10(b) shows a capture from the smoke test video showing the ventilation flow development for this case, reinforcing this theory. The flow reaches the upper part of the West wall where part of it leaves directly the room, being short circuited. This situation produce a stagnation of the contaminants around HW inhalation area. The results are compatible with the results obtained for ε^c that suggested that part of the contaminants are stacked into the room. However, for the same GU ventilation configuration under 6 and 12 ACH, low values of exposition in all the points are obtained. For 6 ACH case, the clean airflow from the grilles moves downward to the exhalation area improving the mixing process of the exhaled contaminants and reducing the exposure indexes, as it can be seen in Figure 10(a). When using 12 ACH, the volume of clean air increases and generates a strong upward flow in the occupied area situated between the inlets and the outlets of the room, as a result of its reaching of the West wall, Figure 10(c). This airflow pattern conduces the exhaled contaminants quickly to the exhausts generating a low risk of exposure to HW.

Figure 10. Video frame captures showing throw development of the GU tests. (a) GU 6 ACH; (b) GU 9 ACH; (c) GU 12 ACH.

Some points with high contaminants exposure values can also be found for GD ventilation configuration. These points are found for 6 and 9 ACH cases. For GD 6 ACH case, high exposure points distribute at H positions, situated at the height of HW head. In this case the clean airflow coming from inlets could be displacing contaminants to the West wall going upward to the area of the HW head. However this fact maintains the breathing area of HW clean of contaminants. For the case of GD 9 ACH the clean airflow from the grilles interacts with the upward convective flow from the manikins making difficult for the exhaled contaminants to find the exhaust and creating a stagnant area. This fact produces a direct influence of the patient exhalation in the contaminant inhalation of HW. The average values of exposure (e_P^c) and the maximum values of exposure $(e_{P,max}^c)$ show a significant difference. This situation changes when 12 ACH is set due to the increase of air volume that penetrates into the exhalation area in despite of the ascending thermal plumes leading the contaminants directly to the exhaust. Previous research on exposure to contaminants released by respiratory events reinforces the idea that an increase of ACH doesn’t necessary leads to a better contaminants exposure indices due to the changes that it produces in airflow patterns inside the indoor space [50–52].

In general for G supply cases, the points where a high exposure value is obtained show a high discrepancy between e^c_P, $e^c_{P,125\%}$ and $e^c_{P,max}$. That reveals that the high contaminants exposure registered is not constant in time but it reveals a transient nature. High contaminant concentration exposure peaks $e^c_{P,125\%}$ arise without any evident periodicity. This situation could be related with the fact that contaminants are not released constantly but they are seeded into CP exhalation flows. That means that the peaks are not homogeneous, being possible high values of $e^c_{P,max}$ with low values of e^c_P. In the inhalation area for GD and 9 ACH the $e^c_{P,max}$ is more than 5 times the e^c_P.These two facts reinforce the idea that despite the conditions of the problem are stationary, the exposure to the contaminants reveals a transient nature.

The frequency of the peaks ($f_{P,125\%}$) registered inside the airways of HW (Inh) is shown in Figure 11.

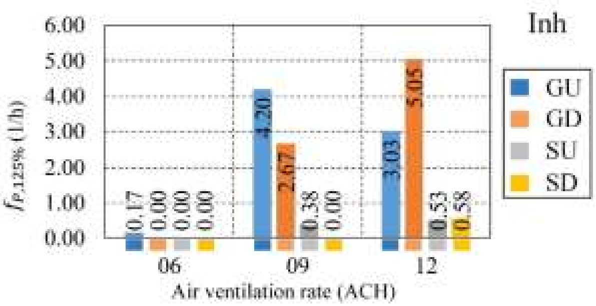

Figure 11. Frequency of maximum exposure coefficients ($e_{P,max}$) inside the airways of HW.

The swirl diffusers used for SU, SD cases avoid the tracer gas peak concentration in the inhalation due to an effective dilution of the contaminants emitted by CP. This way the direct influence of the exhalation on the breathing area of the HW is avoided, maintaining low $f_{P,125\%}$ values. For G supply, it exists a dependency between the air ventilation rate and the $f_{P,125\%}$ value. Very low values of $f_{P,125\%}$ are found when 6 ACH ventilation rate is performed showing a dilution process of the contaminants exhaled. On the contrary, $f_{P,125\%}$ increases for 9 and 12 ACH. This fact shows that the mixing process in the occupied area is not being complete and therefore there is an influence of P exhalation on the breathing area of HW. The high values of $f_{P,125\%}$ combined with the high values of $e^{c}_{P,125\%}$ indicates a high risk of exposure. However, for GU and GD under 12 ACH the high values of $f_{P,125\%}$ are not related with high values of exposure since the values of $e^{c}_{P,125\%}$ are low. That means that also there is an influence of CP exhalation on the breathing area of HW when the occupied zone is maintained clean of contaminants.

The value of *IF* index is obtained to evaluate the amount of contaminants that are inhaled by HW respect to the amount exhaled by CP. Results are shown in Figure 12.

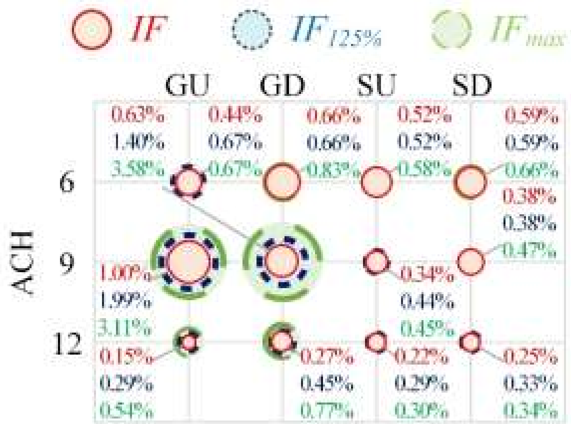

Figure 12. Intake Fraction.

Results show that the ventilation configurations tested present, in general, a similar decreasing IF tendency with the increasing of the air ventilation rate. The more volume of clean air entering the room, the less percentage of inhaled contaminants relative to the exhaled contaminants. The case of GU 9 ACH presents the only exception for this tendency due to a direct influence of the contaminants released by CP in the inhalation area of HW. The airflow pattern generated during this test maintains the exhaled contaminants released by CP in the breathing area of HW, making it difficult for the contaminants to evacuate the room through the exhausts. This phenomenon disappears when air ventilation rate is increased to 12 ACH, decreasing considerably the value of IF. When GD configuration is used, the values of IF are also high for 6 and 9 ACH. It has been observed for these tests that it is difficult for the exhaled contaminants to find the way to the exhaust.

This fact may be due to the interaction between the upward flow of the manikin´s thermal plumes and the downward flow generated by this ventilation strategy. The values of IF and $IF_{125\%}$ show discrepancies which reveals that the high exposure is due to punctual peak concentrations episodes. The value of IF_{max} is also quite higher than $IF_{125\%}$, so it can be stated that the peaks reach different values over the time. IF_{max} can even reach values five times higher than IF ones such in the case of GU 9 ACH. The cases where S supply is used, IF values present a constant decreasing tendency, being in most cases the values of $IF_{P,125\%}$ and IF_{max} very close to IF. This shows that the dilution of the CP exhaled contaminant maintain a low and homogeneous tracer gas concentration in HW inhalation. It has been also noted that the IF values are somewhat lower for SU tests.

4 Discussion

This work examines the effectiveness of different mixing ventilation strategies in the removal of contaminants in an IHR analyzing different indexes.

The mixing ventilation study has been performed using the same experimental setup, thermal gains disposition and experimental equipment and methods than a previous study based on displacement ventilation (DV) [37]. Three different air changes per hour are performed for each ventilation strategy, which consider two different inlet diffusers: wall grilles (G) and swirl diffusers (S), and two different exhausts positions: in the lower part of the wall (D) and in the upper part of the wall (U). That leads to a total of 12 experimental cases studied. The results obtained are of significant relevance in order to understand which ventilation strategy will lead to a less risk of exposure to exhaled contaminants in a IHR. The risk of exposure is obtained for a health worker (HW) placed close to the patient (CP) which is considered the source of exhaled contaminants. Figure 13 shows a comparison of the exposure indices for the different ventilation strategies, GD, GU, SD, SU and DV, in an IHR for Inh point placed inside the inhalation airway of HW.

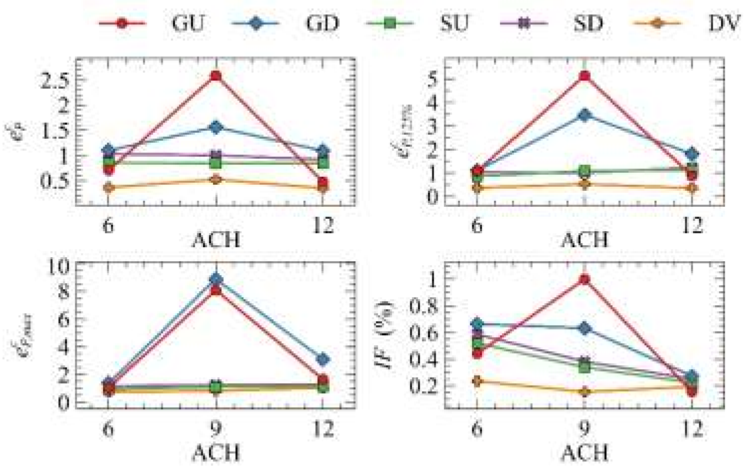

Figure 13. Comparison between exposure indices at Inh point. (a) Local relative contaminant exposition index (e_P^c); (b) Average of peaks relative exposition index ($e_{P,125\%}^c$); (c) Maximum peak exposition index (e_{max}^c); (d) Intake fraction (IF).

Firstly, it is possible to see that the displacement ventilation strategy (DV) shows the best index value with very low exposure of HW for all the exposure indices analyzed. This result is in agreement with previous studies of displacement ventilation [28,53] where it is possible to find low values of the risk of infection with that strategy. In this particular case, the position of the source of contaminants (exhalation of the patient) in a lower position respect to the HW breathing area improve the results. The thermal stratification of the displacement ventilation system maintains the exhaled contaminants in a layer below the breathing area of the HW. Different relative position of the manikins may lead to completely different results.

Secondly, if we observe the results obtained for SD and SU, for the three ACH performed, both strategies show values typical of a complete mixing process, close to 1. The mixing process is complete and independent of the number of ACH. Nevertheless, a slight dependence of the exhaust positions is observed, SU performs slightly better than SD in contaminant removal and HW exposure indices. The values of ε^c together with e_P^c and IF exposure values suggest that part the tracer gas concentration inside the chamber remains higher in SD cases due the exhaust position.

Finally, high exposure values depending on the number of ACH and the position of the exhausts has been found in GD and GU cases. Considering GD and GU 9 ACH cases, the exhaled contaminants remain close to the breathing area of HW, increasing its exposure to contaminants. However, when 12 ACH in GD and GU cases, the increase of airflow decreases its exposure. This result points out that a specific study of a particular case, taking into account: position of the thermal loads, position of the inlets and exhausts, distance between the manikins, and relative positions between all these relevant parts of the room, may play the crucial role in understanding the risk of airborne exposure of people in a room.

4.1 Limitations of the work

It is important to bear in mind that the results obtained and discussed in this work are obtained under specific experimental conditions. The relative position of the source of contaminants, the different positions of the inlets and exhausts or different distances between the manikins may change the conclusions obtained. In the same way, the height at which the contaminants are exhaled plays a crucial role in the exposure to contaminants of the HW, especially for the DV system.

The experimental set up has not been carried out in a real hospital and the problem only treats tracer gas as a strategy to simulate small droplet nuclei, not real biological contaminants. The experimental results are not showing a complete real situation since the manikins are also steady. However, all the results analyzed could be helpful in the design of IHRs in order to create environments where the exposure to exhaled contaminants may be reduced in most of the situations.

The tracer gas measurement sample rate is lower than the periodic breathing process time. This situation implies that the possible fluctuations of tracer gas concentration in the considered locations, as the tracer gas concentration peaks occurence, are not completely registered. Experimental time periods are adjusted to assess this situation following the criterion included as Supplementary Information, however a higher frequency tracer gas concentration probes could enrich the gathered information about the recurrent perturbation registered in tracer gas concentration. The use of a equipment that allows performing a higher measurement frequency could lead to a better understanding of the peaks occurrence.

5 Conclusions

Experimental tests have been carried out to determine ventilation performance and contaminant exposure in a representative case of study of a typical individual hospital room configuration using two different mixing ventilation systems and three air ventilation rates and connected with previous DV studies. In view of the results of each test and the comparisons between them, the following conclusions can be stated:

- Airflow patterns generated by G and S ventilation configurations influence ventilation efficiency (ε^a, ε_P^c and ε_P^a) and contaminant exposure (e_P^c and IF) of HW. Swirl diffusers (S) generate a better mixing ventilation situation, leading to a better performance and exposure indices. So S supply could be considered as a more reliable strategy in hospital rooms. It has also been noted that HW exposure results are better if S supply is combined with D exhaust.
- Air renovation (ACH) has a very low influence in the HW exposure for S supply cases. However, the change of ACH for G supply cases determine completely different behavior of the dispersion of exhaled contaminants. For GU a short circuit between the inlet and the exhaust is generated for 9ACH producing the highest exposure values in the inhalation of HW. For GD using 6 and 9 ACH the lack of a perfect mixing of the air in the room generates high peak values of exposure in the inhalation of HW.
- Being the human exhalation a transient process, the exposure to exhaled contaminants is also observed as a transient process. This fact leads to average (e_P^c) and peak ($e_{P,125\%}^c$ and $e_{P,max}^c$) different exposure values depending on the experimental case. Low average exposure (e_P^c)

cases may present punctual high peak exposure ($e^{c}_{P,max}$) values. The peak frequency ($f_{P,125\%}$), which is lower for S cases, can increase with the air ventilation rate .

- The exposure to contaminants of HW is lower when displacement ventilation strategy is used instead of mixing ventilation strategy. A similar exposure to contaminants is obtained in DV and MV systems when 12 ACH is used.

Considering all the results, it has been found that using a mixing ventilation strategy if a perfect mixing is not reached the ACH and the relative positions between supply and exhaust locations determine the HW exposure. The transient nature observed of the dispersion of the exhaled contaminants makes the authors think of the necessity of study the exposure using high frequency contaminant sensors. A deeper study considering different relative positions between the people occupying the room and the supply/exhaust positions will add knowledge about contaminants exposure in indoor environments.

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7 References

[1] C.B. Beggs, L.D. Knibbs, G.R. Johnson, L. Morawska, Environmental contamination and hospital-acquired infection: factors that are easily overlooked, Indoor Air. 25 (2015) 462–474. doi:10.1111/ina.12170.

[2] M.P. Atkinson, L.M. Wein, Quantifying the routes of transmission for pandemic influenza, Bull. Math. Biol. 70 (2008) 820–867. doi:10.1007/s11538-007-9281-2.

[3] J.W. Tang, Investigating the airborne transmission pathway - different approaches with the same objectives, Indoor Air. 25 (2015) 119–124. doi:10.1111/ina.12175.

[4] I. Eames, J.W. Tang, Y. Li, P. Wilson, Airborne transmission of disease in hospitals., J. R.

Soc. Interface. 6 Suppl 6 (2009) S697–S702. doi:10.1098/rsif.2009.0407.focus.
[5] Centers for Disease Control and Prevention, Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care facilities., MMWR Morb Mortal Wkly Rep. 43 (1994) 1–132. doi:10.2307/42000931.
[6] F.A. Berlanga, I. Olmedo, M. Ruiz de Adana, Experimental analysis of the air velocity and contaminant dispersion of human exhalation flows, Indoor Air. (2016) 1–13. doi:10.1111/ina.12357.
[7] J.W. Tang, A. Nicolle, C. Klettner, J. Pantelic, L. Wang, A. Suhaimi, et al., Airflow dynamics of human jets: sneezing and breathing - potential sources of infectious aerosols, PLoS One. 8 (2013) e59970. doi:10.1371/journal.pone.0059970.
[8] J.K. Gupta, C.H. Lin, Q. Chen, Flow dynamics and characterization of a cough, Indoor Air. 19 (2009) 517–525. doi:10.1111/j.1600-0668.2009.00619.x.
[9] C.Y.H. Chao, M.P. Wan, L. Morawska, G.R. Johnson, Z.D. Ristovski, M. Hargreaves, et al., Characterization of expiration air jets and droplet size distributions immediately at the mouth opening, J. Aerosol Sci. 40 (2009) 122–133. doi:10.1016/j.jaerosci.2008.10.003.
[10] X. Xie, Y. Li, A.T.Y. Chwang, P.L. Ho, W.H. Seto, How far droplets can move in indoor environments - revisiting the Wells evaporation-falling curve, Indoor Air. 17 (2007) 211–225. doi:10.1111/j.1600-0668.2007.00469.x.
[11] W.F. Wells, On air-borne infection. II. Droplets and droplet nuclei, Am. J. Hyg. 20 (1934) 611–618.
[12] A. Jurelionis, L. Gagytė, T. Prasauskas, D. Čiužas, E. Krugly, L. Šeduikytė, et al., The impact of the air distribution method in ventilated rooms on the aerosol particle dispersion and removal: The experimental approach, Energy Build. 86 (2015) 305–313. doi:http://dx.doi.org/10.1016/j.enbuild.2014.10.014.
[13] L. Liu, Y. Li, P. V. Nielsen, J. Wei, R.L. Jensen, Short-range airborne transmission of expiratory droplets between two people, Indoor Air. (2016) 1–11. doi:10.1111/ina.12314.
[14] M. Bivolarova, W. Kierat, E. Zavrl, Z. Popiolek, A. Melikov, Effect of airflow interaction in the breathing zone on exposure to bio-effluents, Build. Environ. 125 (2017) 216–226. doi:10.1016/j.buildenv.2017.08.043.
[15] A. Jurelionis, L. Gagyte, L. Seduikyte, T. Prasauskas, D. Ciuzas, D. Martuzevičius, Combined air heating and ventilation increases risk of personal exposure to airborne pollutants released at the floor level, Energy Build. 116 (2016) 263–273. doi:10.1016/j.enbuild.2016.01.011.
[16] Y. Lv, H. Wang, S. Wei, The transmission characteristics of indoor particles under two ventilation modes, Energy Build. 163 (2018) 1–9. doi:10.1016/j.enbuild.2017.12.028.
[17] A.K. Melikov, Z.D. Bolashikov, E. Georgiev, Novel ventilation strategy for reducing the risk of airborne cross infection in hospital rooms, (2011) 1–6.
[18] N.J. Adams, D.L. Johnson, R. a. Lynch, The effect of pressure differential and care provider movement on airborne infectious isolation room containment effectiveness, Am. J. Infect. Control. 39 (2011) 91–97. doi:10.1016/j.ajic.2010.05.025.
[19] J.D. Siegel, E. Rhinehart, M. Jackson, L. Chiarello, 2007 Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Health Care Settings, Am. J. Infect. Control. 35 (2007). doi:10.1016/j.ajic.2007.10.007.
[20] E. Lingaas, J.P. Rydock, Best practice in design and testing of isolation rooms in Nordic hospitals, Round Table Ser. - R. Soc. Med. (2007) 87–107.
[21] Victorian Advisory Committee on Infection Control, Guidelines for the classification and design of isolation rooms in health care facilities, 1st ed., Victorian Government, Melbourne, 2007.
[22] L. Sehulster, R.Y.W. Chinn, Guidelines for environmental infection control in health-care facilities, Morb. Mortal. Wkly. Rep. 52 (2003) 1–42.
[23] F. Memarzadeh, W. Xu, Role of air changes per hour (ACH) in possible transmission of

airborne infections, Build. Simul. 5 (2012) 15–28. doi:10.1007/s12273-011-0053-4.
[24] P. Kalliomäki, P. Saarinen, J.W. Tang, H. Koskela, Airflow patterns through single hinged and sliding doors in hospital isolation rooms - Effect of ventilation, flow differential and passage, Build. Environ. 107 (2016) 154–168. doi:10.1016/j.buildenv.2016.07.009.
[25] P. Kumar, C. Martani, L. Morawska, L. Norford, R. Choudhary, M. Bell, et al., Indoor air quality and energy management through real-time sensing in commercial buildings, Energy Build. 111 (2016) 145–153. doi:10.1016/j.enbuild.2015.11.037.
[26] W. Yu, B. Li, H. Jia, M. Zhang, D. Wang, Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design, Energy Build. 88 (2015) 135–143. doi:10.1016/j.enbuild.2014.11.063.
[27] A. Kabanshi, H. Wigö, M. Sandberg, Experimental evaluation of an intermittent air supply system - Part 1: Thermal comfort and ventilation efficiency measurements, Build. Environ. 95 (2016) 240–250. doi:10.1016/j.buildenv.2015.09.025.
[28] H. Qian, Y. Li, P. V. Nielsen, C.E. Hyldgaard, T.W. Wong, a T.Y. Chwang, Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems, Indoor Air. 16 (2006) 111–28. doi:10.1111/j.1600-0668.2005.00407.x.
[29] Y. Yin, W. Xu, J.K. Gupta, A. Guity, P. Marmion, A. Manning, et al., Experimental Study on Displacement and Mixing Ventilation Systems for a Patient Ward, HVAC&R Res. 15 (2009) 1175–1191. doi:10.1080/10789669.2009.10390885.
[30] P. V. Nielsen, C.E. Hyldgaard, A.K. Melikov, H. Andersen, M. Soennichsen, Personal exposure between people in a room ventilated by textile terminals—with and without personalized ventilation, HVAC R Res. 13 (2007) 635–643. doi:10.1080/10789669.2007.10390976.
[31] J.W. Tang, C.J. Noakes, P. V. Nielsen, I. Eames, A. Nicolle, Y. Li, et al., Observing and quantifying airflows in the infection control of aerosol- and airborne-transmitted diseases: An overview of approaches, J. Hosp. Infect. 77 (2011) 213–222. doi:10.1016/j.jhin.2010.09.037.
[32] M. Bivolarova, A.K. Melikov, C. Mizutani, K. Kajiwara, Z.D. Bolashikov, Bed-integrated local exhaust ventilation system combined with local air cleaning for improved IAQ in hospital patient rooms, Build. Environ. 100 (2016) 10–18. doi:10.1016/j.buildenv.2016.02.006.
[33] M. Hyttinen, A. Rautio, P. Pasanen, T. Reponen, G.S. Earnest, A. Streifel, et al., Airborne Infection Isolation Rooms - A Review of Experimental Studies, Indoor Built Environ. 20 (2011) 584–594. doi:10.1177/1420326X11409452.
[34] G. Cao, H. Awbi, R. Yao, Y. Fan, K. Sirén, R. Kosonen, et al., A review of the performance of different ventilation and airflow distribution systems in buildings, Build. Environ. 73 (2014) 171–186. doi:10.1016/j.buildenv.2013.12.009.
[35] Y.C. Tung, S.C. Hu, T.I. Tsai, I.L. Chang, An experimental study on ventilation efficiency of isolation room, Build. Environ. 44 (2009) 271–279. doi:10.1016/j.buildenv.2008.03.003.
[36] J.M. Villafruela, F. Castro, J.F. San Jose, J. Saint-Martin, Comparison of air change efficiency, contaminant removal effectiveness and infection risk as IAQ indices in isolation rooms, Energy Build. 57 (2013) 210–219. doi:10.1016/j.enbuild.2012.10.053.
[37] F.A. Berlanga, M.R. de Adana, I. Olmedo, J.M. Villafruela, J.F. San José, F. Castro, et al., Experimental evaluation of thermal comfort, ventilation performance indices and exposure to airborne contaminant in an Airborne Infection Isolation Room equipped with a displacement air distribution system, Energy Build. (2017). doi:10.1016/J.ENBUILD.2017.09.100.
[38] H. Qian, Y. Li, P. V. Nielsen, C.E. Hyldgaard, Dispersion of exhalation pollutants in a two-bed hospital ward with a downward ventilation system, Build. Environ. 43 (2008) 344–354. doi:10.1016/j.buildenv.2006.03.025.
[39] M.P. Wan, C.Y.H. Chao, Y.D. Ng, G.N. Sze To, W.C. Yu, Dispersion of expiratory droplets in a general hospital ward with ceiling mixing type mechanical ventilation system, Aerosol

Sci. Technol. 41 (2007) 244–258. doi:10.1080/02786820601146985.
[40] E. Mundt, H.M. Mathisen, P. V. Nielsen, A. Moser, Ventilation Effectiveness, 2004.
[41] J.W. Tang, Y. Li, I. Eames, P.K.S. Chan, G.L. Ridgway, Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises, J. Hosp. Infect. 64 (2006) 100–114. doi:10.1016/j.jhin.2006.05.022.
[42] F.A. Berlanga, M. Ruiz de Adana, I. Olmedo, Diseño y construcción de maniquíes térmicos para la realización de ensayos experimentales de sistemas de climatización, in: Proc. IX Congr. Nac. Ing. Termodinámica, Cartagena, 2015: pp. 1–8. doi:978-84-606-8931-7.
[43] Technical Comitee for Ergonomics of the physical environment, ISO 7726 Ergonomics of the thermal envinonment - Instruments for measuring physical quantities, 2nd ed., ISO, 1998.
[44] R. Tomasi, M. Krajčík, A. Simone, B.W. Olesen, Experimental evaluation of air distribution in mechanically ventilated residential rooms: Thermal comfort and ventilation effectiveness, Energy Build. 60 (2013) 28–37. doi:10.1016/j.enbuild.2013.01.003.
[45] M. Krajčík, A. Simone, B.W. Olesen, Air distribution and ventilation effectiveness in an occupied room heated by warm air, Energy Build. 55 (2012) 94–101. doi:10.1016/j.enbuild.2012.08.015.
[46] ISO - AEN/CTN 81, ISO 7730. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, ISO, Geneva, 2005.
[47] ASHRAE, F09 SI: Thermal Comfort, in: ASHRAE Handb. Fundam., 2009: p. 9.1-9.30.
[48] J. Laverge, M. Spilak, A. Novoselac, Experimental assessment of the inhalation zone of standing, sitting and sleeping persons, Build. Environ. 82 (2014) 258–266. doi:10.1016/j.buildenv.2014.08.014.
[49] M. De Carli, B.W. Olesen, Field measurements of operative temperatures in buildings heated or cooled by embedded water-based radiant systems, in: ASHRAE Trans., 2002: pp. 714–725.
[50] Z.D. Bolashikov, A.K. Melikov, W. Kierat, Z. Popioek, M. Brand, Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation, in: HVAC R Res., 2012: pp. 602–615. doi:10.1080/10789669.2012.682692.
[51] J. Pantelic, K.W. Tham, Adequacy of air change rate as the sole indicator of an air distribution system's effectiveness to mitigate airborne infectious disease transmission caused by a cough release in the room with overhead mixing ventilation: A case study, HVAC R Res. 19 (2013) 947–961. doi:10.1080/10789669.2013.842447.
[52] A.K. Melikov, Z.D. Bolashikov, W. Kierat, Z. Popiolek, Does increased ventilation help reduce cross-infection in isolation hospital wards?, in: Proc. CLIMA 2010, Antalya, 2010.
[53] I. Olmedo, P. V. Nielsen, M. Ruiz de Adana, R.L. Jensen, P. Grzelecki, Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies., Indoor Air. 22 (2012) 64–76. doi:10.1111/j.1600-0668.2011.00736.x.