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**PREDICTING THE SPREAD OF AIRBORNE
VIRAL INFECTIONS IN ENCLOSED SPACES****Issakhov Alibek** — PhD, Professor, Kazakh-British Technical University, Almaty, Kazakhstan,E-mail: alibek.issakhov@gmail.com, <https://orcid.org/0000-0002-1937-8615>;**Akylbekkyzy Aktolkyn** — al-Farabi Kazakh National university, Almaty, Kazakhstan,E-mail: aktolkyn.akylbekkyzy@bk.ru, <https://orcid.org/0009-0002-5022-1680>;**Abylkassymova Aizhan** — PhD, Associated Professor, Kazakh-British Technical University, Almaty, Kazakhstan,E-mail: Abylkassymova.Aizhan@gmail.com, <https://orcid.org/0000-0002-5967-6959>.

Abstract. The spread of respiratory viral infections in enclosed spaces remains one of the most serious threats to public health in the 21st century. The SARS and MERS epidemics, along with the COVID-19 pandemic, have demonstrated the high vulnerability of indoor building environments to the aerosol transport of pathogens. This article presents the results of numerical modeling of the transport dynamics of virus-containing particles generated during coughing within a room equipped with forced ventilation and domestic air humidification systems. The mathematical model is based on solving the three-dimensional Navier–Stokes equations for incompressible flow using the standard k – ϵ turbulence model. The Lagrangian approach is applied to describe the trajectories of the discrete phase, accounting for the effects of gravity, aerodynamic drag, Saffman lift forces, and Brownian motion. The SIMPLE numerical algorithm is implemented on a computational mesh exceeding 3.1 million elements. The adequacy of the model is confirmed by verifying the calculated velocity profiles against experimental data and the results of previous studies on cough-driven vortex ring dynamics (Renzi et al.). The study analyzes the influence of ventilation diffusers and the concentration of water vapor from domestic humidifiers on the process of droplet sedimentation and transport. It was established that during an impulsive release of particles at a velocity of 6 m/s, the maximum propagation distance reaches 2.5 m. The results

show that active air humidification contributes to a decrease in aerosol concentration and a reduction of the risk zone compared to scenarios without humidity control, where the transport distance exceeds 3.5 m. It is concluded that the standard WHO recommendation for a social distance of two meters may be insufficient without accounting for the operation of indoor climate engineering systems.

Keywords: Computational Fluid Dynamics (CFD), Discrete Phase Model (DPM), COVID-19, airborne transmission, air humidification, indoor ventilation, aerosol transport

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ШЕКТЕУЛІ КЕҢІСТІКТЕРДЕ ӘУЕ ТАМШЫЛАРЫМЕН ВИРУСТЫҚ ИНФЕКЦИЯНЫҢ ТАРАЛУЫН САНДЫҚ МОДЕЛЬДЕУ

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Аннотация. Тыныс алу жолдарының вирустық инфекцияларының жабық кеңістіктерде таралуы ХХІ ғасырдағы қоғамдық денсаулық сақтауға төнетін ең елеулі қатерлердің бірі болып қала береді. SARS және MERS эпидемиялары, сондай-ақ COVID-19 пандемиясы ғимараттардың ішкі ортасының патогендердің аэрозольдік таралуына жоғары дәрежеде осал екенін көрсетті. Мақалада мәжбүрлі желдету және тұрмыстық ауа ылғалдандыру жүйелерімен жабдықталған бөлмеде жөтел кезінде түзілетін вирус құрамды бөлшектердің таралу динамикасын сандық модельдеу нәтижелері ұсынылған. Математикалық модель стандартты k - ϵ турбуленттілік моделін пайдалана отырып, сығылмайтын ағын үшін үш өлшемді Навье–Стокс теңдеулерін шешуге негізделген. Дискретті фазадағы бөлшектердің траекторияларын сипаттау үшін гравитация, аэродинамикалық кедергі,

Саффман көтеру күші және броундық қозғалыс ескерілетін Лагранж тәсілі қолданылды. SIMPLE сандық алгоритмі 3,1 миллионнан астам элементтен тұратын есептеу торында жүзеге асырылды. Модельдің жарамдылығы есептелген жылдамдық профильдерін эксперименттік деректермен және жөтел кезінде пайда болатын құйын сақиналарының динамикасына арналған алдыңғы зерттеулер нәтижелерімен салыстыру арқылы расталды. Зерттеуде желдету диффузорлары мен тұрмыстық ылғалдандырғыштар түзетін су буы концентрациясының тамшылардың тұнуы мен тасымалдануына әсері талданды. Бөлшектер 6 м/с жылдамдықпен импульстік түрде шығарылған кезде олардың максималды таралу қашықтығы 2,5 м-ге жететіні анықталды. Нәтижелер белсенді ауа ылғалдандыру аэрозоль концентрациясын және қауіп аймағын азайтатынын көрсетті, ал ылғалдылық бақыланбайтын сценарийлерде бөлшектердің таралу қашықтығы 3,5 м-ден асады. Осыған байланысты бөлмедегі микроклиматты қамтамасыз ететін инженерлік жүйелердің жұмысын ескермей қолданылатын ДДСҰ-ның екі метрлік әлеуметтік арақашықтық жөніндегі стандартты ұсынымы жеткіліксіз болуы мүмкін деген қорытынды жасалды.

Түйін сөздер: ауа арқылы таралатын вирустық инфекциялар; COVID-19; есептеу сұйықтық динамикасы; дискретті фазалық модель; бөлшектердің тасымалдануы

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ПРОГНОЗИРОВАНИЕ РАСПРОСТРАНЕНИЯ ВИРУСНОЙ ИНФЕКЦИИ ВОЗДУШНО-КАПЕЛЬНЫМ ПУТЕМ В ЗАМКНУТЫХ ПОМЕЩЕНИЯХ

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Аннотация. Распространение респираторных вирусных инфекций в замкнутых пространствах остается одной из наиболее серьезных угроз общественному здравоохранению в XXI веке. Эпидемии SARS и MERS, а также пандемия COVID-19 продемонстрировали высокую уязвимость внутренней

среды зданий к аэрозольному переносу патогенов. В статье представлены результаты численного моделирования динамики распространения вирусосодержащих частиц, образующихся при кашле, в помещении, оснащённом системами принудительной вентиляции и бытового увлажнения воздуха. Математическая модель основана на решении трехмерных уравнений Навье–Стокса для несжимаемого потока с использованием стандартной k - ϵ модели турбулентности. Для описания траекторий дискретной фазы применен лагранжев подход, учитывающий действие гравитации, аэродинамического сопротивления, подъемной силы Саффмана и броуновского движения. Численный алгоритм SIMPLE реализован на расчетной сетке, содержащей более 3,1 млн элементов. Адекватность модели подтверждена путем сопоставления расчетных профилей скорости с экспериментальными данными и результатами предшествующих исследований динамики вихревых колец, возникающих при кашле. В ходе исследования проанализировано влияние вентиляционных диффузоров и концентрации водяного пара, создаваемого бытовыми увлажнителями, на процессы седиментации и переноса капель. Установлено, что при импульсном выбросе частиц со скоростью 6 м/с максимальная дистанция их распространения достигает 2,5 м. Полученные результаты показывают, что активное увлажнение воздуха способствует снижению концентрации аэрозолей и сокращению зоны риска по сравнению со сценариями без контроля влажности, при которых дистанция переноса превышает 3,5 м. Сделан вывод о том, что стандартная рекомендация ВОЗ по соблюдению социальной дистанции в два метра может быть недостаточной без учета функционирования инженерных систем обеспечения микроклимата в помещении.

Ключевые слова: вирусные инфекции, передающиеся воздушно-капельным путем; COVID-19; вычислительная гидродинамика; дискретная фазовая модель; перенос частиц

Introduction. The global spread of viral pathogens, especially acute respiratory viral infections (ARVI), remains one of the major threats to modern public health and economic stability. As demonstrated by the COVID-19 pandemic, airborne transmission of diseases between people is one of the key factors. This situation has highlighted the need for a deeper understanding of infection transmission mechanisms in enclosed spaces such as hospitals, public transport, and educational institutions.

Infectious diseases continue to be a significant global problem, and airborne transmission plays a major role in their spread. The COVID-19 pandemic, first identified in 2019, spread rapidly across the world and demonstrated how vulnerable enclosed spaces are to viral transmission. Today, more than 779 million cases of COVID-19 and over 7.1 million deaths have been recorded worldwide according to the World Health Organization (Figure 1) (WHO, 2019). Several epidemic waves were also observed in Kazakhstan, with approximately 1.5 million confirmed cases

and more than 19 thousand deaths reported. Although the epidemiological situation has stabilized compared with the initial stage of the pandemic, respiratory viruses are still present and continue to pose a risk of transmission, especially in enclosed spaces. Airborne transmission during coughing, sneezing, or speaking plays an important role in the spread of viruses, especially in poorly ventilated enclosed rooms. During these processes, respiratory droplets of different sizes are released into the air. These droplets consist of water vapor, air, mucus, and biological particles that may contain viral agents.

Literary review. The study of virus transmission historically began with the “one-meter rule” proposed by Flügge in 1897, which was based on the spread of large droplets. Later, Wells (1934) demonstrated the important role of droplet nuclei (aerosols). Droplet nuclei can remain suspended in the air for a long time, and their distribution strongly depends on environmental factors such as ventilation, humidity, and temperature. Therefore, when studying infection transmission in enclosed spaces, it is important to consider the physical factors of the environment (Flügge, 1897; Wells, 1934).

In recent decades, Computational Fluid Dynamics (CFD) has been widely used to study such processes. CFD modeling makes it possible to numerically analyze airflow structures and the dispersion of aerosol particles. For example, studies in hospital wards have shown that displacement ventilation systems, which supply air from the lower zone and remove it from the upper zone, significantly reduce the risk of cross-infection (Zhang et al., 2021). In addition, studies in subway cars have shown that a supply-from-floor and return-from-ceiling (SFRC) ventilation system reduces the residence time of aerosol particles in the air (Wu et al., 2025). However, when implementing such engineering solutions, maintaining a balance between efficient removal of viral particles and energy efficiency remains an important challenge.

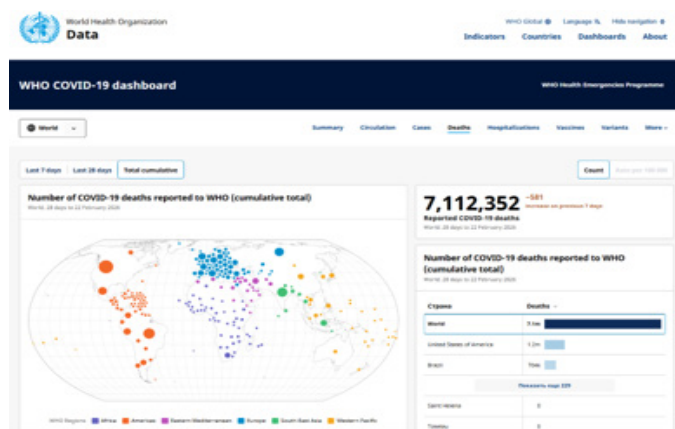


Figure 1 — Statistics of COVID-19 cases according to the World Health Organization (WHO, 2019).

To effectively predict the spread of infection, advanced mathematical models are used alongside physical modeling methods. For example, some studies consider stochastic models that account for random effects when describing the dynamics of viral infections. In addition, research has been conducted to evaluate the influence of climatic factors such as temperature and humidity on infection transmission. These studies indicate that environmental factors play an important role in the spread of infectious diseases (Zhang et al., 2026; Fischer et al., 2025). This disease belongs to the group of severe acute respiratory infections and may occur in mild or severe forms. The most common symptoms are fever and dry cough. The virus tends to affect multiple organs directly. In severe cases, viral pneumonia may develop, leading to deterioration of respiratory function and difficulty in inhalation and exhalation. Reflex processes such as coughing and sneezing also occur.

During these processes, droplets carrying the virus are released into the surrounding environment. This raises several important scientific questions: which physical processes can slow the spread of the virus, how far viral particles travel during coughing, and what safe distance should be maintained to reduce infection transmission. In the paper by Renzi (Renzi and Clarke, 2020) from Loughborough University stated that in many simulated cases the largest droplets can travel distances greater than two meters before falling to the ground. In this study, conducted to the dynamics of coughing and sneezing were modeled using a pressurized aerosol device similar to those used for nasal sprays. As a result, they observed a physical phenomenon known as floating vortex rings. According to the researchers, the presence of such phenomena shows that small liquid particles carrying viruses in coughs or sneezes can spread much farther than previously assumed. Figure 2 shows the results of Renzi's research, illustrating the continuous settling of droplets with diameters larger than $30\text{ }\mu\text{m}$ (Renzi and Clarke, 2020).

According to Renzi (Renzi and Clarke, 2020), the two-meter distancing rule cannot fully protect against the transmission of viruses through large airborne droplets. The researchers note that some factors were simplified in their model and that the full transmission potential of infections has not yet been completely studied. Therefore, further research in this direction remains necessary. In particular, it is important to investigate how factors such as airflow structures in enclosed spaces, ventilation systems, and air humidity influence the dispersion of viral particles.

The virus spreads when a person coughs, sneezes, or speaks. During these processes, droplets containing the virus are released into the air and can be transmitted to other people through inhalation. Airborne droplets may enter another person's eyes, nose, or mouth. Currently, one of the main protective measures against infection is the use of face masks. However, additional measures such as maintaining safe physical distance, frequent ventilation of enclosed spaces, and air humidification are also important. Regular ventilation of indoor spaces, wet cleaning, and the use of humidifiers can improve air quality and help reduce the concentration of aerosol particles.

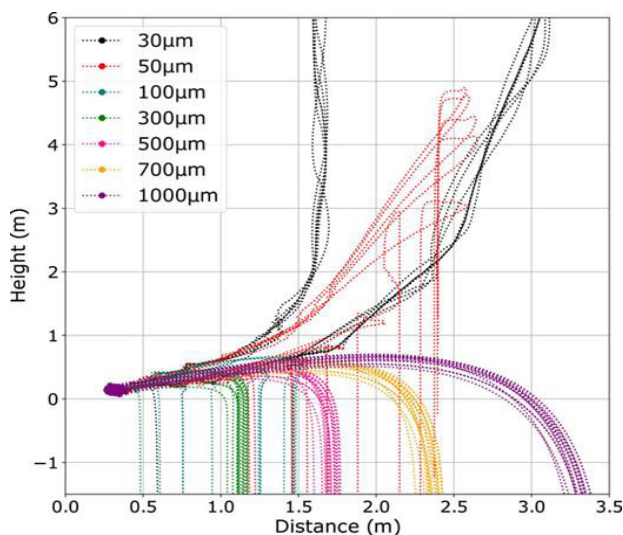


Figure 2 — Continuous settling of droplets with diameters greater than 30 μm according to Renzi's study.

When modeling airflow in enclosed spaces, ventilation elements play a crucial role. Diffusers are one of the main components that supply fresh air into a room. Therefore, accurately representing diffusers in airflow modeling is very important. In CFD simulations, this requires the correct definition of diffuser boundary conditions. For example, the study by Deng (Zhang et al., 2014) proposes an improved method for determining diffuser boundary conditions in CFD simulations. The main objective of this study is to investigate the dispersion of viral particles in an enclosed room equipped with a window and a door when both a ventilation diffuser and an air humidifier are present. As mentioned above, humidifying indoor air can improve air quality in enclosed spaces and reduce the concentration of aerosol particles. Therefore, this study examines the dynamics of viral particle dispersion in a room equipped with a window and a door when both a ventilation diffuser and an air humidifier are used.

The scientific novelty of the study lies in the numerical modeling of the effect of humidifier concentration on the dispersion of viral particles. Although many studies have examined the influence of ventilation systems, the effect of air humidifiers on the dispersion of aerosol particles has not yet been sufficiently investigated through numerical modeling.

In this study, airflow in an enclosed space and the dispersion of virus-carrying particles are analyzed using mathematical modeling. In addition, the distance and velocity of particles generated during coughing are determined. The influence of the ventilation system and the air humidifier on the distribution of aerosol particles inside the room is also analyzed. Furthermore, taking into account the structure of airflow, the dynamics of the dispersion of virus-carrying particles are investigated.

Materials and methods

Mathematical model. For both liquids and gases, the Navier–Stokes equations are considered one of the fundamental governing equations. They can be written in the following form:

$$\frac{d\vec{u}}{dt} = -(\vec{u} \cdot \nabla)\vec{u} - \frac{1}{\rho} \nabla \vec{p} + \nu \Delta \vec{u} + \vec{f} \quad (1)$$

The equation above fully describes the change in fluid velocity $\frac{d\vec{u}}{dt}$ through four main components. These components can be interpreted as follows. The first term, $-(\vec{u} \cdot \nabla)\vec{u}$, represents the convective acceleration and describes the effect of velocity divergence on the flow. From a physical perspective, this can be illustrated by the example of a river: when the river channel narrows, the water velocity increases, and vice versa. The second term, $-\frac{1}{\rho} \nabla \vec{p}$, characterizes the influence of pressure gradients on fluid motion. It reflects the fact that higher fluid density makes displacement more difficult and determines the direction of motion, which is generally oriented from regions of higher pressure toward regions of lower pressure. The third term, $\nu \Delta \vec{u}$, accounts for viscous effects. Here, ν denotes the kinematic viscosity, which represents the interaction between fluid particles. As viscosity increases, the magnitude of this effect becomes more significant. The final term, $\vec{f}$, represents external forces acting on the fluid.

The continuity equation is given by:

$$\text{div}(\rho \vec{u}) = 0 \quad (2)$$

Equations (1) - (2) are applicable to both ideal and real fluids. Thus, for laminar flow, the system consists of four equations: three velocity components along the coordinate axes and the continuity equation (Patankar, 1980).

The Navier–Stokes equations describe the motion of a viscous Newtonian fluid and are widely used in modeling fluid flows in engineering and natural systems. Solving them directly for turbulent flows requires very fine computational grids, which is computationally expensive. Therefore, turbulence models are used to simplify the simulations while maintaining reasonable accuracy.

Standard $k - \varepsilon$ Model. The standard $k - \varepsilon$ model (Rodriguez, 2019; Santolini et al., 2019; Chen et al., 2011) was employed to describe the turbulent airflow (Spalart et al., 1997; Menter, 1994; Menter, 2003). This model calculates the turbulent kinetic energy and its dissipation using additional transport equations. Near-wall effects were accounted for using standard wall functions. The interaction between turbulence and the mean flow is modeled through the Reynolds-averaged Navier–Stokes equations with turbulence closure, considering both the generation of turbulent energy due to velocity gradients and effects related to buoyancy and density variations.

Discrete Phase Model. The transport of virus-laden droplets generated during coughing or breathing was simulated using a Lagrangian discrete phase approach. Particle trajectories were computed in the presence of the carrier airflow. The motion of particles was governed by Newton's second law, accounting for aerodynamic drag, gravity, lift forces, and Brownian motion. Size-dependent corrections and interactions with the surrounding fluid were also included, enabling realistic modeling of droplet dispersion within indoor spaces (Zhang et al., 2009).

Numerical algorithm applied. The numerical algorithm used in this study is the SIMPLE algorithm (Issakhov et al., 2019; Issakhov and Imanberdiyeva, 2019; Issakhov and Zhandaulet, 2019; Han et al., 2019). One of the most widely used methods for the numerical solution of the Navier–Stokes equations is the SIMPLE algorithm. The name of this method is an acronym that describes its principle: Semi-Implicit Method for Pressure-Linked Equations. This algorithm was developed by Spalding and Patankar. Since then, it has been widely applied to solve problems related to fluid flow, gas dynamics, and heat transfer, making a significant contribution to the development of numerical methods.

The main steps of the SIMPLE algorithm are as follows:

- First, the boundary conditions are defined;
- Next, the velocity gradients and pressure are calculated;
- In the third step, an intermediate velocity field is computed by solving the discretized momentum equations;
- Then, the mass fluxes at the boundaries are calculated without correction;
- In the fifth step, the pressure correction values for the computational cells are obtained by solving the pressure correction equation;
- The pressure field is then updated using the following equation:

$$p^{k+1} = p^k + urf \cdot p' \quad (3)$$

where urf – is the relaxation factor used to stabilize and control pressure correction;

- The boundary pressure correction p'_b is updated;
- After that, the corrected mass flux is calculated as:

$$\dot{m}_f^{k+1} = \dot{m}_f^* + \dot{m}'_f \quad (4)$$

- Then, the velocity correction for the cells is computed using:

$$\vec{v}^{k+1} = \vec{v}^* - \frac{Vol \nabla p'}{\vec{a}_p^v} \quad (5)$$

where $\nabla p'$ is the gradient of the pressure correction, $\vec{a}_p^v$ is the central coefficient vector of the discretized linear system for the velocity equations, and Vol denotes the cell volume. Finally, the density is updated according to the change in pressure (Issakhov and Zhandaulet, 2019).

Validation case. As a test case, the study by Deng et al. (Deng et al., 2018) was used. The problem was to perform calculations based on the problem formulation presented in this article and to compare the obtained results with those reported by the authors. This comparison allows evaluating the reliability and performance of the developed numerical approach. Diffusers supply fresh air into the room. Therefore, their proper representation is very important when modeling indoor airflow. Diffusers can be described using two categories of methods: direct and simplified. Although the direct method is intuitive, it requires a very fine mesh near the diffuser due to the large difference between the diffuser and the room scales. For this reason, simplified methods are generally preferred in numerical simulations.

Problem formulation. The problem formulation is as follows: a room with a diffuser of known dimensions was constructed, as shown in Figure 3. The model includes an inlet (diffuser) and an outlet, which are denoted as inlet and outlet respectively (shown in Figure 4). The geometric parameters are presented in Table 1. The diffuser velocity is set to 1.1 m/s.

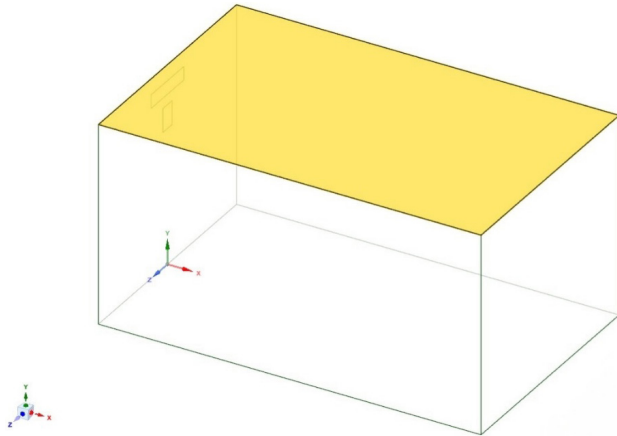
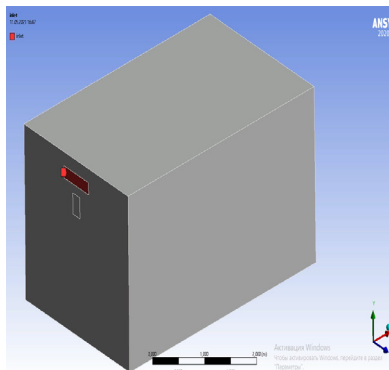
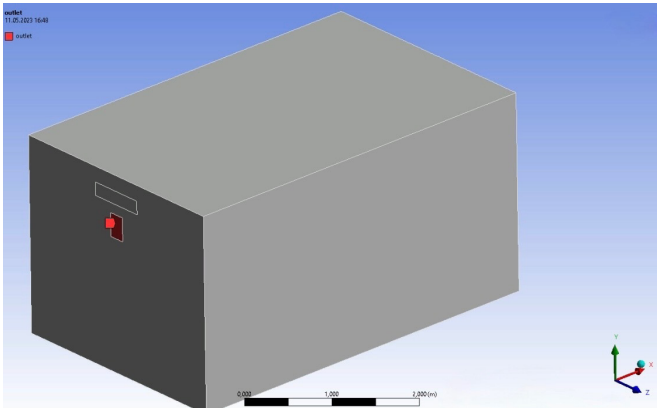


Figure 3 — Room geometry



(a) inlet



(b) — outlet

Figure 4 — Air inlet and outlet:

Table 1 — Geometrical parameters of the test case

Name	X (m)	Y (m)	Z (m)
Room	4.8	2.5	3
Inlet	0.71	0.17	—
Outlet	0.2	0.3	—

Results of the test case. The results are strongly influenced by the structure and size of the computational mesh for the diffusive flow. In the given test problem, the mesh size ranges from $\Delta x = 5.0 \times 10^{-4}$ m to $\Delta x = 5.0 \times 10^{-3}$ m. Therefore, to ensure a correct comparison, a mesh within this range was generated.

The following Figures 5-7 show the velocity profiles as a function of height. These results represent a comparison between the calculated velocity profiles obtained in this work and the results reported in the reference article. Here, the X-axis represents velocity, and the Y-axis represents height along the y-direction. The results of the test case demonstrate that the implemented numerical method provides results consistent with those reported in the reference study. This confirms the reliability and effectiveness of the developed computational approach. Therefore, it can be concluded that this method is suitable for solving the main research problem.

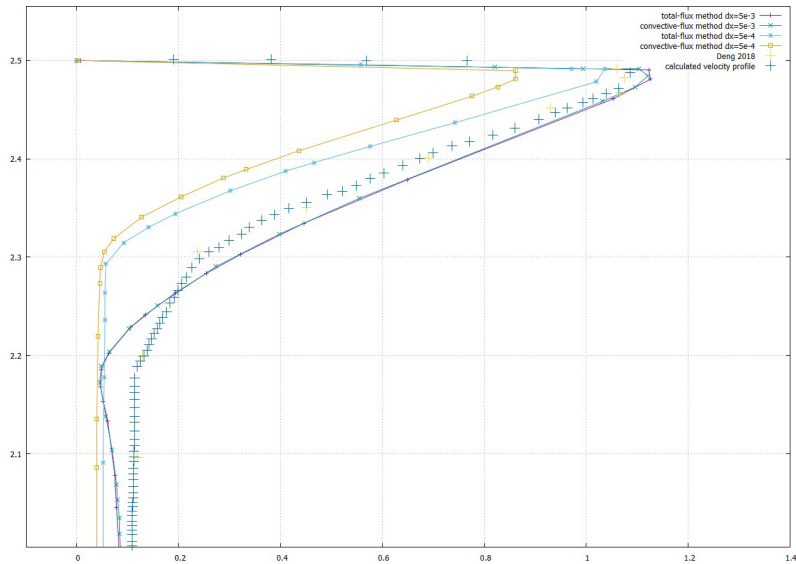


Figure 5 — Comparison of results along a line ($x = 1$ m, $z = 0$ m)

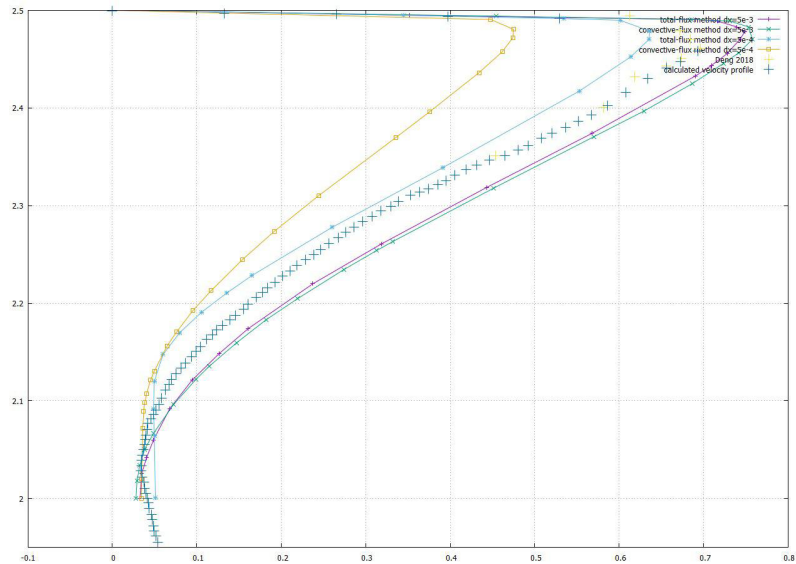


Figure 6 — Comparison of results along a line ($x = 2.2$ m, $z = 0$ m)

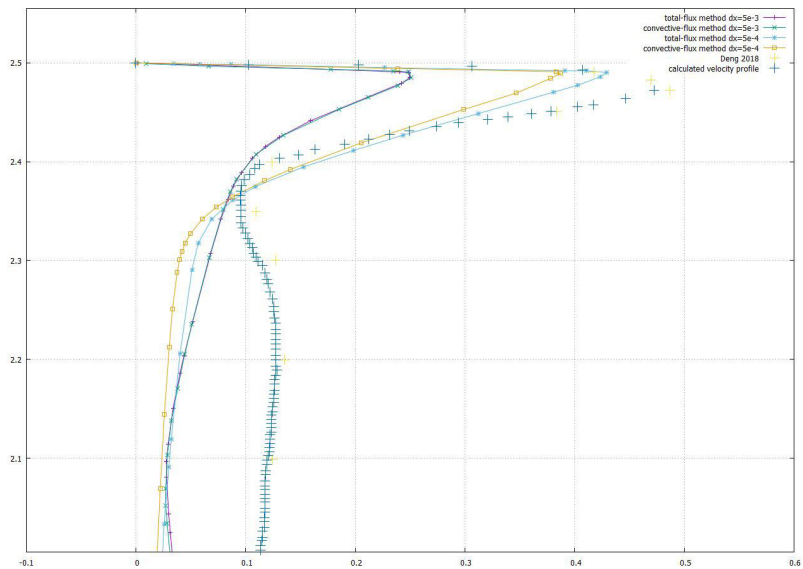


Figure 7 — Comparison of results along a line ($x = 1\text{ m}$, $z = 0.5\text{ m}$)

Boundary conditions and problem statement. The computational domain is a room of dimensions $5\text{ m} \times 3\text{ m} \times 9\text{ m}$, equipped with an open door and window (Figure 8). Fresh air enters through the window at 1 m/s , while air exits through the door. Two wall-mounted air diffusers (0.5 m/s each) and two household air humidifiers (0.15 m/s each) are installed to provide ventilation and maintain humidity. The human model is 1.80 m tall, with the mouth at 1.625 m , positioned 2 m from the window. Two diffusers are mounted at 2.63 m height, 1 m from adjacent walls, and humidifiers are placed at 1.2 m height on opposite walls. Results from other studies indicate that the velocity of particles expelled from the human mouth ranges from 1 m/s to 20 m/s during sneezing and coughing (Gao and Niu, 2006). A coughing event is simulated as a short-duration impulse with air and droplet velocities of 6 m/s in the period $0.1\text{--}0.3\text{ s}$. The computational geometry and airflow velocities are summarized in Table 2, and the flow directions are shown in Figure 9.

Table 2 — Velocity values used in the simulation

Geometry part	Velocity (m/s)	Duration (s)
Inlet_humidity (air humidifier)	0.15	continuous
Inlet_lip (airflow from mouth)	6	0.1–0.3
Inlet_lip (droplets from mouth)	6	0.1–0.3
Inlet_diff (diffuser)	0.5	continuous
Inlet_window (window)	1	continuous

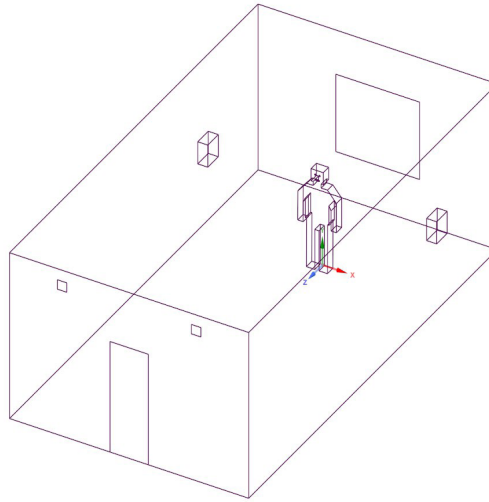


Figure 8 — Complete geometry of the computational domain

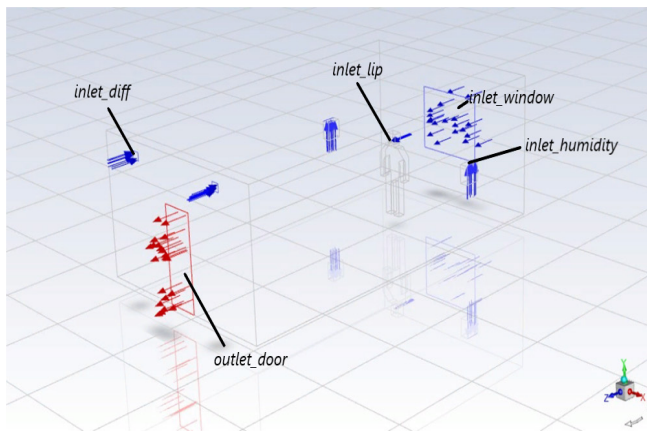


Figure 9 — Flow directions (velocity)

Computation and Results. A fine mesh was applied near the human mouth with a minimum cell size of 1 mm, while the maximum cell size for the overall room geometry was 30 mm (Figure 10). Both discrete and continuous injection methods were applied. The discrete injection method provided clearer visualization of the maximum particle travel distance along the Z-axis. Figures 11-14 illustrate the particle trajectories, maximum dispersion distance, and the influence of air humidifier concentration. Considering the person's position 0.2 m from the origin, the maximum particle travel distance is approximately 2.5 m.

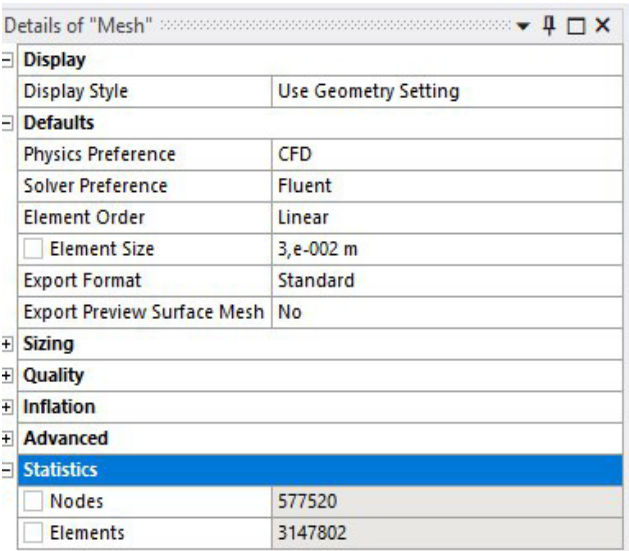


Figure 10 — Total number of mesh elements: 3,147,802

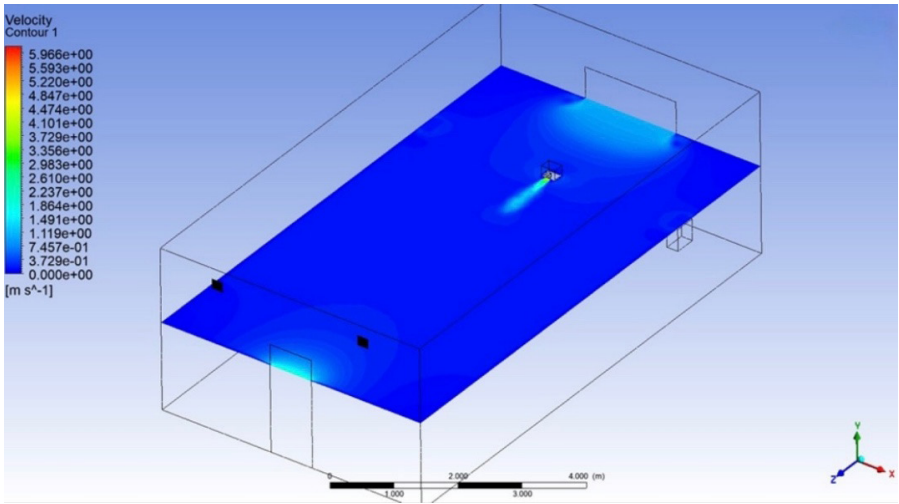


Figure 11 — Velocity distribution characteristics in the specified region

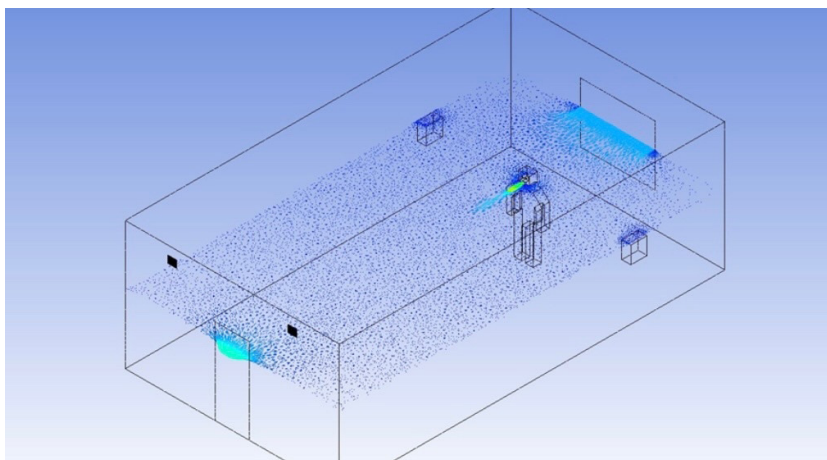


Figure 12 — Velocity vector distribution in the specified region

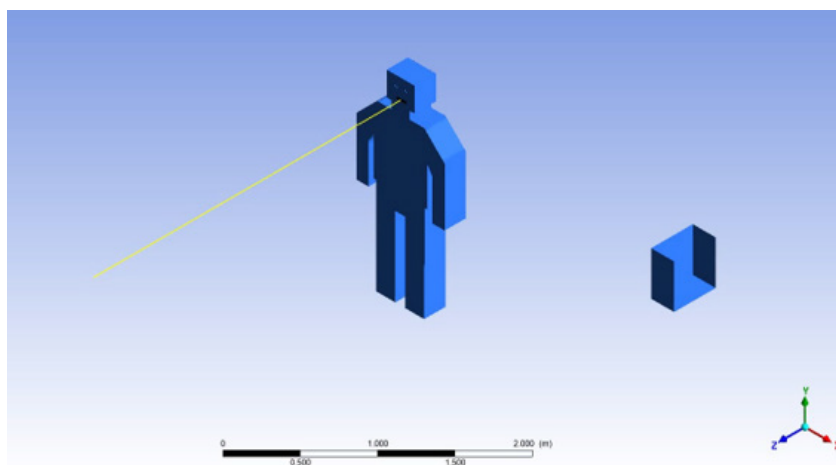


Figure 13 — Line plotted to determine particle travel distance based on velocity

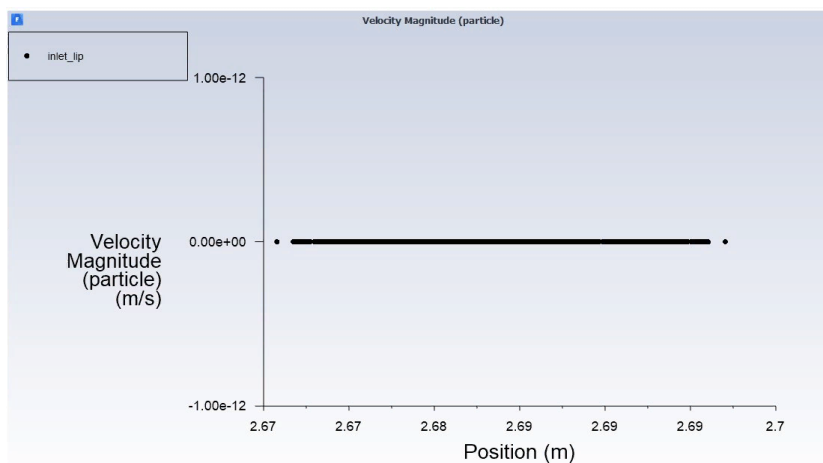


Figure 14 — Maximum dispersion distance of particles

Conclusion. This study presents a comprehensive analysis of virus dispersion dynamics within an enclosed space, utilizing Computational Fluid Dynamics (CFD). By leveraging mathematical modeling, it was developed an expert system designed to rapidly assess the spread of acute respiratory viral infections while accounting for various environmental factors. Through these CFD simulations, it was able to precisely calculate the speed and reach of the infection, specifically identifying the physical behavior of aerosol flows generated during coughing. A primary focus of this research was the critical role of ventilation and humidity control in contaminated environments. One of the central objectives of work was to observe how air humidifiers alongside diffusers and windows influence viral spread. To validate the findings, it was compared the results against scenarios where no humidification was present.

Early in the research, it was examined the work of Renzi, who stated that the standard "two-meter rule" is insufficient to protect against virus transmission via larger respiratory droplets. In this findings align with this perspective; the simulations clearly demonstrate that viral particles can travel significantly further than two meters during a cough. While Renzi's research indicated a maximum particle travel distance of 3.5 meters, in this obtained results showed a reduced distance of 2.5 meters when specific countermeasures were active. This discrepancy highlights the profound impact of external factors such as active ventilation, the use of diffusers, and air humidifiers. These elements effectively mitigate the spread, making them essential tools for room purification. This underscores why, during the peak of the 2019 pandemic, public health guidelines emphasized room ventilation, wet cleaning, and the avoidance of crowded spaces where social distancing was impossible. Ultimately, adhering to these safety measures remains vital for protecting both human and animal life.

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