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AIR FLOW DYNAMICS IN THE CABIN OF A LOW-ENTRY CITY BUS

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Abstract The paper investigates the dynamics of air flows in the cabin of a low-entry city bus to improve passenger comfort and energy efficiency. The modeling was performed by CFD analysis in Ansys Fluent using the Mercedes-Benz Citaro Hybrid cabin model. Under winter conditions (flow inlet temperature - 27°C, bus body walls - 0°C), the maximum flow velocity reached 3.69 m/s in the doorway area, while insufficient ventilation was found in the front and rear parts of the cabin (velocity <0.8 m/s). It is recommended to introduce multi-flow ventilation with optimization of air supply angles by diffusers, as well as additional flows in the floor area to heat passengers' feet in winter (temperature < 290 K). The results obtained allow us to formulate effective solutions to improve the cabin microclimate and reduce discomfort zones.

Keywords Low-entry bus, ventilation, airflow dynamics, CFD analysis, Ansys Fluent, microclimate, multi-flow ventilation, energy efficiency, passenger comfort, temperature gradient.

Introduction

Modern low-entry city buses must provide a high level of comfort for passengers, especially in densely populated urban areas. This includes creating an optimal microclimate in the cabin, which directly depends on the dynamics of air flow. The relevance of the topic is also determined by regulatory requirements that set standards for passenger comfort and safety. In particular: UNECE Regulation No. 107 defines the requirements for ventilation, heating and air conditioning in buses to ensure a proper microclimate; ISO 14505-2 establishes methods for assessing the thermal comfort of passengers, including air movement parameters; UNECE Regulation No. 118 concerns ventilation and fire safety measures that also take into account air circulation. Despite the regulation, the issue of ventilation optimization remains insufficiently studied for buses of the Low-entry and Low-floor type, which are undergoing a stage of transformation to electric traction. Avoiding discomfort zones and increasing the energy efficiency of HVAC systems is a key task for transport manufacturers, which is why there is a scientific interest in this topic.

Problem Statement

Uneven air distribution can lead to overheating or cooling zones, which reduces passenger comfort and can affect their health. The problem is compounded by the need to take into account the architectural features of low-entry buses: the location of equipment (e.g., heating systems, HVAC) concentrated in the rear overhang; low floors in the central and front parts of the body, etc. All these structural elements affect the air distribution in the cabin. As part of the presented research, the authors set the task of modeling the dynamics of air flows from the air conditioner in the cabin of a low-floor bus in the cold season, depending on the location of the inlet and outlet channels.

Review of Modern Information Sources on the Subject of the Paper

Let's consider modern scientific publications on the ventilation and microclimate of buses. Study [1] analyzes the impact of ventilation conditions on the development of fires in electric buses by modeling combustion processes using the Fire Dynamics Simulator (FDS 6). It was found that opening all windows increases the air flow rate to 8 m/s. Opening the rear window first minimizes the risks, which can serve as a basis for improving evacuation and rescue efforts. The authors of [2] analyze the dynamics of COVID-19 transmission in intercity buses using CFD modeling, which reflects the spread of respiratory particles in the air flow. The results demonstrate that increasing the flow of clean air and using personal ventilation significantly reduce the risk of infection, especially if you stay near an infected passenger for a long time. Publication [3] describes the impact of droplet transmission mechanisms in overcrowded and poorly ventilated buses on the risk of respiratory disease infection using CFD simulations. It was found that increasing ventilation reduces the risk of infection for small droplets (5 microns), while large droplets (50-100 microns) mostly settle near the infected person, regardless of the air exchange rate. Study [4] analyzes the January 2020 COVID-19 outbreak in Hunan Province, China, which occurred due to inadequate ventilation in two buses with an infected passenger. It was found that a ventilation rate of less than 3.2 l/s per person facilitated airborne transmission, which explains the higher infection rate in the first bus (B1) compared to the second (B2). Paper [5] presents the effect of ventilation strategy on respiratory droplet concentration in a coach using CFD modeling in Ansys FLUENT. The results show that general ventilation reduces the spread of droplets, but the addition of personal vents above passenger seats significantly reduces particle concentrations and the risk of airborne infection. Publication [6] assesses the risk of SARS-CoV-2 infection in public transport using a combined approach to assessing the proximity and scale of the room. For city buses, the key factor is close contact, which limits occupancy to passengers without masks, while for intercity buses, full occupancy is only possible with FFP2 masks, air filtration, and/or high immunization rates (>80%). Study [7] analyzes airflows, air exchange rates (ACH) and respiratory aerosol trajectories in car, bus and airplane interiors using CFD modeling. The results showed that the risk of infection is highest in buses due to insufficient ventilation, which requires improving the location of outlets or increasing their number, while in airplanes, optimal air flows can be improved by increasing the air exchange rate. According to [8], the risk of SARS-CoV-2 infection among elderly passengers in public transport was assessed using CFD modeling and a modified Wells-Riley model. The results showed that the greatest reduction in the risk of infection is achieved at a personal air supply angle of 30°, and the rear seats of the bus were found to be areas with a low risk of infection, which is recommended for elderly passengers to choose during an epidemic. The authors of [9] study the impact of optimized natural ventilation in buses on the risk of COVID-19 infection using CFD modeling to analyze the impact of different window opening options and the use of wind traps. The results showed that opening the front and rear windows significantly reduces the risk of infection by increasing the air exchange rate, especially in high ambient temperatures. Study [10] analyzes the effect of ventilation strategy on the concentration of respiratory droplets in a coach using numerical modeling in Ansys FLUENT. The results showed that ventilation, both general (from windows and vents) and personal (for each passenger), significantly reduces the droplet concentration, thus reducing the risk of airborne infection. Publication [11] describes the effectiveness of ventilation measures in school buses to reduce airborne droplet infection. The results demonstrated that measures such as windshield deflectors, opening hatches and windows can achieve the required air change values (ACH) that can reduce the risk of virus transmission among drivers and passengers during the COVID-19 pandemic. Paper [12] presents a numerical study using CFD to investigate the effect of different ventilation settings on airflow velocity and temperature distribution inside a bus cabin. The turbulent flow simulation was performed using the Fluent software. In a study [13] conducted in the Kathmandu Valley, the average PM2.5 concentrations in the bus cabin were 95.9 ± 40.4 μg/m³, and 94.7 ± 32.4 μg/m³ on the street. CO2 concentrations in the cabin ranged from 513 to 1230 ppm. Most of the buses did not meet the recommended ventilation standards, which increased the risks to passenger health. Using CFD simulations, [14] assessed the risk of COVID-19 infection in a city bus under four scenarios: with HVAC off and windows closed, with HVAC on and air recirculation, and when the bus was running with windows open. The results showed that open windows significantly reduce the risk of infection, while the use of HVAC also reduces the risk, but less effectively. A study [17] proved that to improve ventilation in tourist buses, it is necessary to install air outlets in the rear upper part of the bus and use a few high-powered outlets instead of many weaker ones. This promotes better air circulation and reduces the risk of infections. In fact, the location of the forced air deflector in the rear was also used in the model presented in the current study. This improves air circulation and reduces the risk of infections. Actually, the location of the deflector for forced airflow in the rear part is used in the model presented in the current research, which is a further development of the subject started in [16-17].

Objectives and Problems of Research

Determination of the features of ventilation of a city low-floor bus depending on the multi-flow air conditioning system with the establishment of conclusions about the configuration of diffusers, optimal temperatures and flow rates, etc. In the course of the research, the authors set the following tasks: forming a mathematical model of bus interior simulation based on the Navier-Stokes equation for a simplified parallelepiped shape. This approach is relevant at the early stages of designing new models of urban transport. The next step is the CFD analysis of a detailed Solid object obtained by extruding the interior space of the Mercedes-Benz prototype, followed by simulation in Ansys Fluent Flow.

Main material presentation

Before starting the FEA modeling of the aerodynamics of the internal volume of the bus interior, it is advisable to familiarize yourself with the theoretical foundations of this process. Let's simplify the bus interior in the form of a parallelepiped, so to determine the airflow rate, we can use the equations of mass transfer and the law of energy conservation, as well as the basics of hydrodynamics. The equation of continuity (conservation of mass) for a stationary flow within a parallelepiped is given by the equation:

$$\rho_1 \upsilon_1 A_1 = \rho_2 \upsilon_2 A_2, \tag{1}$$

де ρ_1, ρ_2 - air density at the inlet and outlet (can be considered constant for isothermal conditions); υ_1, υ_2 – flow rate at the inlet and outlet; A_1, A_2 – cross-sectional areas at the inlet and outlet.

A simplified form of the Navier-Stokes equation for laminar or turbulent flow can be used to describe the distribution of air velocities in a parallelepiped:

$$\rho \frac{\partial \nu}{\partial t} + \rho(\nu \cdot \nabla)\nu = -\nabla p + \mu \nabla^2 \nu, \tag{2}$$

where ν – air velocity vector; p – pressure; μ – dynamic air viscosity; ρ – air density.

Taking into account the much higher complexity of the organization of the interior space of a bus compared to the theoretical parallelepiped, turbulence caused by various elements (seats, floor height differences, side ventilation ducts, etc.) should be taken into account. For turbulent flows, the Navier-Stokes equations are supplemented by the Reynolds-Averaged Navier-Stokes:

$$\rho \frac{\partial \bar{\nu}_i}{\partial t} + \rho \bar{\nu}_j \frac{\partial \bar{\nu}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \mu \frac{\partial^2 \bar{\nu}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}}{\partial x_j}, \tag{3}$$

where $\bar{\nu}_i$ –average flow rate along the axis i; $\bar{p}$ – average pressure; $\tau_{ij} = -\rho \overline{\nu_i'} \overline{\nu_j'}$ –Reynolds stress, which takes into account turbulent velocity fluctuations (ν_i').

Reynolds stress requires the use of additional turbulence models, for example, $k - \varepsilon$ (energy conservation). This model is based on the equation for the kinetic energy of turbulence (k):

$$\frac{\partial k}{\partial t} + \overline{v_j}\frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial \overline{v_i}}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j}\left(\nu_t \frac{\partial k}{\partial x_j}\right) \quad (4)$$

where ε – energy dissipation rate; $\nu_t = C_\mu \frac{k^2}{\varepsilon}$ – turbulent viscosity.

For dissipation rate (ε):

$$\frac{\partial \varepsilon}{\partial t} + \overline{v_j}\frac{\partial \varepsilon}{\partial x_j} = C_1 \frac{\varepsilon}{k}\tau_{ij}\frac{\partial \overline{v_i}}{\partial x_j} - C_2\frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}\left(\nu_t \frac{\partial \varepsilon}{\partial x_j}\right) \quad (5)$$

This model is effective for homogeneous turbulent flow, but can be inaccurate for complex geometries. Model $k - w$ is similar $k - \varepsilon$, but uses a specific dissipation $w = \varepsilon/k$, which allows more accurate modeling of flows near walls.

To consider heat flows, we can refer to the heat transfer equation:

$$\frac{\partial T}{\partial t} + \overline{v_j}\frac{\partial T}{\partial x_j} = \alpha \nabla^2 T, \quad (6)$$

де T – temperatures; $\alpha = \frac{k_t}{\rho c_p}$ – thermal diffusion number; k_t – heat transfer coefficient; c_p – heating capacity.

Turbulence affects heat transfer due to additional turbulent heat flow:

$$q_t' = -\rho c_p \frac{\partial T}{\partial x_j}, \quad (7)$$

For predicting the aerodynamics and microclimate of a simplified parallelepiped cabin model, the above equations are an effective analysis tool in the early stages of bus body design. When the body layout is complete and the seating map, the front panel, and the driver's seat are available, CFD (Computational Fluid Dynamics) based on the finite element method is a more effective approach. We will use Ansys Fluent as a computational module. This is a module for numerical modeling of liquid and gas flows based on the Finite Volume Method (FVM). It allows you to simulate laminar and turbulent flows, heat transfer, mass transfer, chemical reactions, etc. The cabin body model is created in Ansys DesignModeler or SpaceClaim, and can also be imported from SolidWorks, as was done in the current study. Ansys Fluent Flow solves systems of equations that describe flow physics based on the Navier-Stokes equation (3) and the energy equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [(\rho E + \rho)v] = \nabla \cdot (k_t \nabla T) + S, \quad (8)$$

де $E = h + {v^2}/{2}$ – complete energy; S – volumetric density of heat sources (e.g., heaters).

To create a model of the interior volume of the Mercedes-Benz Citaro Hybrid low-floor concept city bus (Fig. 1a) in SolidWorks, the interior space must be cut into a separate solid body by extrusion (Fig. 1b).

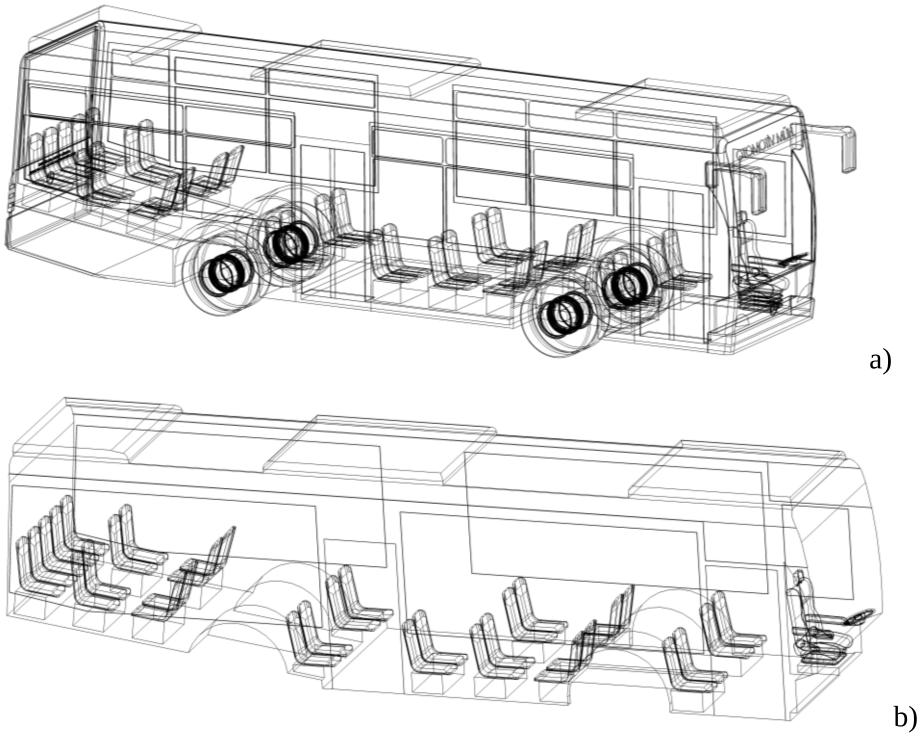


Fig. **1**. Solid- model of Mercedes-Benz Citaro Hybrid prototype:

(a) general view; (b) bus interior volume body

The next step is to resolve the solid body (Fig. 1b) into an FE mesh: 5960966 elements connected by 1088024 nodes, which is a rather difficult model to compute (Fig. 2).

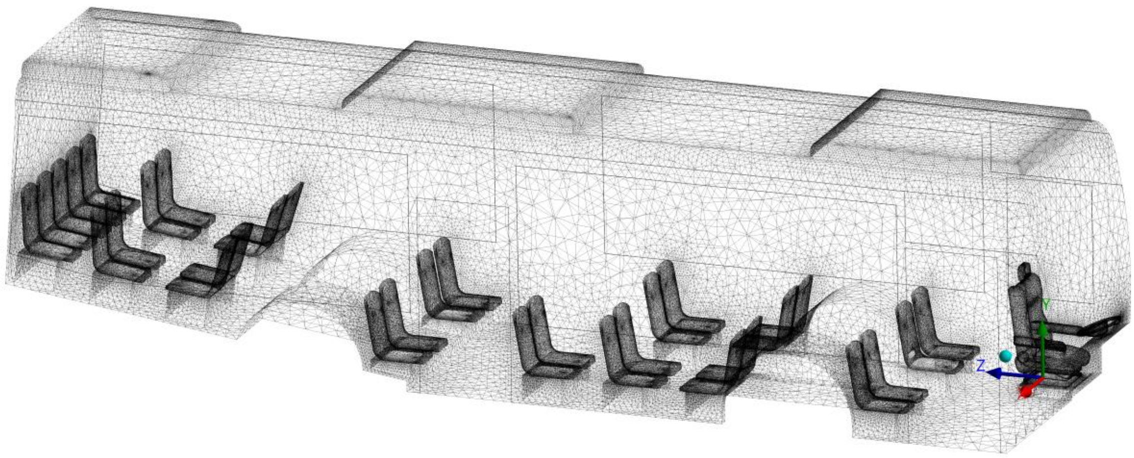


Fig. **2.** FE mesh of the interior volume

In this study, we consider the case of the Inlet air duct under the windshield and roof of the bus in the rear overhang, where the air conditioner is located (Fig. 3). The outlet channel is the doorway in front of the rear axle.

Model boundary conditions in Ansys Fluent Flow include:

- Earth gravity – 9.81 m/s^2;

- Air environment (density – 1.225 kg/m^3; c_p (Specific Heat) – 1006.43 J/(kg·K); Thermal Conductivity – 0.0242 W/(m·K); Viscosity – 1.7894·10^5 kg/(m·s);
- Inlet Velocity – 1 m/s;
- Inlet Temperature – 300 K;
- Walls temperature – 273 K;

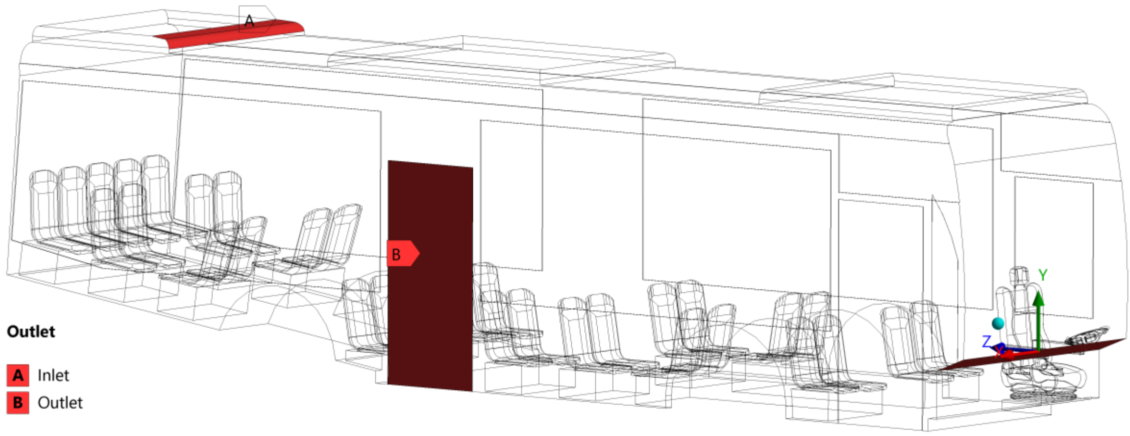


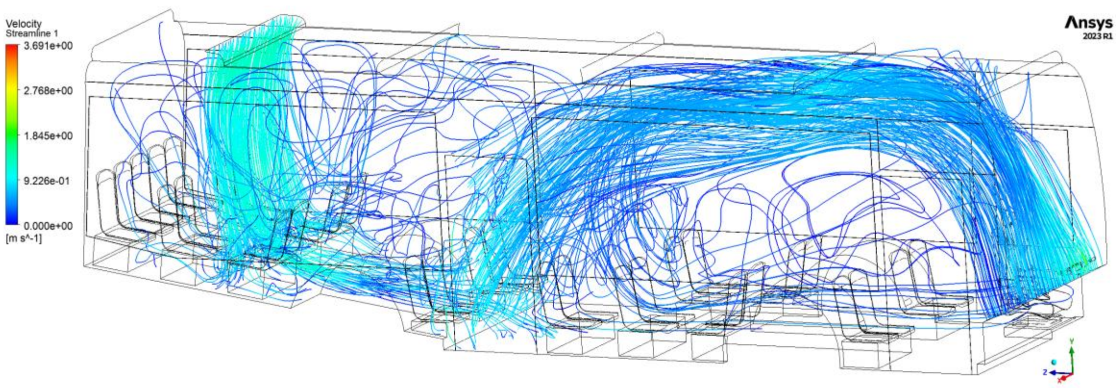
Fig. **3**. Inlet and Outlet airflow areas of the model

Walls temperature characterizes the zero temperature of the bus body, which corresponds to winter operating conditions. Inlet temperature is 27°C due to the air conditioner operation.

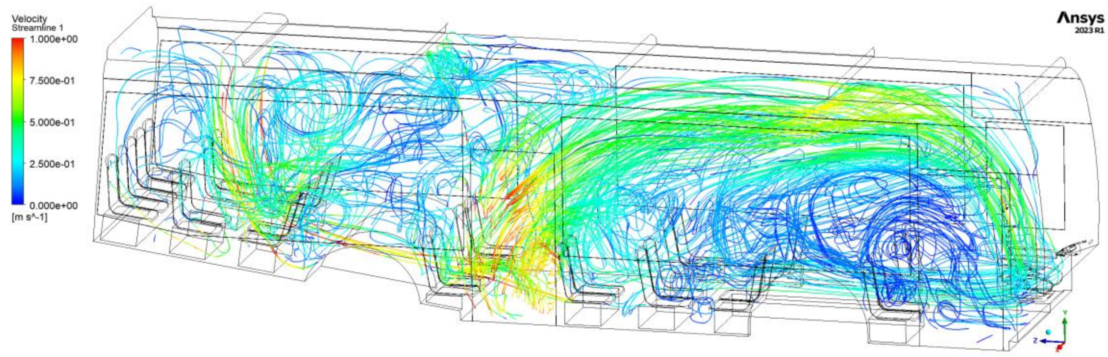
Let's analyze the air velocity map (Fig. 4a), the maximum value was 3.69 m/s and was recorded in the doorway, which corresponds to the Outlet area. It should be noted that the Inlet Velocity is set to 1 m/s according to the boundary conditions. This result is due to the formation of a rarefaction zone in the doorway as a result of the temperature drop (drop to 0°C). For better visualization of the flow map, let's reduce the velocity range to 0-1 m/s (Fig. 4b).

The three-dimensional full view (Fig. 5) allows you to visually judge the fullness of the bus interior. The results show that the front row of seats and the extreme rear row receive insufficient forced ventilation. The movement of air masses in the upper part of the cabin (at the height of standing passengers) is more active than in the lower part, which is positive in terms of better ventilation and protection against viruses. The latter point is a major part of scientific publications on COVID-19.

Let's analyze the distribution of velocities in the longitudinal section on a plane located at a distance of 1 m relative to the central axis of the bus (Fig. 6). In the rear overhang, there is a zone of high velocities (over 1 m/s), although the rear row of seats is poorly ventilated. This suggests the need to increase the airflow angle by changing the configuration of the inlet blades in the bus ceiling.



a)



b)

Fig. 4. Streamline map of air mass movement velocities: a) standard representation; b) range 0-1 m/s

The central part (storage area) received effective circulation, which has a positive effect on the comfort of standing passengers (speed at the level of 0.65-0.8 m/s). The front part of the cabin in the upper tier has been actively ventilated, which is also an acceptable result given that the movement of standing passengers is most active in the span between these two doors. The rear overhang, which does not have a separate door, is designed primarily for seated passengers, due to the increased floor height due to the layout of the bus (concentration of the engine, transmission and related systems in the rear).

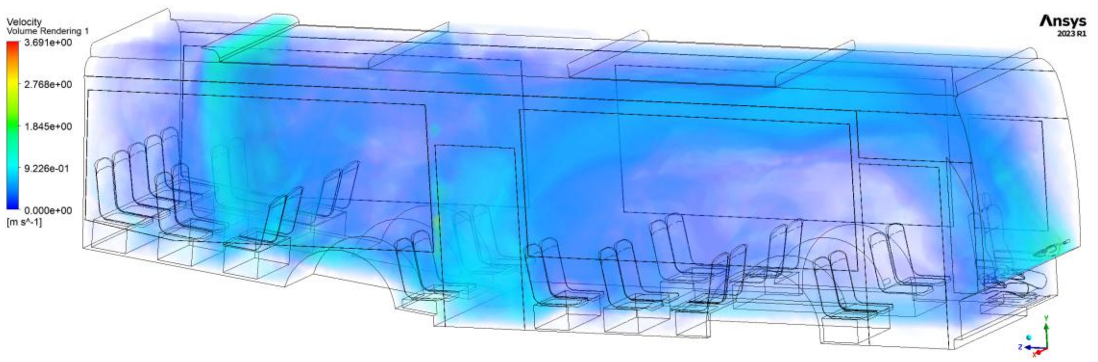


Fig.5. Three-dimensional view of the speed distribution in the cabin

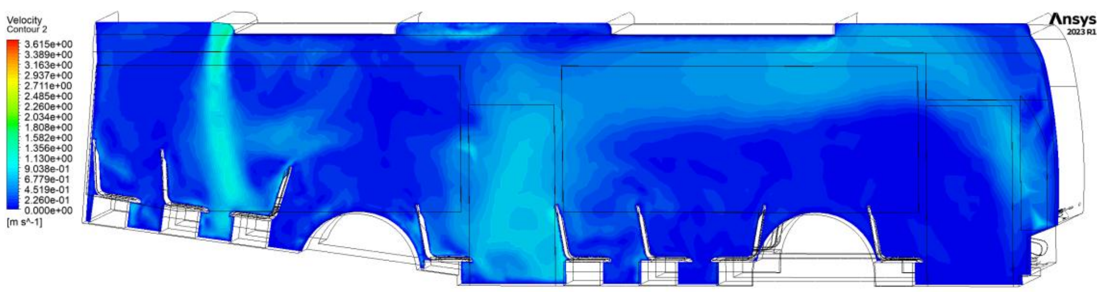


Fig. 6. Velocity distribution in the longitudinal section (1 m relative to the symmetry axis)

The value of the air flow rate is important not only in terms of circulation and ventilation, but also heat transfer, which is especially important in the cold season. According to the temperature distribution map (Fig. 7), we observe blue areas (of the order of 0°C) close to the body surface, which corresponds to winter operating conditions.

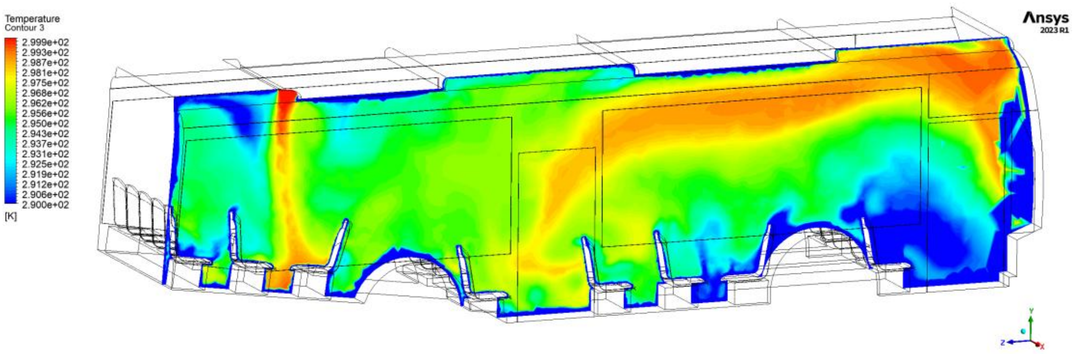


Fig. 7. Temperature distribution in the longitudinal section

For visualization of temperature gradients, the map scale (Fig. 7) is limited to the range of 290-300 K (17-27°C). From the point of view of comfort for passengers' feet (especially in the front of the bus), it is advisable to direct additional air flow at floor level - this is a recommended measure for winter operation.

Conclusions

Based on the analysis of the forced ventilation of a city low-floor bus, a number of conclusions were drawn. Effective circulation can be achieved only if there is multiple flows, not only in different parts of the cabin but also at different heights. Thus, the difference in flow velocity is almost 4 times in the analyzed model (Inlet velocity is 1 m/s, and the maximum recorded velocity is 3.69 m/s). For better ventilation during stops (especially in the warm season), it is advisable to operate the central door, and to keep the heat (in winter) - the front door (the heat will be stored in the main part of the cabin). The configuration of the diffuser in the rear overhang of the bus should provide a large airflow angle or multi-flow to ensure sufficient circulation in the last rear row of seats. The front diffuser in the windshield area also needs to be differentiated into separate streams at different angles and variable intensities. The temperature level at the floor and body level of the seated passengers in the front of the cabin does not exceed 290 K (17°C), which leads to the conclusion that additional flow is needed in this area, especially in winter. Thus, the conclusion about the need to use different flows in different periods of the year or day is organically formed. Additional areas for future research include localized analysis of flows around interior elements such as seats, trim, driver's workstation elements, etc.

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