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MODELLING OF AIR EXCHANGE "AIR SUPPLY FROM ABOVE - REMOVAL FROM ABOVE"

Abstract: *The efficiency of the air exchange scheme "air supply from above - removal from above" is considered. Heat and mass exchange of the system including: mathematical model of a human being (breathing process with release of carbon dioxide, heat and water vapour into the environment) with simultaneous heat release from the clothed body surface; supply ventilation system (CO_2, water vapour and heat input with atmospheric air); exhaust ventilation system (removal of the above-mentioned harmful substances contained in the air). Application of numerical modelling ANSYS CFD (Computational Fluid Dynamics) based on continuity equations and averaged Reynolds-Averaged Navier-Stokes equations "RANS" (Reynolds-Averaged Navier-Stokes) gave the following results: the inverse problem of ventilation was solved - for the initially polluted investigated space of the room the interaction of systems (human and operating supply and exhaust ventilation unit) was considered; monitoring and visualisation of changes in CO_2 concentration, temperature and relative humidity in the investigated space by time and by height of the room; the obtained results are compared with the previously obtained results of changes in carbon dioxide concentration, temperature and relative humidity in the ventilated space under the air exchange scheme "air supply from above - removal from below" (Scheme A) and normative documents. The dynamics of excess heat,* *humidity and carbon dioxide (CO_2) assimilation allowed us to assess the efficiency of ventilation systems and predict an increase in their energy efficiency when bringing air parameters up to standard values. Changes in the air environment are typical for premises with mechanical supply and exhaust ventilation (flow classrooms of educational institutions, classrooms of schools, group rooms of kindergartens, conference halls, offices). For this type of premises the main air pollutants are carbon dioxide, water vapour and heat.*

Keywords: mathematical model, "air contaminant", aerodynamics, computational fluid dynamics, air change scheme, relative humidity, temperature, carbon dioxide concentration, room working area, rebranding, supply and exhaust ventilation.

Introduction. Based on the patterns of distribution of "air contaminants" in the volume of isolated air space, it became possible to solve the inverse problem of supply and exhaust ventilation. The change in the state of the air environment initially polluted with carbon dioxide, heat and water vapor was studied when people were in the space and the supply and exhaust ventilation was operating [1]. A study of the efficiency of four generally accepted indoor air change schemes has been conducted:

- Scheme A "air supply from above – removal from below" [1];
- Scheme B "air supply from above – removal from above";
- Scheme C "air supply from above – removal of air from two zones above and below";
- Scheme D "air supply from below – removal from above" (displacement ventilation).

The results of the studies for the scheme B are presented in this publication.

Tasks related to the design, installation, adjustment and control of supply and exhaust ventilation systems require careful monitoring of changes in the air environment. This is due to both the implementation of the requirements of the legislative framework of Ukraine and its harmonization with the standards of the European Union [2, 3], and the solution of problems to prevent the spread of pandemics that are currently haunting humanity [4].

Changes in the air environment are typical for rooms with mechanical supply and exhaust ventilation (flow classrooms of educational institutions, classrooms of schools, group rooms of kindergartens, conference rooms, offices). The main "air contaminants" that are released in this case are carbon dioxide, water vapor and heat.

Literature review and problem statement. Lecture halls, classrooms, preschool children's groups, conference halls, auditoriums (theatres, cinemas, indoor stadiums) – all these premises are united by the type of harmful substances that pollute the air in them:

- carbon dioxide;
- heat;
- water vapor.

The limitation on the concentration of CO_2, the temperature and relative humidity in the working area (WA) of the premises are supplemented by the mobility of air in (WA), the speed of the air stream entering from the air distributor in (WA), the temperature difference between the temperature of the stream and the air temperature in (WA) according to the regulatory documents of Ukraine [2, 3].

In the practice of calculating changes in the state of the air environment in rooms for various purposes, different methods and approaches were used [4-12]. Examples of successful solutions to applied ventilation problems do not remove the question of the accuracy of the results obtained using mathematical modeling. Currently, mathematical modeling methods are used in engineering calculations, which provide an estimate of flow parameters based on the numerical solution of the Reynolds equations of stationary or non-stationary Navier – Stokes equations. (English RANS/URANS: Steady/Unsteady Reynolds Averaged Navier – Stokes) [10].

The aim and objectives of the study. The aim of the study is to develop a mathematical model that determines the processes of heat and mass exchange between humans and the environment. Based on this model, it is possible to solve applied problems related to the creation of a comfortable microclimate in rooms, increasing the energy efficiency of systems that provide air change [2].

Research results. Modeling of the intake of "air contaminants", scheme B. Among practically used air change schemes for rooms, scheme b is the most common. It is effective at assimilating heat and humidity. When carbon dioxide is removed, this air contaminant first falls to floor level under the action of gravitational forces, and then rises, passing through the human breathing zone due to air circulation created by the exhaust ventilation system.

Scheme B (Fig. 1) provides the following constructive conditions for ventilation functioning:

- air supply from above using a static chamber and a ceiling diffuser with a working diameter of Ø150mm;

- consumption of supply and exhaust air: 120 m^3/h;

- exhaust ventilation is organized in the upper part of the wall using a ventilation grid.

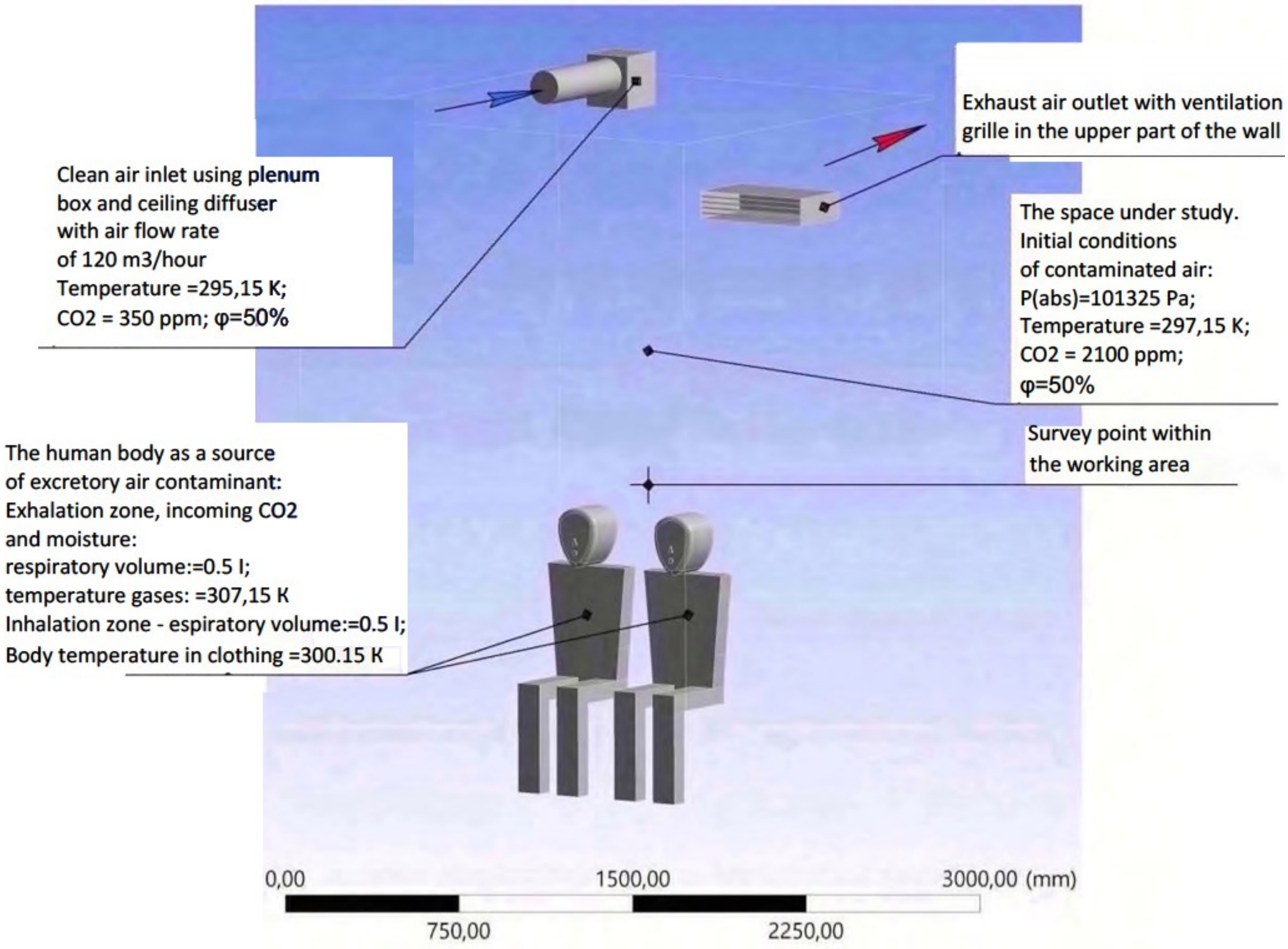

Fig. 1 Modeling and research according to scheme B

The dynamics of changes in the CO_2 concentration at the monitoring point in a 680-second period of time is presented in Fig. 2.

Volumetric visualization of changes in carbon dioxide content in a 680-second period of time according to scheme B is shown in Fig. 3-5

Discussion of research results. Based on the developed mathematical model, it became possible to solve such problems using the ANSYS software package as:

- Intake of "air pollutants" by a person in an isolated space.
- Modeling the intake of "air pollutants", scheme A;
- Modeling the intake of "air pollutants", scheme B.

The ANSYS mathematical apparatus allows analyzing the operation of a supply and exhaust unit for the redistribution and removal of the main "air pollutants" (carbon dioxide, heat, water vapor) from a room and tracking the values of temperature, moisture content, relative humidity, enthalpy and air velocity. In particular, based on the contour distribution of air pollutants in the surveyed space (Fig. 18-25), it became possible to evaluate and compare the efficiency of various air distribution schemes in the WA.

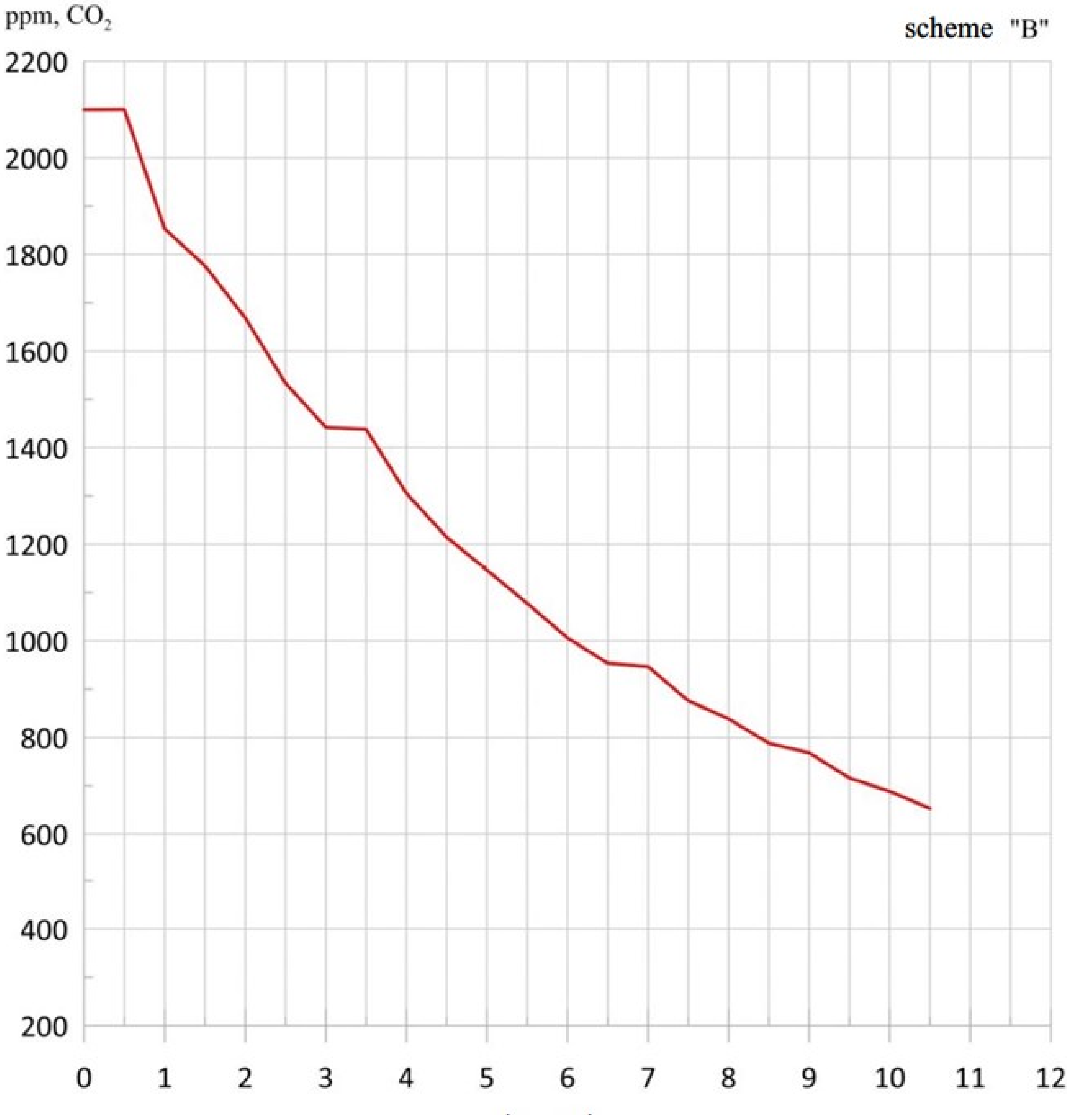

Fig. 2 Dynamics of changes in CO_2 concentration over time of observation

The rendering (visualization) of temperature and volumetric humidity content over time relative to the observation point is presented in Fig. 8-13. Stream lines from the ceiling diffuser of scheme B are in Fig. 6. Graphs of changes in temperature and relative air humidity for scheme B are presented in Fig. 7. The boundary contours of the distribution of "air contaminants" between the upper zone of the room and the WA after nine minutes of operation of supply and exhaust ventilation are shown in Fig. 14-17.

Fig. 18-29 shows the contours of temperature, air velocity, moisture content and carbon dioxide distribution over the height of the study space after 9 minutes of the study.

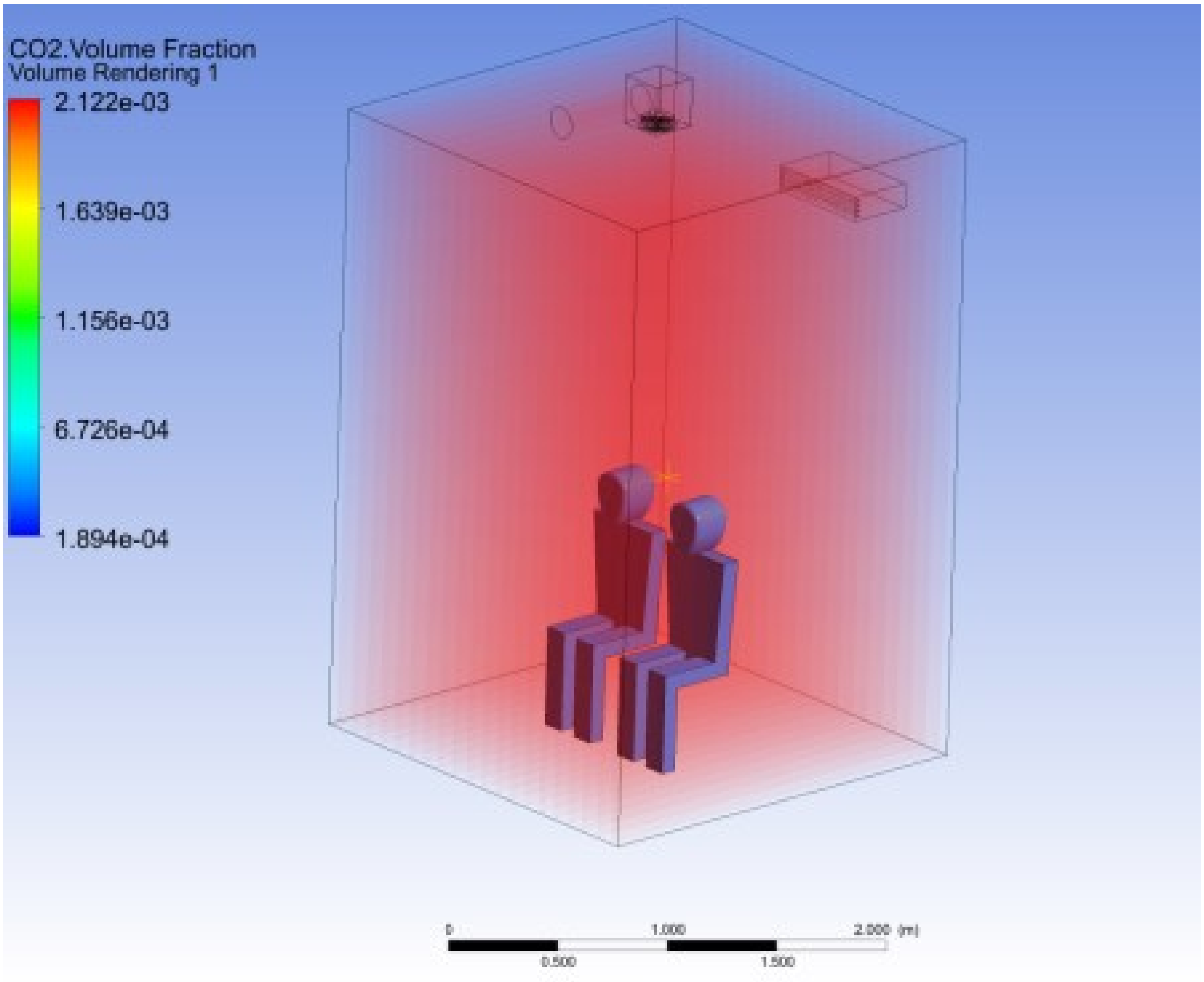

Fig. 3 Volumetric rendering of CO_2 over time relative to the observation point, scheme B, $T = 0$ s

Data processing in Fig. 18-29 made it possible to compare the obtained results with the regulatory requirements for the optimal parameters for introducing an air stream from a ceiling diffuser into a WA room (see Table 1).

Conclusions. With the use of the ansys software package, mathematical modeling of processes of changing the state of the air environment has become possible. An objective opportunity has appeared to study: processes of heat and mass exchange and hydrogas dynamics during the interaction of systems (human and air handling unit operating according to various air change schemes); obtain intermediate results of the efficiency of various air change schemes in the room. Subsequent publications will allow a comprehensive assessment and comparison of the efficiency of all four air change schemes we have chosen, when solving the inverse problem (bringing the parameters of the polluted air environment of the room to optimal standard parameters by means of general exchange ventilation).

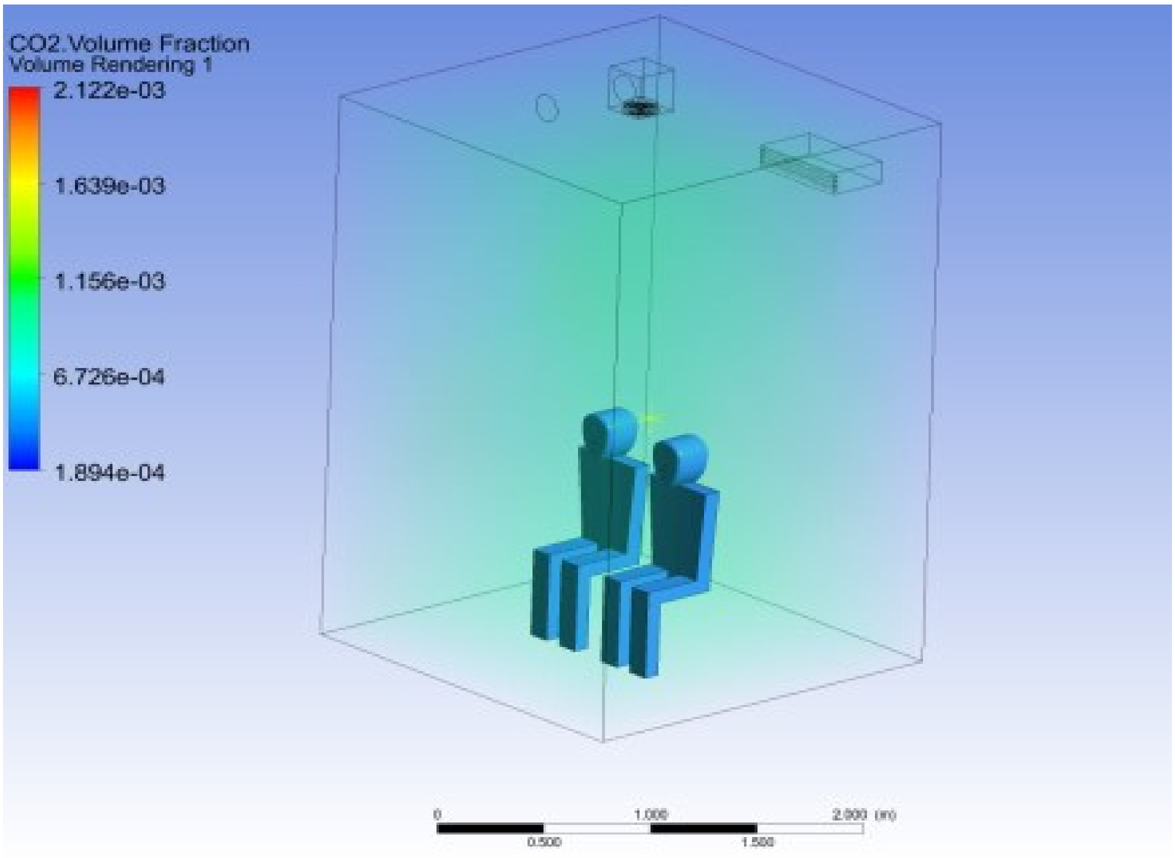

Fig. 4 Volumetric rendering of CO_2 over time relative to the observation point, scheme B, T=340 s

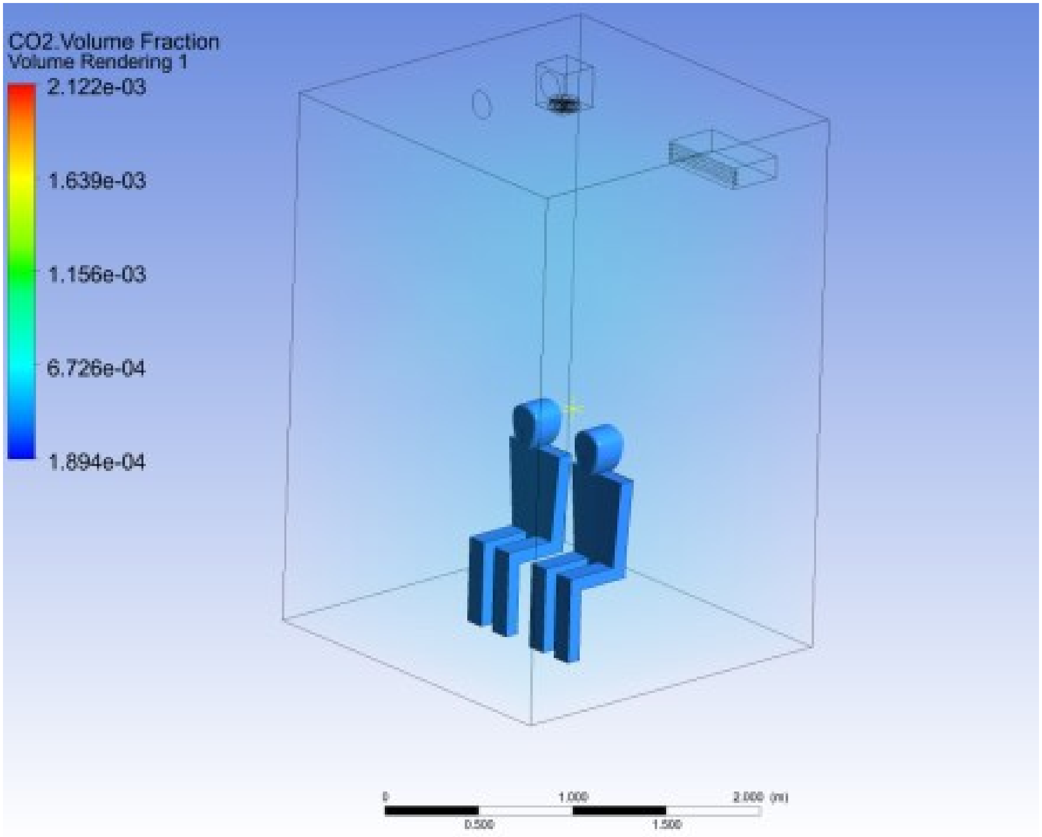

Fig. 5 Volumetric rendering of CO_2 over time relative to the observation point, scheme B, T = 680 s

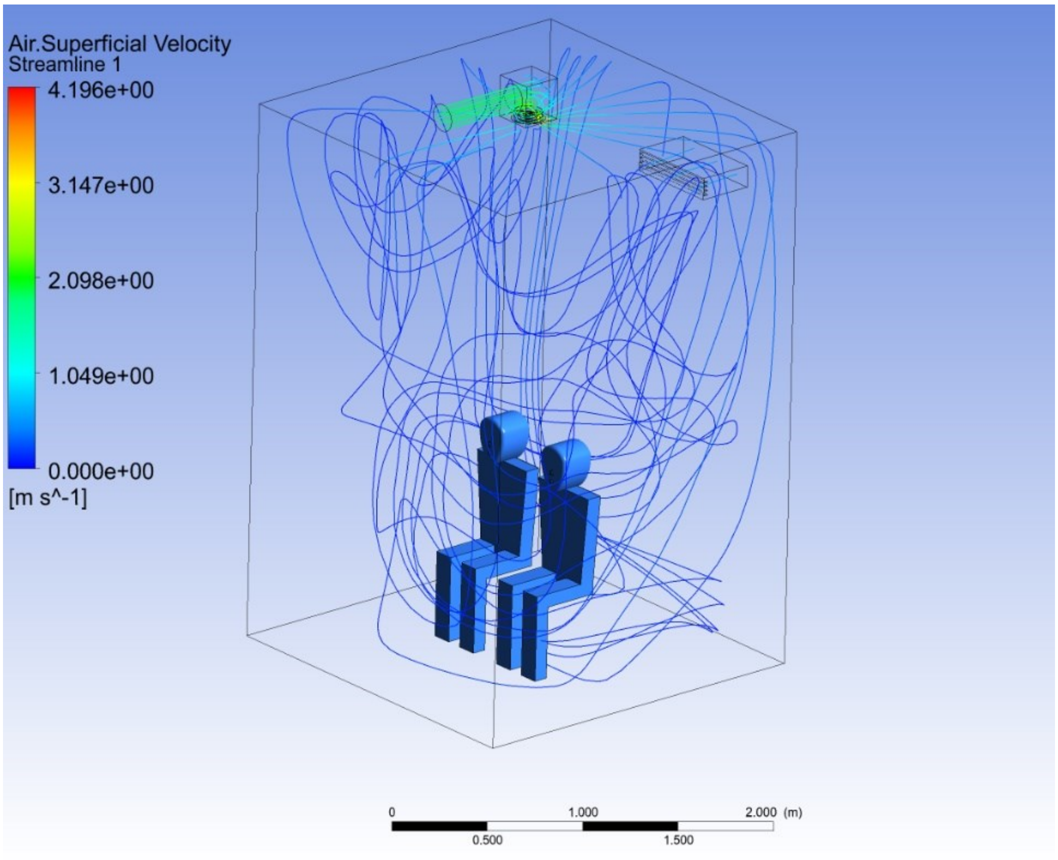

Fig. 6 Stream lines

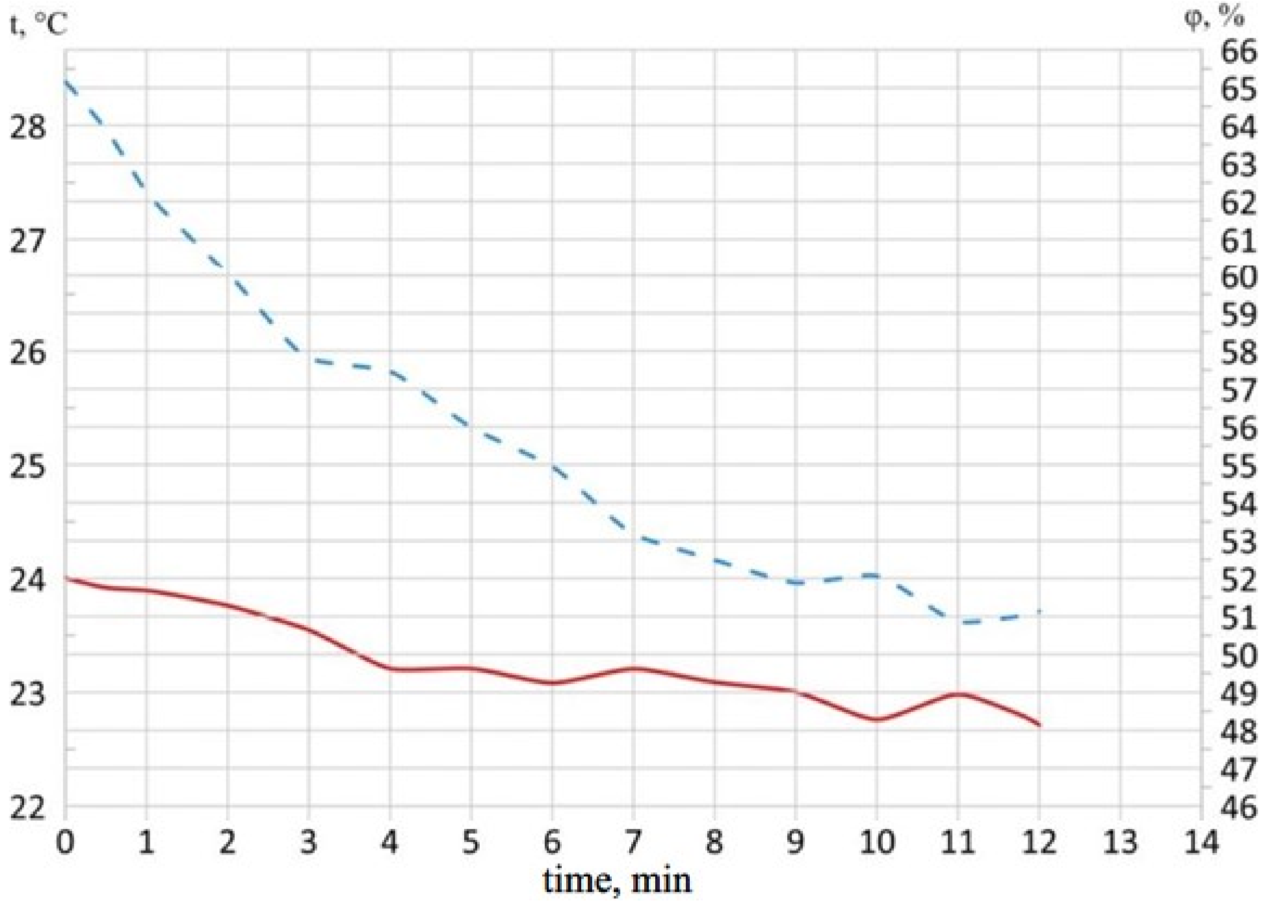

Fig. 7 Graph of changes in temperature and relative air humidity

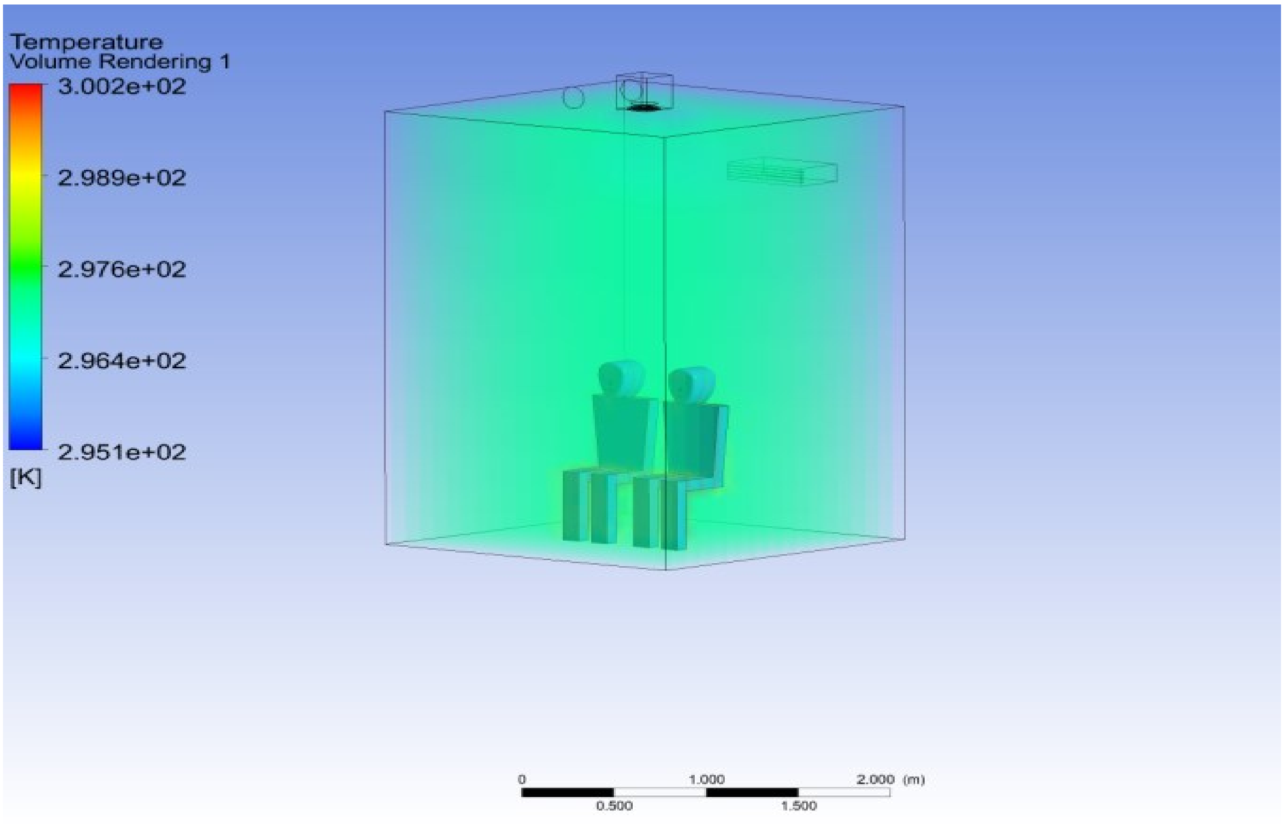

Fig. 8 Rendering of temperature and volumetric humidity content over time relative to the observation point: t_1=24.0 °C, T_{1}= 0 s

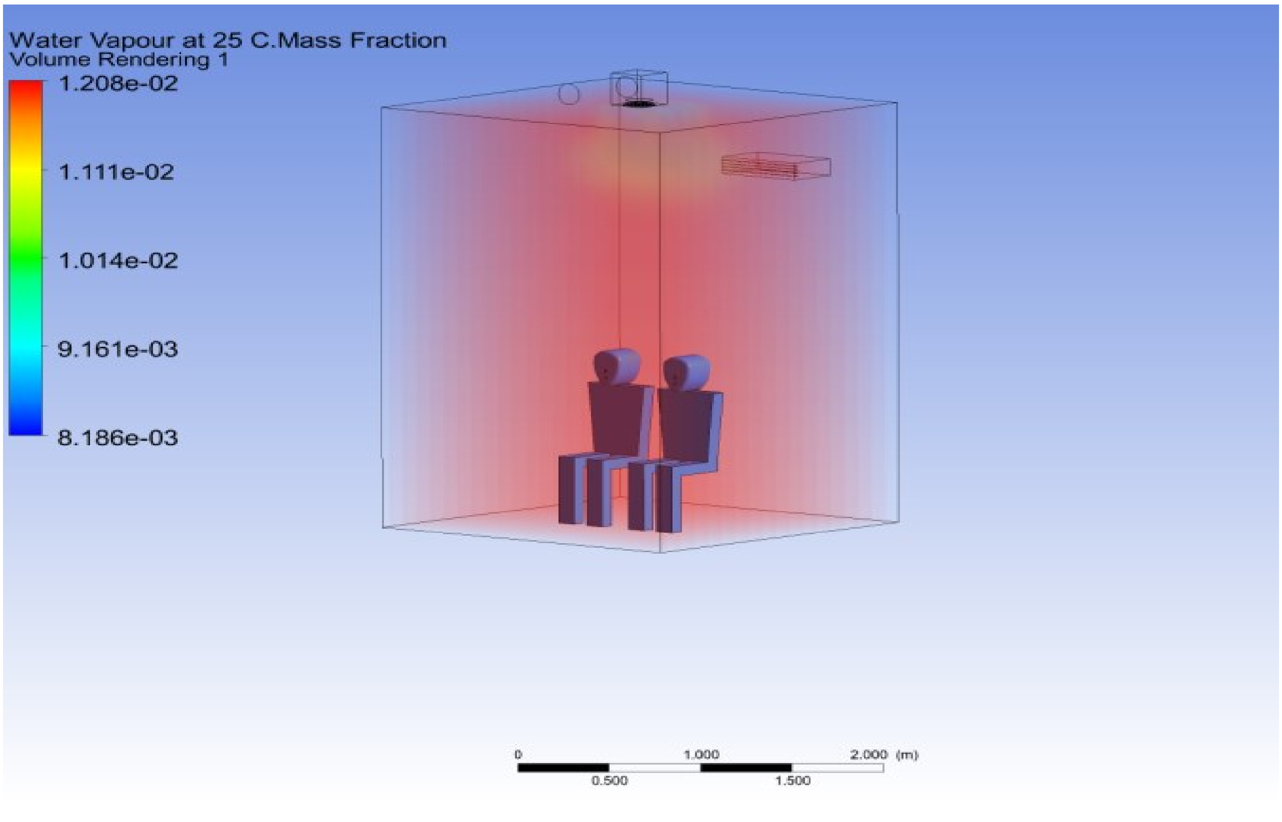

Fig. 9 Rendering of temperature and volumetric humidity content over time relative to the observation point: d_1=12.0 g/kg, T_1=0 s

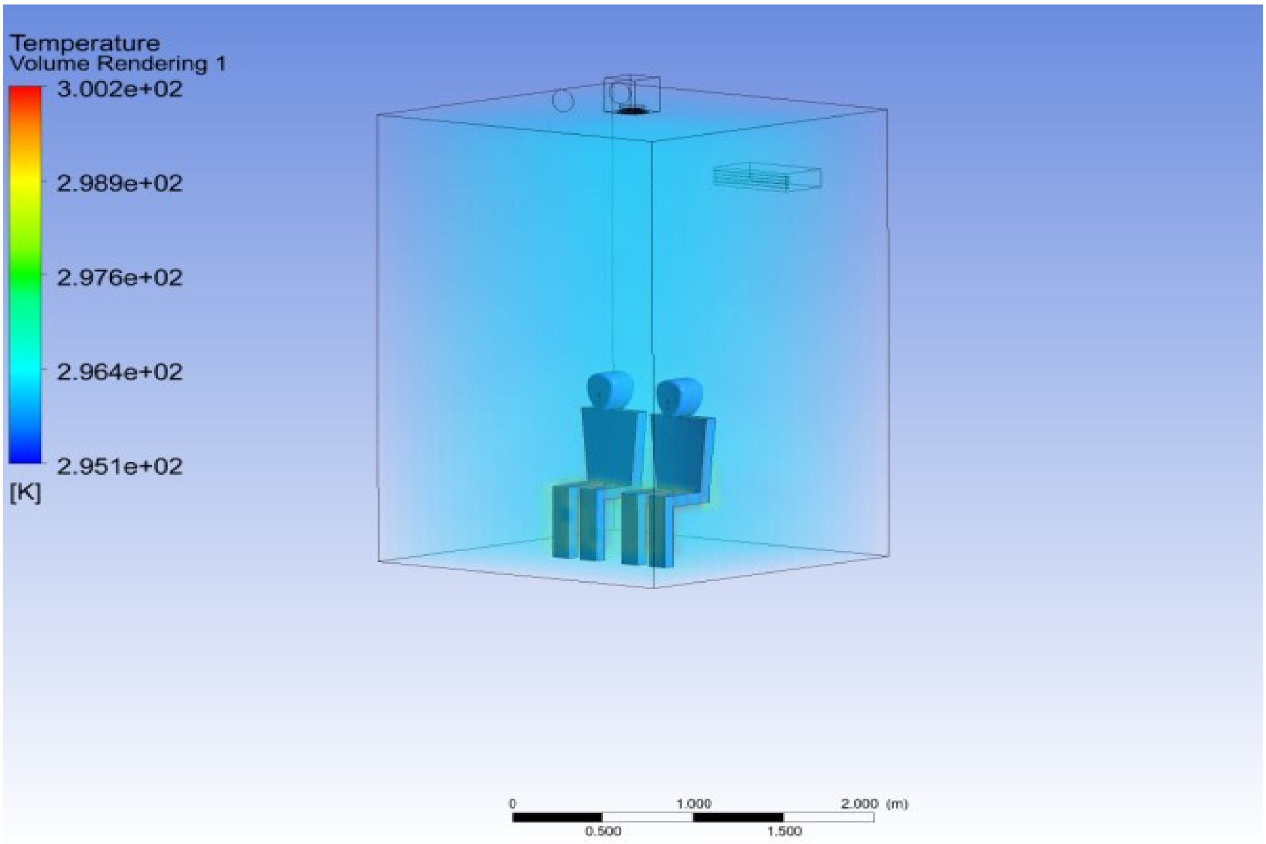

Fig. 10 Rendering of temperature and volumetric humidity content over time relative to the observation point: t2=23.08 °C, T2= 360 s

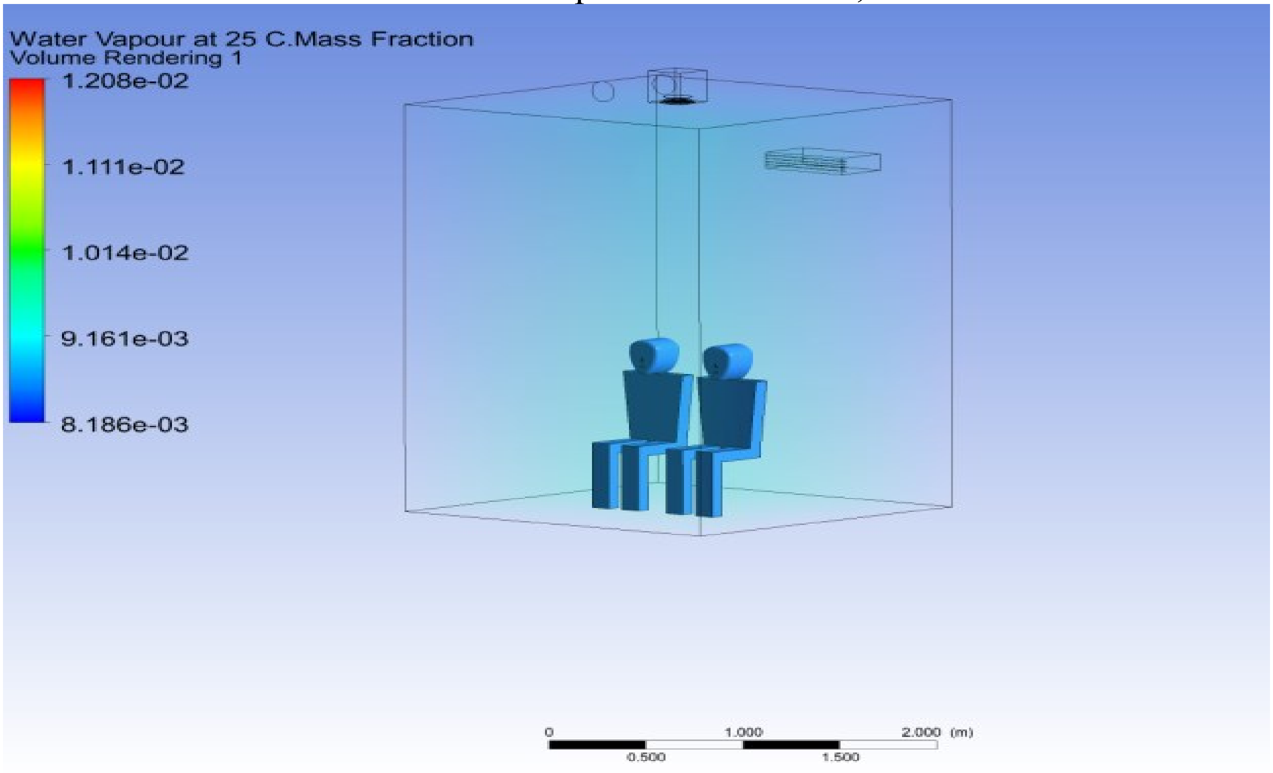

Fig. 11 Rendering of temperature and volumetric humidity content over time relative to the observation point: d2=9.56 g/kg, T2=360 s

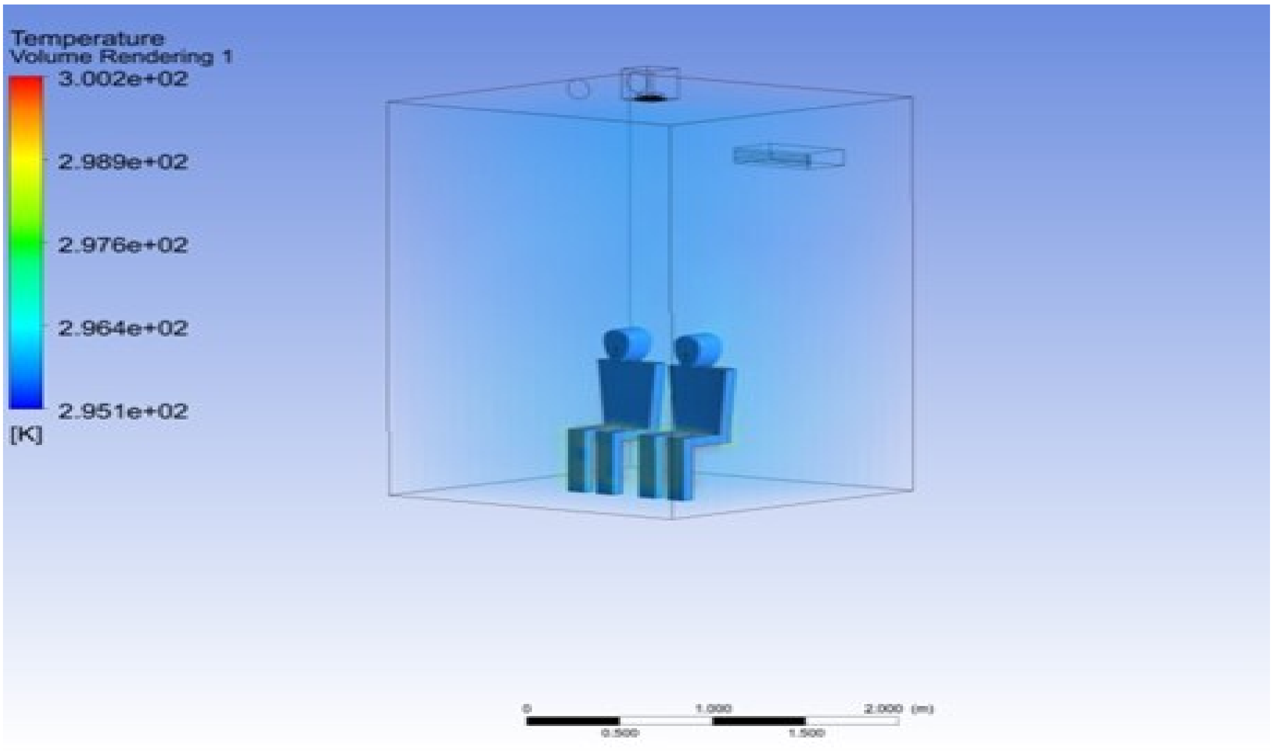

Fig. 12 Rendering of temperature and volumetric humidity content over time relative to the observation point:t3=22.71 °C, T3=720 s

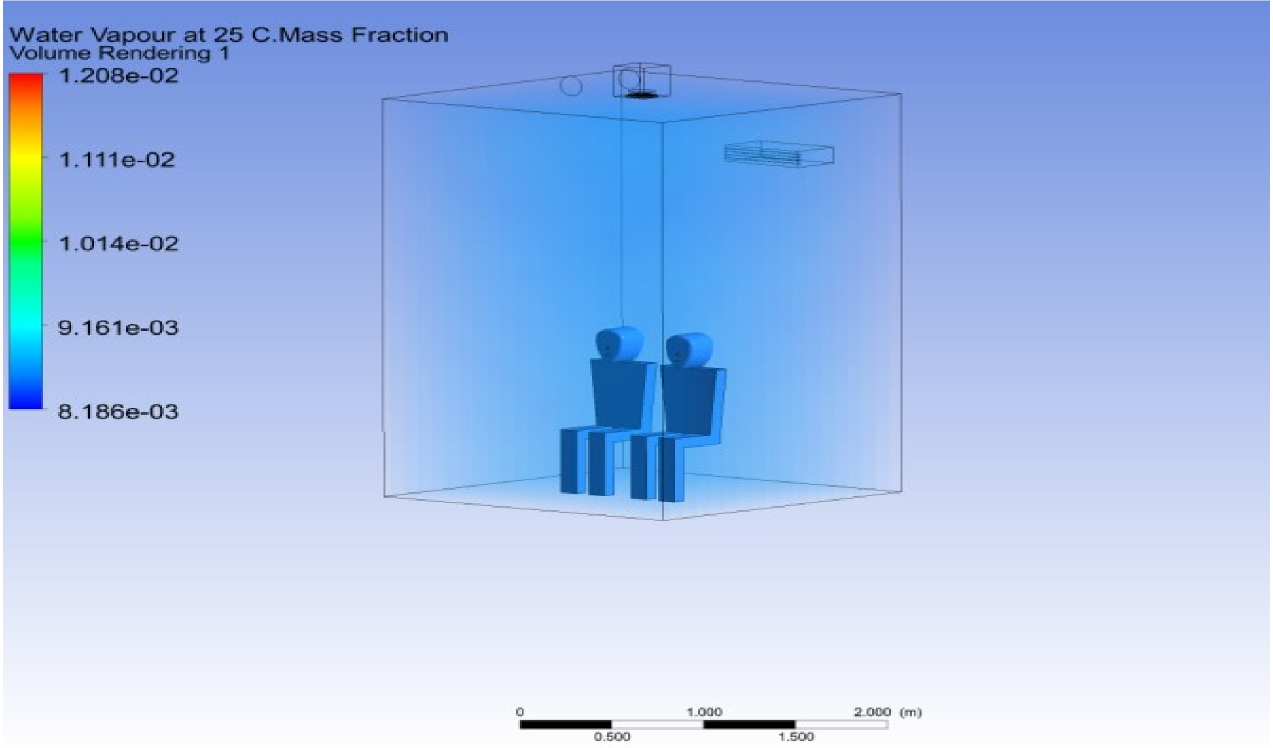

Fig. 13 Rendering of temperature and volumetric humidity content over time relative to the observation point: d3=8.7 g/kg, T3=720 s

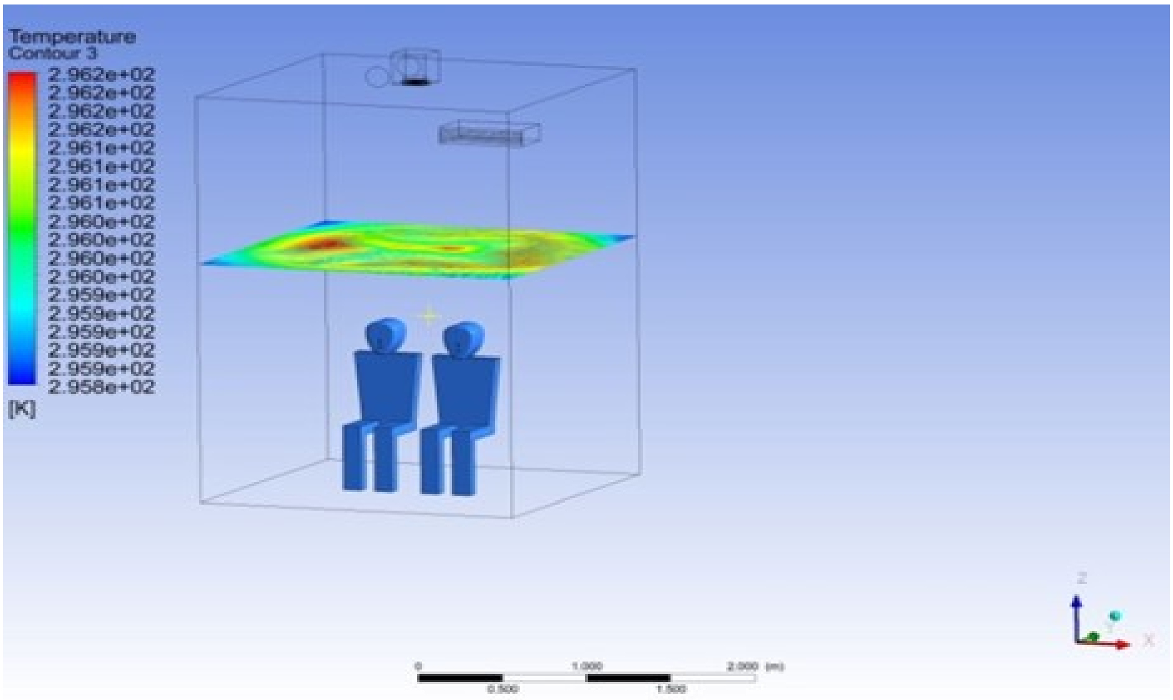

Fig. 14 Boundary WA contours of: temperature distribution (t); humidity content (d); air velocity (v); carbon dioxide (CO2) concentration, scheme B: d_{min}=8.87 g/kg, d_{max}=9.05 g/kg,

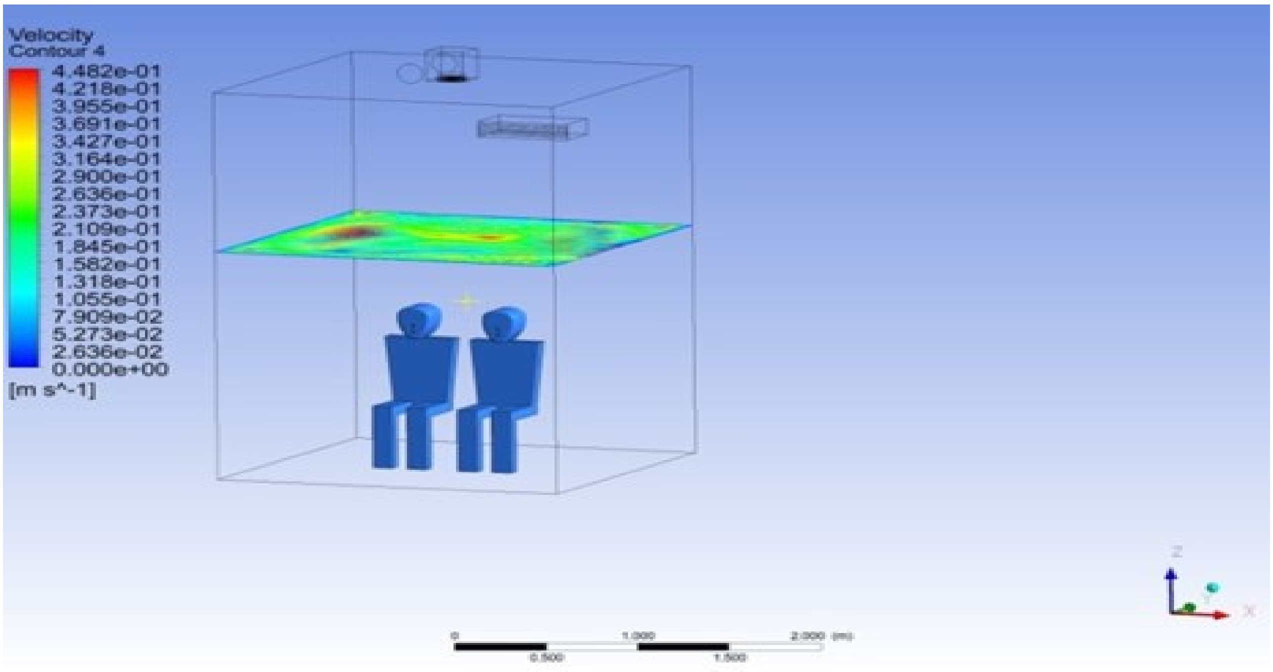

Fig. 15 Boundary WA contours of: temperature distribution (t); humidity content (d); air velocity (v); carbon dioxide (CO2) concentration, scheme B: v_{min}=0 m/s, v_{max}=0.482 m/s,
T=540 s

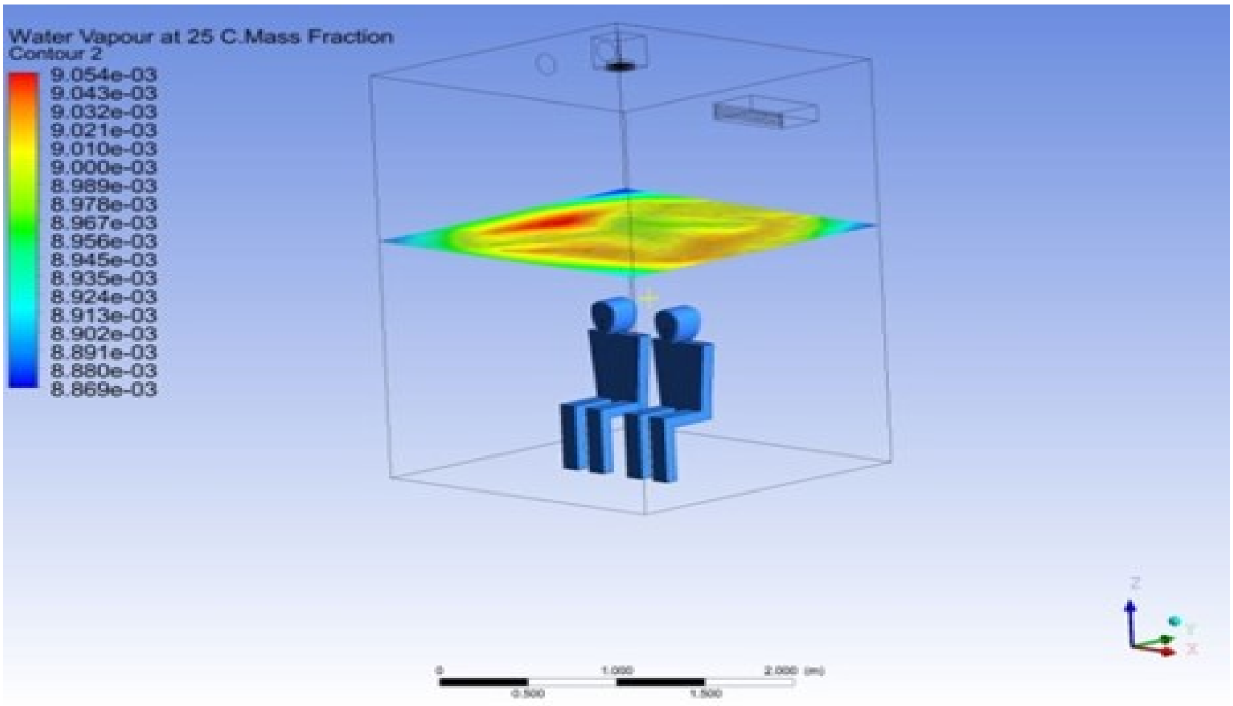

Fig. 16 Boundary WA contours of: temperature distribution (t); humidity content (d); air velocity (v); carbon dioxide (CO2) concentration, scheme B: d_{min}=8.87 g/kg, d_{max}=9.05 g/kg

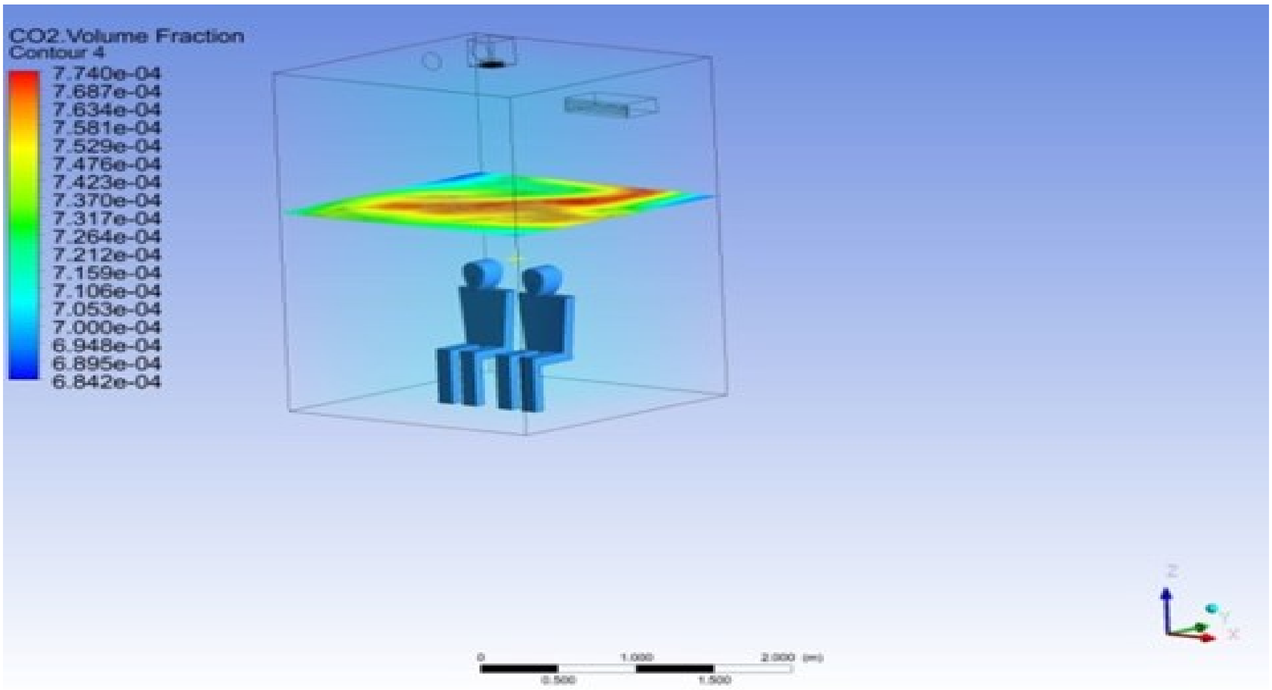

Fig. 17 Boundary WA contours of: temperature distribution (t); humidity content (d); air velocity (v); carbon dioxide (CO2) concentration, scheme B: $CO2_{min}$=684 ppm, $CO2_{max}$=774 ppm,

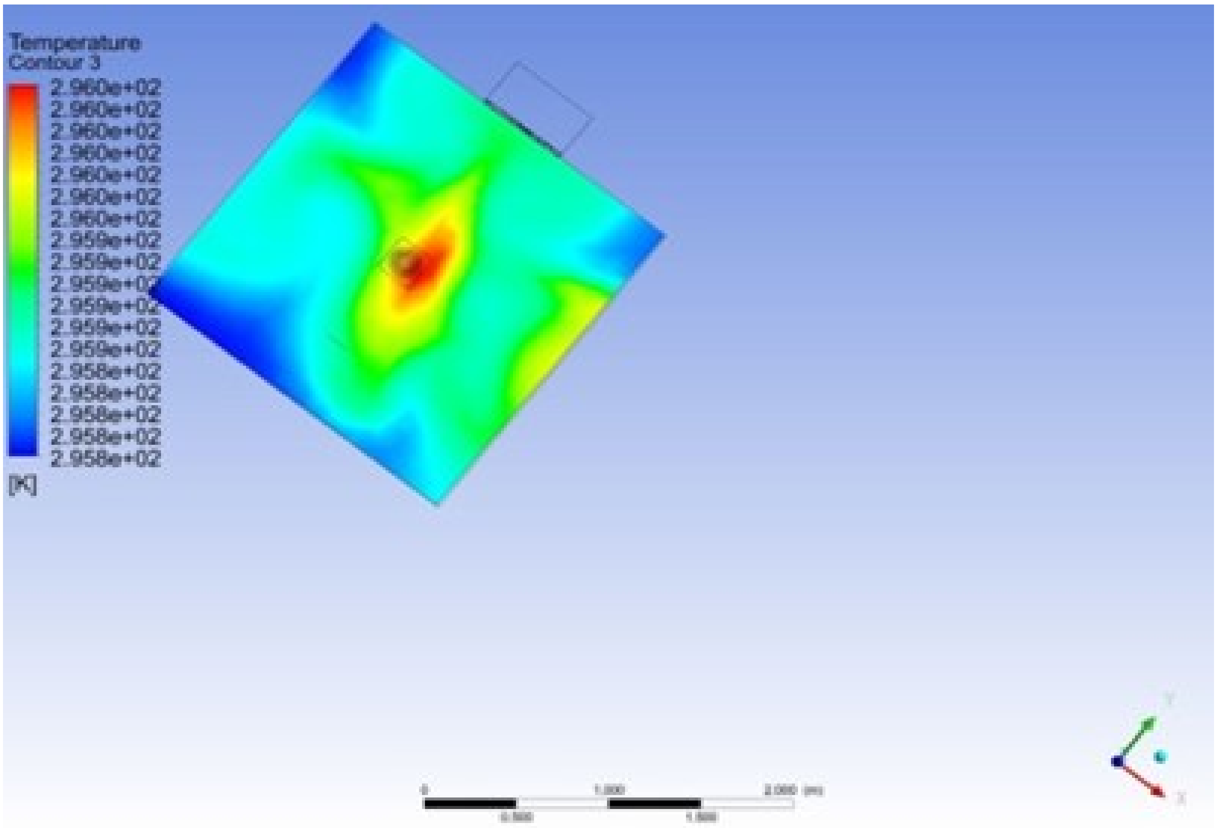

Fig. 18. Temperature contours of the considered air exchange schemes at the entrance/exit to/from the WA: t_{min}=22.65 °C, t_{max}=22.85 °C T=540 s Scheme A

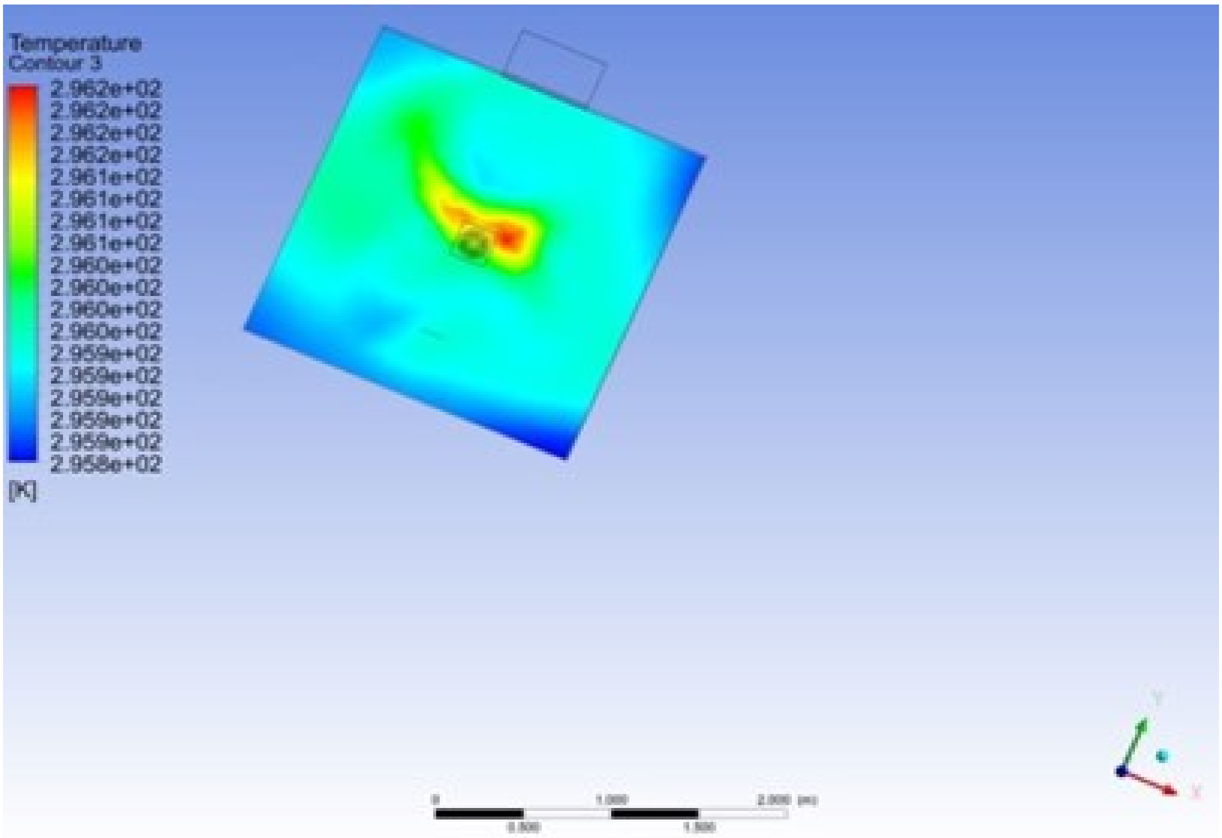

Fig. 19. Temperature contours of the considered air exchange schemes at the entrance/exit to/from the WA: t_{min}=22.65 °C, t_{max}=23.05 °C T=540 s Scheme B

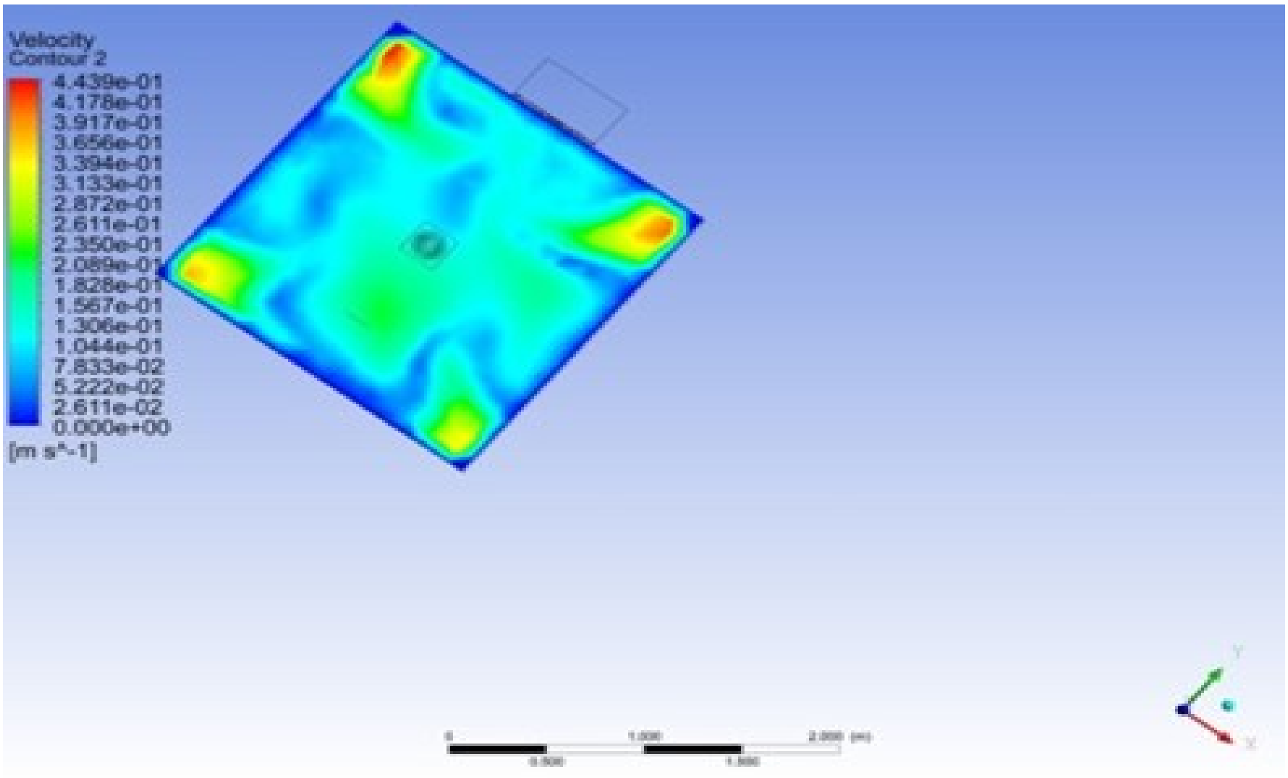

Fig. 20. Air velocity contours for the considered air exchange schemes at the entrance/exit to/from the WA: vmin=0 m/s, vmax=0.439 m/s,T=540 s Scheme A

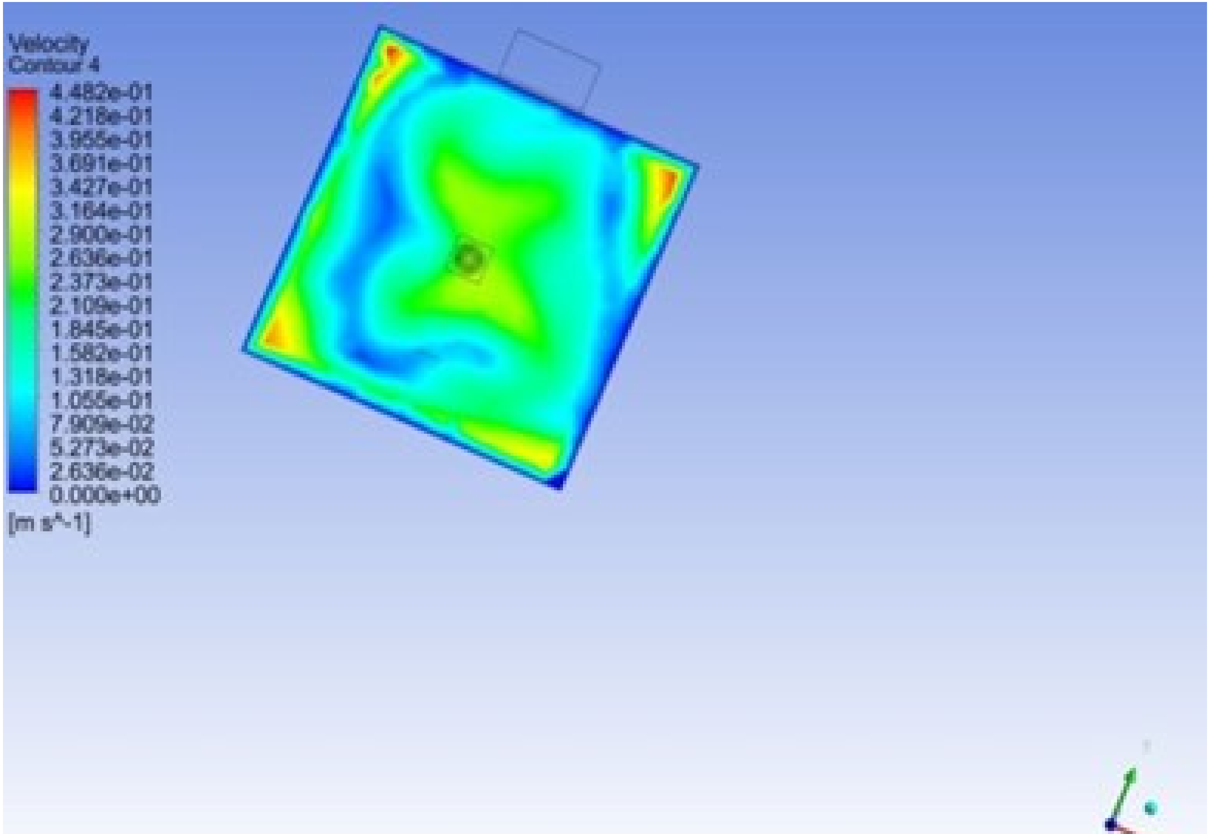

Fig. 21. Air velocity contours for the considered air exchange schemes at the entrance/exit to/from the WA: vmin=0 m/s, vmax=0.448 m/s,T=540 s Scheme B

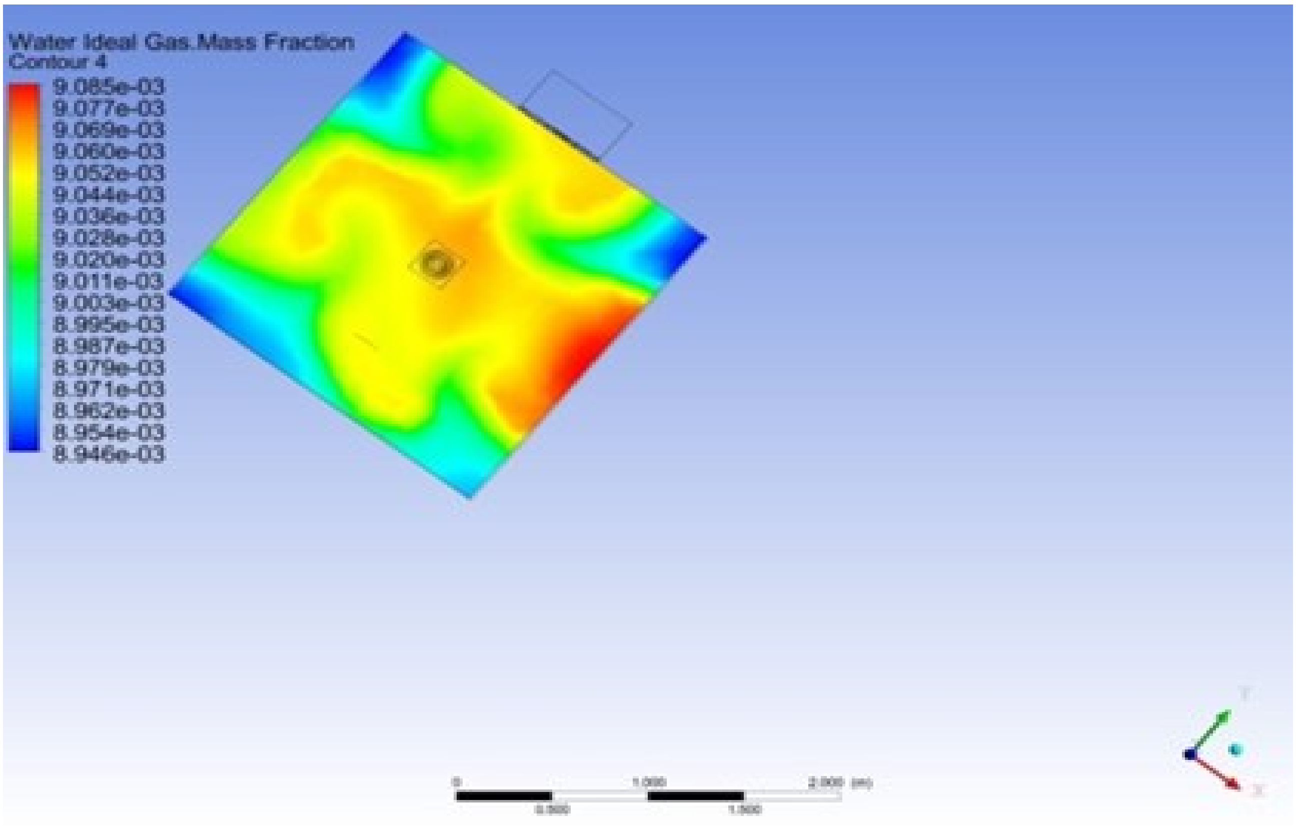

Fig. 22 Moisture content contours for the considered air exchange schemes at the entrance/exit to/from the WA: dmin=8.95 g/kg, dmax=9.09 g/kg,T=540 c Scheme A.

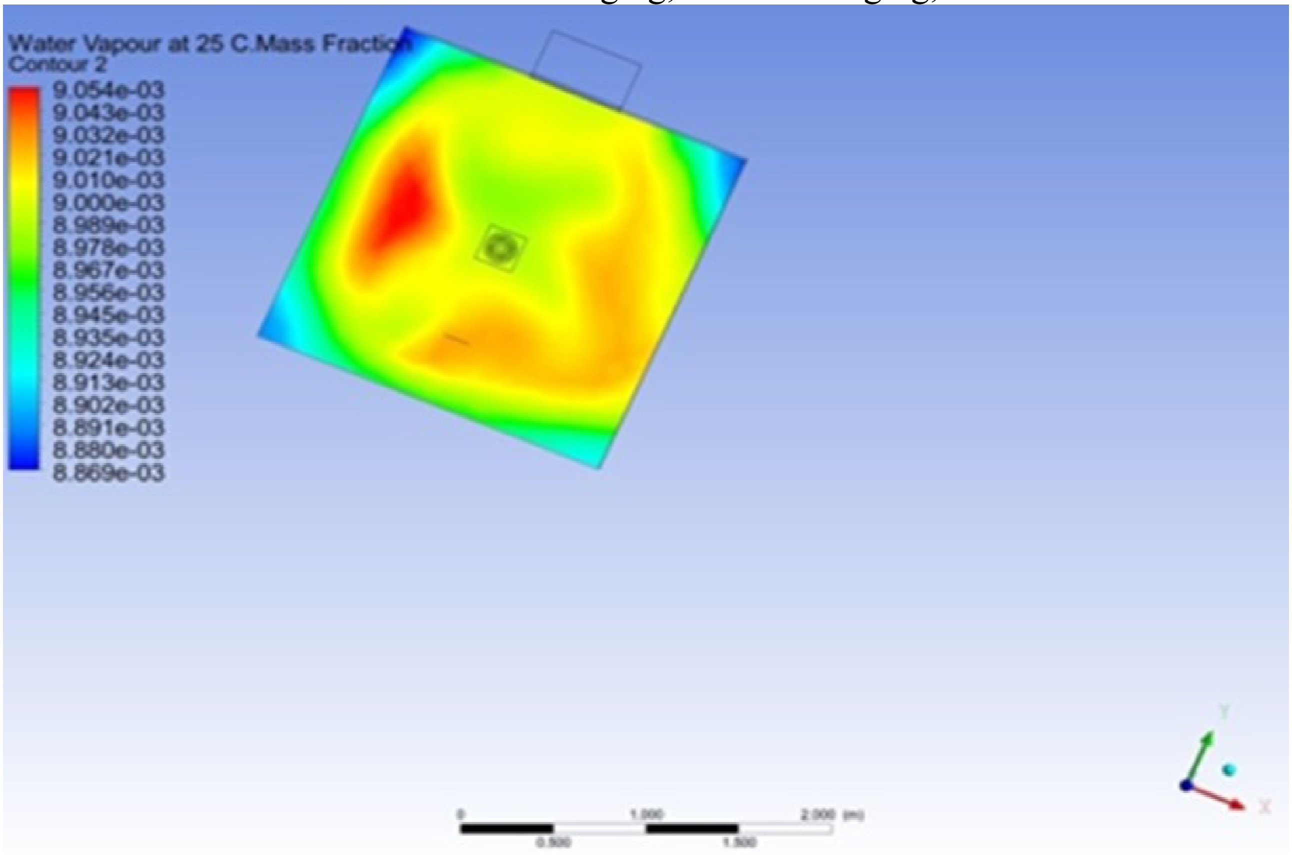

Fig. 23 Moisture content contours for the considered air exchange schemes at the entrance/exit to/from the WA: d_{min}=8.86 g/kg, d_{max}=9.05 g/kg,T=540 c Scheme B

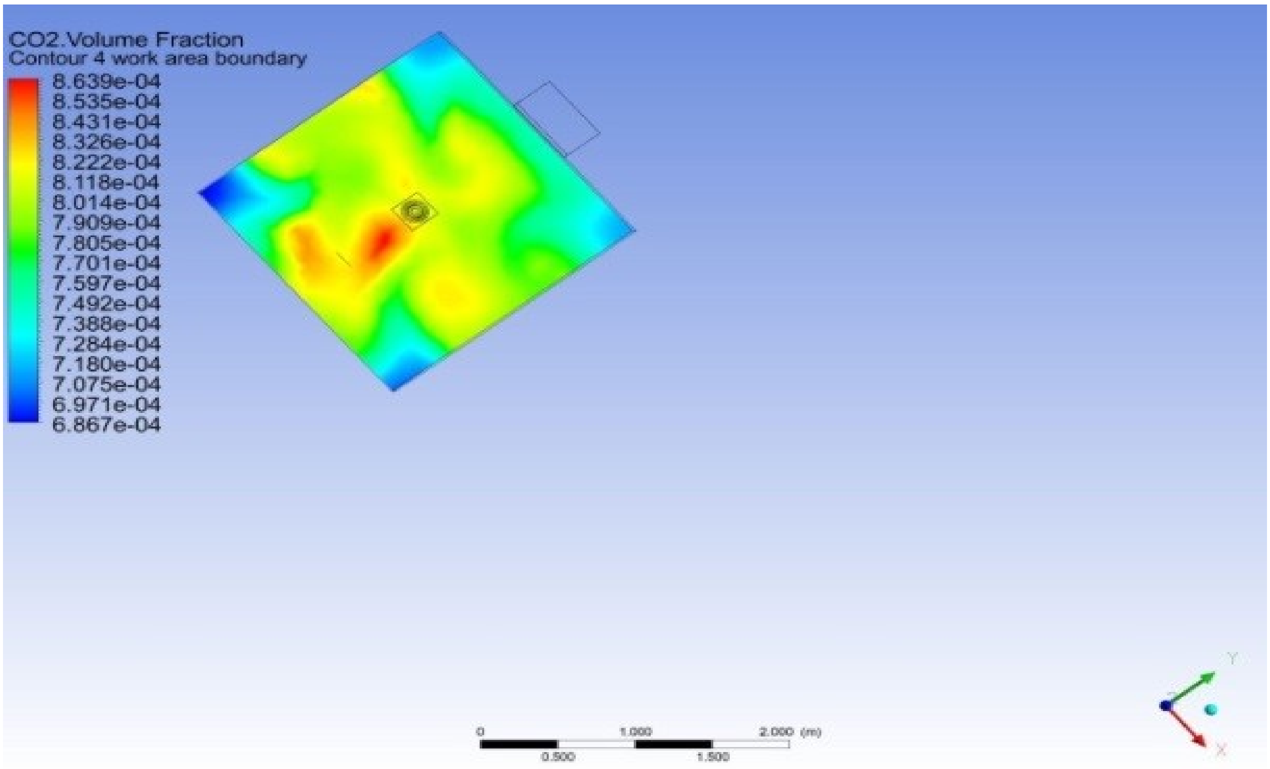

Fig. 24 CO_2 concentration contours for the considered air exchange schemes at the entrance/exit to/from the WA: CO_{2min}=687 ppm, CO_{2max}=864 ppm,$T_{=}$540 c Scheme A

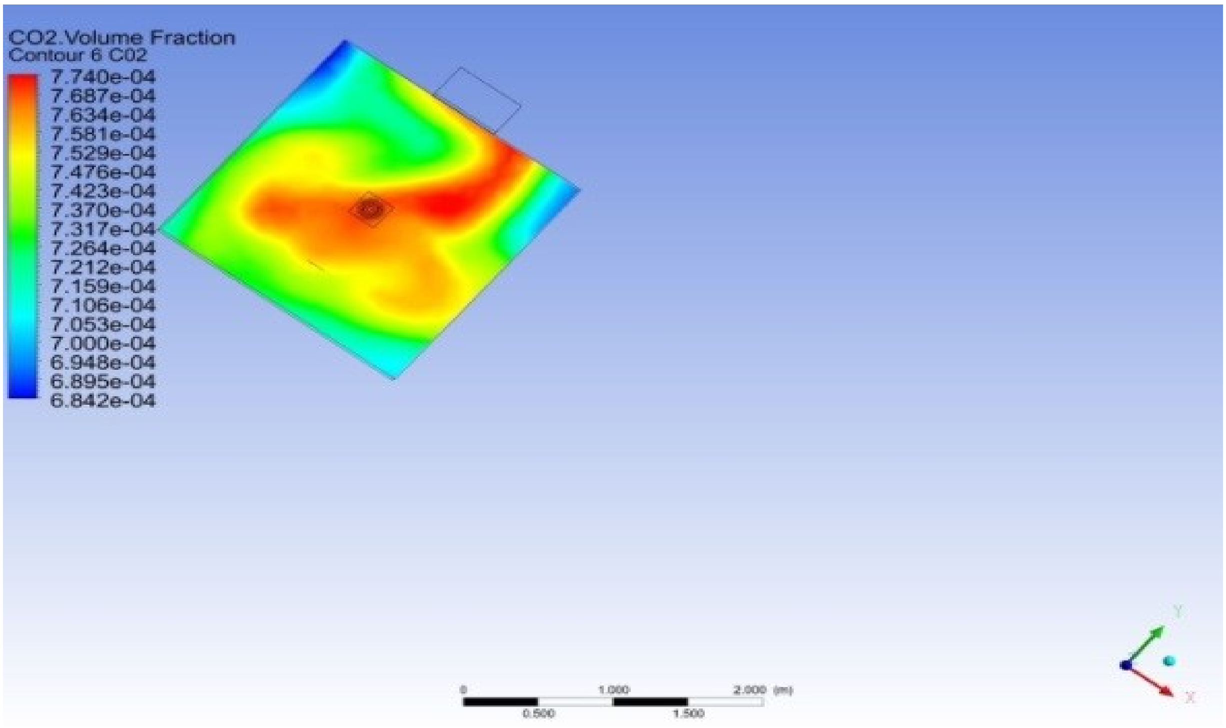

Fig. 25 CO_2 concentration contours for the considered air exchange schemes at the entrance/exit to/from the WA: CO_{2min}=684 ppm, CO_{2max}=774 ppm,$T_{=}$540 c Scheme B

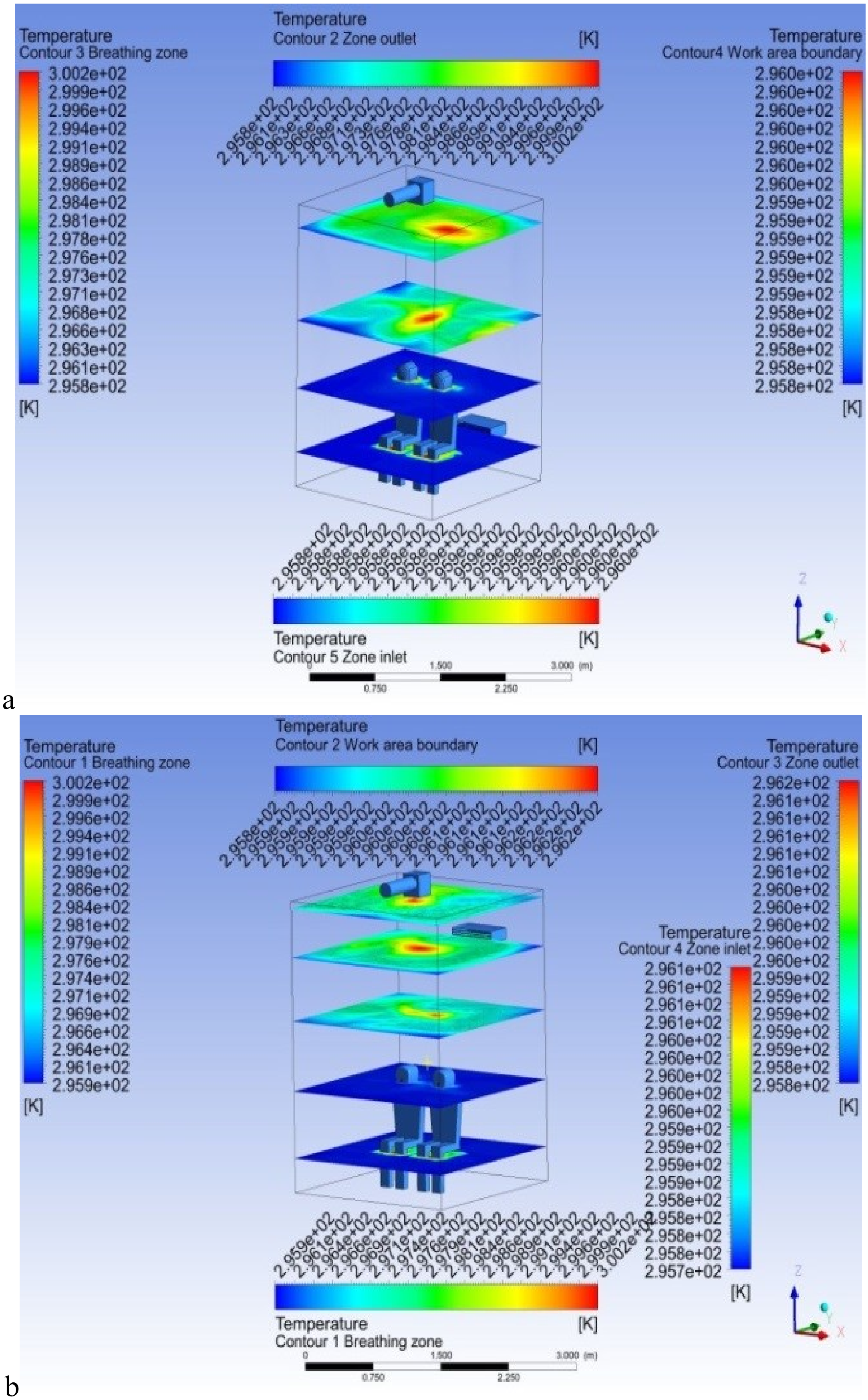

Fig. 26 Variation of air temperature by height of the investigated space: a – scheme A,T-540c; b – scheme B T-540 c

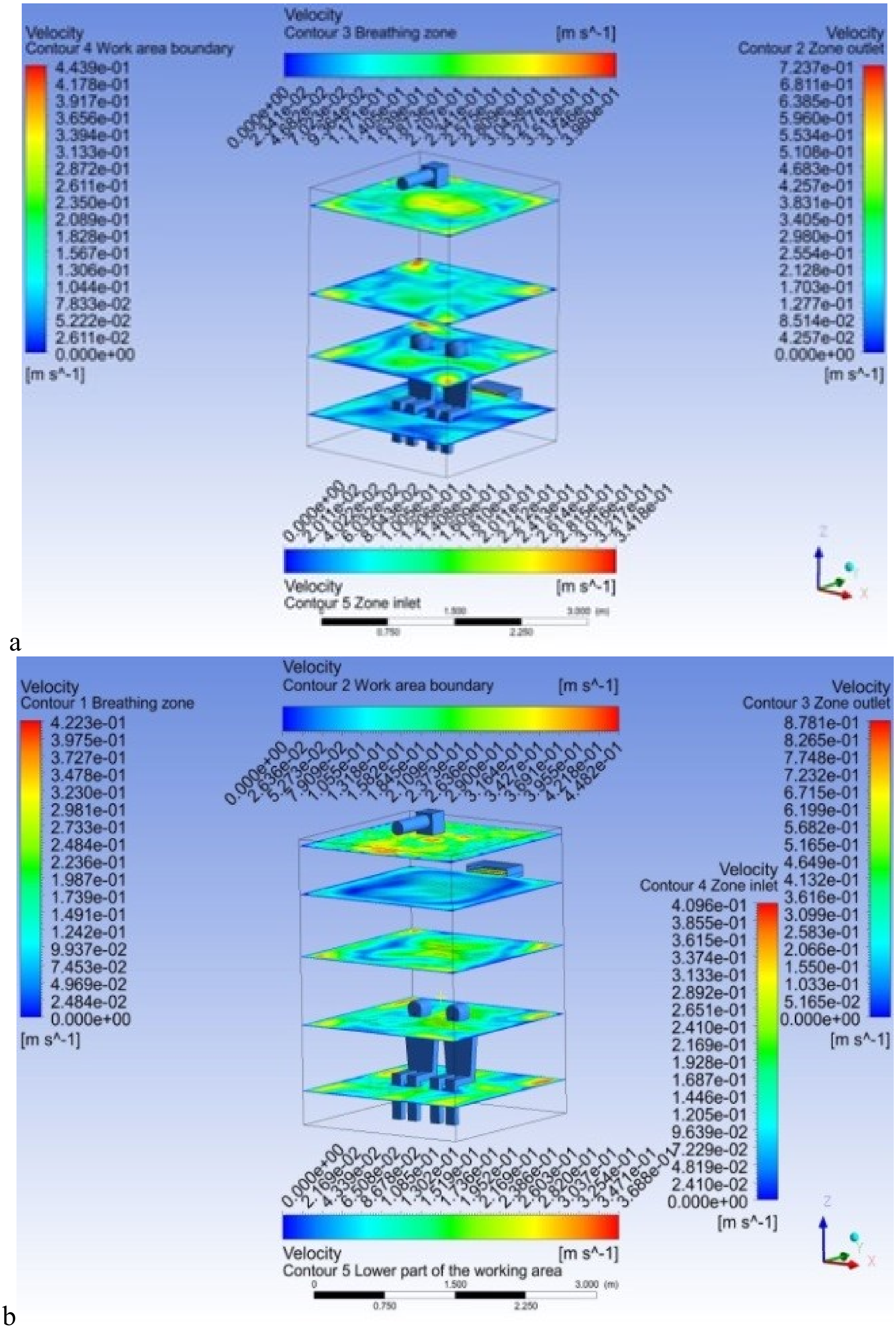

Fig. 27 Variation of air velocity along the height of the investigated space:
a – scheme A, T-540 c; b – scheme B, T-540 c

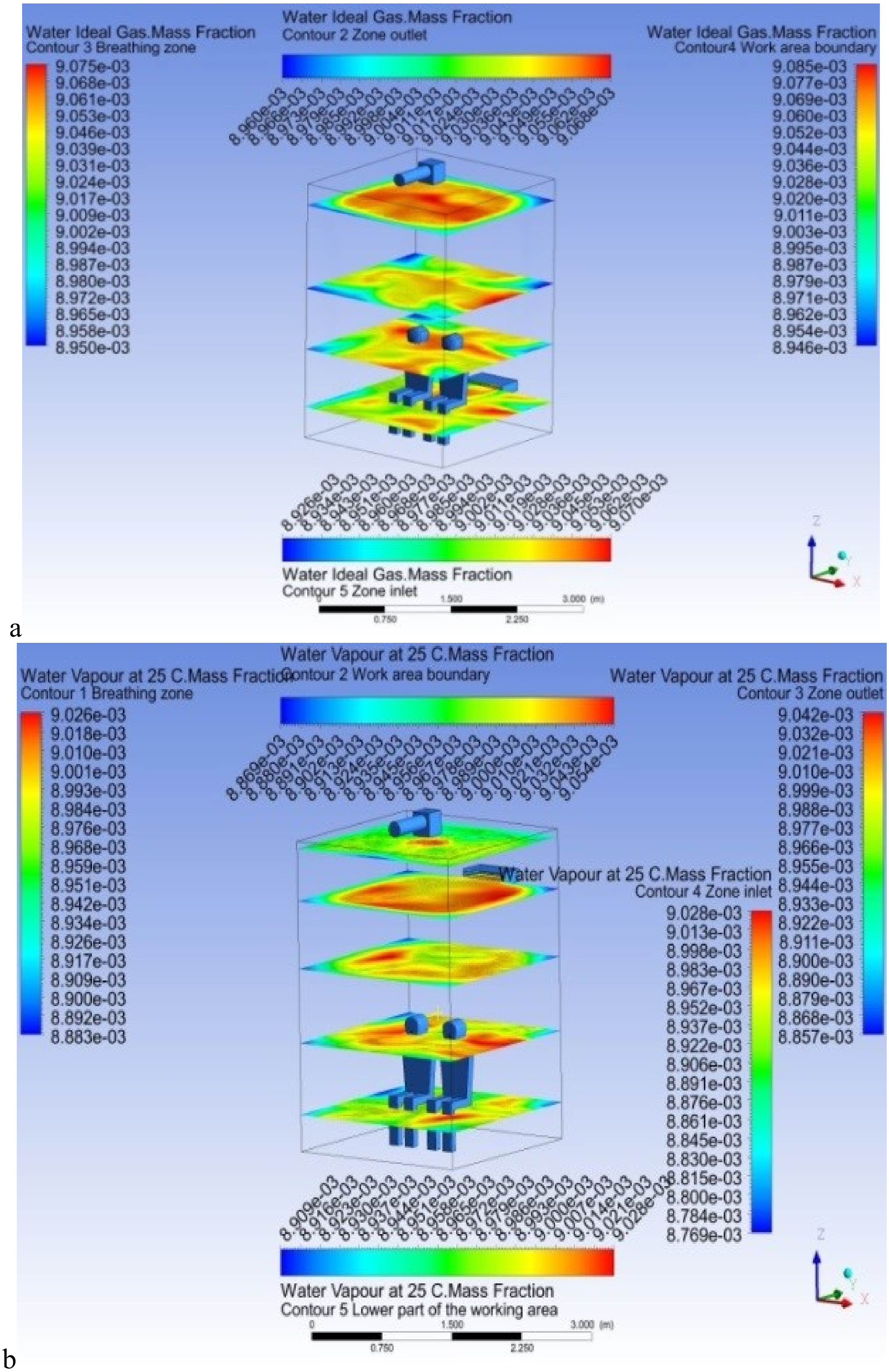

Fig. 28 Variation of air moisture content by height of the investigated space: a – scheme A, T-540 c; b – scheme B, T-540 c

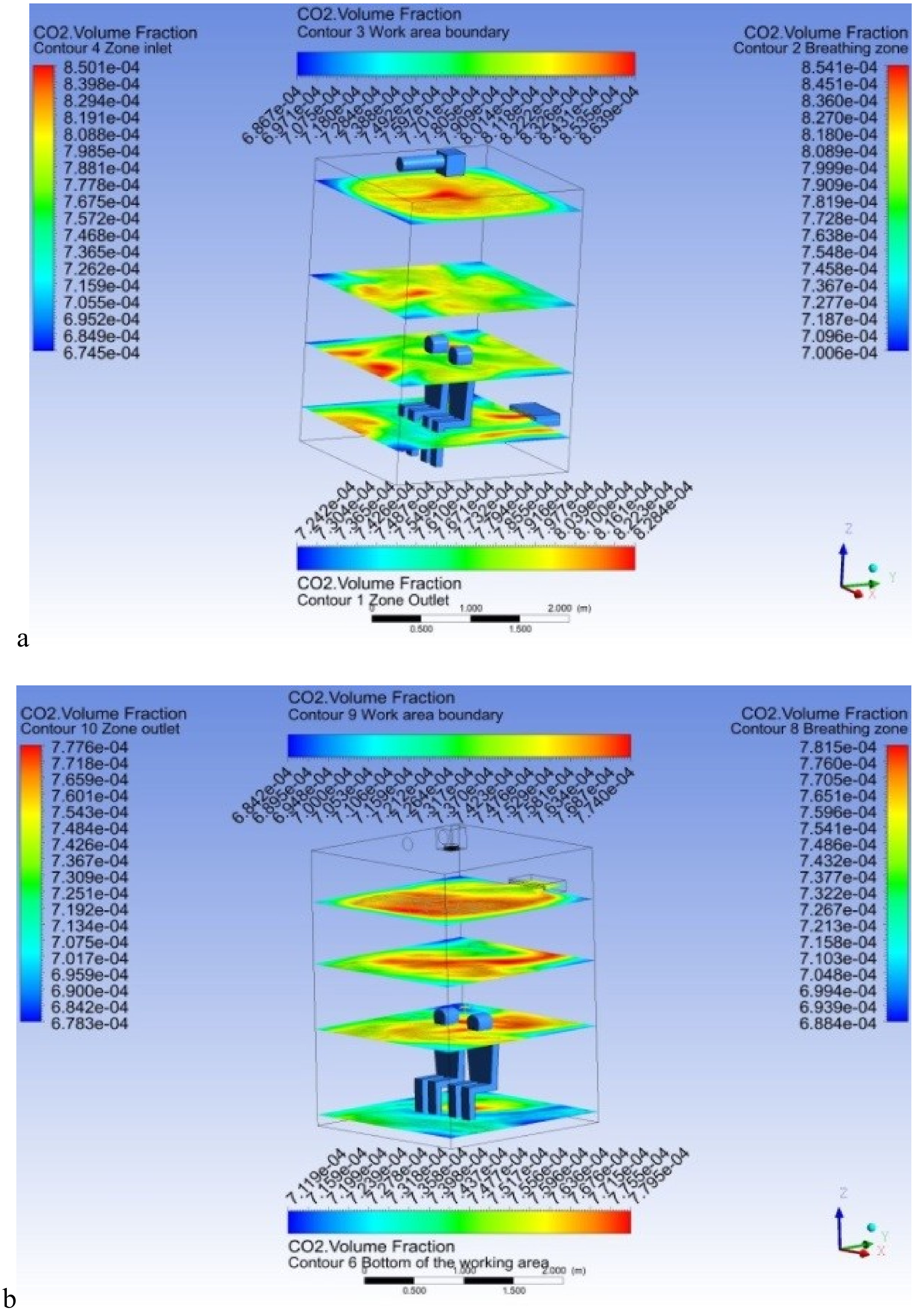

Fig. 29 Variation of CO_2 content by the height of the investigated space: : a – scheme A, T-540 c; b – scheme B, T-540 c

Table 1

Air parameters at the entrance of the supply jet into the working area of the room

Parameters	The range of changes in the indicator is from min to max in the boundary plane of the room WA		Optimal parameters when the jet enters the working area of the room [2,3]			
	Value	Temperature difference	Δt, °C	v, m/s	φ, %	CO_2, ppm
Scheme A (data after 540 s)						
Temperature, t °C	22.6-22.9	Δt=1.6-1.9	1-1.5			
Velocity, v m/s	0-0.4			0.1-0.2		
Humidity content, d g/kg	8.8-8.9					
Relative humidity, φ %	52.2-51.8				25-60	
Carbon dioxide CO_2, ppm	686-864					400-600
Scheme B (data after 540 s)						
Temperature, t °C	22.7-23.1	Δt=0.7-1.1	1-1.5			
Velocity, v m/s	0-0.45			0.1-0.2		
Humidity content, d g/kg	8.8-9.1					
Relative humidity, φ %	52.6-52.4				25-60	
Carbon dioxide CO_2, ppm	684-774					400-600

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провідний фахівець

МОДЕЛЮВАННЯ ПОВІТРООБМІНУ «ПОДАЧА ПОВІТРЯ ЗВЕРХУ – ВИДАЛЕННЯ ЗВЕРХУ»

Анотація: *Розглянуто ефективність схеми повітрообміну «подача повітря зверху – видалення зверху». Тепломасообмін системи, що передбачає: математичну модель людини (процес дихання з виділенням в навколишнє середовище вуглекислого газу, тепла і водяної пари) з одночасним виділенням тепла від одягненої поверхні тіла; систему припливної вентиляції (надходження* CO_2*, водяної пари та тепла з атмосферним повітрям); систему витяжної вентиляції (видалення зазначених вище шкідливих речовин, що містяться в повітрі). Застосування чисельного моделювання ANSYS CFD (Computational Fluid Dynamics) на основі рівнянь неперервності та усереднених рівнянь Рейнольдса Нав'є-Стокса «RANS» (Reynolds-Averaged Navier-Stokes) дало наступні результати: вирішено обернену задачу вентиляції - для первинно забрудненого досліджуваного простору приміщення розглянуто взаємодію систем (людини та діючої припливно-витяжної вентиляційної установки); моніторинг та візуалізація змін концентрації* CO_2*, температури та відносної вологості в досліджуваному просторі за часом і за висотою приміщення; отримані результати порівнюються з раніше отриманими результатами* *зміни концентрації вуглекислого газу, температури та відносної вологості у вентильованому приміщенні за схемою повітрообміну «подача повітря зверху – видалення знизу» (схема А) та нормативними документами. Динаміка надлишкового тепла, вологості та асиміляції вуглекислого газу (CO_2) дозволила оцінити ефективність систем вентиляції та спрогнозувати підвищення їх енергоефективності при доведенні параметрів повітря до нормативних значень. Зміна повітряного середовища характерна для приміщень з механічною припливно-витяжною вентиляцією (проточні класи навчальних закладів, класи шкіл, групові кімнати дитячих садків, конференц-зали, офіси). Для цього типу приміщень основними забруднювачами повітря є вуглекислий газ, водяна пара і теплота.*

Ключові слова: математична модель, «шкідливості повітря», аеродинаміка, обчислювальна гідрогазодинаміка, схема повітрообміну, відносна вологість, температура, концентрація діоксиду вуглецю, робоча зона приміщення, ребрендинг, припливно-витяжна вентиляція.