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Velocity Field Evolution and Aerosol Cloud Dynamics

Generated by Human Coughing and Sneezing

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Abstract

Human respiratory activities such as coughing and sneezing generate turbulent airflows containing droplets and aerosol particles that may be transported over significant distances in indoor environments. Understanding the evolution of velocity fields and respiratory aerosol clouds is essential for predicting aerosol transport and assessing exposure risks.

In this study, the spatial and temporal characteristics of velocity fields generated by coughing and sneezing. A measurement technique based on an array of flexible flow indicators combined with automated video analysis was developed and calibrated using an anemometer. Experiments were performed with 50 volunteers under controlled indoor conditions.

The measured respiratory jets were characterized by Reynolds numbers in the range of approximately 10^4 – 10^5 , indicating fully turbulent flow conditions. The maximum cloud velocity decreases approximately according to an inverse–distance relationship. A transition from a jet–dominated regime to a turbulent aerosol cloud was observed within 1–3 s after the end of exhalation. The highest velocities and aerosol concentrations were detected within the near–field region, whereas at larger distances aerosol transport became increasingly dependent on ambient airflows and ventilation conditions.

The proposed experimental approach provides quantitative information on the evolution of respiratory aerosol clouds and the associated velocity fields generated during coughing and sneezing.

Keywords: Respiratory aerosol clouds; Turbulent respiratory jets; Velocity field measurements; Aerosol transport; Indoor airflow; Aerosol dispersion; Flow visualization.

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1. Introduction

Human respiratory activities such as breathing, speaking, coughing, and sneezing generate complex multiphase flows consisting of warm humid air, liquid droplets, and aerosol particles spanning a wide range of sizes. These expiratory flows form turbulent jets and aerosol clouds whose evolution governs the transport, dispersion, and residence time of airborne particles in indoor environments. Understanding the dynamics of respiratory aerosol clouds is therefore important for predicting aerosol transport and assessing the influence of ventilation on aerosol dispersion in indoor environments.

Traditional concepts of respiratory infection transmission were primarily based on large droplets that settle within one or two meters of the source. However, numerous experimental and epidemiological studies have demonstrated that fine aerosol particles can remain suspended in air for extended periods and may be transported over considerable distances by indoor airflow. Only a small fraction of aerosol particles may contain infectious agents; however, owing to the large number of emitted particles and their long residence time in air, even a small fraction may contribute to airborne transmission. In addition, the probability of inhalation depends not only on particle concentration but also on exposure duration. Consequently, prolonged residence in an enclosed space may increase the inhaled aerosol dose even when particle concentrations are relatively low.

From a fluid-dynamics perspective, expiratory flows produced by coughing and sneezing can be considered finite-duration turbulent jets. During the initial stage, these jets are characterized by high velocities and intense turbulent mixing. After the cessation of exhalation, the jet gradually evolves into a turbulent aerosol cloud, whose subsequent motion is controlled by interactions with ambient airflow and ventilation-induced circulation. Previous studies have shown that the structure of respiratory jets strongly influences aerosol dispersion and the formation of regions with elevated particle concentrations. Turbulent entrainment of surrounding air leads to continuous growth of the cloud volume, while later stages of cloud evolution are increasingly affected by environmental conditions.

Despite significant progress in the study of respiratory aerosol emissions, important questions remain regarding the spatial and temporal evolution of velocity fields within exhaled aerosol clouds and their influence on aerosol transport. Particular attention should be paid to the near-field region, where jet velocities and aerosol concentrations reach their maximum values.

The aim of the present study is to experimentally investigate the spatiotemporal structure of velocity fields in aerosol clouds generated by human coughing and sneezing and to examine the relationship between flow dynamics and aerosol transport. Special attention is devoted to identifying regions characterized by the highest aerosol concentrations and to obtaining quantitative data that can be used for validation of computational and theoretical models of respiratory aerosol transport.

2. Flow Regimes of Respiratory Aerosol Clouds

Jet and Puff Regimes

Human coughing and sneezing generate turbulent expiratory flows that initially behave as turbulent jets and gradually evolve into aerosol clouds after the cessation of exhalation. [1, 2].

During coughing and sneezing, a person emits a transient multiphase flow consisting of warm humid air, liquid droplets, and aerosol particles spanning a broad size range. Because of the high exhalation velocities and the corresponding Reynolds numbers, the resulting flow is typically turbulent, with velocity fields that vary continuously in space and time. The jet formation stage usually lasts less than 0.5 s and is characterized by rapid momentum transfer and intense turbulent mixing.

Figure 1 illustrates the evolution of a respiratory aerosol cloud at time intervals of 0.1 s. The cloud shapes shown in the figure were reconstructed from flow visualization experiments using smoke tracers.

After the cessation of exhalation, the momentum supplied by the source rapidly decreases and the jet gradually transforms into a turbulent puff. During this stage, turbulent entrainment of the surrounding air leads to cloud growth, dilution of aerosol concentration, and progressive decay of the velocity field. The subsequent evolution of the aerosol cloud is governed by interactions with ambient airflow, the buoyancy of warm exhaled air, and ventilation-induced circulation.

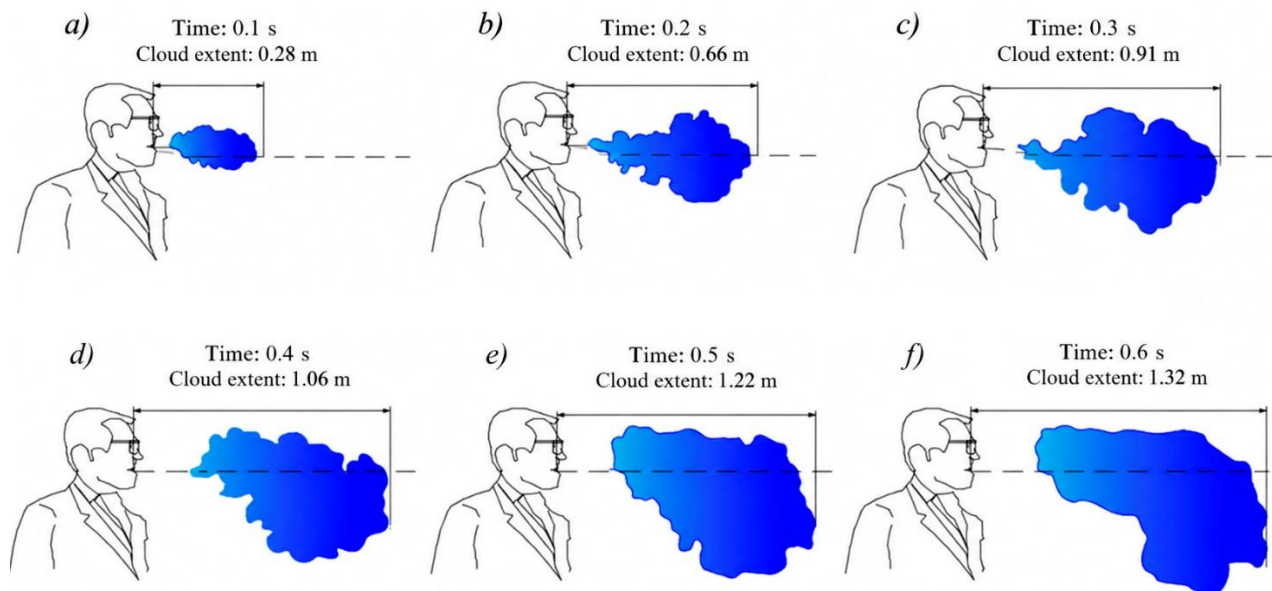


Figure 1. Evolution of the respiratory aerosol cloud shape at 0.1 s intervals.

Average initial velocities of exhaled air for different respiratory activities are summarized in Table 1.

Table 1.

Respiratory activity	Maximum initial velocity at the mouth (m/s)
Quiet breathing	0.5–1
Speaking	1–3
Coughing	8–15
Sneezing	20–50

In the immediate vicinity of the mouth opening, a region of maximum velocity is formed, corresponding to the initial jet core. This region is also characterized by the highest concentrations of aerosol particles. As a first approximation, the flow may be considered axisymmetric; however, the jet orientation depends on head position, anatomical features, and the nature of the expiratory event, and therefore may deviate from the horizontal direction. In the near-field region, the velocity distribution can be approximated using relationships commonly applied to free turbulent jets.

$$v(x) = \frac{v_0 d}{x}, \quad (1)$$

where (v_0) is the initial exhalation velocity, (d) is the effective mouth diameter, and (x) is the distance from the source.

The effective mouth diameter is defined as the diameter of a circle having the same area as the mouth opening.

After the cessation of active exhalation, typically within 0.5–3 s, the jet gradually evolves into a turbulent aerosol cloud, in agreement with previous studies [1, 2].

Equation (1) indicates that the estimated velocity is highly sensitive to the initial exhalation velocity and the effective mouth diameter. Both parameters vary considerably among individuals and depend on physiological characteristics, the nature of coughing or sneezing, and other factors. Therefore, statistical characteristics obtained from a series of experiments should be used when analyzing respiratory aerosol flows.

The Reynolds number was calculated using the standard expression:

$$\text{Re} = \frac{\rho v d}{\eta} = \frac{v d}{\nu}.$$

For air at room temperature, the kinematic viscosity was taken as $\nu \approx 1.5 \times 10^{-5} \text{ m}^2/\text{s}$, while the effective mouth diameter was assumed to be $d = 0.02 \text{ m}$. Substituting these values into Eq. (2) yields $\text{Re} = 1.33 \times 10^3 v$, where v is the airflow velocity (m/s).

Table 2.

Average initial exhalation velocities and corresponding Reynolds numbers.

Respiratory activity	Maximum initial exhalation velocity at the mouth (m/s)	Re
Quiet breathing	0.5–1	670–1330
Speaking	1–3	1300–4000
Coughing	8–15	10700–20000
Sneezing	20–50	26700–66700

For characteristic coughing and sneezing velocities, the Reynolds number is of the order of $Re \approx 10^4 - 10^5$. These values greatly exceed the transition range for free turbulent jets ($Re \sim 10^3$). Therefore, the expiratory flow should be regarded as a turbulent transient jet already in the immediate vicinity of the source, which is consistent with the experimental observations.

Characteristic Features of the Velocity Field

As the aerosol cloud propagates, the axial velocity decreases rapidly, while the development of large-scale vortical structures leads to an increase in transverse velocity components.

As the jet evolves, turbulent entrainment of the surrounding air leads to a continuous increase in the mass and volume of the aerosol cloud, accompanied by its expansion and dilution.

The velocity field acquires a pronounced three-dimensional and unsteady character, with velocity values varying both spatially and temporally.

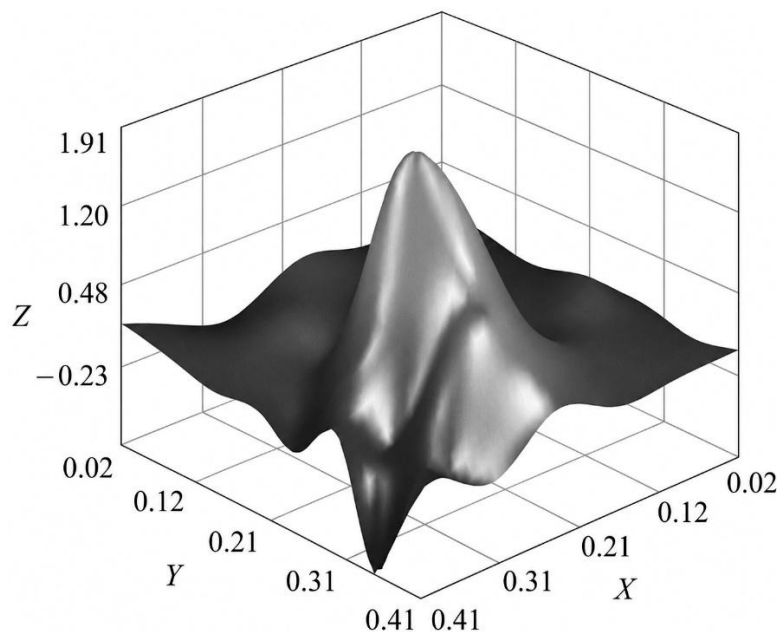


Figure 2. Velocity distribution across the aerosol cloud cross-section at a distance of 1 m from the source during coughing.

Figure 2 shows a representative velocity distribution across the cloud cross-section. The observed velocity field demonstrates a pronounced spatial heterogeneity of the aerosol cloud structure and the absence of a smooth frontal boundary. The cloud dynamics are governed by the development of turbulent vortical structures over a wide range of scales. Consequently, cloud propagation should be characterized using statistical quantities such as mean velocity and average propagation distance, since the turbulent nature of the flow significantly influences the motion of the exhaled aerosol cloud.

Figure 3 illustrates the formation of vortical structures within the aerosol cloud.

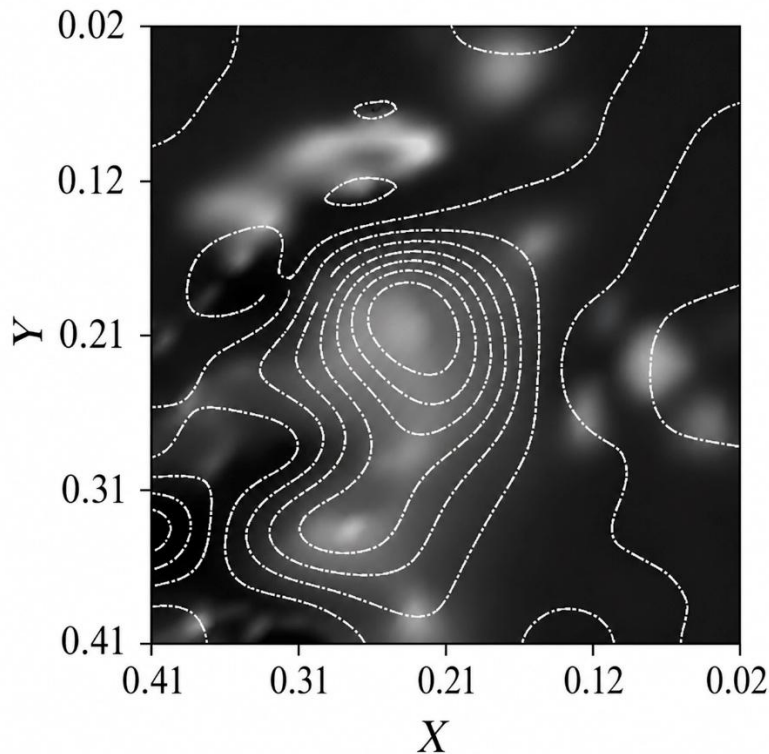


Figure 3. Vortical structures in a cross-section of the aerosol cloud.

Approximately 3 s after exhalation, the aerosol cloud changes its shape and the velocity field changes accordingly. At later stages, cloud motion becomes increasingly influenced by environmental factors, particularly ambient temperature and humidity. The buoyancy of warm exhaled air (30–35 °C) promotes the upward motion of the aerosol cloud and may increase its propagation distance.

In addition, a thermal convective plume develops above the human body as a result of body heat release. The characteristic velocity of this upward airflow is relatively low, typically on the order of 0.3–0.5 m/s. Interactions between the expiratory jet and the thermal plume may alter the cloud trajectory and enhance its upward transport. However, no statistically significant influence of this mechanism was observed in the present experiments.

Following the cessation of exhalation, aerosol particles continue to move owing to the residual momentum of the flow and the presence of turbulent vortical structures. For fine aerosol particles with diameters below 5 µm, particle motion is governed primarily by the surrounding airflow, while gravitational settling becomes of secondary importance [6, 9].

At this stage, characteristic cloud velocities decrease to values on the order of a few centimeters per second. Consequently, aerosol transport becomes increasingly controlled by ventilation, convective airflows, and human movement. Under these conditions, the evolution of the aerosol cloud is determined mainly by the indoor microclimate. Fine aerosol particles (<5 µm) closely follow the airflow and may remain suspended for periods ranging from minutes to hours. As a result, such particles can be transported over considerable distances within indoor environments.

Subsequent Transport and Dispersion of Aerosol Particles

Human respiratory emissions constitute a polydisperse aerosol consisting of saliva droplets spanning a wide range of sizes. The droplet size distribution depends on the mechanisms of droplet formation within the respiratory tract and is influenced by the type of respiratory activity, ambient humidity, saliva properties, and evaporation rate.

After being released into the surrounding environment, liquid droplets undergo rapid evaporation, causing their diameter to decrease substantially and resulting in the formation of so-called aerosol nuclei, which may retain infectious agents.

Table 1 summarizes the characteristic size ranges and the most probable particle sizes commonly reported in medical and aerosol studies.

Table 3. Characteristic size ranges of particles generated during different respiratory activities.

Respiratory activity	Particle diameter (µm)	Predominant size range (µm)	Characteristics
Speaking	1–100	5–20	Fine particles predominate
Coughing	1–500	10–40	Broad particle-size distribution
Sneezing	0.5–1000	20–200	Large particles predominate

The particle-size distribution does not follow a normal distribution. For aerosols generated during speaking, coughing, and sneezing, the distribution with respect to the logarithm of particle diameter is approximately normal: $\frac{dN}{d \ln d} = \frac{1}{N} f(\ln d)$, where (N) is the total number of particles and (d) is the characteristic particle diameter.

Table 4. Relationship between particle size and airflow velocity field.

Particle diameter (μm)	Settling velocity (m/s)	Coupling with airflow
< 0.1	10^{-6} – 10^{-5}	Follow the airflow
0.1–1	10^{-5} – 10^{-4}	Closely follow the airflow
1 – 5	10^{-3} – 3×10^{-3}	Partially follow the airflow
10–100 and larger	3×10^{-3} – 0.2	Weakly coupled to the airflow

The data presented in Table 4 were taken from previous studies [6, 9, 14] and should be regarded as approximate estimates. It should be noted that quantitative values reported in the literature vary depending on the experimental methods and measurement conditions. This variability highlights the need for repeated measurements under controlled conditions. Differences in particle density, ambient humidity, and droplet evaporation time can significantly affect the obtained results.

Theoretical Analysis

Governing Equations of Airflow

The motion of air transporting aerosol particles is described by the Navier–Stokes equations with buoyancy effects taken into account using the Boussinesq approximation [7, 8].

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \nabla \vec{v} \right) = -\nabla p + \mu \Delta \vec{v} + \rho \vec{g} \beta (T - T_0) \quad (1)$$

where ($\vec{v}$) is the velocity vector, (p) is pressure, (ρ) is the air density, (μ) is the dynamic viscosity, and (β) is the coefficient of thermal expansion.

The last term accounts for the buoyancy of warm exhaled air.

The incompressibility condition is $\nabla u = 0$.

Numerical simulations based on the Navier–Stokes equations and turbulence models are widely used to analyze airflow structure and the influence of ventilation on aerosol transport [5, 7].

Despite significant advances in computational fluid dynamics (CFD), simulation results remain sensitive to the choice of turbulence model, computational mesh, and boundary conditions. Therefore, experimental data remain essential for the validation of numerical predictions [5], highlighting the need for detailed experimental investigations.

Aerosol Transport: Convection and Diffusion

For aerosol particles with diameters smaller than approximately 5 μm , inertial effects are negligible, and particle transport can be described by a scalar concentration field governed by the convection–diffusion equation [6, 9]:

$$\frac{\partial n}{\partial t} + \vec{v}\nabla n = D\Delta n - \lambda n + S(t, x), \quad (2)$$

where (D) is the effective diffusion coefficient (including both molecular and turbulent diffusion), (λ) is the particle removal coefficient (deposition and filtration), and ($S(t, x)$) is the aerosol source term.

This equation is applicable to particles whose transport is governed primarily by airflow rather than gravitational settling. It should be noted that determining the effective diffusion coefficient is a challenging problem, and uncertainties associated with inverse estimation procedures are often substantial. Therefore, experimental measurements play a key role in evaluating the spatial distribution of aerosol particles.

The performed estimates indicate that the contribution of molecular diffusion to changes in aerosol concentration is significantly smaller than the effects of convective transport and turbulent mixing [6]. Figure 4 presents a calculated particle concentration distribution for particles with a diameter of 5 μm .

The visualization results make it possible to employ simplified geometric models of the aerosol cloud (spherical or cylindrical) when performing approximate calculations of aerosol concentration. In the present analysis, the cloud was assumed to have a cylindrical shape.

The molecular diffusion equation is

$$\frac{\partial n}{\partial t} = D \left(\frac{\partial^2 n}{\partial r^2} + \frac{2}{r} \frac{\partial n}{\partial r} \right) \quad (3)$$

Approximate and exact solutions of Eq. (3) show that, for ($D \approx 10^{-13} \text{ m}^2/\text{s}$), molecular diffusion changes the aerosol concentration by less than 0.5% during the cloud transport time, as illustrated in Figure 4.

For example, during 1 s, a 50 μm droplet is displaced by only about 1 μm due to molecular diffusion, whereas its gravitational settling velocity is on the order of several centimeters per second.

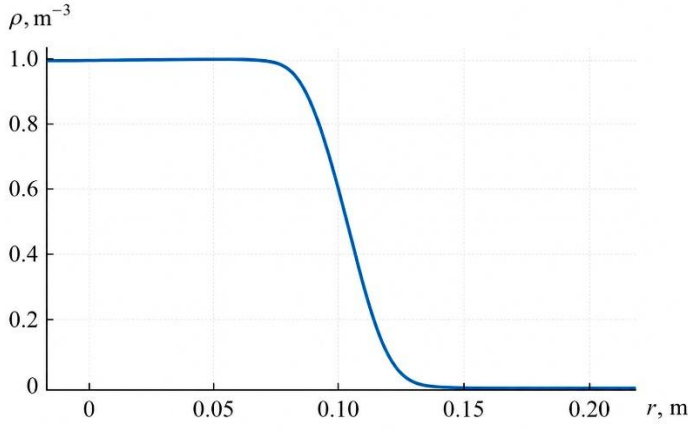


Figure 4. Particle concentration as a function of radial distance from the center of the sphere at $t = 600$ s.

Experimental Methods

A quantitative description of aerosol cloud dynamics requires determination of the spatiotemporal structure of the velocity field, particle concentration evolution, and the principal geometric characteristics of the cloud. The measured parameters depend not only on environmental conditions but also on individual characteristics of the participants, resulting in considerable variability between experiments. Therefore, a sufficiently large number of volunteers is required to obtain statistically representative results, determine mean values, and estimate confidence intervals.

In addition to average characteristics, particular attention should be paid to extreme parameter values corresponding to the most unfavorable aerosol transport scenarios.

Experimental Program

1. Flow Visualization

Visualization of density gradients, turbulent cloud structures, and particles suspended within the cloud was performed using smoke tracers. The experiments provided images of particle distributions, cloud geometry, and cloud evolution.

The validity of this approach is determined by the ability of smoke particles to accurately follow the local velocity field.

The motion of aerosol particles in a flow is characterized by the Stokes number:

$$St = \tau_p U / l, \text{ where } \tau_p = \frac{\rho_p d_p^2}{18\eta},$$

where (τ_p) is the particle relaxation time, (U) is the mean cloud velocity, (l) is the characteristic propagation distance, (ρ) is the particle density, (d) is the particle diameter, and (η) is the dynamic viscosity of air.

The relaxation time (τ_p) is the characteristic time required for a particle velocity to become approximately equal to the surrounding air velocity, so that the particle becomes fully entrained by the airflow. This parameter is sometimes referred to as the particle response time.

For the smoke particles used in the experiments, the characteristic diameter is approximately ($d \sim 1 \mu\text{m}$). Even when accounting for possible variations in particle density, the corresponding relaxation time (τ_p) remains extremely small. Estimates show that, under the conditions considered here, the Stokes number satisfies the inequality $St \ll 1$.

This indicates that inertial effects for smoke particles are negligible and that the particles adapt almost instantaneously to changes in the surrounding airflow velocity. Consequently, the trajectories of smoke particles closely follow the streamlines of the airflow, allowing them to be used for visualization of flow structures and turbulent vortical motions.

A similar conclusion applies to fine aerosol particles (diameters below $5 \mu\text{m}$) generated during coughing, sneezing, and speaking. For such particles, the condition ($St \ll 1$) is also satisfied, and their motion is therefore governed primarily by the airflow velocity field.

Thus, smoke particles provide a convenient tool for visualizing the airflow structure generated during human coughing, sneezing, and speaking. It should be noted that the interactions of liquid droplets and solid smoke particles with the surrounding environment are different. However, for the fine-particle fraction, these differences have little influence on the visualization of the velocity field.

Larger droplets (diameters greater than $10\text{--}20 \mu\text{m}$) possess appreciable inertia and are subject to gravitational settling. Their trajectories may deviate from the streamlines, and such effects cannot be reproduced by smoke visualization. Therefore, the use of smoke particles in the present study is appropriate for analyzing the velocity field structure and the transport of the fine aerosol fraction, which plays a dominant role in long-range aerosol transport.

2. Direct Measurement of the Velocity Field

To obtain direct measurements of the velocity field, a dedicated experimental setup was developed together with specialized software for determining airflow velocities.

Experimental Setup

The experiments were conducted in a room measuring $6 \times 4 \text{ m}$, allowing the propagation of respiratory jets and aerosol clouds to be observed over distances of several meters from the source.

Velocity measurements were performed using an array of lightweight paper flags acting as flow indicators, mounted within two frames separated by an adjustable distance [11, 12]. The spacing between adjacent indicators was 3 cm. This configuration enabled measurements of the spatial velocity distribution within the region occupied by the aerosol cloud.

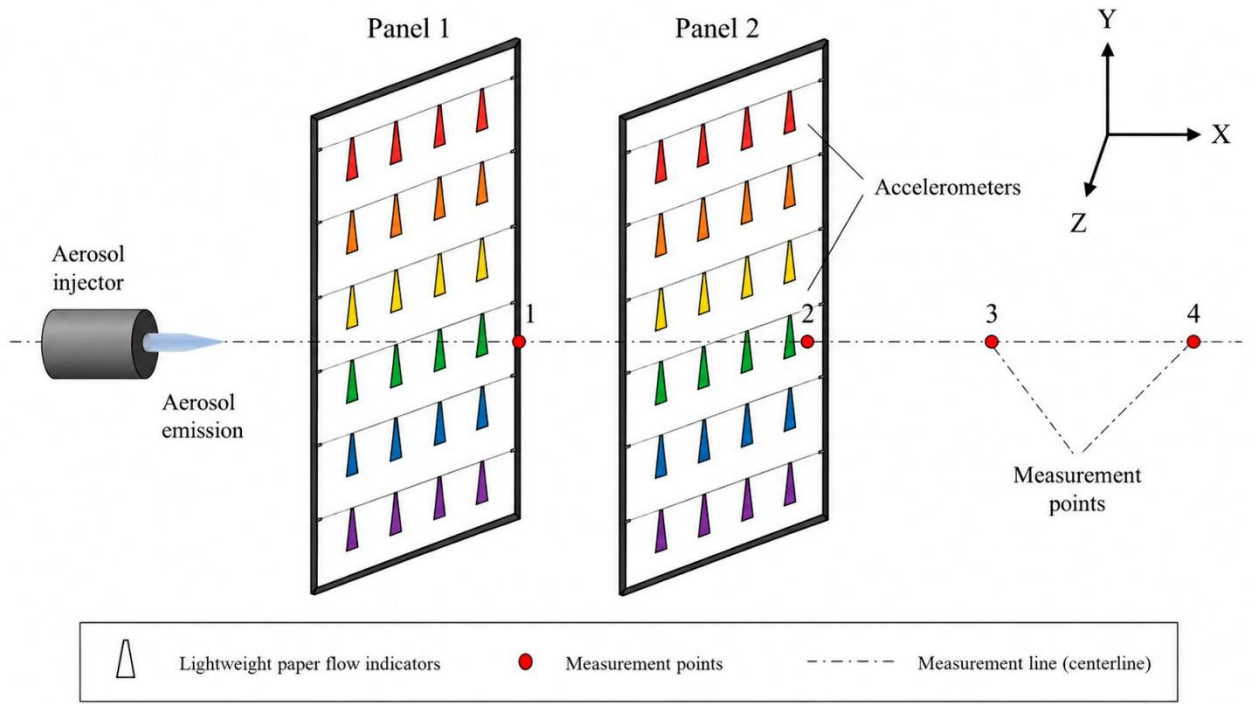


Figure 5. Experimental setup for measuring the spatial velocity distribution within an aerosol cloud.

The positions of the frames were varied relative to the aerosol source, allowing reconstruction of the three-dimensional velocity field. In addition, the influence of the flow indicators on the airflow structure and aerosol cloud propagation was investigated. It was found that the presence of the indicators altered the cloud propagation distance by less than 0.1%, while their effect on the measured velocity distribution remained within the experimental uncertainty. This behavior is attributed to the small size and low mass of the lightweight paper indicators.

Fifty volunteers participated in the study. Each experiment was repeated multiple times to ensure statistical reliability of the results and to obtain representative characteristics of respiratory airflow generated during coughing, sneezing, and speaking.

The direction of cloud propagation, propagation distance, and cloud width evolution were evaluated.

The experimental data obtained in this study can be used for validation of numerical models of aerosol cloud transport and for assessing the influence of external factors, such as walls, convective air currents, and other environmental effects, on cloud evolution.

Velocity Measurement Method

The local airflow velocity was determined from the deflection angle of a flexible flow indicator subjected to aerodynamic forces. The indicator deflection angle, (θ) , was obtained automatically from the analysis of sequential video frames.

The local airflow velocity was determined using a previously established calibration relationship, $u = f(\theta)$,

where (u) is the local airflow velocity.

Calibration was performed in a controlled steady airflow using a reference anemometer. The calibration range covered velocities from

$$0 \leq u \leq 5 \text{ m/s.}$$

Video data were processed using custom-developed software that automatically determined the indicator deflection angles and calculated the corresponding local airflow velocities.

For each experimental configuration, at least ten repeated measurements were performed. The final reported value was taken as the arithmetic mean of the measured results. Confidence intervals were calculated based on Student's t-distribution at a confidence level of 95%. The maximum absolute error of the velocity measurements did not exceed 0.1 m/s.

The influence of the flow indicators on the measured velocity field was investigated separately using a sensitive anemometer and a standard airflow jet. Owing to the small size and low mass of the indicators, their effect on the velocity field was found to be negligible.

Results

1. Velocity Field of the Expiratory Flow

A series of experiments was performed to obtain spatiotemporal velocity distributions within aerosol clouds generated by coughing and sneezing. Measurements were carried out at distances ranging from 0.4 to 1.6 m from the source, corresponding to the period from the end of exhalation to the transition of the jet into a diffuse aerosol cloud.

At a distance of 0.4 m from the source, the flow exhibits the characteristic structure of a turbulent jet with a well-defined axial core of elevated velocities. The velocity field is characterized by the presence of this axial core, where the maximum velocity reaches values of approximately

$$u_{\max} \approx 2.0\text{--}2.5 \text{ m/s.}$$

The velocity distribution across the jet cross-section is well approximated by a Gaussian profile, consistent with the classical behavior of free turbulent jets.

As the distance from the source increases, a monotonic decrease in axial velocity is observed, accompanied by jet spreading and enhanced turbulent mixing with the surrounding air.

Based on the experimental data, the dependence of the maximum aerosol-cloud velocity on the distance from the source was determined for coughing (Figure 6). The measurement range extends from 0.4 to 1.2 m, corresponding to the time interval between the end of exhalation and the transition of the jet into a diffuse aerosol cloud.

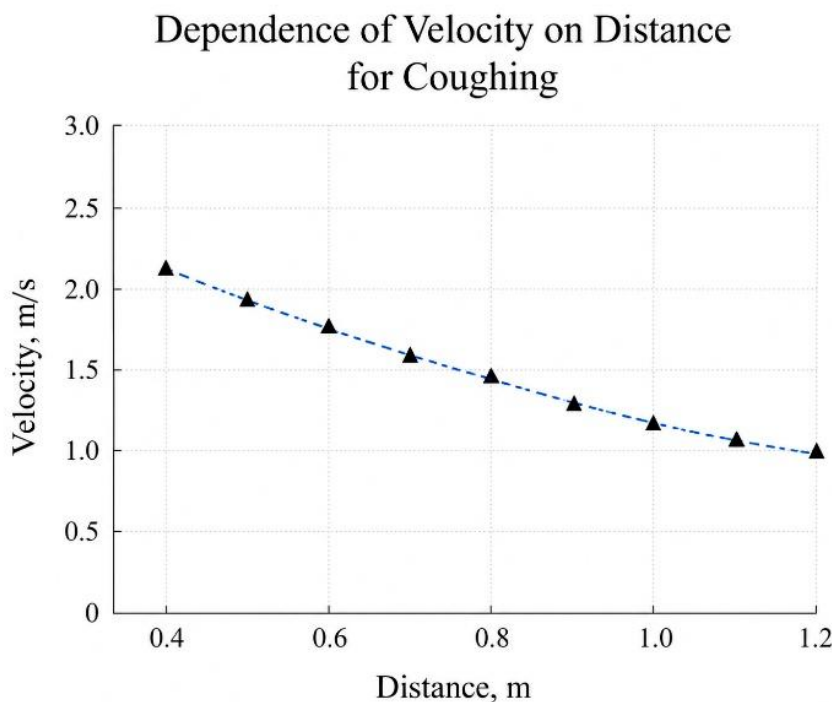


Figure 6. Maximum aerosol-cloud velocity as a function of distance from the source during coughing.

At a distance of 0.4 m from the mouth (Figure 6), a classical turbulent jet profile is observed [1, 12]. The velocity field exhibits a well-defined core with axial velocities reaching approximately 2.1 m/s. The velocity gradient at the jet boundaries is maximal, indicating intense turbulent mixing and entrainment of the surrounding air. The velocity profile in the central region is close to a Gaussian distribution, characteristic of the initial stage of a free turbulent jet. Aerosol particle concentrations are highest in this region, corresponding to the greatest potential for aerosol exposure.

At a distance of 0.6 m from the source (Figure 6), the velocity decreases and the aerosol cloud becomes increasingly dispersed. At this location, the influence of the jet potential core has largely vanished, while large-scale vortical structures characteristic of the transitional regime begin to dominate [1,3]. Active mixing with the surrounding air occurs. Particles of intermediate size (10–50 μm) remain strongly coupled to the airflow; however, their trajectories become increasingly influenced by the combined effects of inertia, gravitational settling, and buoyancy.

At distances greater than 1.2 m from the source (Figure 6), the velocity decreases further [4,6], and the transport of the fine aerosol fraction becomes governed not by the initial momentum of the expiratory jet but primarily by external factors, including convective air currents, ventilation systems, and Brownian diffusion.

The dependence of velocity on distance from the source can be approximated by $v(x) = v_0 \frac{1.3}{x}$, which is analogous to Eq. (1) for a turbulent jet. However, the coefficient in this expression does not have the same physical interpretation as in Eq. (1), because continuous entrainment of the surrounding air modifies the structure of the exhaled flow. Nevertheless, the turbulent character of the motion is preserved.

Figure 7 shows the dependence of aerosol-cloud propagation velocity on distance from the source during sneezing.

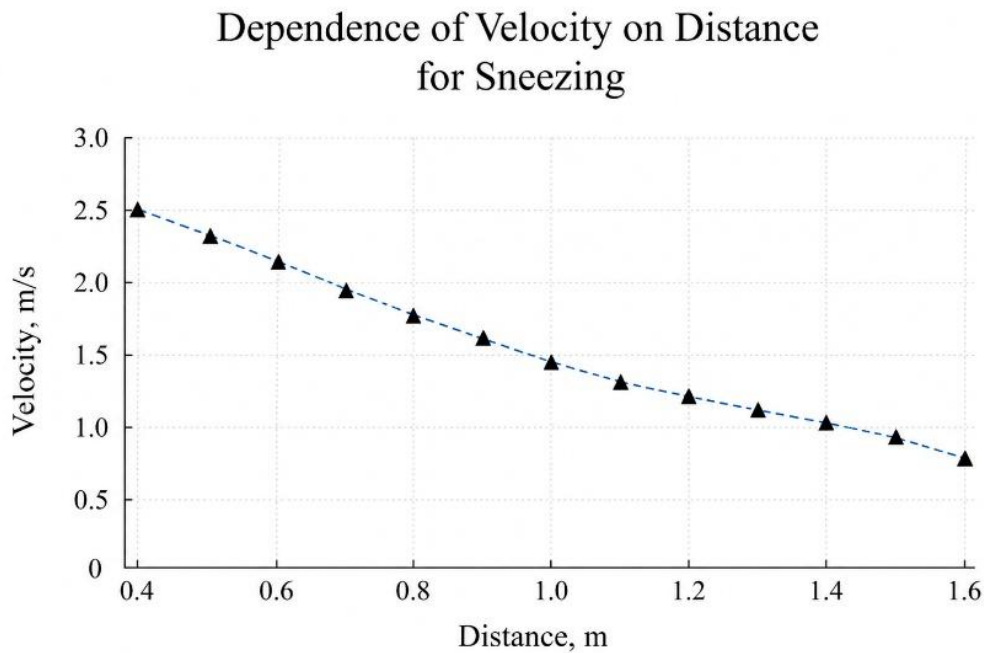


Figure 7. Aerosol-cloud propagation velocity as a function of distance from the source during sneezing.

A series of experiments was performed to determine the dependence of aerosol-cloud velocity on distance during sneezing (Figure 7). Analysis of the data reveals a pronounced monotonic decrease in velocity with increasing distance from the source. At a distance of 0.4 m, the velocity is approximately 2.5 m/s, whereas at 1.6 m it decreases to about 0.8 m/s, indicating a substantial reduction in aerosol-cloud velocity as the cloud propagates away from the source.

The observed dependence is close to a hyperbolic decay, with the velocity decreasing by nearly a factor of 2.5 over the measurement range. This behavior can be attributed to intense turbulent mixing between the expiratory jet and the surrounding air, entrainment of additional ambient air, and energy dissipation due to viscous effects.

The near-field region, corresponding to distances close to the source and times shorter than approximately 1 s after exhalation, is characterized by high axial velocities, intense turbulence, and the highest aerosol concentrations, resulting in the greatest potential for aerosol exposure.

Within the time interval from 1 to 10 s, the mean velocity decreases rapidly while large-scale vortical structures remain present, in agreement with previous studies [4–6]. After approximately 10 s, characteristic air velocities decrease to the order of centimeters per second, and particle transport becomes governed primarily by ventilation and convective air currents. Fine aerosol particles may remain suspended in air for periods ranging from several minutes to several hours.

In addition, a series of consecutive coughing events was investigated to simulate typical respiratory behavior during illness.

Analysis of 50 experiments showed that the probability of aerosol-cloud propagation beyond a distance of 1.2 m was 28% for a single cough and 36% for a sneeze. For a sequence of consecutive coughing events, this probability increased to 52%. At the same time, the characteristic transverse dimensions of the aerosol cloud increased, indicating enhanced turbulent mixing.

2. Dependence of Velocity on Distance

The experimental data show that, up to distances of approximately 1–1.2 m from the source, the aerosol-cloud velocity decreases according to a relationship close to a hyperbolic law:

$$u(x) = C/x,$$

where (x) is the distance from the source and (C) is an empirical coefficient.

For coughing, the coefficient was found to be

$$C \approx 0.8\text{--}1 \text{ m}^2/\text{s}$$

This relationship is consistent with the classical theory of free turbulent jets and indicates approximate conservation of momentum flux within the near-field region.

At distances greater than approximately 1–1.2 m, deviations from this relationship are observed. These deviations are associated with the transition from a jet-dominated flow regime to the aerosol-cloud stage, as well as with the increasing influence of external factors.

3. Transition from a Turbulent Jet to an Aerosol Cloud

The experiments showed that the transition from the jet-dominated regime to the aerosol-cloud stage occurs after approximately $t \approx 1\text{--}3$ s.

The transition is characterized by a rapid decrease in axial velocity, disappearance of the well-defined jet core, and the formation of large-scale vortical structures.

Following this transition, aerosol transport is no longer governed primarily by the initial momentum of the expiratory jet, but instead by turbulent mixing and external airflows.

4. Width of the Aerosol Cloud

Knowledge of the aerosol-cloud width, (d) , is important for determining potential exposure zones and evaluating the ability of the cloud to spread around obstacles. To estimate the cloud width, relationships based on the law of momentum conservation for a free turbulent jet were used.

During cloud formation (coughing, sneezing, etc.), the momentum flux is conserved because the air entrained into the jet is initially at rest and no external forces act on the flow. Assuming that the velocity profile at the beginning of the jet follows a Gaussian distribution, standard transformations yield the following expression for the momentum flux, under the assumptions of constant air density, cylindrical jet geometry, and flow directed along the (X) -axis:

$Q_p = \rho 2\pi u_{xc}^2 d^2$, where (ρ) is the air density, (d) is the jet diameter, and (u_{xc}) is the velocity along the (X)-axis.

Therefore, along the jet,

$$u_{xc}^2 d^2 = \text{const.}$$

and

$$u_{xc} \sim 1/d.$$

At the same time, it is well known that for a turbulent jet

$$u_{xc} \sim 1/x,$$

where (x) is the distance from the source.

In the near-field region ($x \approx 0.15\text{--}0.2$ m), the jet width can therefore be approximated, to first order, by a linear relationship:

$$d = kx,$$

where the spreading coefficient is approximately

$$k \approx 0.5\text{--}0.7.$$

Experimental data showed that the linear relationship remained valid up to a distance of approximately 15 cm from the source, with

$$k = 0.6.$$

The obtained spreading coefficient is somewhat larger than values typically reported for steady isothermal jets. This difference may be attributed to the unsteady nature of exhalation, the presence of an aerosol phase, and the influence of temperature and humidity effects.

At larger distances, the linear relationship no longer holds, and the cloud width is better approximated by

$$d = kx^{1/2},$$

where

$$k \sim 1.6.$$

All experiments reported here were performed under conditions of quiescent indoor air, i.e., the airflow was generated solely by coughing and sneezing. In future studies, it will be necessary to account for air currents produced by natural and mechanical ventilation [4, 5].

5. Dynamics of the Aerosol Cloud

Analysis of the experimental data indicates that the evolution of an aerosol cloud can be divided into several stages.

During the first second after exhalation, a jet core is formed, characterized by the highest velocities and the greatest aerosol-particle concentrations. Between approximately 1 and 10 s after exhalation,

the cloud undergoes intense turbulent mixing with the surrounding air, accompanied by a decrease in mean velocity while large-scale vortical structures remain present.

At later stages, the characteristic velocities decrease to values on the order of centimeters per second. Under these conditions, further aerosol transport is governed primarily by ventilation and convective air currents within the room.

6. Influence of Particle Size

The experimental results and theoretical analysis indicate that particles smaller than 5 μm closely follow the airflow velocity field, whereas particles of intermediate size (10–50 μm) exhibit partial deviation from the flow. Large droplets ($>100 \mu\text{m}$) move predominantly under the influence of inertia and gravitational settling.

The obtained results confirm that the fine aerosol fraction plays the key role in the long-range transport of aerosol particles within indoor environments.

7. Role of Ventilation at Later Stages

At later stages of aerosol-cloud evolution, the influence of the initial jet momentum becomes negligible, and aerosol transport is governed primarily by ventilation flows, convective air currents, and human movement.

Under these conditions, molecular diffusion contributes only a minor fraction (approximately 0.5%) to changes in particle concentration.

Discussion

Comparison with Previous Studies

The results obtained in the present study are consistent with current understanding of the hydrodynamics of human expiratory flows as reported by Bourouiba et al. (2014), Tang et al. (2013), Abkarian et al. (2020), and Liu et al. (2017). At the same time, several features associated with the measurement methodology and experimental conditions were identified.

Bourouiba et al. [1] demonstrated that coughing and sneezing generate a multiphase turbulent gas cloud rather than isolated droplets, enabling aerosol transport over distances substantially greater than those predicted by simple ballistic droplet motion. The present results support this conclusion. It was experimentally observed that, following the end of active exhalation, the jet does not stop immediately but evolves into a turbulent aerosol cloud characterized by developed vortical structures. The observed vortex formation and cloud expansion are consistent with the entrainment mechanism described by Bourouiba et al.

Unlike Bourouiba et al. [1], whose work focused primarily on cloud visualization and droplet transport distance, the present study measured the spatial distribution of velocities within the aerosol cloud. This made it possible to quantify the decrease in velocity with distance from the source and to identify regions associated with the greatest potential aerosol exposure.

Tang et al. [3] investigated airflow structures generated by coughing and breathing using optical visualization techniques and reported a pronounced jet regime near the source, followed by progressive development of turbulence. The present results are in good agreement with these observations. In the near-field region, a distinct axial core with maximum velocities and strong velocity gradients at the jet boundaries was observed. The experimentally determined velocity decay followed an approximately hyperbolic law, consistent with the classical theory of free turbulent jets and with the conclusions of Tang et al.

A key difference is that Tang et al. primarily provided a qualitative description of the flow, whereas the present study reconstructed the velocity field quantitatively in multiple measurement planes. In addition, statistical analysis was performed using data obtained from a series of experiments involving human volunteers.

Abkarian et al. [2] showed that speaking generates a directed airflow capable of maintaining coherence over considerable distances and transporting aerosol particles even in the absence of coughing or sneezing. The present findings are consistent with the existence of a jet-dominated flow regime during the initial stage of human exhalation. The persistence of directed aerosol-cloud motion during the first seconds after exhalation agrees with the conclusions of Abkarian et al. regarding the significant momentum of expiratory flows.

However, the present study focused primarily on coughing and sneezing, which are characterized by substantially higher initial velocities and greater turbulence intensity than speech. Consequently, the observed cloud expansion and vortex development were more pronounced than those reported for speech-generated flows.

Liu et al. [5] investigated aerosol transport between individuals in indoor environments using a combination of numerical simulations and experimental measurements. Their results demonstrated that, at distances of approximately one meter, aerosol transport depends not only on the characteristics of exhalation but also on the structure of indoor airflow patterns.

The present results are in good qualitative agreement with these findings. It was experimentally observed that, beyond distances of approximately 1–1.2 m, the intrinsic velocity of the aerosol cloud decreases substantially, and subsequent transport becomes governed primarily by ventilation, convective air currents, and other room-scale airflow motions.

Some quantitative differences may be attributed to the fact that Liu et al. [5] considered controlled ventilation conditions and focused on person-to-person aerosol transmission, whereas the present study examined the characteristics of the aerosol cloud itself under conditions of nearly quiescent air.

Overall, the present results are in good agreement with previously published experimental and theoretical studies and confirm several established features of expiratory aerosol transport:

1. Human exhalation generates an unsteady turbulent jet that subsequently evolves into an aerosol cloud (Bourouiba et al., 2014).
2. Velocity in the near-field region decreases according to a law close to that of a free turbulent jet (Tang et al., 2013).
3. Even relatively weak expiratory flows can produce directed transport of aerosol particles (Abkarian et al., 2020).
4. At later stages, ventilation and convective room airflows become the dominant transport mechanisms (Liu et al., 2017).

The principal contribution of the present study is the experimental determination of spatial velocity distributions within aerosol clouds using an array of flexible flow indicators combined with statistical analysis of repeated experiments. This approach provided quantitative information on the evolution of the velocity field and its relationship to the transport of fine aerosol particles.

Limitations of the Study

Despite the results obtained, the present study has several limitations that should be considered when interpreting the findings.

First, velocity-field measurements were performed using an array of lightweight flow indicators positioned within the airflow. This approach makes it possible to obtain spatial velocity distributions within the measurement plane; however, it does not provide a complete three-dimensional description of the turbulent flow. In addition, the accuracy of the method is limited by the inertial properties of the indicators and by the sensitivity of the image-processing system at low airflow velocities.

Second, the experiments were conducted in a room with a specific geometry and boundary conditions. In real indoor environments, room layouts, locations of air supply and exhaust openings, and thermal conditions may differ substantially, affecting both airflow structure and aerosol transport.

Third, the study considered typical coughing and sneezing events generated by volunteers. However, the characteristics of expiratory jets may vary considerably depending on individual physiological features, exhalation intensity, and respiratory conditions.

Furthermore, the aerosol-transport analysis was based on the assumption that fine particles follow the airflow velocity field and possess negligible inertia. The effects of large-droplet settling, particle inertia, and droplet evaporation were not examined in detail and may contribute to aerosol-cloud

evolution under certain conditions. A comprehensive investigation of these processes is beyond the scope of the present study.

The assessment of aerosol exposure presented here was based primarily on aerosol-particle concentration and potential inhalation dose. Biological factors such as viral viability, infectious dose, and individual susceptibility to infection were not considered [13].

Despite these limitations, the results provide valuable insight into the fundamental mechanisms governing aerosol-cloud evolution and demonstrate the important role of airflow velocity fields in determining the spatial distribution of aerosol particles within indoor environments.

Practical Significance of the Results

1. The results of the present study confirm that respiratory aerosol clouds should be considered unsteady turbulent jet flows. In the near-field region, particle transport is governed primarily by jet dynamics, whereas at later stages ventilation and convective room airflows become the dominant transport mechanisms.

2. Experimental observations confirm that fine aerosol particles with diameters of a few micrometers or less may remain suspended in air for extended periods. Therefore, determination of the spatial extent of aerosol-cloud propagation is an important component in assessing potential aerosol-exposure zones in indoor environments.

Conclusions

1. Aerosol emissions generated during coughing and sneezing form unsteady turbulent jets that gradually evolve into aerosol clouds.
2. The transition from the jet-dominated regime to the aerosol-cloud stage occurs approximately 1–3 s after the end of active exhalation.
3. The greatest potential for aerosol exposure corresponds to the near-field region, where both airflow velocities and aerosol-particle concentrations reach their maximum values.
4. Jet velocity decreases with distance approximately according to the relationship $u \sim 1/x$.
5. At later stages of cloud evolution, aerosol transport is governed primarily by ventilation and convective air currents within the room.
6. Ventilation effectiveness depends not only on the air-exchange rate but also on the spatial structure of the generated airflow patterns.

Scientific Novelty

The scientific novelty of this work lies in the development and experimental validation of a low-cost, non-invasive method for measuring spatial velocity distributions within aerosol clouds using an array of flexible flow indicators combined with automated video-data processing.

Because fine aerosol particles closely follow the airflow velocity field, a direct relationship was established between the dynamics of aerosol-cloud velocity fields and the spatial distribution of aerosol particles within indoor environments. The measured geometric and kinematic characteristics of aerosol clouds provide a basis for addressing indoor ventilation problems within the framework of unsteady turbulent-flow hydrodynamics.

Note. Numerical estimates of expiratory-flow velocities and flow regimes are based on the experimental results obtained in the present study and on previously published investigations [1–3].

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Ethics Approval, Consent to Participate and Consent to Publish

Not applicable.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

N.A. Parfentyeva conceived the study, designed the experiments, performed data analysis, and drafted the manuscript.

S.N. Gavrilin contributed to the experimental methodology and manuscript revision.

I.D. Bykovskaya participated in data processing and interpretation of results.

N.V. Radionov contributed to the experimental work and critical revision of the manuscript.

All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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Clinical Trial Number

Not applicable.