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CHANGE IN THE STATE AIR IN THE ROOM UNDER THE INFLUENCE OF HEAT, WATER VAPOUR AND CO_2 EMITTED BY THE HUMAN MODEL AND THE SUPPLY AND EXHAUST VENTILATION UNIT

The work continues to develop a mathematical model of the respiration process, taking into account the peculiarities of heat and mass transfer between humans and the environment, in particular, the release of carbon dioxide, water vapor and heat. Estimates of air pollution in an isolated room are obtained using a model of a dressed person. The time a person spends in the room and the number of people are taken into account.

Based on these estimates, the inverse ventilation problem for the room was solved, i.e. the process of bringing the previously polluted air to the standard parameters was studied.

Changes in the state of air parameters were modelled taking into account the impact of the following:

- *model of a dressed person;*
- *the supply ventilation system (i.e., the intake of CO_2, water vapor, and atmospheric heat);*
- *exhaust ventilation system (i.e. removal of carbon dioxide from the air environment, reduction of humidity, air cooling).*

The ventilation scheme is studied when the supply is from the top of the room and the exhaust is from the bottom near the floor.

The application of ANSYS CFD (Computational Fluid Dynamics) numerical modelling based on continuity equations and Reynolds-Averaged Navier-Stokes (RANS) equations has yielded the following results:

- *the inverse ventilation problem was solved – for the previously contaminated room space under study, the interaction of the systems ‘a dressed person and a working supply and exhaust ventilation unit’ was considered;*
- *monitoring and visualisation of changes in the concentration of carbon dioxide CO_2, temperature and relative humidity in the room, depending on the time of operation of the ventilation unit and the height of the room;*
- *the efficiency of the adopted air exchange scheme in the room was compared to match its characteristics with the requirements of regulatory documents.*

The dynamics of the absorption of excess heat, humidity and carbon dioxide (CO_2) made it possible to assess the efficiency of ventilation systems and predict an increase in their energy efficiency when air parameters are brought to standard values. Changes in the air environment are typical for rooms with mechanical supply and exhaust ventilation.

Key words: mathematical model, air contaminant, aerodynamics, computational fluid dynamics, air change scheme, relative humidity, temperature, carbon dioxide concentration, room working area (WA), rebranding, supply and exhaust ventilation.

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ЗМІНА СТАНУ ПОВІТРЯ В ПРИМІЩЕННІ ПІД ВПЛИВОМ ТЕПЛА, ВОДЯНОЇ ПАРИ ТА CO_2, ЩО ВИДІЛЯЮТЬСЯ МОДЕЛЛЮ ЛЮДИНИ ТА ПРИПЛИВНО-ВИТЯЖНОЮ ВЕНТИЛЯЦІЙНОЮ УСТАНОВКОЮ

У роботі продовжується розробка математичної моделі процесу дихання з урахуванням особливостей тепломасообміну людини та навколишнього середовища, зокрема, виділення діоксиду вуглецю, водяних парів та тепла. Отримані оцінки забруднення повітря в ізольованому приміщені з використанням моделі одягненої людини. Враховується час перебування людини в приміщенні та кількість людей.

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На основі цих оцінок розв'язано обернену задачу вентиляції для приміщення, тобто вивчено процес доведення попередньо забрудненого повітря до нормативних параметрів.

Моделювалися зміни стану параметрів повітря та вплив на це:

– моделі одягненої людини;

– припливної системи вентиляції (тобто надходження CO_2, водяного пару, тепла атмосферного повітря);

– витяжної системи вентиляції (тобто видалення з повітряного середовища вуглекислого газу, зниження вологості, охолодження повітря).

Вивчається схема вентиляції, коли подання відбувається зверху приміщення, а відбір – знизу біля підлоги.

Застосування числового моделювання ANSYS CFD (Computational Fluid Dynamics) на основі рівнянь неперервності та усереднених рівнянь Рейнольдса-Нав'є-Стокса RANS (Reynolds-Averaged Navier-Stokes) дало такі результати:

– розв'язана обернена задача вентиляції – для попередньо забрудненого досліджуваного простору приміщення розглянута взаємодія систем «одягнена людина та припливно-витяжна вентиляційна установка, що працює»;

– виконано моніторинг та візуалізацію зміни концентрації вуглекислого газу CO_2, температури та відносної вологості в приміщені залежно від часу роботи вентиляційної установки та висоти приміщення;

– порівняно ефективність роботи прийнятої схеми обміну повітря в приміщені для узгодження його характеристик з вимогами нормативних документів.

Динаміка засвоєння надлишкового тепла, вологості та вуглекислого газу (CO_2) дала змогу оцінити ефективність роботи вентиляційних систем і спрогнозувати підвищення їх енергоефективності при доведені параметрів повітря до нормативних значень. Зміни повітряного середовища характерні для приміщень з механічною припливно-витяжною вентиляцією.

Ключові слова: математична модель, забруднювач повітря, аеродинаміка, обчислювальна гідродинаміка, схема повітрообміну, відносна вологість, температура, концентрація вуглекислого газу, робоча зона приміщення, ребрендинг, припливно-витяжна вентиляція.

Introduction

The energy efficiency of life support systems (ventilation and air conditioning) is directly related to the regulatory constraints on indoor air parameters [2; 3]. The main harmfulnesses of air, by which the performance of ventilation systems is calculated:

– temperature;

– relative humidity:

– concentration of carbon dioxides.

Normed also:

– the speed of the air flow into the working area of the room;

– the temperature difference between the temperature of the air in the working area and the temperature of the supply air flow entering the working area (WA).

In the practice of climatotechnics, the efficiency of ventilation and air conditioning systems is also significantly affected by the air exchange scheme.

This paper considers the efficiency of supply and exhaust ventilation according to the scheme “air supply from above – removal from below”.

Literature review and problem statement

The developed mathematical model of human impact on the air environment of an isolated room allowed to analyse the intensity of pollution of the studied space [1]. In the same work, the study of normalisation of air environment parameters from the state of pollution to the normative parameters on CO_2 concentration was carried out using the air exchange scheme “air supply from above – removal from below”. Generalisation of results of researches of multifactor interaction:

– of a person (CO_2, heat and water vapour emission);

– polluted space of a premise (CO_2, heat and water vapour emission);

– supply ventilation (CO_2, heat and water vapour emission);

– removal of air mixture by exhaust ventilation system (a person + polluted space of a premise + supply ventilation) is presented in this paper.

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Various methods and approaches have been used in the practice of calculating changes in the state of the air environment in rooms for various purposes [4–8]. Examples of successful solutions of applied ventilation problems do not remove the question of the accuracy of the results obtained by mathematical modelling. Nowadays, mathematical modelling methods are used in engineering calculations, which allow obtaining an estimate of flow parameters based on numerical solution of the Reynolds equations of stationary or unsteady Navier-Stokes equations. (RANS/URANS: Steady/Unsteady Reynolds Averaged Navier-Stokes).

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 [1].

Research results

Modeling of air contaminant intake

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 (RANS/URANS: Steady/Unsteady Reynolds Averaged Navier – Stokes) [4].

Continuity equation:

$$\frac{d\rho}{dt} + \nabla\left(\rho u\right) = 0, \tag{1}$$

where ρ – air density, u – flow velocity, ∇ – Nabla operator.

Navier – Stokes equation:

$$\frac{\partial}{\partial x_j}\left(p\overline{u_i}\,\overline{u_j}\right) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial \overline{u_i}}{\partial x_i}\right)\right) - \delta_{i3}pg + \frac{\partial}{\partial x_j} - \left(p\overline{u_i}\,\overline{u_j}\right), \tag{2}$$

$$-p\overline{u_i'}\,\overline{u_j'} = \mu_t\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(pk + \mu_t\frac{\partial \overline{u}_i}{\partial x_j}\right)\delta_{ij}, \tag{3}$$

where p – pressure; Pa, μ – dynamic viscosity, kg/m·s; μ_t – turbulent dynamic viscosity, kg/m·s; g – acceleration of gravity, m/s^2; k – kinetic energy of turbulence, m^2/s2, j=1, 2, 3; δ_{ij} – Kronecker symbol.

Absorption of excess heat, humidity and carbon dioxide (CO_2) in the study space.

The parameters of air pollutants that are assimilated by the ventilation system are adopted as follows:

– air temperature: 24 °C;
– initial level of CO_2 concentration: 2100 ppm;
– atmospheric pressure: 101325 Pa;
– relative humidity: φ = 65 %;
– average surface temperature of a clothed person: 27 °C.

Results of studies of the “air contaminant” assimilation.

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Scheme (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/hour;

– exhaust ventilation is organized in the lower part of the wall using a ventilation grid.

First of all, it is reasonable to consider the time required to bring the microclimate of the room to the normative state during CO_2 assimilation. In turn, preliminary studies have established that the highest concentration is concentrated in the working zone, which is due to the physical properties of carbon dioxide compared to the surrounding air.

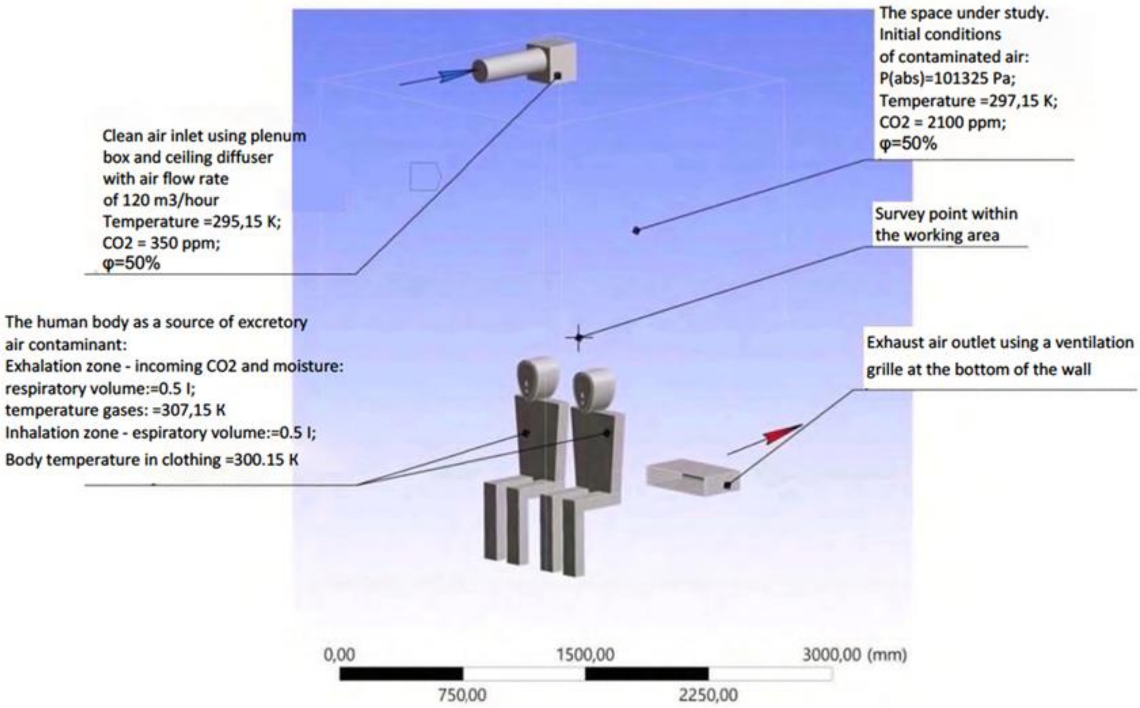

Fig. 1. Initial data for modeling and research according to scheme

There is an interest in the organization of exhaust ventilation in the lower plane of the working area, where the extraction of polluted air has the shortest path and the possibility of repeated ascent of carbon dioxide into the human breathing zone is excluded. The dynamics of changes in CO_2 concentration at the monitoring point in a 9-minute period is presented in Fig. 2.

The value of carbon dioxide on a vertical scale during the functioning of the ventilation system (Fig. 3) is distributed with a fluctuation within 200 ppm, which indicates uniform assimilation of polluted air in the study area over the time of observation.

Volumetric visualization of changes in the carbon dioxide content over a 9-minute period of time is shown in Fig. 4.

The formation of a uniform distribution of air is due to the geometric properties of the ceiling diffuser (Fig. 5), which forms stream lines of a cyclic nature along the adiabatic walls of the study space. The analysis of the jet (stream line) acquires a stable character, where the velocity vector of the supply air coincides with its direction. That is, the use of static pressure chambers in supply devices of air supply systems has advantages in terms of hydrodynamics and acoustics.

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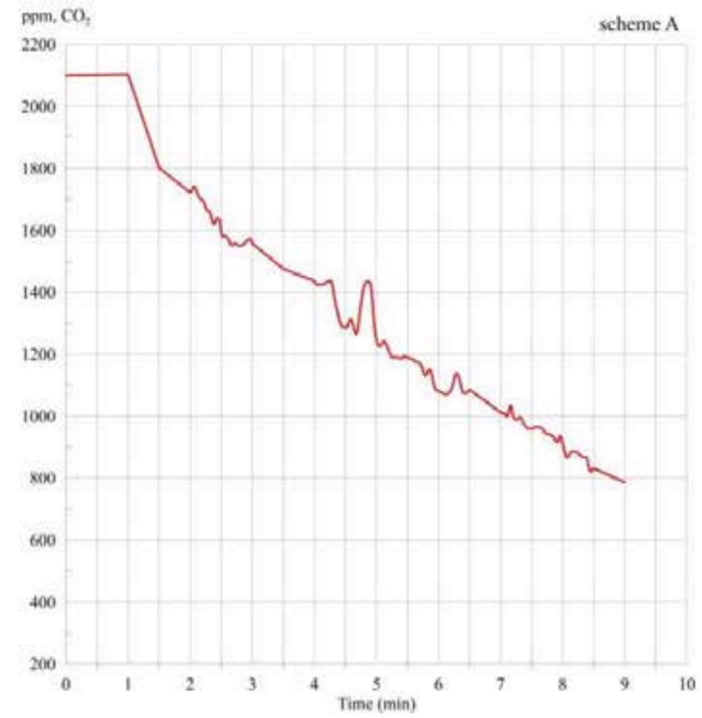

Fig. 2. Dynamics of changes in CO_2 concentration over the time of observation

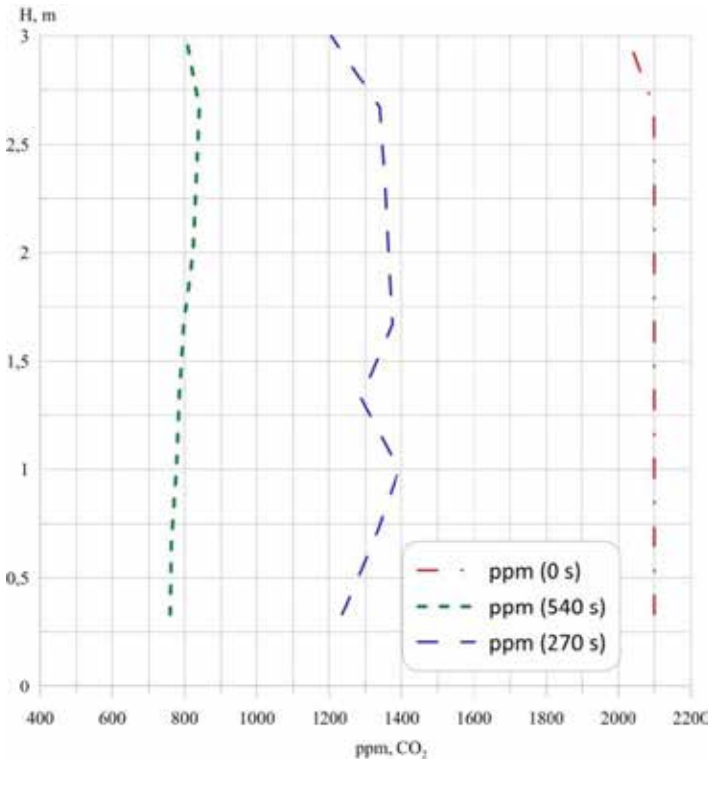

Fig. 3. Monitoring the distribution of CO_2 concentration on a vertical scale

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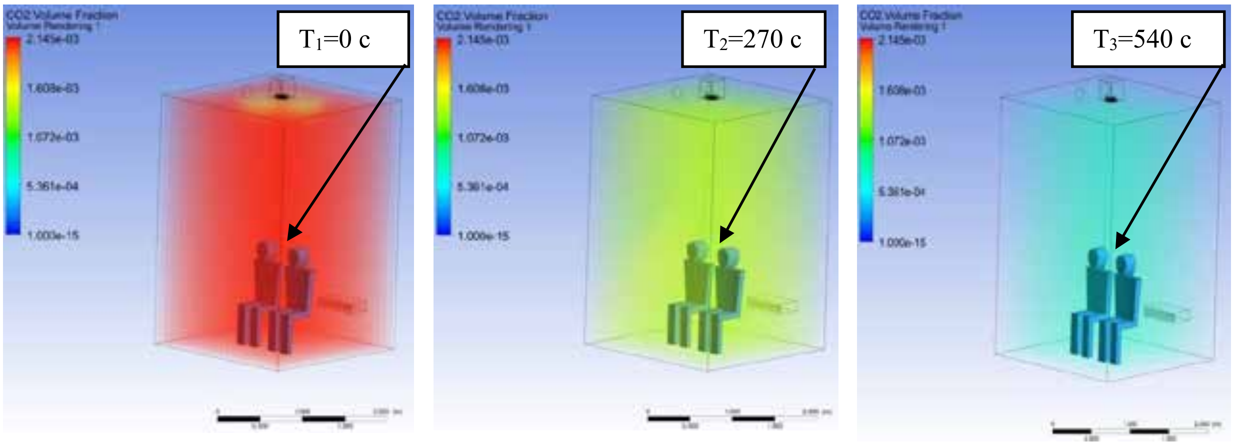

Fig. 4. Volumetric CO_2 rendering over time relative to the observation point

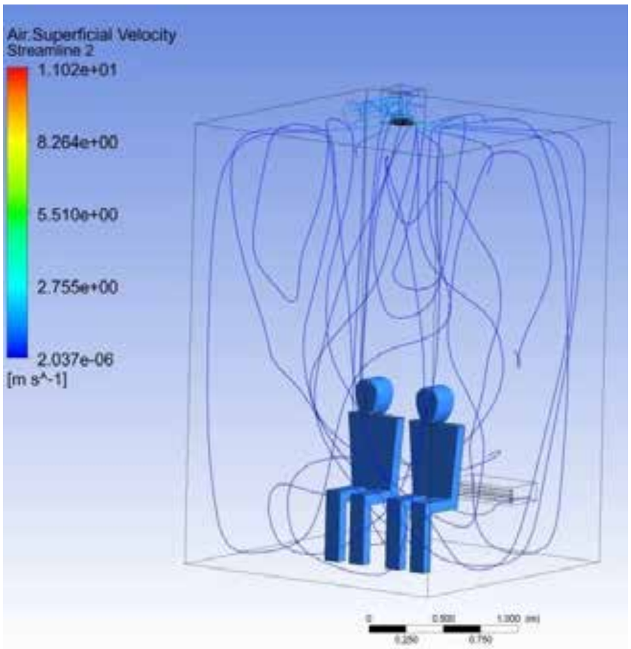

Fig. 5. Stream lines

The rendering of temperature and volumetric humidity content over time relative to the observation point is presented in Fig. 6.

Graphs of changes in temperature and relative air humidity are presented in Fig. 7.

Of special interest for research is the border plane between the upper zone of the room and the working area (WA). According to regulations [2; 3], the velocity of the jet entering the air distribution system (v, m/s) from the air distributor into it, the temperature difference of the jet at the entrance to the air WA and the air temperature in the WA (Δt, °C) and the concentration of carbon dioxide in the WA boundary space (CO_2, ppm) are regulated for WA. The boundary contours of interest to us between the upper zone of the room and the WA of distribution of air contaminants after nine minutes of operation of supply and exhaust ventilation are shown in Fig. 8.

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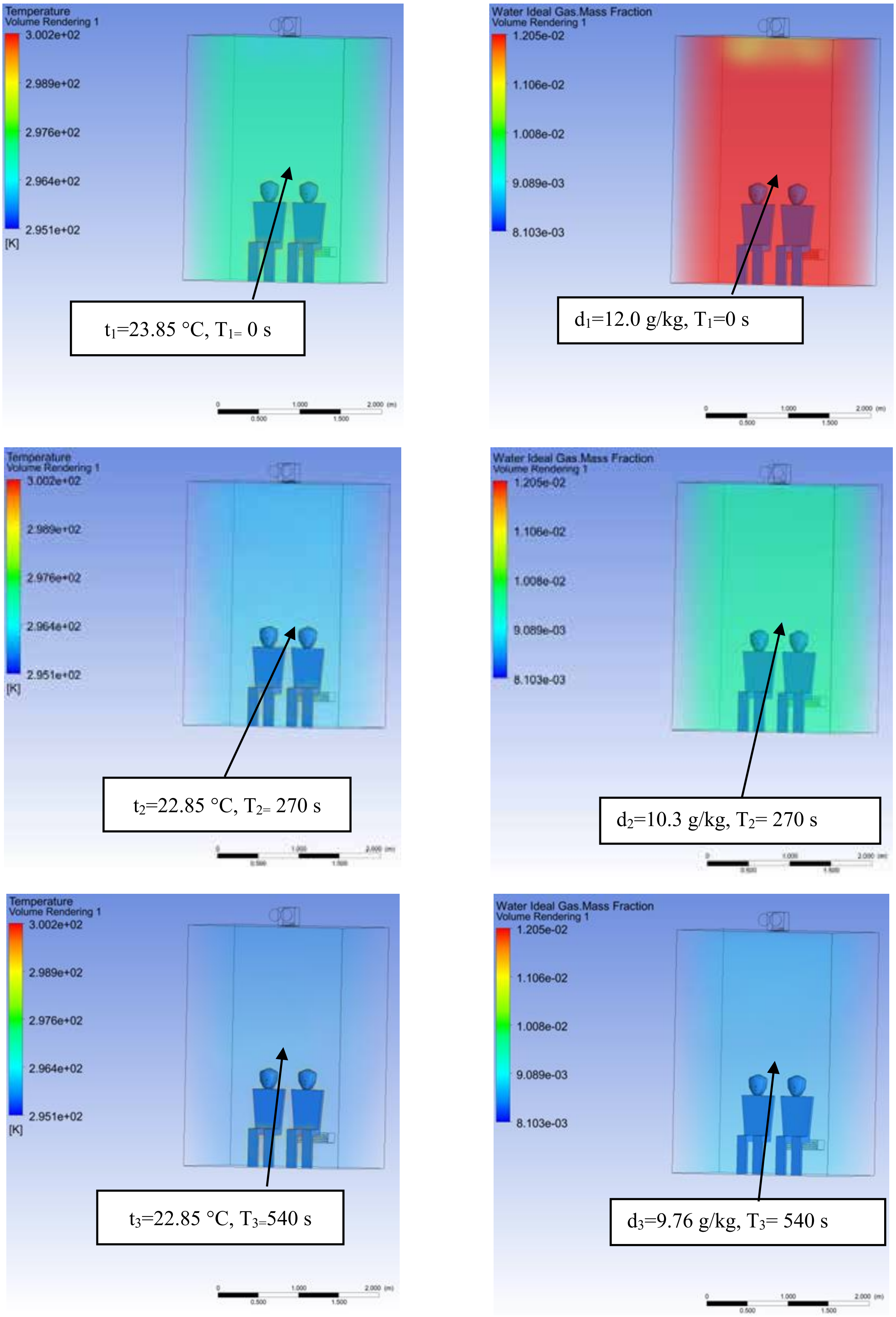

Fig. 6. Rendering of temperature and humidity content over time relative to the observation point

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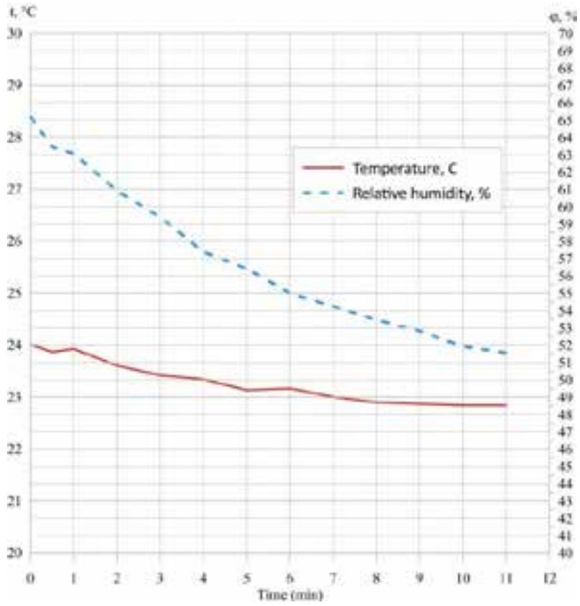

Fig. 7. Graphs of changes in temperature and relative air humidity

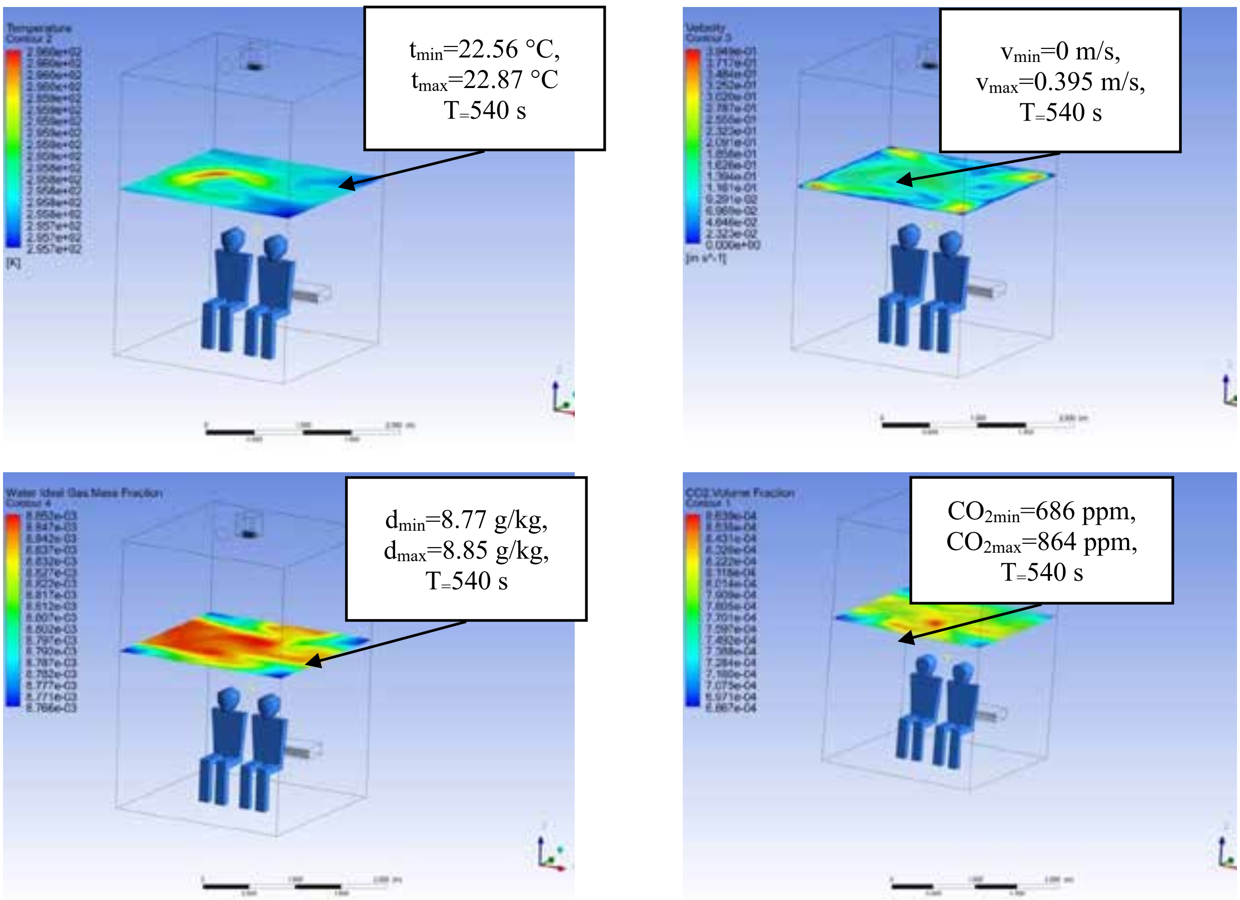

Fig. 8. Boundary WA contours: temperature distribution (t); humidity content (d); air velocity (v); carbon dioxide concentration (CO_2)

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Discussion of research results

On the basis of the developed mathematical model, it became possible to solve such problems using the ANSYS software complex as:

• Human air contaminant intake in an isolated space.

• Modeling of the «air contaminant» intake, scheme «air supply from above – removal from below».

The ANSYS mathematical apparatus allows to analyze the operation of air handling unit to redistribute and remove the main "air contaminants" from the room (carbon dioxide, heat, water vapor) and track the values of temperature, humidity content, relative humidity, enthalpy, and air velocity. In particular, on the basis of the contour distribution of the air handling unit (Fig. 8), it became possible to evaluate and compare the efficiency of the work of various air distribution schemes in the room WA.

Data processing of Fig. 8 made it possible to compare the obtained results with the regulatory requirements for the optimal parameters of the air jet entry from the ceiling diffuser in the room WA (see Table 1).

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 (min-max)	Temperature difference	Δt, °C	v, m/s	φ, %	CO_2, ppm
Scheme «air supply from above – removal from below» (data after 540 s)						
Temperature, t °C	22.6–22.9	Δt=0.6–0.9	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 %	52.2–51.9				25–60	
Carbon dioxide CO_2, ppm	686–864					400–600

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).

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