Experimental studies of aerosol cloud parameters of human-expelled aerosol cloud

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Abstract. The study developed an experimental methodology to characterize the volumetric velocity field and frontal geometry of exhaled air clouds containing aerosol parti-cles. The research focused on establishing the movement patterns of air expelled during human respiratory activities (speaking, sneezing, coughing) to identify potential infection zones. The experimental approach incorporated video re-cording of exhaled air dynamics under various conditions, followed by computational processing and modeling. The methodology included derivation of analytical formulas for data processing, description of experimental data analysis tech-niques, and temporal evolution analysis of results. The proposed method will allow the determination of aerosol cloud geometry, propagation velocity, and direc-tional characteristics through video analysis. Time-resolved imaging at 1/25-second intervals permits detailed study of geometric and velocity field dynamics. Computational transformation of results into vector format was achieved through specialized algorithms. Analysis revealed complex airflow patterns within mov-ing aerosol clouds, including recirculation components characteristic of turbulent flow regimes. Distinct cloud geometries were identified for different expulsion mechanisms (speech, sneeze, cough). The methodology provides foundational data for computational modeling of respiratory particle dispersion and infection risk.

1 Introduction

The increasing connectivity of human societies located in different countries and on different continents due to migration, tourism and business travel leads to increased economic interaction. A negative side effect of this is the accelerated movement and spread of human microflora. As a result, microbial species characteristic of one of the private human communities and harmless to this group, getting into a group of people who are not immune to this microflora, may turn out to be pathogenic. The existing crowding of population in cities and technogenic risks contribute to the spread of diseases. The most rapid and active way of spreading viruses and bacteria is by airborne transmission. An example is the COVID-19 pandemic [1]. This requires the study of the nature of air currents emitted from humans and ways to prevent the spread of microflora [1, 2].

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Modeling of airflow movement is important. In this case, the resulting model should correspond to the real process.

Aerosols are tiny particles or droplets suspended in a gas, in this case air, expelled from a person's respiratory system. When a person exhales or coughs, droplets of varying sizes are formed, typically ranging from submicron levels to several hundred micrometers. These droplets are formed from the fluid lining the airways, and their size distribution is critical in determining their post-exhalation behavior.

The work [1] reveals the presence of three phases of jet cloud flow. The initial phase is dominated by jet dynamics without buoyancy with high cloud velocity. In the second phase of the flow the negative buoyancy is the basis. In the final phase of the flow, gravity dominates, which deflects the cloud downward. The behavior of the jet, depending on the distance from the human mouth, is revealed.

The paper [3] solves the problem of droplet movement in the indoor air. It is argued that larger droplets (>100 μm) tend to settle rapidly under gravity, while smaller droplets (<10 μm) can remain in the air for long periods of time. This study reconsiders the Wells evaporation-drop curve, which is crucial for understanding how droplet size affects the dynamics of evaporation and deposition. It can be assumed that the size distribution of liquid droplets in a human exhaled air stream obeys the normal [4], but this is a complex process and the droplet distribution can change over time. Let us list the factors that change particle sizes: 1) condensation and evaporation, 2) the value of the humidity of the air in the room where the person is (at small values of relative humidity the particle size decreases, at large values it increases), 3) the way the aerosol cloud is emitted (for example, when talking or coughing) [5].

Smaller droplets (<5 μm) can evaporate rapidly after formation, leaving behind droplet nuclei, which are essentially solid or semi-solid remnants of the original droplets (effectively condensation centers). These nuclei can remain in the air indefinitely under typical indoor conditions [6]. In their paper, the authors provide a detailed analysis of the droplet evaporation dynamics under different humidity and temperature conditions.

The flow dynamics of aerosol clouds after coughing, sneezing is governed by complex hydrodynamics, in particular the interaction between the ejected jet, the environment and the physical properties of the droplets. The proposed work is devoted to the first stage of the study - aerosol cloud formation and determination of the volumetric velocity field.

Consider the formation of an air medium (cloud). When coughing, a turbulent jet of air is ejected at a velocity that can exceed 10 m/s. This jet, carries droplets of various sizes into the environment. This process is analyzed in the work [5]. In their study, the authors used high-speed visualization of the initial diffusion of the aerosol cloud. Their results show that the droplets are initially transported by the momentum of the ejected air, which forms a turbulent jet that traps the surrounding air, resulting in rapid dispersion of the droplets. It is obvious that the greater the velocity of the generated stream is, the greater the mass of “clean” room air that is captured, and the lower the concentration of aerosol particles. It should be noted that the interaction between the aerosol cloud and the environment plays a significant role in determining the trajectory and dispersion of the cloud. As stated in the work [7], moist air expelled from the lungs has greater mobility (buoyancy) than cooler ambient air, causing the aerosol cloud to rise initially; buoyancy effects can cause the aerosol cloud to travel farther than expected, especially in conditions with minimal ventilation.

The paper [8] analyzes the numerical solution of the problem and shows that in the one-dimensional case there is a significant decrease in the temperature of the mixture in the mixing zone due to heat absorption during evaporation, the intensity of which is mainly determined by humidity. Numerical calculations in the three-dimensional setting confirmed that evaporation contributes to the cooling of the cloud and it moves downward, i.e., the buoyancy of the cloud changes its sign.

From the above, it is clear that accurate aerosol cloud flow modeling requires sophisticated computational fluid dynamics (CFD) simulations that must account for features related to flow turbulence, droplet evaporation, and interaction with ambient air currents.

The solution to the problem has been stimulated by the spread of viral diseases. The results of modeling the spread of aerosols during human coughing, sneezing, and talking are presented in [9]. This work emphasized the importance of turbulence in the dispersion process and demonstrated how different ventilation strategies can either soften or worsen the spread of aerosols indoors. However, the work did not take into account phase transformation processes that significantly affect aerosol cloud dynamics.

Aerosol and cloud dynamics are often modeled using multiphase flow equations that consider the interaction between liquid droplets and the gaseous phase. Thus, the work [10] presents a discussion of how multiphase flow models can be used to model the behavior of respiratory aerosols, emphasizing the role of such models in explaining airborne virus transmission processes.

Once again, we note that a physical understanding of aerosol cloud dynamics has significant public health implications, particularly in the context of infectious disease transmission. The ability of small aerosols to remain in the air for long periods of time and to travel long distances necessitates strict indoor control measures. In addition, it is important to know the rate of spread of an aerosol cloud and the distance over which it travels. This task is closely related to the problems of ventilation and accommodation of people in the room, which is an independent task.

In the article [11], the authors presented evidence that poorly ventilated rooms contribute to the accumulation of aerosol masses in the air volume, increasing the risk of airborne virus transmission. Their findings emphasize the importance of adequate ventilation and air filtration to reduce the risks associated with aerosol pathogens.

So, studying the physical aspects of aerosol cloud dynamics following exhalation, coughing and sneezing is important for understanding the risks associated with airborne disease transmission and for solving practical problems faced by the engineer, such as how to provide ventilation in rooms where people are present and ensure that their risk of contamination is minimized.

Key factors such as droplet size distribution, flow dynamics, evaporation and interaction with the environment play a crucial role in determining the behavior and transformation of aerosol particles in the air. Advanced modeling techniques, including CFD and multiphase flow models, have provided valuable insights into these complex processes, informing public health strategies to reduce the spread of infectious diseases. However, many unresolved and controversial issues remain, as there is no accurate understanding of the direction of cloud motion, changes in cloud size, and aerosol particle concentrations.

Analytical solution of the problem is rather complicated and cannot give exact ideas about the motion and values of particle velocity and concentration. Numerical solution requires correct physical and mathematical models of the processes. Therefore, experimental study and computer modeling of the results obtained on the basis of videofixation are very important.

The purpose of the study was to develop the methodology of the experiment to determine the volumetric velocity field in the cloud, the shape of the front, to create a program for processing the results of the experiment, as well as to establish the nature of the movement of exhaled air cloud emitted by a person when talking, sneezing and coughing, to determine the geometry of the cloud carrying aerosol particles, which will allow to determine the area of possible contamination.

2 Research Methods

The research methodology included experimental determination of the velocity field of air masses when a person exhales air under different conditions by means of video recording and subsequent computer processing and modeling of the experimental results.

For a clear understanding of the phenomenon and its subsequent numerical modeling, obtaining analytical expressions allowing to calculate the concentration of particles and the area of cloud diffusion under different initial conditions, it is necessary to conduct experimental studies of the formed aerosol cloud. The source of the aerosol cloud can be a person when talking, coughing and sneezing.

In this paper, measurements were carried out on a setup that allows measuring the values of air velocities in the aerosol cloud volume for a given direction. From the change in the aerosol cloud volume, the average particle concentration is estimated.

However, such calculations are not accurate because they do not take into account vaporization and particle fallout from the cloud due to the increase in size, as well as the downward settling of droplets due to gravity. In addition, the total or partial trapping of aerosol particles by the air flow depends on their diameter. Therefore, the size distribution of aerosol particles must be taken into account during the calculation. Assuming that all particles move with the airflow, a result predicting an increased risk of infection from the presence and concentration of virus-containing particles can be obtained. It should be noted that calculations of particle diffusion showed that this process practically does not affect the distribution of particles in the cloud.

The study was carried out on a setup proposed by the authors and consisting of two rectangular frames, a detailed description of the methodology of which is given in [12].

The setup allows to determine the change in cloud volume. By varying the position of the frames and the distance between them, data on the geometry and, most importantly, on the distribution of velocities at different points of the cloud were obtained. The proposed method of measuring the 3D velocity distribution of an aerosol cloud requires the use of a matrix of miniature sensitive anemometers grouped in two 2D panels positioned one behind the other on the path of the aerosol cloud. A stepwise measurement of the 3D velocity distribution by moving the two panels along the cloud path was used.

Calibration of the operating characteristic of the above anemometers (dependence of the deviation angle on velocity) is performed using a standard electronic anemometer and a fan. The standard anemometer measured the air flow velocity at a given point, and then the panel was moved so that the corresponding flag appeared at the specified point.

In operating mode, the deviations of all flags of each panel were measured using a WEB camera permanently mounted at the bottom of the panel on the side away from the source. The sources of flag illumination were fixed in the same place. Necessary synchronization of video recordings obtained from two panels was achieved by simultaneous switching on the sources of flag illumination with video recording of both cameras switched on beforehand.

In order to obtain contrasting images, a holder for creating a black color surface (background) was fixed on the panel from above, on the side of the aerosol cloud source. As a result, the received image contained a contrasting picture of white paper flags on a black background.

It should be noted that the developed registration system using a large number of sensors (with different operating characteristics) as the only alternative involves computer processing of sensor readings.

Computer processing of the obtained videos consists of the following steps:

- video storyboarding,
- calculation of the angle of deflection of all panel flags using known geometric parameters,

- calculation of two-dimensional distribution of aerosol flow velocity using the working characteristic of anemometers.

The mathematical algorithm for determining the angle of deviation of the sensor from the parameters of its image obtained from the Web-camera is given below.

The geometrical parameters of the measuring panel are shown in Fig. 1.

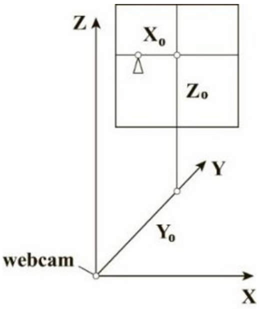

Fig. 1. Geometrical parameters of the measuring panel. The dots mark the ends of the indicated segments.

The size of the flag image in pixels can be calculated using the formula:

$$L_p = K_w \ \operatorname{arctg}\left(\frac{h\sin\left(\operatorname{arctg}\dfrac{\varphi}{\sqrt{X_0^2 + Y_0^2 + Z_0^2}} - \varphi \right)}{\sqrt{X_0^2 + Y_0^2 + Z_0^2}} \right),$$

where K_w – the ratio of frame height in pixels to the angle of view of the camera; φ – the angle of deflection of the flag from the vertical under the action of the aerosol flow; X_0, Y_0, Z_0 – the coordinates of the top of the flag; h - the height of the flag.

Fig. 2 shows the dependence of the angle of deflection of the flag sensor observed by the camera depending on the angle of deflection of the sensor from the vertical and the aerosol velocity.

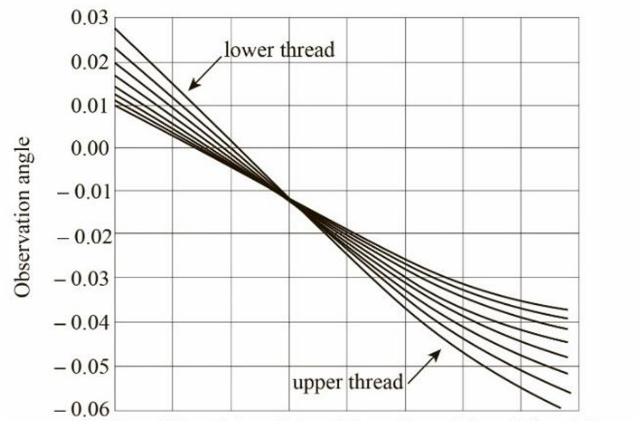

Fig. 2. The dependence of the sensor observation angle on the deflection angle when the sensor is centrally placed on different strands.

The above calculations of the two-dimensional distribution of aerosol flow velocity are made according to the working characteristic of anemometers.

At the next stage of measurement processing with the help of industrial anemometer the calibration of the installation is performed. As a result, the operating characteristic of an individual sensor is determined: the dependence of the flag deflection angle on the air velocity (Fig. 3).

As a result of processing the values of indicators, a sequence of relations is calculated:

$$\frac{v_{x,y,z2}}{v_{x,y,z1}},\ \frac{v_{x,y,z3}}{v_{x,y,z2}},\ \frac{v_{x,y,z4}}{v_{x,y,z3}}\ldots.$$

The spatial 3D instantaneous velocity distribution of the aerosol cloud is determined from the obtained data.

After image processing, the dynamics of aerosol cloud development in the period from the act of creation to the moment when the air velocity becomes lower than the sensitivity limit of sensors was obtained for all video frames.

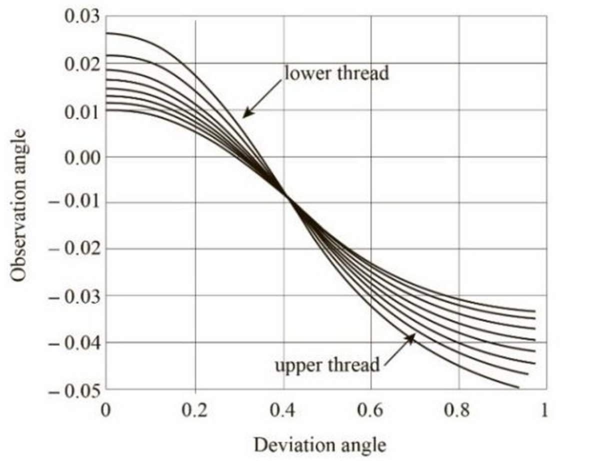

Fig. 3. The dependence of the sensor observation angle on the aerosol velocity when the sensor is centrally placed on different strands.

3 Experiment and calculations

Computer data processing.

Fig. 4 shows a typical record of the edge position of the flag sensor as a function of the frame number of the video recording, obtained with the program [8].

As follows from Fig. 4, the airflow during coughing is pulsed, with a duration of about 0.7 sec. At the same time, the motion of the sensors does not correspond to their behavior in laminar flow. The sensors perform oscillatory motion during the pulse, which indicates air turbulence after the passage of the cloud front. Fig. 5 shows the dependence of the relative magnitude of the image of the flags on the 3 strands of the registration system at two moments of time given by the frame number.

The movements are not synchronized, which is an additional confirmation of air flow turbulence.

Fig. 6 shows the characteristic dependence of the air flow velocity on the coordinates in the plane of the frame, on which 5x5 flag sensors are placed. As follows from Fig. 6, for a short time after the arrival of moving air (at coughing) the front ceases to exist and the air movement becomes turbulent.

In further studies it is supposed to conduct a sufficiently large number of experiments, which will allow us to obtain average values of velocities during conversation, as well as during coughing and sneezing, which accompany different respiratory diseases.

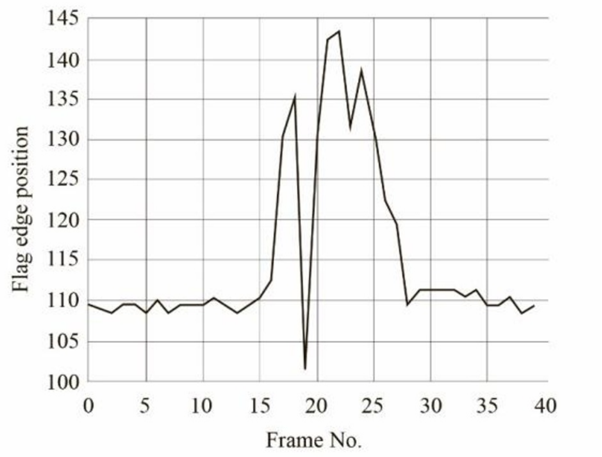

Fig. 4. Dependence of the position of the lower edge of the sensor flag 3 (4th thread) on the video recording frame number (frame rate 25 fps).

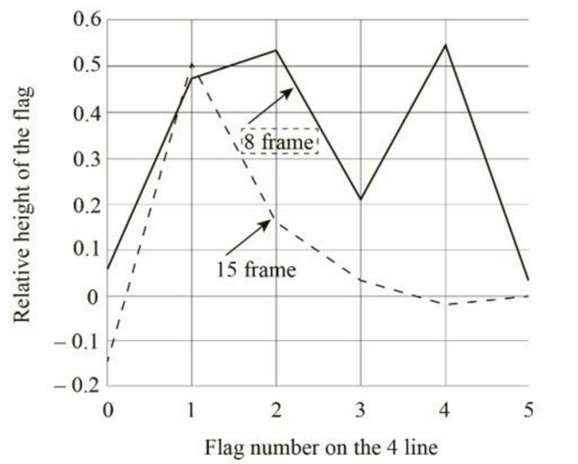

Fig. 5. Dependence of the relative height of a group of flagging sensors at different moments of the air pulse passage.

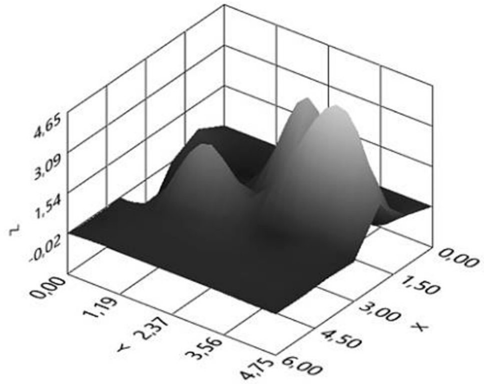

Fig. 6. Distribution of air flow velocities at the moment of 0.2 sec. after the beginning of cloud motion in space.

The results of the study of the air velocity field using a smoke front.

In addition to the study of the velocity field in the aerosol cloud using the above setup, smoke exhaled by a person when talking, coughing and sneezing was used to determine macro characteristics such as cloud size and maximum diffusion range. The fact is that the available literature gives very different values for these parameters, so it is necessary to clarify these data for further studies and conclusions. The cloud visualization is shown in Fig. 7 and 8.

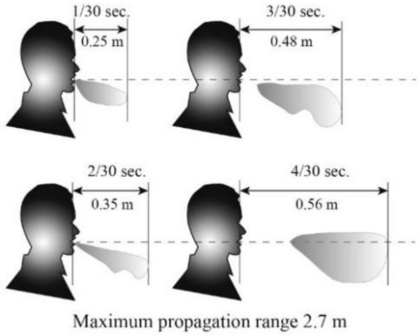

Fig. 7. Dynamics of aerosol air during coughing.

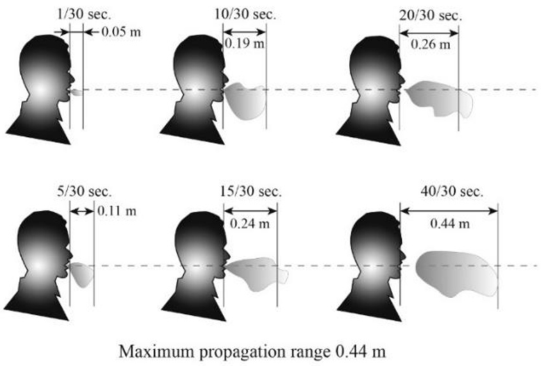

Fig. 8. Dynamics of aerosolized air during conversation.

It follows from the figures that the aerosol cloud shape is unstable, reverse currents are observed, which leads to swirls. This once again confirms the velocity fields found earlier. Such motion can contribute to the merging of droplets and their falling out of the cloud. In the future, the found shape of the cloud and this phenomenon will be taken into account when creating a mathematical model.

The obtained results are of practical importance for recommending the distribution of employees in the room to ensure their safety, in case any of them is sick and there is a risk of infection. Also, the revealed direction of the cloud movement (downward) requires certain actions of enterprise managers, for example, the requirement to wear masks by employees serving seated customers, etc.

4 Discussion

This study is of interest because a number of questions have not yet been definitively answered, such as the maximum distance a cloud moves when a person talks, coughs, and sneezes. Very interesting is the experimental proof of the downward direction of cloud motion, which contradicts the assumptions about its higher temperature compared to the temperature of the surrounding air, and, accordingly, lower density. In fact, the results of the numerical calculation of the paper are confirmed and the conclusions about the cloud motion in the paper [9] are refuted. In addition to studies of the cloud propagation range, it is of considerable interest to measure the velocity field in the cloud, since it is the velocities that determine the movement of aerosol particles, which in turn affects their concentration in the cloud and allows us to refine the numerical models. The turbulent character of the motion is proved, which is also important for estimation calculations.

5 Conclusion

The developed methodology for processing experimental results at the proposed installation for determining the geometry of the aerosol cloud, velocity and direction of its propagation allows the method of video recording to determine the coordinates, direction and velocity of the cloud flows during the investigated period of time. A frame-by-frame filming of air movement makes it possible to study the dynamics of geometry and velocity modes at 1/25 sec. intervals. Computer recalculation by the proposed program allows to translate the results into vector format. The given example of data processing realization gives grounds to speak about creation of the algorithm of data acquisition for computer modeling. The results presented in the paper indicate that the character of air movement in the moving aerosol cloud has a complex character with elements of return motion, characteristic of turbulent flow motion. The shape of the moving cloud in dynamics at different ways of its appearance (talking, sneezing and coughing) is established.

6 Acknowledgements

The research was funded by the National Research Moscow State University of Civil Engineering (grant for fundamental scientific research, project No.15-661/130).

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