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Computational Fluid Dynamics Simulation of Airflow and Air Pattern in the Living Room for Reducing Coronavirus Exposure

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Abstract

Viruses can be transmitted in indoor environments. Important factors in Indoor Air Quality (IAQ) are air velocity, relative humidity, temperature, and airflow pattern and Computational fluid dynamics (CFD) can use for IAQ assessment. The objective of this study is to CFD simulation in the living room to the prediction of the air pattern and air velocity. A computational fluid dynamic model was applied for airflow pattern and air velocity simulation. For simulation, GAMBIT, FLUENT, and CFD post software were used as preprocessing, processing, and post-processing, respectively. CFD validation was carried out by comparing the computed data with the experimental measurements. The final mesh number was set to 1,416,884 elementary cells and SIMPLEC algorithm was used for pressure-velocity coupling. PERSTO, and QUIK schemes have been used for the pressure terms, and the other variables, respectively. Simulations were carried out in ACH equals 3, 6 and 8 in four lateral walls. The maximum error and root mean square error from the air velocity were 14% and 0.10, respectively. Terminal settling velocity and relaxation time were equal to 0.302×10^{-2} m/s and 0.0308×10^{-2} s for $10 \mu\text{m}$ diameter particles, respectively. The stopping distance was 0.0089m and 0.011m for breathing and talking, respectively. The maximum of mean air velocity is in scenario 4 with ACH= 8 that mean air velocity is equal to 0.31 in 1.1m height, respectively. The results of this study showed that avoiding family gatherings is necessary for exposure control and suitable airflow and pattern can be improving indoor air conditions.

Keyword: CFD simulation, air velocity, airflow pattern, living room, COVID-19

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Introduction

With the rapid development of the social economy, the living standard has developed and the residential environment has gained more attention (Han, Zhou et al. 2018). Indoor Air Quality (IAQ) is important to occupant health, especially around the human body (Luo, Weng et al. 2019). The breathing activities generate bioaerosols that may carry viruses and other substances. These bioaerosols might be causing adverse health impacts, such as contagious infectious diseases (Kim, Kabir et al. 2018; Coccia 2020).

Coronavirus disease-2019 (COVID-19) is a severe respiratory disease that originated from the devastating coronavirus family (2019-nCoV) and has become a pandemic across the globe (Bhattacharyya, Dey et al. 2020). COVID-19 is a respiratory disease with an evolving and expanding list of systemic manifestations (Acter, Uddin et al. 2020) and caused by a single-stranded RNA virus with a lipid envelope that has a diameter of approximately 120 nm (range of 80-160 nm) (Asadi, Bouvier et al. 2020; Di Maria, Beccaloni et al. 2020; Vuorinen, Aarnio et al. 2020). COVID-19 disease is with over 111,102,016 known infections and over 2,462,911 deaths reported by February 22, 2021, worldwide. In Iran, as of February 22, 2021, more than 1,574,012 cases of COVID-19 had been confirmed, including over 59,483 reported deaths (WHO 2021).

Coronavirus particles spread between people more readily indoors than outdoors (Chirizzi, Conte et al. 2020). These particles spread through respiratory droplets produced when an infected person coughs, sneezes, talks, or exhales (Blocken, Malizia et al. 2020; Dhand and Li 2020; Scheuch 2020). The contact and droplet transmission is currently considered as the two likely main transmission pathways of the coronavirus from person to person (Morawska, Tang et al. 2020; Xu, Luo et al. 2020). Another way is through direct contact by hands with the polluted surfaces or objects having virus on them (Wang, Feng et al. 2020). The virus may further enter the eyes, mouth or nose by hand touching (Li, Wang et al. 2020). Also, another possible way of virus transmission that has recently been introduced is family parties and gathering takes a place in residential homes.

Using face masks and staying at least six feet away from other people, good air circulation inside buildings will reduce the spread of coronavirus particles (Atangana and Atangana 2020; Klompas, Baker et al. 2020). There is a strong association between transmission of COVID-19 and the air movement in indoor environments which is largely influenced by ventilation system types (Contini and Costabile 2020; Correia, Rodrigues et al. 2020). Ventilation is recognized as the most influential engineering method for reducing airborne transmission indoors. Ventilation airflow rate and room air pattern are two key factors shaping indoor air distribution (Melikov, Ai et al. 2020). Ways to increase ventilation including the windows, dedicated exhaust fan, portable air purifier, upgrade the Heating, Ventilation, and Air Condition (HVAC) system. Also, a limitation in the number of occupants in the room can be suggested (RHODE 2021). Mechanical ventilation systems are implemented in the residential home for thermal comfort and to regulate indoor air distribution (Babu and Suthar 2020). During an epidemic, such as the COVID-19 pandemic, air recirculation should be avoided, and the system operated on 100% outdoor air if possible (Joppolo and Romano 2017; Guo, Xu et al. 2020). But, there is a limitation in the use of the outdoor air in the autumn and winter seasons. One way to assess ventilation is to determine Air Changes per Hour (ACH). A higher ACH can reduce the risk of the disease spreading through the air (Bhagat, Wykes et al. 2020). ACH in the living room recommended 3-6 (Morawska, Tang et al. 2020; Sauermann 2020) and 6-8 (Suwardi, Ooi et al. 2021).

In assessing IAQ, the air movement inside the built space is quite important. Important factors comprise velocity, relative humidity, temperature, and airflow pattern. The airflow pattern depends upon various factors i.e., the position of air supply and exhaust, position and size of window/door, furniture arrangement in room, availability of energy source etc. To simulate and predict the indoor airflow, numerical models were made in accordance with the size of the building. Computational Fluid Dynamics (CFD) is used as an alternative numerical method to study the impact of different variables on the IAQ i.e., airflow pattern and velocity fields (Fareed, Iqbal et al. 2020; Ma, Aviv et al. 2021).

CFD has been used to obtain spatial and temporal solutions of the characteristics of indoor airflow patterns. Development leads to CFD application in various areas i.e. indoor air, biological flows etc. The numerical results of CFD in indoor environments were based on predicting velocity fields and air distribution in rooms. In this method, the fundamental equations describing the conservation of mass, momentum, and energy are solved numerically for a given flow domain (Azari, Sadighzadeh et al. 2018; Bayatian, Ashrafi et al. 2018). Now, CFD using as a reliable tool for the simulation and estimation of velocity fields and airflow patterns in indoor environments (Tong, Hong et al. 2019). On the other, the CFD program user should have good knowledge of fluid dynamics, numerical technique, and indoor air distribution (Sosnowski, Gnatowska et al. 2019).

Most simulation studies are limited to numerical analyses. For example, Sun and Zhai (2020) carried out a study on the efficacy of ventilation effectiveness in preventing COVID-19 transmission. They found that minimum ventilation or fresh air requirement should vary with distancing conditions, exposure time, and effectiveness of air distribution systems (Sun and Zhai 2020). European Centre for Disease Prevention and Control (2020) reported the effect of HVAC systems in the context of COVID-19 (Control 2020). Yang et al (2014) carried out a CFD simulation study in residential indoor air quality. They found that wall-hanging air conditioning systems can undertake indoor heat load and conduct good indoor thermal comfort. Eventually, they reported, compared with the traditional measurement method, CFD simulation has many advantages in simulating indoor environment, so it is hopeful to create a more comfortable, healthy living environment by CFD in the future (Yang and Ye 2014). One of the ways of coronavirus transmitting is to participate in gathering night. On the other, windows are closed in the autumn and winter season and there isn't natural ventilation, therefore, the objective of this study is to CFD simulation in the living room to investigate the air pattern and air velocity in different air supplied and ACH.

Materials and Methods

Case study

The case study was carried out in a living room with $7\text{m} \times 5\text{m} \times 2.5\text{m}$ dimensions in the x, y and z directions, respectively, and 8 occupants. In order to simulate and analyze the effect of air velocity and air supply location on airflow pattern, 3D simulations have been applied. In this living room, air supplies continuously from the entrances door bottom and there are two radiators as heat sources to the room.

Geometry generation

GAMBIT software has been used for geometry building and meshing (Fig. 1). Due to the complex geometry of the case study, the numerical domain has been divided into 31 sub-regions blocks, and a combination of unstructured/structured grid systems has been applied. Mesh generation has been performed by a T-grid algorithm with tet/ hybrid elements (Fig. 2) in each block, and meshes have been adjusted at the block's boundary.

Fig. 1 Geometry of computational domain

Fig. 2 Isometric view of the surface mesh of the flow domain

For mesh independency study, five different numbers of meshes with characteristics shown in table 1 have been tested. Mesh independency analysis ensured that the flow fields at the computational domain were not affected by mesh dimension (Wen and Malki-Epshtein 2018). As shown in figure 3, the final number of the mesh is set to 1,416,884 elementary cells. In this mesh number, the cell spacing size used is 0.02 m (next to occupants and air supply) to 0.33 m (far from occupants and air supply).

Table 1 Mesh characteristics of five cases in mesh independency study

cases	Mesh No.	Node No.	Min. grid spacing (m)	Max. grid spacing (m)
I	515080	95981	0.030	0.50
II	890761	169540	0.025	0.40
III	1153472	210171	0.020	0.35
IV	1416884	251307	0.020	0.33
V	1564255	278773	0.020	0.30

Fig. 3 The effects of the cell number on the average air velocity

Boundary conditions

Boundary conditions are specifications of properties of the surfaces of the computational domains and are required to fully define the airflow simulation. The operating pressure and operating densities were 101,325 Pa and 1.19 kg/m^3 , respectively, and the thermal expansion coefficient was considered 0.003 K^{-1} . The inlet boundary condition was a uniform velocity (2.3m/s), calculated based on the experimental measurement. Table 2 shows boundary conditions used in this study.

Table 2 Summary of boundary conditions		
Boundary	Type	Notes
Air inlet	Inlet velocity	V=2.3m/s, Location: bottom of entrance door
Air outlet	outflow	
Radiators	Wall	T= 345 K
Air inlet	Inlet velocity	V=2 m/s, Location: exhaled of occupants
Obstacles	Wall	No-slip conditions (include: furniture and TV)
Air inlet	Inlet velocity	Refer to Scenario section

Governing equation

In the present study, the commercial package ANSYS FLUENT 16 has been used to solve all governing equations, including conservation of mass (1), momentum (2), energy (4):

$$\nabla \cdot V = 0 \quad (1)$$

$$\rho V \cdot \nabla V = -\nabla P + \mu_{eff} \nabla^2 V + \rho g \beta (T - T_{ref}) \quad (2)$$

where P is pressure, ρ the air density, V the velocity, β the thermal expansion coefficient of air, μ_{eff} the effective dynamic viscosity, g the gravity acceleration, T_{ref} the temperature of a reference point, t the temperature. The turbulent influences are lumped into the effective viscosity as the sum of the turbulent viscosity μ_t and laminar viscosity μ_l :

$$\mu_{eff} = \mu_t + \mu_l \quad (3)$$

$$\rho C_p V \cdot \nabla T = \lambda_{eff} \nabla^2 T \quad (4)$$

where C_p is the specific heat at constant pressure (J/kg °C) and λ_{eff} is the effective thermal conductivity (W/m °C) which can be expressed as,

$$\lambda_{eff} = \lambda_l + \lambda_t \quad (5)$$

where λ_l is the laminar thermal conductivity and λ_t is the turbulent thermal conductivity which depends on the local flow field.

Airflow pattern calculations use the Boussinesq approximation for thermal buoyancy. This approximation takes air density as constant in the momentum terms and considers the buoyancy influence on air movement by the difference between the local air weight and the pressure gradient. Also, in this study, standard k - ε turbulence model has been used that the governing equations for k (6) and ε (7) are:

$$\frac{\partial}{\partial x_i} (\rho u_i k) = \left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla^2 k + \mu_t S^2 - \rho \varepsilon \quad (6)$$

$$\frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla^2 \varepsilon + C_{\varepsilon 1} \frac{\varepsilon}{k} \mu_t S^2 - C_{\varepsilon 2} \rho \frac{S^2}{k} \quad (7)$$

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \quad (8)$$

where coefficients $C_\mu, \sigma_k, \sigma_\varepsilon, C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are 0.09, 1.0, 1.3, 1.44 and 1.44, respectively, and $S = (S_{ij} S_{ji})^{0.5}$

Solver settings

In the present work, the continuity and the incompressible Navier-Stokes equations with gravitational force as well as the energy equation for the airflow pattern have been numerically resolved. The flow is in a steady state without any reaction. The SIMPLEC algorithm was used for pressure-velocity coupling. Also, PERSTO, and QUIK schemes have been used for the pressure terms, and the other variables, respectively.

CFD model validation

The CFD results need to be well validated against relevant experiments (Middha 2010). Therefore, to validate the simulation, air velocity has been measured in the computational domain. Measurements of air velocity have been carried out with two thermal anemometers (Kimo VT100 model). Finally, CFD model results have been compared with air velocity measurements by the root mean square error and regression statistical tests (Ni, Wang et al. 2021).

Scenarios

The air change rate is the velocity at which all the air inside a room is replaced by the ventilation system. It is calculated as the airflow from each ventilation system inlet relative to the total volume of the room in question, and is expressed per hour.

$$ACH = \frac{Q}{V} \quad (9)$$

where Q is the inlet flow rate (m^3/s), A_i the inlet opening area (m^2), and V the room volume (m^3). For the living room, ACH is 3-6 (Sauermann 2020) and 6-8 (Suwardi, Ooi et al. 2021). This study has considered the four air supply in walls (Fig.1) for three ACH (3, 6, and 8). Air supply dimension is $0.4\text{m} \times 0.5\text{m}$ in the x, y respectively. Therefore, air velocity in the inlet opening area has been 0.37, 0.74 and 0.975 m/s in ACH equal 3, 6 and 8, respectively. Air exchange out the frequency in minutes (n_m) can be calculated as $n_m = \frac{60}{n}$, where n in ACH. Therefore, n_m is 20, 10 and 7.5 min for ACH equals to 3, 6 and 8, respectively.

Analytical Solution

Coronavirus transferred via infected microscopic airborne particles and contaminated aerosol droplets. Small particles and droplets of a broad spectrum of diameters get generated during talking and breathing. Particles number maximum produced have $10 \mu\text{m}$ diameter in talking (ISHRAE 2020) and exhaled air velocity during breathing and talking is 2 and 3.9 m/s, respectively (Xu, Nielsen et al. 2017). Hence, we have calculated particle Reynolds number (10) relaxation time (11) stopping distance (12), and terminal settling velocity (13) for particles with $10 \mu\text{m}$ diameter in breathing and talking functions:

$$\text{Re}_p = \frac{\rho V_r d_p}{\mu} \quad (10)$$

$$\tau = \frac{\rho_p d_p^2 C_c}{18\mu} \quad (11)$$

$$S = \frac{\rho_p d_p^2 C_c}{18\mu} V \quad (12)$$

$$V_{TS} = \frac{\rho_p d_p^2 g C_c}{18\mu} \quad (13)$$

where d_p is the particle (μm), V_r the relative velocity of the particle to the fluid, ρ_p the particle density (Kg/m^3), μ the viscosity (Pa. s), C_c the Cunningham correction factor, Re_p the particle Reynolds number, τ the relaxation time, S the stopping distance (m) and V_{TS} the terminal settling velocity of particles (m/s)(Zhang 2004).

Results and Discussions

This section presents the results obtained during the experiments and simulations, validation of simulation, and finally results obtained during the simulations in 4 scenarios (12 cases). As mentioned in the previous section, numerical simulation has been done for a living room in the actual condition. There isn't mechanical ventilation in this condition, and all the doors and windows have been closed; therefore, the computational domain did not have natural ventilation. But air supplied continuously from the bottom entrance door. In this case, the mean air velocity was 1.4×10^{-3} and 1.32×10^{-3} m/s in inhalation zone height (1.1m) for isosurface and plane surface, respectively. Since, most of the exhaust particles from the human respiratory system are $10 \mu\text{m}$ diameter particles in breathing and talking (ISHRAE 2020), calculated particle dynamics parameters as analytically (Tab 3).

Table 3 Particle dynamics parameters for 10 μ diameter particle in breathing and talking

	V_i (m/s)	Re_p	C_D^*	F_D (N)	S (m)
Breathing	2	1.3	22.96	0.98×10^{-14}	0.0089
Talking	3.9	2.6	13.73	0.58×10^{-14}	0.011

* C_D is the Drag Coefficient (dependent on the Re_p), dimensional less

Terminal settling velocity of the particle (V_{TS}) was equal to 0.302×10^{-2} m/s for 10 μ m diameter particles that are similar to Rohit et al studies (less than 2% difference) (Rohit, Rajasekaran et al. 2020). Singh et al reported the terminal settling velocity is 3mm/s for 10 μ m diameter particles (Singh and Kaur 2020) and Wei et al indicated V_{TS} is 0.246 m/s and 0.07 m/s for 100 μ m and 50 μ m particles, respectively (Wei and Li 2015). The relaxation time was 0.0308×10^{-2} s for 10 μ m diameter particles that are approximately similar to the Wei et al studies. After this time, the particle's velocity becomes uniform and occurs terminal settling. Singh et al reported the relaxation time is 0.0003s for the 5 μ m particles (Wei and Li 2015). Stopping distance is the maximum distance a particle can travel with an initial velocity V_i from the mouth in still air in the absence of external forces. This parameter is 0.0089m and 0.011m for breathing and talking, respectively. But, Wei et al reported stopping distance to the initial velocity of 10 m/s is 2.3×10^{-3} m that is equal to 8.97×10^{-4} m for $V_i=3.9$ m/s (Wei and Li 2015). This difference between the results is due to the difference in particle diameter. Since the drag force is very low, the particles can be easily dispersed in the living room. In this condition, due to lack of air displacement in the living room, particles and viruses can remain suspended for a long time and therefore may be inhaled by occupants.

Particle exhaust velocity ($V(t)$) at any time from the mouth depended on initial velocity, relaxation time, terminal settling velocity and particle exhaust time (t) from the mouth. This velocity can be determinate for breathing (14) and talking (15) as:

$$\text{Breathing: } V(t) = 0.302 \times 10^{-2} + 1.99 \exp\left(-\frac{t}{0.0308 \times 10^{-2}}\right) \quad (14)$$

$$\text{Talking: } V(t) = 0.302 \times 10^{-2} + 3.89 \exp\left(-\frac{t}{0.0308 \times 10^{-2}}\right) \quad (15)$$

Where t is time (second). By using these equations, particle exhaust velocity from the mouth can be calculated at any time. When $t \gg \tau$, $V(t) = V_{TS}$. Theoretically, $V(t)$ never reaches its terminal settling velocity, but in practice, $V(t)$ reaches 63.2% of $(V_{TS} - V_i)$ when $t = \tau$, and 99.3% of $(V_{TS} - V_i)$ when $t = 5 \tau$.

Air velocity measured and simulated in the computational domain shown in Figure 4. The maximum error and root mean square error from the air velocity are 14% and 0.10, respectively. Therefore, this model has good validity and different scenarios can be defined and simulated. Figure 5 shows the streamlines of air velocity in the actual condition. In this case, air distribution in the living room is not suitable and air supplies from the entrance door bottom and exhaust from the exterior door without air circulation.

Fig. 4 Q-Q plot of air velocity (m/s)

Fig. 5 Airflow pattern and streamlines of air velocity in actual condition

Fig. 6 Mean air velocity in different air changes per hour at $z=1.1$ m at the Isosurface

There is clear evidence that poor ventilation contributes to coronavirus spread (Bhagat, Wykes et al. 2020). Mechanical ventilation can reduce the airborne concentration of coronavirus. Figures 6-7 show the effect of the supply air location (scenarios 1 to 4) and the air change rate in the living room (ACH equal to 3, 6 and 8) on the mean air velocity in the 1.1 m height for Isosurface and plane surfaces. The maximum of mean air velocity is in scenario 4 with ACH= 8, so that mean air velocity is 0.31 and 0.32 m/s in Isosurface and plane, respectively. Gupta et al. reported that the air velocity should be in the range of 0.25–1.0 m/s that improves the air movement and thus increases comfort (Gupta and Khare 2021). In this condition, particles remain suspended in the living room for a longer time, increasing the likelihood that particles enter the occupant's respiratory system. But, increasing the air velocity and turbulence reduces the concentration of the particles in the living room, which occurring a significant reduction in occupant's exposure and reduces the risk of airborne transmission. Therefore, it can be said, increased air velocity and turbulence causes reduce exposure and infection probability.

Fig. 7 Mean air velocity in different air changes per hour at $z=1.1$ m at the plane

Air movement is an important parameter that affects particle and virus dispersion (Gupta and Khare 2021). Figure 8 shows the airflow pattern streamlines in scenarios 1 to 4 with ACH= 8 (velocity maximum in breathing zone). In scenarios 2 and 4, the most mixing occurred in the living room, and in scenario 4 there is the mean air velocity highest in the room (figs. 6-7), therefore, there is the lowest risk of infectious diseases such as coronavirus in scenario 4. Guo et al. found that effective airflow patterns are the most important infectious disease control strategy by air diluting the around the infectious agent's sources (Guo, Xu et al. 2020). Hence, it is recommended that occupants seat near the air supply or locate the air supply close to the breathing zone because using ventilation can reduce the risk of infectious aerosols.

Fig. 8 Airflow streamlines for 4 scenarios in ACH=8

Figure 9 shows the vectors of air velocity in occupants exhale for 4 Scenarios. Because the exhaust air velocity of the exhaled (2 m/s for breathing mode and 3.9 for talking) is higher than the mean air velocity at 1.1m height (approximately 0.3 m/s in ACH=8), air velocity vectors are similar approximately in all scenarios. After breathing zone, air velocity the exhalation is closed to zero, thus micron particles can be settling at a short distance and sub-micron and nanoparticle can be suspending in the living room for a long time.

Temperature and humidity can influence the COVID-19 stability. Hence, controlling the temperature and humidity is beneficial for controlling the airborne transmission of the virus. But, there are limitations in temperature and humidity changes in residential homes. Morris et al. found that in 21–23 °C temperature and relative humidity of 65%, COVID-19 will not be reduced significantly (Morris, Yinda et al. 2020). Therefore, controlling the temperature and humidity are impossible to exposure reduce to the coronavirus in the residential home.

Fig. 9 Vectors of air velocity in occupants exhale for 4 scenarios

Conclusions

Considering the potential of CFD modeling for indoor air simulating, this study focused to verify and confirm the numerical simulation model in a living room of a residential home in a family gathering for exposure control strategies in the coronavirus pandemic. The data obtained were then used for airflow pattern and air velocity assessment in different scenarios. Coronavirus can be spread in the indoor environment, and poorly ventilated places are considered to be high risk. Current advice is for buildings to be as well ventilated as possible. The results showed that the air supply location and air change rate in the room could reduce exposure to microorganisms such as coronavirus. However, our analysis suggests that avoiding family gatherings in biological diseases outbreak. Otherwise, it is necessary to create a suitable airflow and pattern by the natural and mechanical ventilation systems. It is also necessary to consider other health protocols such as maintaining social distance, surface cleaning and disinfection, handwashing, and other strategies of good hygiene as well as heating ventilation and air condition system.

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Authors' Contributions

Majid Bayatian: Study design, Data collection, Simulation, Measurement, Validation

Khosro Ashrafi: Study design, Simulation

Zahra Amiri: Analytical Solution

402 Elahe Jafari: Experimental sampling, Validation

403 All authors read and approved the final manuscript.

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410

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421 **Competing Interests**

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Figures

Figure 1

Geometry of computational domain

Figure 2

Isometric view of the surface mesh of the flow domain

Figure 3

The effects of the cell number on the average air velocity

Figure 4

Q-Q plot of air velocity (m/s)

Figure 5

Airflow pattern and streamlines of air velocity in actual condition

Figure 6

Mean air velocity in different air changes per hour at $z=1.1$ m at the Isosurface

Figure 7

Mean air velocity in different air changes per hour at $z=1.1$ m at the plane

Figure 8

Airflow streamlines for 4 scenarios in ACH=8

Figure 9

Vectors of air velocity in occupants exhale for 4 scenarios