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Abstract. Airborne virus transmission is a key mechanism for the spread of infectious diseases in enclosed spaces, where asymptomatic carriers are especially dangerous, which can increase the rate of infection foci formation. The behavior of aerosol particles in the air is determined by the complex dynamics of air flows, thermal effects, and characteristics of ventilation systems, which makes the problem relevant for developing effective strategies to prevent indoor contamination. In this paper, a numerical study of the propagation of droplets and virus particles in ventilated rooms is performed based on the solution of three–dimensional Navier-Stokes equations for incompressible flows in combination with the discrete phase (DPM) model and the turbulent SST k–ω model. The developed mathematical model takes into account the influence of human body temperature, gravitational deposition, room geometry, location of ventilation openings, as well as the behavior of particles during breathing, coughing and sneezing. Two room configurations and two particle ejection rates are considered (6, 20 m/s), which makes it possible to cover a wide range of real-world scenarios. The simulation results demonstrate that particles can spread over a distance of more than 5-6 meters, and improper or uneven ventilation leads to the formation of zones of increased aerosol concentration. The nonlinear effect of the human heat plume and ventilation design on the dynamics of air flow, precipitation and particle transport is shown. The data obtained can be used to optimize ventilation systems, design safe indoor spaces, and develop protocols to reduce the risk of indoor transmission of infections. Computational Fluid Dynamics (CFD) provides valuable information for substantiating safety protocols and reducing the risk of airborne transmission, which makes the proposed approach particularly relevant for practical applications**.**

Key words: particles, enclosed space, SST k-omega, viral diseases

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АУА ТАМШЫЛАРЫ АРҚЫЛЫ ВИРУСТЫҚ ИНФЕКЦИЯНЫҢ ШЕКТЕУЛІ КЕҢІСТІКТЕ ТАРАЛУЫН САНДЫҚ МОДЕЛЬДЕУ

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Аннотация. Вирустардың ауа-тамшылары арқылы таралуы инфекция ошақтарының қалыптасу жылдамдығын арттыруға қабілетті, асимптоматикалық тасымалдаушылар аса қауіпті жабық үй-жайларда жұқпалы аурулардың таралуының негізгі механизмі болып табылады. Ауадағы аэрозоль бөлшектерінің әрекеті ауа ағындарының күрделі динамикасымен, жылу әсерлерімен және желдету жүйелерінің сипаттамаларымен анықталады, бұл мәселені ішкі инфекцияның алдын алудың тиімді стратегияларын әзірлеу үшін өзекті етеді. Бұл жұмыста дискретті фазалық модельмен (DPM) және SST K–ω турбулентті моделімен біріктірілген сығылмайтын ағындар үшін үш өлшемді Навье–Стокс теңдеулерін шешу негізінде желдетілетін бөлмелерде тамшылар мен вирустық бөлшектердің таралуын сандық зерттеу жүргізілді. Әзірленген математикалық модель адамның дене температурасының, гравитациялық тұндырудың, бөлме геометриясының, желдеткіш саңылаулардың орналасуының және тыныс алу, жөтелу және түшкіру кезіндегі бөлшектердің әрекетінің әсерін ескереді. Бөлменің екі конфигурациясы және екі бөлшектердің шығарылу жылдамдығы қарастырылады (6, 20 м/с). Бұл нақты сценарийлердің кең ауқымын қамтуға мүмкіндік береді. Модельдеу нәтижелері бөлшектердің 5-6 метрден астам қашықтыққа таралуы мүмкін екенін көрсетеді, ал дұрыс емес немесе біркелкі емес желдету аэрозоль концентрациясының жоғарылау аймақтарының пайда болуына әкеледі. Адамның жылу шлейфі мен желдету құрылымының ауа ағынының динамикасына, тұндыруға және бөлшектердің тасымалдануына сызықтық емес әсері көрсетілген. Нәтижелер желдету жүйелерін оңтайландыру, қауіпсіз ішкі кеңістіктерді жобалау және үй ішінде инфекциялардың таралу қаупін азайту хаттамаларын әзірлеу үшін пайдаланылуы мүмкін. Есептеу гидродинамикасы (CFD) қауіпсіздік хаттамаларын негіздеу және ауа арқылы жұқтыру қаупін азайту үшін құнды ақпарат береді, бұл ұсынылған тәсілді практикалық қолдануға ерекше маңызды етеді.

Түйін сөздер: бөлшектер, жабық бөлме, SST k-omega, вирустық аурулар

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЕ ВИРУСНОЙ ИНФЕКЦИИ ВОЗДУШНО-КАПЕЛЬНЫМ ПУТЕМ В ЗАМКНУТЫХ ПОМЕЩЕНИЯХ

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Аннотация. Воздушно-капельная передача вирусов является одним из ключевых механизмов распространения инфекционных заболеваний в закрытых помещениях, где особую опасность представляют бессимптомные носители, способные ускорять формирование очагов заражения.Поведение аэрозольных частиц определяется сложной динамикой воздушных потоков, тепловыми эффектами и характеристиками вентиляционных систем, что обуславливает актуальность разработки эффективных стратегий предотвращения внутрипомещенного заражения. В работе выполнено численное моделирование распространения капель и вирусных частиц в вентилируемых помещениях на основе решения трёхмерных уравнений Навье–Стокса для несжимаемых течений в сочетании с моделью дискретной фазы (DPM) и турбулентной моделью SST k–ω. Разработанная математическая модель учитывает влияние температуры тела человека, гравитационного осаждения частиц, геометрии помещения, расположения вентиляционных отверстий, а также режимов дыхания, кашля и чихания. Рассмотрены две конфигурации помещения и два режима скорости выброса частиц (6 и 20 м/с), что позволяет охватить широкий диапазон реальных сценариев. Результаты моделирования показывают, что частицы способны распространяться на расстояние более 5–6 метров, а неравномерная или неэффективная вентиляция приводит к формированию зон повышенной концентрации аэрозолей. Выявлено нелинейное влияние теплового шлейфа человека и параметров вентиляции на динамику воздушных потоков, перенос и осаждение частиц. Полученные результаты могут быть использованы для оптимизации систем вентиляции, проектирования безопасных внутренних пространств и разработки мер по снижению риска передачи инфекций в помещениях. Методы вычислительной гидродинамики (CFD) предоставляют важную информацию для обоснования санитарно-гигиенических рекомендаций и повышения эффективности систем вентиляции.

Ключевые слова: частицы, замкнутое помещение, SST k-omega, вирусные заболевания.

Introduction. In the last decades, it became evident that understanding and modelling the spreading of airborne droplet particles, such as viruses, is of great importance to public health and safety. The COVID-19 pandemic clearly demonstrated the significance of studying the aerosol ways of infection transmission to develop efficient prevention strategies. The global statistics of COVID-19 are as follows: the number of infected exceeds 775 million people, and more than 7 million people have passed away (World Health Organization WHO, 2023). Among the symptoms of virus, the most common are: an increase in body temperature to 38° C, significant fatigue and loss of sense of smell and taste. One of the foremost aspects of such research is the modelling of the behavior and dynamics of particles in air flows, which requires accounting for multiple factors, such as turbulence, lift forces, and inter-particle interaction. The primary mode of disease transmission is recognized as droplets containing viral particles expelled by an infected individual through breathing, coughing, and sneezing (Bipasha et al., 2015). Data from the study indicate that a healthy individual typically coughs twice and sneezes four times daily (Hansen et al., 2002; Surinder et al., 2006). SARS-CoV-2, the coronavirus SARS-CoV-2, as many other viruses, are mainly transmitted through the airborne droplet route (Busco et al., 2020). The primary transmission mechanisms include:

The SARS-CoV-2 coronavirus, like many other viruses, is transmitted mainly through airborne droplets. The main transmission mechanisms include:

Drip transmission: Large droplets released when coughing, sneezing or talking may contain viral particles. These droplets settle on the surface within a few meters of the source.

Aerosol transmission: Fine particles (aerosols), also released when breathing, talking or coughing, can remain suspended in the air for a long time and travel long distances, especially in conditions of insufficient ventilation. In fact, the speed of reflex processes can vary significantly, averaging between 1 - 22 m/s (Gao et al., 2007; Gupta et al., 2009).

Contact transmission: The virus can be transmitted by touching contaminated surfaces and then to mucous membranes (eyes, nose, mouth) (Wolfer et al., 2020; Pan et al., 2019).

The main focus of this work is on the study of the behavior of aerosol particles containing SARS-CoV-2 virus particles. In particular, three basic physical models were used: the Saffman lifting force, stochastic collision, and the particle rupture model. Each of these models plays an important role in accurately describing the dynamics of particles in turbulent flows.

The Saffman lifting force takes into account the effect of the velocity gradient on particles, which is especially important for small particles in streams with high shear rates. Stochastic collision describes the probabilistic interactions between particles, and the rupture model takes into account the process of breaking large particles or droplets into smaller ones under the action of turbulence and shear forces.

To accomplish this task, modern numerical modeling methods were used, including discrete phase models (DPM) (Pirker et al., 2011) and turbulence models. The use of such models makes it possible to obtain a detailed picture of particle propagation under various conditions, as well as to assess the influence of various physical factors on this propagation.

The thesis also considers the initial and boundary conditions used in modeling, including temperature and particle composition, which allows us to reproduce the real conditions of the spread of viral particles in the air as accurately as possible.

The ventilation rate of the room, along with both the individual’s body temperature and the ambient room temperature, exert significant influence on the characteristics of infectious aerosols (Mutlu et al., 2020). The human body temperature was set at 37°C (310.15 K), which was taken into account in the simulation to accurately reproduce the thermal effect on air flows and, consequently, on the propagation of particles.

To assess the nature of the flow, the Reynolds number was calculated, which made it possible to determine the flow regime and take into account its influence on the behavior of particles. The turbulent nature of the air flow plays a key role in the spread of particles, especially in confined spaces where viral particles can remain suspended in the air for a long time. Therefore, proper modeling of turbulence and its effect on the trajectory and distribution of particles is a critically important aspect of this study.

Various numerical methods, including the finite element method and the finite volume method, have also been used to better understand and predict the behavior of particles in air flows. These methods make it possible to solve complex systems of equations describing the motion and interaction of particles in a multicomponent medium.

Literature Review. Computational fluid dynamics (CFD) was used to study the formation and spread of viruses. Experimental investigation of such processes presents significant difficulties, therefore CFD offers a valuable tool for modeling the distribution and spread of viral droplets that occur during reflex processes such as coughing, sneezing and breathing. Numerical modeling in the study (Hamid et al., 2021), various ventilation options were considered in order to influence ventilation on the transfer of pathogen droplets. The authors of the work (Mengfan et al., 2022) numerically analyzed the spread of droplets during coughing in different seasons of time indoors. It was concluded that the rate of droplet transmission accelerates at low temperature and the exhalation height of droplets plays an important role in droplet transmission. The study (Aliyu et al., 2021) considered airborne transport with and without masks in ventilated rooms. As a result, in cases of wearing masks, more than 96% of all discarded droplets were trapped within the recommended social distancing radius of 2 m. Without wearing masks, 80% of the drops were trapped, and 20% of the drops got into the air and spread. CFD was used in the above-mentioned works and the authors of these works suggest using CFD for such tasks, namely particle propagation.

The purpose of this thesis is to develop and apply an integrated approach to modeling the aerosol spread of viruses, which can make a significant contribution to understanding the mechanisms of transmission of infections and developing measures to prevent them. The results of the study can be used to improve ventilation systems, develop more effective disinfection methods and reduce the risk of transmission of infections in public places.

Materials and methods

Mathematical model. A mathematical model has been developed to study the spread of viral particles in airborne droplets in a confined spaces. To simulate the airflow and particle dynamics within a confined indoor environment, the incompressible Navier–Stokes equations were employed as the governing equations for fluid motion:

$$\nabla u = 0, \tag{1}$$

$$\rho\,(\frac{\partial u}{\partial t} + (\nabla u)u) = -\nabla p + \mu \nabla^2 u - \rho \beta g (T - T_0), \tag{2}$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + u_j \frac{\partial \mathrm{T}}{\partial x_j} = D_a \left(\frac{\partial^2 T}{\partial x_j^2}\right) + \frac{S_T}{\rho c_p}, \tag{3}$$

Where u – velocity vector, $(\nabla u)u$ – the convective term describing the change in velocity due to fluid motion, ρ – density, p – pressure, μ – effective dynamic viscosity, β – thermal expansion coefficient, g – acceleration due to gravity, T – temperature, T_0 – initial temperature, D_a - thermal diffusivity, S_T- heat source, c_p - specific heat capacity.

To describe the conservation of mass in a fluid flow, the continuity equation shown in equation (1) is used. To describe the dynamics of air in a room, the equations of motion presented in equation (2) is used and equation of temperature (3).

To model the thermal effects due to human body temperature, the Boussinesq approximation was applied, assuming that density variations are negligible except in the buoyancy term. The human body acts as a localized heat source, generating thermal plumes that influence particle movement. “β” is an indicator of the relative change in the density of a liquid depending on temperature. It is defined as:

$$\beta = \frac{2}{T_1 + T_2}. \tag{4}$$

The particle motion was modeled using a dispersed phase (DPM), which is solved by integrating the force balance. In a set of differential equations that calculate the positions and velocities of particles. In the CFD code, all particles are considered as point masses, the kinematic relationship between the position of the particles (respiratory droplet) and the velocity of the particles (respiratory droplet) is equal to

$$\frac{dx_p}{dt} = u_p, \tag{5}$$

$$m_p \frac{du_p}{dt} = F_D + F_G. \tag{6}$$

The trajectory of particles is determined by these forces, since they include the main effects on their movement. F_D - It is calculated as follows:

$$F_D = \frac{1}{2}\rho_f \frac{\pi d_p^2}{4} C_D (u_f - u_p)|u_f - u_p|, \tag{7}$$

$$C_D = \begin{cases} \dfrac{24}{Re}; & (Re < 1) \\ \dfrac{24}{Re}(1 + 0.15Re^{0.687}); & (1 \le Re \le 1000) \end{cases} \tag{8}$$

Re is the Reynolds number, calculated as follows:

$$Re = \frac{\rho d_p |u - u_p|}{\mu_d}. \tag{9}$$

Where x_p - the location of the particles, u_p - particle velocity, m_p- particle mass, u_f- the speed of movement of liquids, F_D - drag force, F_G– gravity, C_D - drag coefficient, d_p- particle diameter, Re - Reynolds number, μ_d - dynamic viscosity, ρ_ρ- particle density, ρ_f - the density of the liquid.

There are two fundamental concepts that play a crucial role in the accurate modeling of particle propagation in airflow: drag force and drag coefficient.

The drag force represents the resistance exerted by the surrounding medium on a moving particle. It arises due to viscous friction and inertial effects as the particle travels through a fluid (gas or liquid).

The drag coefficient is a dimensionless parameter that characterizes the magnitude of this resistance. It depends on the Reynolds number, particle shape, and flow conditions.

These two concepts are essential for describing the interaction between particles and the ambient air, especially when modeling particle transport and deposition in aerosols, liquid droplets, or solid particles. In the current study, the drag force influences both the trajectory and the eventual settling of particles, while the drag coefficient helps determine how particles of different sizes behave under airflow conditions in confined spaces.

Turbulent model. To calculate turbulent flows, a two-level k- SST turbulence model was used. At the same time, this method predicts the behavior of the boundary layer, especially in areas with a high velocity gradient. The main advantage of this method is that it demonstrates stable and accurate results for problems with complex geometry. It should be noted that this method has also proven its reliability and stability when modeling the air flow inside the room (Issakhov et al., 2021).

These equations are discretized using the finite volume method. The equations for the k-ω model can be written as follows:

SST k-ω

$$\frac{\partial k}{\partial t} + u\frac{\partial u_j}{\partial x} = \frac{1}{\rho}(P_k - \eta^* k\omega + \frac{\partial}{\partial x_j}((\mu + \delta^* \mu_t)\frac{\partial k}{\partial x_j})), \tag{10}$$

$$\frac{\partial \omega}{\partial t} + u\frac{\partial u_j \omega}{\partial x_j} = \frac{1}{\rho}\left(\alpha S^2 - \eta\omega^2 + \frac{\partial}{\partial x_j}\left((\mu + \delta_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right) + \right.$$

$$\left. + 2(1 - f_1)\delta_{\omega_2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}\right), \tag{11}$$

where:

$$\mu_t = \frac{\alpha_1 k}{max(\alpha_1 \omega_1 f_2 S)}, \tag{12}$$

$$P_{k_1} = \mu_t(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})\frac{\partial u_i}{\partial x_j} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}(3\mu_t\frac{\partial u_k}{\partial x_k} + \rho k), \tag{13}$$

$$P_k = min(P_{k_1}, 10\eta^* k\omega), \tag{14}$$

$$f_1 = tanh((min(max(\frac{2\sqrt{k}}{\eta^* \omega y}, \frac{500\mu}{y^2 \omega}), \frac{4\delta\omega_2 k}{CD_{k\omega} y^2}))^4), \tag{15}$$

$$f_2 = tanh((max(\frac{2\sqrt{k}}{\eta^* \omega y}, \frac{500\mu}{y^2 \omega}))^2), \tag{16}$$

$$CD_{k\omega} = max(2\rho\delta_{\omega_2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega_i}{\partial x_i}, 10^{-10}), \tag{17}$$

$$\phi = \phi_1 f_1 + \phi_2(1 - f_1). \tag{18}$$

k - kinetic energy of turbulence, u_j – components of the velocity vector, ω - specific dissipation rate, P_k - turbulent kinetic energy production, μ_t - turbulence viscosity, η^* - the constant of the model, δ^* - the constant of the model, S – rate of deformation, f_1 – function for switching between different model modes, $CD_{k\omega}$ – the correction term for ω, φ – is a unified function, φ_2 – function values in the second zone.

Constants of the model:

$$\alpha_1 = 1, \quad \alpha_2 = 0.52, \quad \eta_1 = \frac{3}{40}, \quad \eta_2 = 0.0828,$$
$$\eta^* = 0.09, \quad \delta_{k_1} = 1.178, \quad \delta_{k_2} = 1, \quad \delta_{\omega_1} = 2, \quad \delta_{\omega_2} = 1.168$$

Boundary conditions. Boundary conditions are conditions that are set at the boundaries of the area necessary for accurate and complete determination of the behavior of the simulated system. The following boundary conditions were set for my thesis:

Inlet (ventilation):

- The air velocity at the inlet is set constant and is 1 m/s.
- The inlet pressure is set according to the Neumann condition and is equal to 0 Pa.
- The temperature of the incoming air is set to 291° K, which corresponds to standard ventilation conditions.
- The conditions of the discrete phase model were like an escape.

Outlet (exhaust):

- The outlet pressure is set to 0 Pa.
- By default, the temperature on the outlet is set at 300 K.
- The air velocity through the outlet is determined by the mass balance in the design area.
- The conditions of the discrete phase model were like an escape.

Inlet (mouth):

- The particles are ejected in the time interval from 0.1 to 0.3 seconds.
- The rate of particle release varies depending on the reflex process (for example 6, 20 m/s).
- The particle temperature is set as 310.15 K.
- The particle composition was set to 0.59% for water, and the remaining 0.41% for air.
- The conditions of the discrete phase model were like a reflect.

Walls and desks:

- The walls and desks of the room are set to be impenetrable and smooth. (No slip)
- The heat flow on the walls and desks are set, which means that the walls and desks temperature will be calculated in the process of solving the problem.
- The conditions of the discrete phase model were like a trap.

People

- The surface of the body (teacher and students) is set at a constant temperature equal to 309.7 K.

- The condition of zero normal velocity is set on the surface of the body. (No slip)
- The conditions of the discrete phase model were like a reflect.

Numerical simulation. Numerical modeling allows to describe the modeling process in detail and solve the problem using computational algorithms. If we cannot solve the equation analytically and make an experiment, then a numerical solution is the best and less expensive way to study the problem. At the same time, the error that may be in the solution is not quite large, but exactly what error we cannot say for sure. By solving the problem numerically, we can take the results more natural and more accurate than nothing. For my research on solving equations, numerical methods implemented in the ANSYS Fluent package were used. The relationship between pressure and velocity was achieved using the SIMPLE numerical algorithm (Semi-Implicit Method for Pressure-Linked Equations). The SIMPLE method is an effective and reliable method for solving the Navier-Stokes equations in problems with incompressible flows. The SIMPLE method has a number of advantages, namely stability and convergence, ease of implementation and can be applied to various sampling schemes and used to solve complex geometries and boundary conditions (Han et al., 2019). Its use in this study allows us to obtain accurate and stable results of modeling the spread of viral particles in confined spaces. Complete the SIMPLE algorithm includes following steps:

1. Guess the pressure field and solve the momentum equations to obtain .

$$\frac{u^{**}-u^{n}}{\Delta t}=-\frac{1}{\rho}\frac{\partial P^{*}}{\partial x}+L_1 \rightarrow\; u^{**}=u^{n}+\Delta t\left(-\frac{1}{\rho}\frac{\partial P^{*}}{\partial x}+L_1\right), \qquad (19)$$

2. Solve the equation by substitute into the continuity equation and we get the Poisson equation.

$$\frac{u^{n+1}-u^{**}}{\Delta t}=-\frac{1}{\rho}\frac{\partial P'}{\partial x}+L_1 \;\rightarrow\; u^{n+1}=u^{**}-\frac{\Delta t}{\rho}\frac{\partial P'}{\partial x} \qquad (20)$$

$$\frac{\partial^2 P'}{\partial x^2}+\frac{\partial^2 P'}{\partial y^2}+\frac{\partial^2 P'}{\partial z^2}=\frac{\rho}{\Delta t}\left(\frac{\partial u^{**}}{\partial x}+\frac{\partial v^{**}}{\partial y}+\frac{\partial w^{**}}{\partial z}\right), \qquad (21)$$

3. Correct pressure field $P=P^{*}-P'$, (22)

4. Correct velocity field $u=u^{*}-u'$, (23)

For simplicity, the derivation above considers only the x-component of the velocity field. The corresponding expressions for the y- and z-components can be obtained analogously by applying the same discretization procedure to the respective momentum equations

Table 1— Simulation scenario.

Variant	Scenario	Particle velocity (m/s)	Supply air velocity (m/s)	Particle diameter (м)
1	1	V = 6	1	$1 \times 10^{-6} to\, 1 \times 10^{-4}$
	2	V = 20	1	$1 \times 10^{-6} to\, 1 \times 10^{-4}$
2	3	V = 6	1	$1 \times 10^{-6} to\, 1 \times 10^{-4}$
	4	V = 20	1	$1 \times 10^{-6} to\, 1 \times 10^{-4}$

All equations in the discrete phase model and turbulent models are solved by default using the explicit method.

The momentum was discretized utilizing the second-order discretization

scheme. The energy which means temperature was discretized utilizing the first-order discretization scheme. The solution is considered converged when all the scaled residuals stabilize and reach a minimum of for the k, ω, continuity, and x, y, and z momentum equations, as well as for the energy equation.

Geometry and mesh. The COVID-19 pandemic has highlighted the importance of maintaining social distance, which has led to increased interest in analyzing the geometry of classrooms with the presence of teachers and students. The creation of a geometric model of the classroom was carried out taking into account the average parameters of the room. I conducted a detailed study of the geometry of the classroom, including its dimensions and the location of the entrances and exits. Thus, for the study, I took the average room size of X*Y*Z = 7*3*4 m. This room served as the main model for analyzing the spread of viral particles in a confined space

We examined two types of geometry of the classroom where the infected teacher is, and also took into account the presence of ventilation and entrance to the room. The height of the teacher inside the room was 1.94 m, and the teacher stood 0.2 m taller, which could affect the propagation of particles, as shown in Figure 2. The height of the infected person's mouth was about 1.76 m.

Ventilation in the room was carried out using a single grate on the side wall with a size Y*Z = 0.125*0.5 m, while an extractor hood of the same size was located 0.275 m below the ventilation on the opposite wall. All geometries consider made a standing teacher and four sitting students. The teacher looked at the students or at the blackboard, depending on the geometry option. For the realism of the model, desks in front of the students with dimensions X*Y*Z = 0.5*0.9*0.8 m were added.

The following distances were taken into account when describing the geometry in detail:

- The distance from the teacher to the students was 2.5 m.
- The distance between the students is 1.5 m and between the desks is 1 m.
- The distance from the wall to the desk is 0.7 m.
- The distance between the desk and the front wall is 2.5 m.

- The distance to the wall at the back is 2 m.

In this study, two types of geometry were considered:

1)The teacher looks at the students taking into account ventilation and exhaust. (which is shown in the Figure 1).

2)The teacher looks at the board, taking into account ventilation and exhaust. (which is shown in the Figure 1).

The simulation also took into account various velocities (1 m/s, 6 m/s, 20 m/s) corresponding to reflex processes (breathing, sneezing, coughing) in order to fully study the spread of viral particles.

Figure 3 shows a three-dimensional (3D) computational grid of the study area, in which the total number of elements is 2898449. The value of the grid size plays a key role in ensuring the accuracy of the results. The unstructured geometry caused by the presence of people in the room was taken into account when choosing a hexahedral grid. This choice of technology is due to its efficiency when working with solids and simplification of the grid generation process. Given this unstructured nature, creating a grid requires additional efforts to ensure its quality and accuracy. Nevertheless, the hexahedral grid remains the preferred choice, as it provides sufficient accuracy of the results and successfully solves the tasks set. It is important to note that the resulting hexahedral elements are used in the Finite Volume Method (FVM) for subsequent numerical analysis.

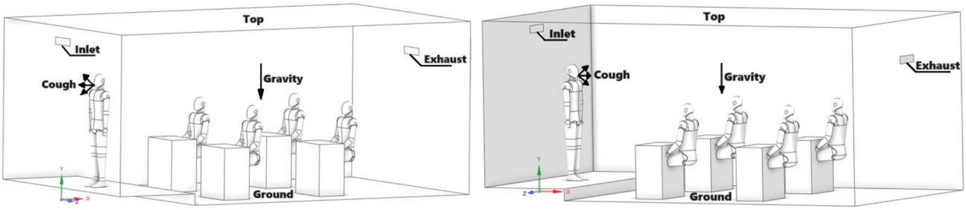

Figure 1— The geometry of the area under study.

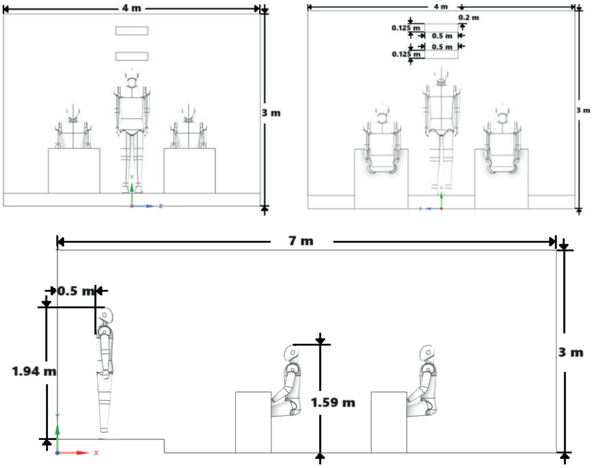

Figure 2— The geometry of the area under study.

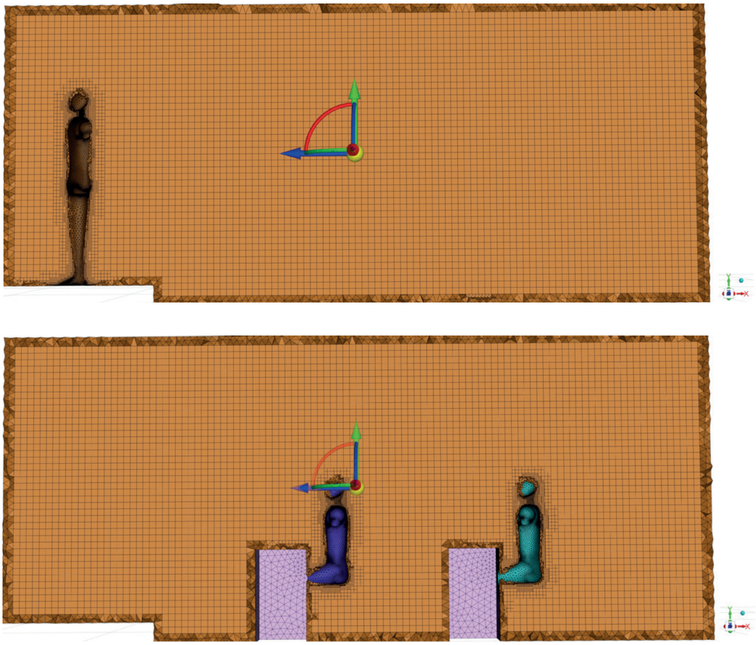

Figure 3 — Computational grid of the studied area.

Properties of materials. Air was modeled as an incompressible fluid with constant properties which shown in **Table 2.** The coefficient of thermal expansion was calculated using the formula given in 1.1.6, which indicates temperatures corresponding to the air through ventilation (291 K) and human body temperature (309.7 K), respectively. These values were chosen to most accurately reflect the conditions in the real system.

Table 2 — The property of air.

Property	Value	Unit
Density	1.225	kg/m^3
Specific Heat	1006.43	$J/(kg\ K)$
Thermal Conductivity	0.0242	$W/(m\ K)$
Viscosity	1.7894e-05	$kg/(m\ s)$
Molecular Weight	28.966	$kg/kmol$
Thermal Expansion Coefficient	0.00332696	K^{-1}

The particles were modeled as a mixture of water and air, simulating the composition of real respiratory droplets. The average particle density was set to 600 kg/m³, based on an assumed composition of 59% water and 41% air.

$$\rho_p = 0.41\rho_{air} \cdot 0.59\rho_{water}, \tag{24}$$

$$\rho_p = 0.41 \cdot 1.225 + 0.59 * 1000 = 590.5\ kg/m^3. \tag{25}$$

This allowed us to take into account the peculiarities of the composition of viral particles and their impact on the environment. These steps provide a more accurate and realistic simulation of the spread of viral particles in the air, which is important for understanding and preventing transmission of infection.

Results

Particle distribution. The results of a numerical study of scenarios 1-2 are presented in Figures 4, 5. Figures 4, 5 show the results of particle propagation in a room with ventilation of 1 m/s at different points in time. Figure 4 shows the results of particle propagation at different points in time when coughing or sneezing 6 m/s. These results show that after 30 seconds the particles are transported by 3.36 m in length, which exceeds the social distance. The results presented in Figure 5 show that after 30 seconds the particles travel a distance of 4.94 m in length, which exceeds the social distance recommended by WHO. This means that option 3 is also dangerous for people in this range. As can be seen from this scenario, the spread has reached the opposite wall in the room. As we have seen, options 1 and 2 differ only with ventilation and exhaust. It should be noted that when using ventilation, particles spread a much longer distance than without ventilation, since particles with a smaller diameter under the ventilation flow can spread longer and further around the room.

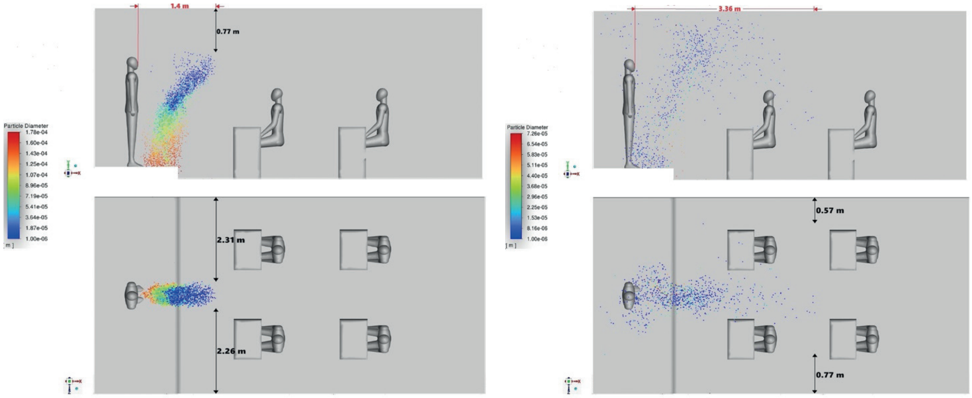

Figure 4 — Particle distribution during coughing = 6 m/s and ventilation = 1 m/s (5 s, 30 s)

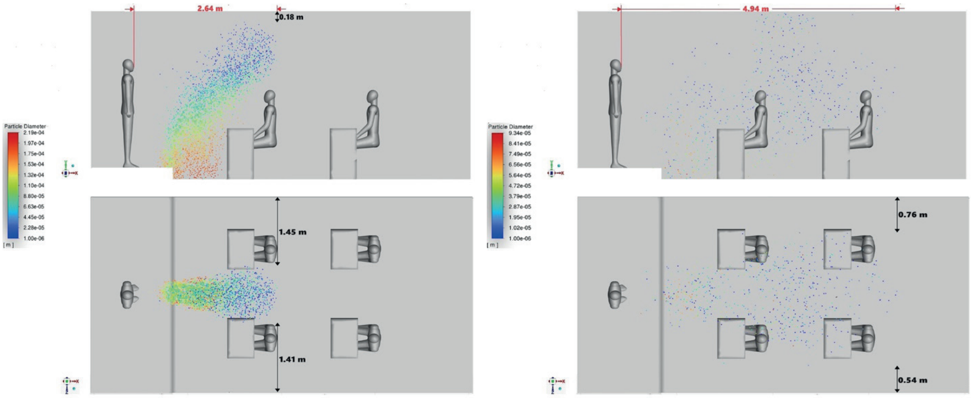

Figure 5 — Particle distribution during coughing = 20 m/s and ventilation = 1 m/s (5 s, 30 s)

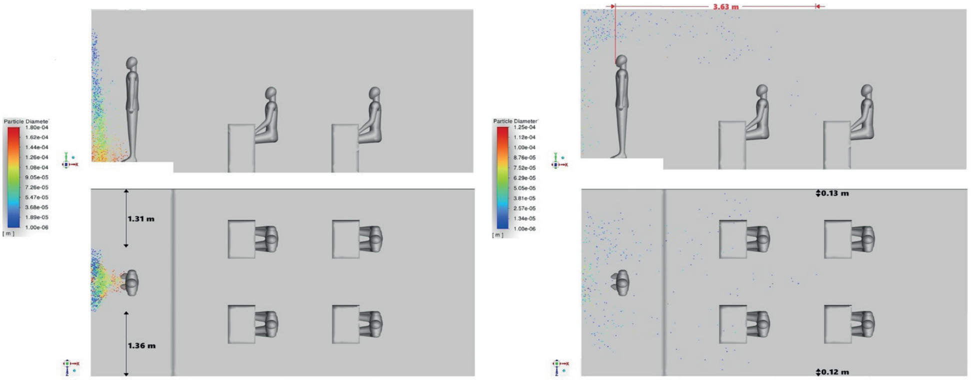

Figure 6 — Particle distribution during coughing = 6 m/s and ventilation = 1 m/s (5 s, 30 s)

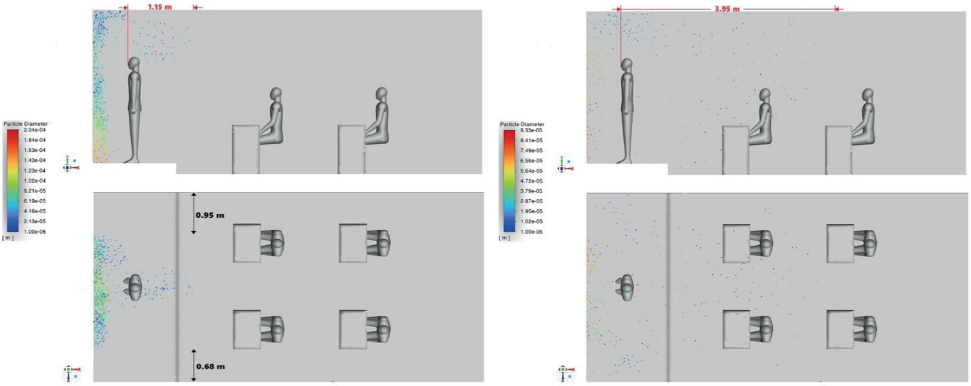

Figure 7 — Particle distribution during coughing = 20 m/s and ventilation = 1 m/s (5 s, 30 s)

Temperature of human body. Figures 8-11 show the results of human body temperature for all variants. It should be noted that in the ventilation and exhaust versions, the air flow significantly affects the temperature distribution, which leads to a higher temperature at the end of the room. The ventilation options have shown that the air temperature is more evenly distributed throughout the room, creating comfortable conditions.

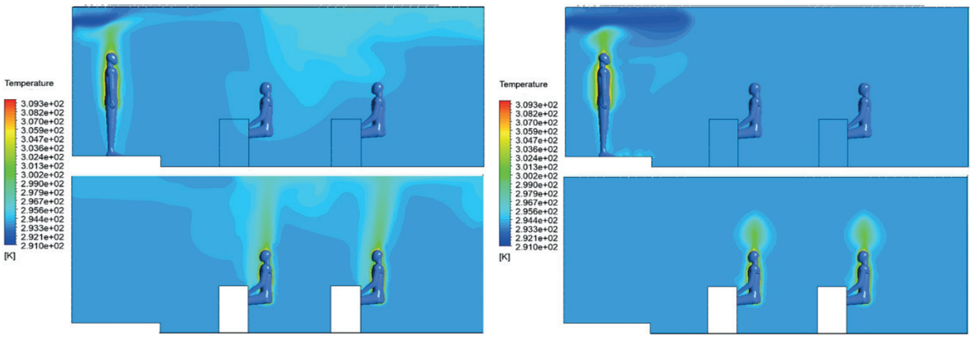

Figure 8 — The effect of body temperature on particle distribution during coughing = 6 m/s and ventilation = 1 m/s (5 s, 30 s)

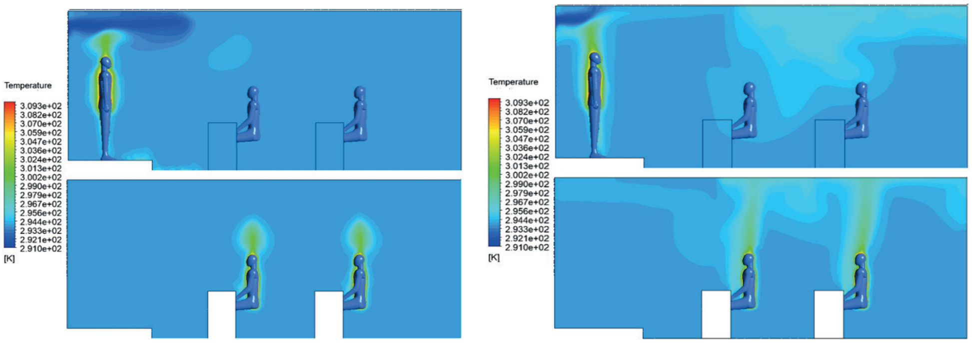

Figure 9 —The effect of body temperature on particle distribution during coughing = 20 m/s and ventilation = 1 m/s (5 s, 30 s)

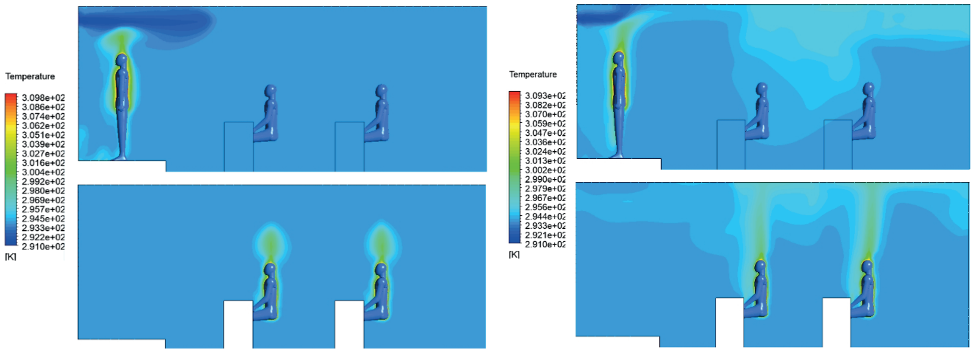

Figure 10 —The effect of body temperature on particle distribution during coughing = 6 m/s and ventilation = 1 m/s (5 s, 30 s)

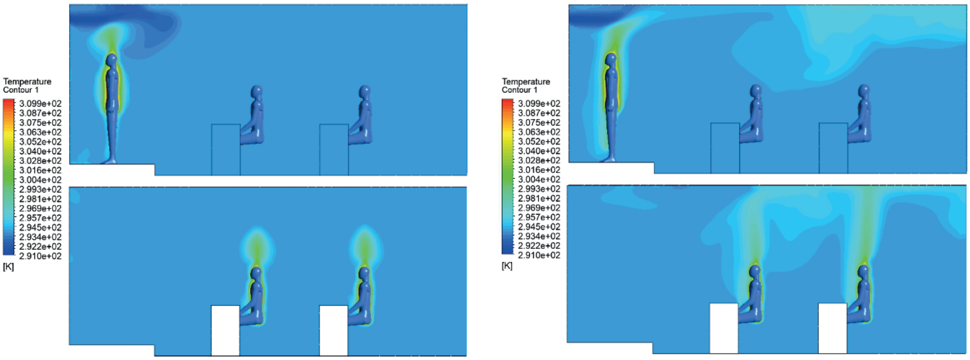

Figure 11— The effect of body temperature on particle distribution during coughing = 20 m/s and ventilation = 1 m/s (5 s, 30 s)

Discussion. The results of a numerical study of scenarios 3-4 are presented in Figures 6, 7 Figures 6, 7 show the results of particle propagation in a room with ventilation of 1 m/s at different points in time. Figure 6 shows the results of particle propagation at different points in time when coughing or sneezing 6 m/s. These results show that after 30 seconds the particles are transported by 3.63 m in length, which exceeds the social distance. The results presented in Figure 7 show that after 30 seconds the particles travel a distance of 3.95 m in length, which exceeds the social distance recommended by WHO. This means that option 2 is also dangerous for people in this range. As can be seen from this scenario, the spread has reached the opposite wall in the room. As we have seen, options 2 differ only with ventilation and exhaust. It should be noted that when using ventilation, since particles with a smaller diameter under the ventilation flow can spread longer and further around the room. Thus, this means that rooms with ventilation and exhaust are more dangerous than rooms. Because particles travel social distances and even spread further.

The processes of evaporation and condensation of particles depend on temperature conditions, and ventilation options contribute to faster evaporation of particles, which can reduce their concentration in the air. Efficient ventilation systems have shown their ability to quickly remove viral particles from the room, which underscores their importance for hygiene and safety.

Active ventilation creates turbulent flows that contribute to the chaotic spread of particles, increasing the likelihood of their deposition on surfaces or removal from the breathing zone.

However, the analysis of particle propagation showed that options with ventilation can be more dangerous for humans, since particles spread over a longer distance. This indicates the need for careful design of ventilation systems to minimize the risk of spreading viral particles. A possible solution may be to optimize the direction of air flows and use additional methods of air filtration and purification.

Conclusion. In this thesis, numerical modeling of the spread of viral particles in various scenarios is carried out, taking into account the presence or absence of ventilation and exhaust. The study covered 4 scenarios, the results of which are shown in Figures 4-7 and 8-11. Data analysis allowed us to draw several important conclusions about the influence of various conditions on the distribution and deposition of particles.

Main conclusions:

- Particles with large diameters are deposited by gravity, which somewhat limits their propagation.
- Ventilation promotes the chaotic movement of particles due to turbulent flows, which increases the likelihood of their deposition on surfaces or their removal from the breathing zone.
- Poorly designed ventilation systems may unintentionally direct contaminated air toward occupants, increasing the risk of infection.
- Thermal effects from the human body induce upward convective currents that prolong particle suspension and affect their vertical distribution.

These findings emphasize the importance of optimizing HVAC systems in public indoor environments, especially classrooms, to minimize the transmission of airborne pathogens. The computational approach applied in this study can serve as a practical tool for assessing infection risks and guiding preventive strategies.

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