DESIGNING A SMALL CLIMATE CHAMBER TO CHARACTERIZE PEOPLE AS A SOURCE OF DETERIORATION OF INDOOR AIR QUALITY BY RESPIRATION

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Abstract: People are one of the sources for deterioration of the indoor air quality. They worsen indoor air quality by their presence (respiration, bio-effluents), activities and habits. Through respiration, people decrease the oxygen concentration in the air of the occupied space and increase carbon dioxide and water vapor concentration in the indoor air as well as its temperature. The goal of the AIRMEN project is to find out if the rate of consumption of oxygen and emission of carbon dioxide (and water vapor) by people depends on the indoor air temperature as well as carbon dioxide concentration in the inhaled air. In order to achieve this goal a small climate chamber must be designed and constructed which allows for controlling and measuring both inflow and exposure parameters as well as for measuring outflow parameters. The principal goal of this paper is to present some important details, obtained by CFD simulations, from the design process of the climate chamber which precondition the air distribution in the chamber and hence the exposure parameters.

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Introduction

People are one of the strongest sources of pollution to indoor air. They influence indoor air quality in two general ways: continuously and discontinuously. The continuous impact is due to their decisions about the building construction materials and elements, interior and furniture materials, heating and ventilation systems, etc. The discontinuous impact is due to their presence in a space. Then they deteriorate the indoor air quality by their physiology (respiration, bio-effluents, desquamation, etc.), activities (cooking, cleaning, sport, etc.), and habits (hobbies, smoking, aromatizing, etc.).

People significantly change the composition of the indoor air through respiration. For example, according to Despopolous & Silbernagl (2003), at rest, the body maintains a $\dot{V}_E$ (expiratory volume) of about 8 L/min, with a corresponding oxygen consumption rate ($\dot{V}_{O_2}$) of about 0.3 L/min and a CO_2 elimination rate ($\dot{V}_{CO_2}$) of about 0.25 L/min. Under these conditions, in one hour a person would change volume fractions of O_2 and CO_2 in a 25 m^3 room without ventilation by 720 ppm and 600 ppm, respectively.

In EN 15251-2007 standard there is a procedure to calculate the required ventilation rate based on a mass balance and required criteria for the CO_2 level (B.1.4). In ANSI/ASHRAE 62.1-2016 there is a similar procedure entitled the Indoor Air Quality procedure. Both procedures use the CO_2 mass balance equation under steady state for the calculation of outdoor air required for diluting metabolic CO_2 emissions in the occupied space. This equation reads:

$$\dot{V}_{out} = \frac{\dot{G}_{t,CO2}}{X_{i,x} - X_a} 10^6 \qquad (1)$$

where: $\dot{V}_{out}$ is the flow rate of outdoor air required to dilute the generated metabolic CO_2 in the room, *L/s*; $\dot{G}_{t,CO2}$ is the rate of generation of CO_2 in the room at room conditions by all occupants, *L/s*; $X_{i,x}$ is the maximum allowed volume fraction of CO_2 in indoor air, *ppm*; X_a is the CO_2 volume fraction in outdoor air, *ppm*.

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The standard approach for the calculation of CO_2 elimination rate by a person, based on ASTM D6254-2012 standard and ISO 8996-2004 standard, is given by a set of three equations:

$$\dot{G}_{CO2} = RQ.\dot{V}_{O2} \tag{2}$$

$$\dot{V}_{O2} = \frac{0.00276A_D}{0.23RQ+0.77}M \tag{3}$$

$$A_D = 0.203H^{0.725}W^{0.425} \tag{4}$$

where $\dot{V}_{O2}$, is oxygen consumption rate, *L/s*; RQ=0.83 is the respiratory quotient; M is the metabolic rate per unit of surface area, met (1 met = 58.2 W/m^2); A_D is the DuBois body surface area, m^2; H is body height, m; and W is body weight, kg.

Data about the metabolic rate of standard persons, man (30 years old, W=70 kg, H=1.75 m, A_D=1.8 m^2) and woman (30 years old, W=60 kg, H=1.70 m, A_D=1.6 m^2) are tabled in ISO 8996-2004 as a function of body posture and type of work. ASTM D6245-2012 standard recommends that data about M to be taken from *ASHRAE Fundamentals Handbook* (2009), again as a function of body posture and type of work, and about A_D from *EPA (2011).* No one of those sources of data about M mentions that it depends on temperature.

Chapter 21 by Pulev & Zubieta (2011) provides graphical data about metabolic rate variation with indoor temperature for a healthy, lightly dressed sitting person in thermal balance. According to this document at 18 ºC metabolic rate is about 12% higher than the metabolic rate at 22 ºC, while at 28 ºC it is 5% lower than the one at 22 ºC. From equations, 2 and 3 one may conclude that both O_2 consumption rate and CO_2 elimination rate must vary the same way.

According to Guyton & Hall (2006) ”The goals of respiration are to provide oxygen to the tissues and to remove carbon dioxide. To achieve these goals, respiration can be divided into four major functions: (1) *pulmonary ventilation,* which means the inflow and outflow of air between the atmosphere and the lung alveoli; (2) *diffusion of oxygen and carbon dioxide between the alveoli and the blood;* (3) *transport of oxygen and carbon dioxide in the blood and body fluids* to and from the body’s tissue cells; and (4) *regulation of ventilation* and other facets of respiration.”

Since the mechanism for the exchange of both O_2 and CO_2 between the blood and alveoli is diffusion, one may conclude that CO_2 elimination rate by a human depends on the CO_2 concentration of the air in its breathing zone.

Having all this in mind, the AIRMEN project was initiated. It aims to find out if the rate of consumption of oxygen and emission of carbon dioxide by people depends, and to which extent, on the indoor air temperature as well as carbon dioxide concentration in the inhaled air. In order to achieve this goal, a small climate chamber must be designed and constructed which allows for controlling and measuring both inflow and exposure parameters as well as for measuring outflow parameters.

The principal goal of this paper is to present some important details, obtained by CFD simulations, from the design process of the climate chamber, which precondition the air distribution in the chamber and hence the exposure parameters.

Method

Physical situation

A person is sitting at thermal neutrality, and doing office work, in a small climate chamber (Exposure Box - EB), which is located within a bigger climate chamber (CC). The floor area of EB is 0.8x1.4 m^2, and its height is 1.6 m. In front of the person, there is a table with dimensions 0.5x0.5 m^2, which is positioned at 0.15 m from EB left, right and front wall and its upper surface is at 0.7 m above the EB floor. The floor area of the CC is 1.9x1.9 m^2, and its height is 2.57 m.

Outdoor air is supplied at the desired temperature to the space between the EB and CC. Part of this air, with known flow rate, is forced to pass at very low velocity through the EB by a suction fan installed at its outlet. The rest of the air leaves the CC through its walls via transfer grills. In this way, it is ensured that the radiant asymmetry in the EB in all directions is equal to zero and the mean radiant temperature is equal to the air temperature.

Technically pure CO_2 gas is injected into the supply air in order to change the CO_2 volume fraction in the breathing zone of the subject. Supply air relative humidity and oxygen concentration, as well as barometric pressure and gage pressure in the EB, are measured. The air temperature and RH, as well as O_2 and CO_2 volume fractions, are measured at the outlet of the EB.

CO_2 concentration in the breathing zone is a result of the interaction of three flows: the ventilation flow, the free convection flow around the occupant's body and the respiration flow. Both the ventilation flow and the free convection flow are unidirectional and could be at a quasi-steady state while the respiration flow is unsteady and bidirectional.

A typical breathing cycle is composed of 2.5 sec of inhalation, followed by 2.5 sec of exhalation and 1 sec of pause, i.e. no flow. Under these conditions, measuring CO_2 in the inhaled air, even in the breathing zone air, is difficult due to the limitations of the sampling rate of the existing CO_2 sensors. Due to the interaction between the three flows, there is a high probability for re-inhalation of the exhaled air. Under these conditions, the CO_2 concentration in the inhaled air may differ from the CO_2 concentration in the supply air. Hence, it must be ensured by the design of the air distribution system that the CO_2 concentration in the inhaled air is known. A proper design of the air distribution under these conditions can be done by CFD simulations only.

Numerical model

The scanned body of a female thermal manikin with a body surface area of 1.5 m^2 represents the sitting person in the EB. Its nostrils are located at 0.4 m from the side walls, 0.9 m from the front wall and 1.22 from the floor. The metabolic rate of the person is 105 W. Since the manikin is naked, it is assumed that the heat flux is evenly distributed over its surface, and is equal to 70 W/m^2. The breathing cycle is represented by continuous exhalation at a temperature of 36 ^oC, a flow rate of 0.19466044 L/s and CO_2 volume fraction of 31637 ppm, which corresponds to the expiratory volume of 10.8 L/min, oxygen consumption rate of 7.155 mg/s and CO_2 generation of 9.963 mg/s.

Here only the cases, under which ventilation air is supplied to EB with a flow rate of 10 L/s, a temperature of 18 ^oC and CO2 volume fraction of 400 ppm, are considered. Resulting air velocity at the EB inlet is 0.009 m/s. Absolute pressure in the EB is 94490 Pa (10 Pa of suction pressure).

Two general modes of air supply to EB are studied: Diffusion ceiling (Case 1) and Diffusion floor (Case 2). They are presented in Figure 1.

Computational details

The SnappyHexMesh utility of Helyx software, an enhanced version of OpenFoam by Engys, was used for the generation of the computational grid. The base cell size within the fluid volume is 25 mm. Cell size over the EB walls is 3 mm. The first layer of cells over the surface of the manikin is 0.8 mm. Local refinement is used as well in the breathing zone, where cell size is 0.8 mm too. The computational grid for Case 1 is composed of 1962362 cells, and for Case 2 is 1956872 cells.

Steady-state RANS simulations were performed by the *buoyantBoussinesqSimpleFoam* solver included in Helyx software. SIMPLE algorithm was used for velocity-pressure coupling. For turbulence modeling, the Shear Stress Transport k-ω model was used. It is a two equations model, for turbulent kinetic energy (k) and for the specific dissipation rate of turbulent kinetic energy (ω), which applies the eddy-viscosity concept. The main advantage of this model is that it behaves as the Low Re turbulence model in the boundary layer, including the viscous sub-layer, and as the κ-ε model far from the surfaces (Menter, 2011). CO_2 concentration field was predicted by the passive scalar technique.

For both cases over the manikin surface, a fixed heat flux boundary condition was set, and the vertical walls and the table were treated as adiabatic. The inlet and outlet for Case 1 were set, respectively, to free surface and fixed extract flow rate, while for Case 2 they were set as a fixed inlet flow rate and a free surface outlet.

Results and discussion

The Risk of draught (DR) distribution in the vertical planes, passing through the manikin's nostrils, is visualized in Figure 2 by contour plots.

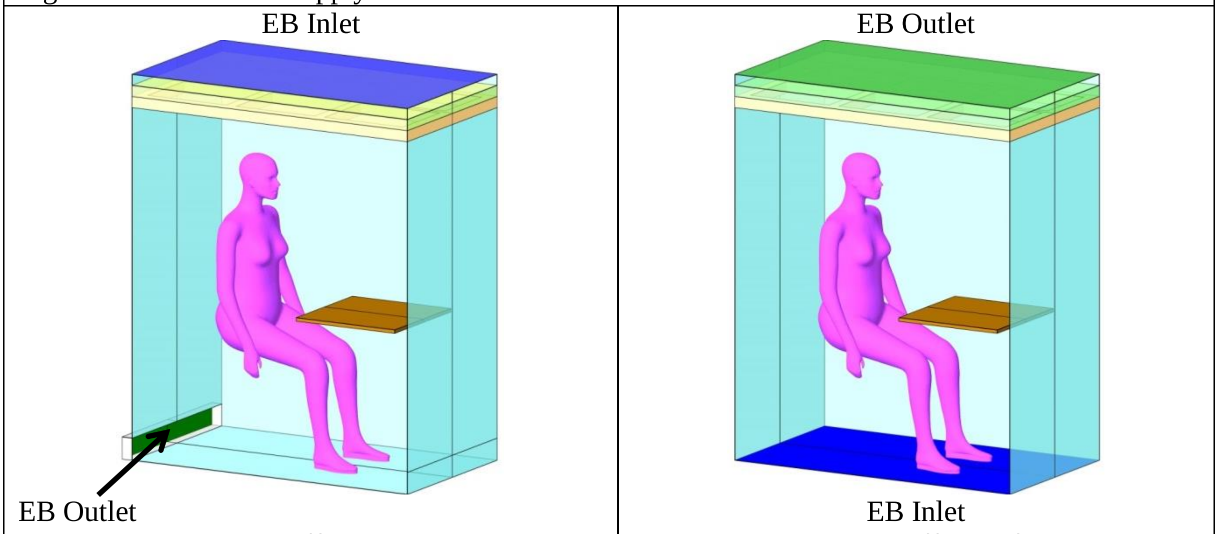
DR, which characterizes the local heat exchange by convection, is defined in ISO 7730-2007 as

$$DR = (34 - t_a)(\bar{V} - 0.05)^{0.62}(0.37\bar{V}T_u + 3.14) \quad (5)$$

where DR is the percentage of people dissatisfied due to draught, %; t_a is the local air temperature, ^oC; $\bar{V}$ is the local mean velocity (magnitude), m/s; T_u is the local turbulence intensity, %.

The CO_2 volume fraction distribution in the vertical planes, passing through the manikin's nostrils, is visualized in Figure 3 by contour plots.

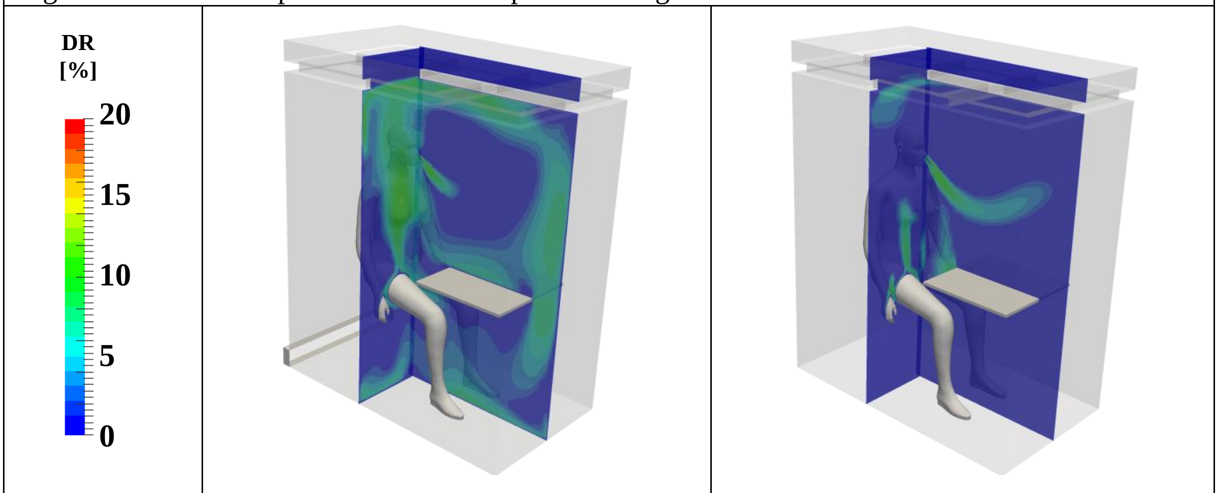
Figure 1: Modes of air supply to EB



a) Case 1: Diffusion ceiling b) Case 2: Diffusion floor

Source: Authors

Figure 2: DR contour plots in the vertical planes through manikin nostrils



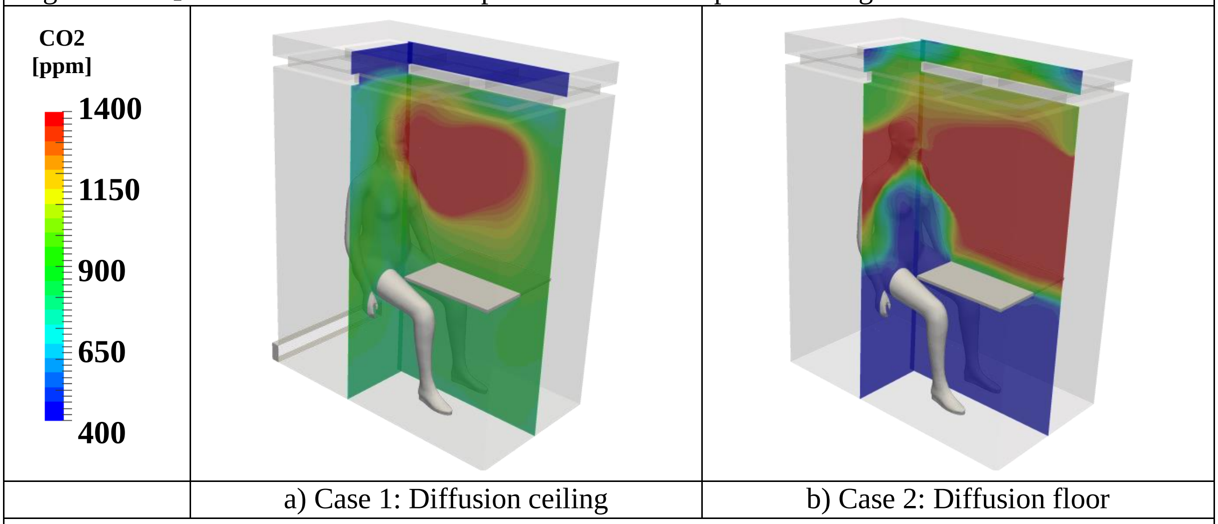
a) Case 1: Diffusion ceiling b) Case 2: Diffusion floor

Source: Authors

In Case 1, in front of the manikin's face a zone with a very small risk of a draft is formed. In this zone the exhaled air jet is clearly seen. In this case, supply air flow direction is opposite to the direction of the free convection flow around the manikin's body, but the impulse of both the ventilation flow (with very low velocity) and respiration flow (with a very small flow rate) is too small to introduce intensive mixing in the zone concerned. As a result, a recirculation flow is generated, and a bubble with high CO_2 concentration (around 1400 ppm) is formed in front of the occupant's face. The risk of re-inhalation of the exhaled air is high. Clearly, complete mixing is not possible without introducing another source of impulse (a mixing fan) in the air volume of EB. There is a risk for the occupant to feel uncomfortable due to draught at the upper part of its torso and the head, as well as at the thighs near to the edge of the table.

In Case 2, both the ventilation flow and the free convection flow around the occupant's body act in the same direction. In this case, DR is close to zero almost in the whole domain and especially in front of the occupant above the table. The exhaled air jet is longer than in Case 1, and it changes its direction above the table since exhaled air temperature is higher than the supply air temperature. The plane of the upper surface of the table splits the EB fluid volume into two sections: clean, below the plane, and rich of CO_2 above the plane. The extent of the zone with high CO_2 concentration in front of the occupant is more significant than in Case 1, but clean air is fed directly to occupant's nostrils by the free convection flow. Like in Case 1, there is a risk of draught at the thighs near to the edge of the table.

Figure 3: CO_2 volume fraction contour plots in the vertical planes through manikin nostrils



a) Case 1: Diffusion ceiling

b) Case 2: Diffusion floor

Source: Authors

Conclusion

With the help of CFD at the stage of conceptual design of an air distribution system, one could obtain valuable information about the advantages and disadvantages of each of the cases concerned.

Based on the numerical results obtained Case 2 provides better conditions for the planned experiment.

Although the numerical model used does not take into account the periodic character of the respiration flow the main advantage of Case 2 is made clear – the supply air is transported to the nostrils of the occupant by the free convection flow around the body. In this way, the CO_2 concentration to which the EB occupant is exposed is known.

The next step is a detailed design of the exposure box with diffusion floor.

In order to avoid the risk of draught at thighs, the distance between the occupant and the table has to be adjusted.

For the purpose of the experiment planned at the outlet of the EB the emitted CO_2 by the occupant has to be completely mixed with the ventilation air. In order to achieve this, the EB height has to be increased, the position and the size of the table have to be adjusted.

At the end of the design based on this simplified numerical model, a transient simulation must be performed, which takes into account the periodic character of the respiration flow.

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