Numerical Modelling of the Draught Rate in a Mechanically Ventilated Climate Chamber

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Abstract. The thermal environment in an indoor space is determined by the thermal state of the human body, and the local thermal discomfort. The draught rate (DR) is one of the indices for thermal discomfort. The achievement of air distribution without draught is one of the goals of the ventilation methods. It is especially important in the design of climate chambers, where the volume is small, and the research studies may require prolonged occupants’ exposure. Our study shows results from the CFD simulations of a mechanically ventilated climate chamber, performed in the design stage of the chamber’s construction. Velocity profiles distribution, temperature distribution and DR are used to assess the thermal comfort of the person in the chamber. The results obtained allowed designing of the proper indoor environment with desired characteristics for air distribution and human exposure.

1. Introduction
The thermal environment in an indoor enclosure is assessed on the base of two main indices: the Predicted Percentage of Dissatisfied (PPD) that reflects the thermal state of the occupants and the draught rate (DR), which is one of the indices for the local discomfort [1-3]. A goal of the ventilation methods for indoor spaces is to create air distribution without draught; otherwise, the high air velocity is easily perceived as draught, assessed as thermal discomfort. The appearance of draught, together with thermal asymmetry is among the most critical factors for occupants’ complaints [4].

The design of a climate chamber, aimed to be used for performing tests with human subjects or a thermal manikin, should satisfy the requirements of the standards for indoor environment in terms of the thermal satisfaction of the occupants. At the design stage, numerical modelling of the climate chamber could only be applied as a tool for solving the problems with high air velocity and DR. The approach is primarily used for assessment of the DR in various enclosures: an indoor swimming pool [5], a naturally ventilated plan office [6] or a hospital [7]. Different studies [8-10] concluded that DR could be the leading cause of thermal dissatisfaction even when other characteristics of the thermal environment correspond to the requirements of the standards.

Our literature survey showed that there is a lack of information on the reported application of CFD at the design stage of a climate chamber construction, used for assessment of the indoor air quality. The specifics of these devices involve small dimensions, restricted volume, use of ventilation facilities, a prolonged stay of the occupants. The design of a climate chamber should be carefully made before the final construction, having in mind the large scale of its possible applications, e.g. thermal comfort assessment, spreading of respiratory diseases, occupants’ performance, health and safety [11].
Our paper aims to present results from the CFD simulation of a mechanically ventilated climate chamber, performed in the design stage of the chamber construction within the AIRMEN project [12]. Velocity profiles distribution, temperature distribution and DR are used to assess the thermal comfort of the person in the chamber. The results obtained allowed designing of the proper indoor environment with desired characteristics for air distribution and human exposure.

2. Requirements towards the climate chamber’s design

The design of the climate chamber should fulfil the following requirements:

- The climate chamber should have a small volume: to be able to reach a relatively fast equilibrium (in approx. 15 min) in terms of thermal environment and air quality in the presence of an occupant.
- The thermal environment should be controlled in terms of physical parameters that affect the dominant mechanisms of heat dissipation from the surface of the human body: *air temperature; *air velocity; *turbulent intensity of the airflow; *temperature of the walls; *temperature of the surfaces in direct contact with the body of the occupant.
- To maintain the operating temperature from 18°C to 28°C, which corresponds to the range of possible thermal conditions, according to EN 16798-1:2019 [13].
- To assure controlled air quality in terms of the concentration of oxygen and carbon dioxide in the breathing zone.
- To allow measuring the air temperature and the concentration of active substances at the inlet and the outlet of the occupied zone.
- To allow airflow measurement at the outlet.
- To allow dosing of technically pure CO₂ in the supplied air.
- To assure the comfort of the occupant in a sitting position while performing tasks on a computer for 3 hours.

These requirements could be met through the construction of a thermally insulated, environmentally closed volume (climate chamber) in which another volume (exposure box) is placed. The exposure box must separate the air in the climate chamber from the air in the occupied zone (exposure box), not allowing them to mix. The separation can be achieved with a thick (100 μm) transparent polyethylene film attached to a wooden frame. Thus, the air temperature on both sides of the barrier will be the same, while the air composition is different. The operating temperature (determined by the air temperature and the temperature of the walls) in the exposure box will also be equal to the air temperature in the climate chamber. Similarly, the temperature of the surfaces in contact with the occupant's body is equal to the temperature of the air in the exposure box. To avoid the draught feeling the speed of the ventilation air and its turbulent intensity have to be very low.

3. Numerical procedure

3.1. Mathematical model and CFD background

The simulations are based on the Steady-state Reynolds Averaged Navier-Stokes (RANS) equations and the energy equation. Helyx CFD code (an enhanced version of OpenFoam by Engys) with “buoyantBoussinesqSimpleFoam“ solver is used. The SST k-ω turbulence model is applied to solve the closure problem and the SIMPLE algorithm – for the discretization of the system of partial differential equations.

3.2. Simulated enclosure

The simulated climate chamber is 1.90 m in length, 1.90 m in width and 2.57 m in height. Inside the chamber, aimed to assure and control different environmental conditions, an exposure box must be built. The dimensions of the exposure box are 1.40 m length, 0.80 m depth and 1.60 m height. The exposure box shelters a sited person; thus, a table, located at 0.7 m above the floor, and a chair are also
simulated. The exposure box is needed for the planned CO₂ measurements within the AIRMEN project [12].

3.3. Simulated body

A virtual thermal manikin is used as an occupant in the numerical experiment: a standard Scandinavian woman, with weight 60 kg and height 1.7 m. It corresponds to the Pernille thermal manikin (PT Teknik, Denmark), which body and dimensions have been scanned at the International Center for Indoor Environment and Energy (Danish Technical University). The body surface is 1.5 m², and its volume is 58 L. The manikin completes a sedentary work, producing 70 W/m² of heat [14]. Under these conditions, the amount of CO₂, generated by the occupant, is 9.841 mg/s [15].

3.4. Computational grid and boundary conditions

SnappyHexMesh tool of Helyx is used to build the computations grid. The discretization of the volume of the exposure box is done using cubical control volumes (CVs) with 25 mm length of the edge. On the manikin surface, the breathing zone, and near-wall regions local grid refinement is applied (3 mm edge length of the CVs in the near-wall regions and 0.8 mm edge length of the CVs in the breathing zone of the manikin).

The following boundary conditions are applied: *Walls: adiabatic, with a temperature equal to the ventilation air temperature; *Table: adiabatic, with a temperature equal to the ventilation air temperature; *reference pressure in the exposure box: 94490 Pa; *Ventilation air (inlet): 10l/s volume flow rate, temperature of 18-22-26°C; 400 ppm volume fraction of CO₂; *Exhaled air (inlet): 0.1947l/s volume flow rate; temperature 36°C, 0.04844 kg/kg mass concentration of CO₂; *Virtual manikin: uniform heat flux of 70W/m²;

3.5. Simulated cases

Several cases were simulated within the AIRMEN project, but our paper presents 6 of them, as shown in Table 1 and Figure 1.

Table 1. Simulated cases.

| Design | Description | Flow parameters |
|--------|-------------|-----------------|
| 1      | Diffusion ceiling (6 panels, even supply), Exhaust (front 18°C / 22°C / 26°C wall, bottom, 0.08m²), solid table top | 10 l/s |
| 2      | Diffusion ceiling (6 panels, even supply), Exhaust (back 18°C / 22°C / 26°C wall, bottom, 0.08m²), solid table top | 10 l/s |
| 3      | Diffusion ceiling (4 panels, 2 panels blocked, even supply),18°C Exhaust (back wall, bottom, 0.08m²), solid table top | 10 l/s |
| 4      | Diffusion ceiling (4 panels, 2 panels blocked, uneven 18°C supply), Exhaust (back wall, bottom, 0.08m²), solid table top5+5, 6+4, 7+3, 4+6, 3+7 l/s | |
| 5      | Diffusion floor (even supply), Exhaust (ceiling), solid table 18°C/ 22°C / 26°C top | 10 l/s |
| 6      | Diffusion floor (even supply), Exhaust (ceiling & front wall 18°C corner, 72cm x 36cm), porous table top | 10 l/s |
Case 1
Case 2
Case 3
Case 4
Case 5
Case 6

Figure 1. Simulated cases

4. Results and discussion
Figure 2 presents the results for the velocity magnitude of the airflow. The velocity fields show that the best flow mixture and lowest velocity is obtained with the even air supply from the floor (diffusion floor) and exhaust from the ceiling (Cases 5 and 6). All other cases (Cases 1-4), where the air is supplied through the ceiling and led away from the floor, provoke the appearance of zones with a different velocity around the most sensible parts of the body: ankles, neck, shoulders.

Figure 2. Numerical results for the velocity field: velocity magnitude \( U \), m/s.
The comparison of the results for Case 5 and Case 6 shows that porous table use (Case 6) leads to better velocity distribution, due to the decreased effect of the table in front of the sitting person as an obstacle.

Figure 3 shows the numerical results for the temperature field. In all reported cases, there is a difference in the air temperature above and below the table. This difference is most notable in Cases 1, 3, 5 and 6. The air supply through the floor turns the table in an obstacle that impedes the even temperature distribution around the manikin, thus affecting the thermal sensation of the upper and lower part (under the table) of the body.

![Case 1](image1.png) ![Case 2](image2.png) ![Case 3](image3.png)

Case 1  Case 2  Case 3

![Case 4](image4.png) ![Case 5](image5.png) ![Case 6](image6.png)

Case 4  Case 5  Case 6

**Figure 3.** Numerical results for the temperature field: temperature T, K.

The numerical results for the DR, calculated as a post-processing procedure, following [16], are shown in Fig. 4. They correspond very well to the results for the velocity distribution around the virtual manikin. The DR is highest for Cases 3 and 4 that is the design with 4 panels on the ceiling (2 panels blocked).

The exposure box design, with airflow movement from bottom to top, simulated in Cases 5 and 6, would allow the best comfort conditions for the occupants in terms of the felt draught. The DR as an average is below 4%, and in small zones of the chests, the DR increases to an average of 8%. The use of porous table leads to an improvement of the DR (Case 6).

### 5. Conclusions
The results from the simulation show that from the six investigated cases, the best results for the DR would be obtained following the design strategy in Cases 5 and 6. The supply of ventilated air from the floor and its drawing away from the ceiling would allow the best conditions for the sitting person to perform prolonged (up to 3 hours) tests in the exposure box. The use of porous (perforated) table would facilitate the air transfer from the bottom to the top of the exposure box, decreasing the obstacle effect. The porous table helps the achievement of a more even temperature field below and above the table, thus decreasing the difference in the air temperature around the lower and upper parts of the sited body.
The CFD modelling is a powerful tool for making decisions for the design of such a unique type of enclosures as a climate chamber. The numerical results help to preliminary design the climate chamber for the particular tasks that are needed to be performed in the chamber, avoiding general purpose, expensive and non-effective constructive solutions that could be made without the simulation.

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