Determination of the geometry of a smoke plume from an aerosol generator using digital stereophotogrammetry

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The current state of the experimental and theoretical research into the gas and aerosol diffusion in the atmospheric boundary layer using the smoke plume method is reviewed. A new method that uses the digital stereophotogrammetry, GIS technology, and a mobile aerosol generator with the regulated particle size distribution is described. The data of field experiments on measurement of the smoke plume geometry are presented. Theoretical grounds for determining the dimensions of an aerosol cloud are described. The capabilities and the accuracy of the method are estimated as applied to determining the coordinates of an object under study.

Introduction

For a long time, artificial aerosols are widely used to study atmospheric diffusion in the atmospheric surface and boundary layers. The theoretical principles of this method for practical application of the obtained data to justify various models of atmospheric pollution with gases and aerosols are considered in sufficient detail in Refs. 3, 22, and 28.

The technique of smoke jets is often employed in correctly comparing the experimental data and theoretical description of the behavior of a weightless (gaseous) pollutant in the turbulent atmosphere. In this technique, a model smoke cloud is formed either by an aerosol generator of the thermocondensation type or by a pyrotechnic smoke pots generating masking smokes.[6,21] Such smokes are formed by submicron-sized aerosol particles with the low sedimentation rate, which are well entrained by turbulent pulsations of the atmosphere. In the most of published papers, the experimental technique of smoke jets was used either to check theoretical models describing the behavior of a weightless pollutant emitted from smoke stacks[1,2,14–16,29–31] or to obtain empirical constants entering into statistical models of turbulent diffusion in the atmospheric surface and boundary layers.[5,7–11,17,18,23–25]

The most experiments with smoke jets conducted by now have been carried out under conditions close to the horizontally homogeneous surface in the quasistationary stratified atmosphere and under homogeneous boundary conditions accounting for the interaction of the diffusing pollutant with the surface.

In real natural situations, these conditions are never fulfilled. Therefore, in quantitative interpretation of experimental data with that or other theoretical description, the domain of applicability of the approximation used is always specified.

Since experiments under natural conditions are rather complicated, laborious, and expensive, many problems concerning the regularities of atmospheric turbulent diffusion of a pollutant, which are important from the scientific and practical points of view, are still open. First of all, these are the problems on the diffusion of a heavy pollutant, spreading of a pollutant in a nonstationary stratified atmosphere, including temperature and dynamic inhomogeneities, and the allowance for the pollutant interaction with the surface. Each of the above problems has its own specification features and requires application of specialized investigation techniques. The detailed analysis of these aspects can be found in Refs. 4, 5, and 26.

Stereophotogrammetry is one of the methods for processing experimental data on temporal variations of the dimensions of a smoke jet. This method allows one not only to determine the diffusion characteristics, but also to describe the complex trajectory of the smoke jet caused by the slower variation of the wind speed and direction in the atmospheric surface and boundary layers.[1,12,26] For this purpose, we have tested the technique of ground-based digital stereophotography. However, the attempts to realize the combined investigations of pollutant spreading in the real atmosphere in the experiment were not successful as yet.

Experimental technique and results

This paper describes the technique of experimental investigations, which overcomes some principal limitations arising in the field experiments described earlier. It generalizes and develops the techniques used to study the behavior of an aerosol cloud in the atmospheric surface and boundary layers with the allowance for the interaction of particles with plants and the surface.[19,20,26,32,33] Without going into detail of the proposed approach, we show two most significant aspects, which strongly impact the

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possibilities of making a correct comparison of the theoretical and experimental results.

The first aspect is the possibility of modeling different properties of a pollutant under natural conditions by the same source in particular scenarios, and the second one consists in the possibility of tracking the dynamics of the studied processes by digital cameras for the following analysis of trajectories in stereo images.

Within the framework of the existing theoretical models, it can be shown that the coefficient of turbulent diffusion of a gaseous pollutant under conditions of the atmospheric surface and boundary layers is close to the same parameter for the particles with the diameter smaller than 200 μm (Ref. 19). On the other hand, the theoretical analysis shows that, with the increase of distance from the source, the concentrations of the depositing and nondepositing pollutants differ considerably. The difference is observed both in the near zone (maximum concentration) and in the far zones depending on the character of interaction with the surface.[4] The ratio of the rate of dry sedimentation to the rate of turbulent friction, which significantly depends on the characteristics of the vegetation cover, can serve a measure of the interaction.[4,19,20] Therefore, to conduct field experiments, it is desirable to have a mobile source of a smoke jet with the controllable particle size and the capability of varying the jet geometry in the horizontal and vertical directions. In the experiments conducted, the smoke cloud was produced by an aerosol generator (AG) producing aerosols with controllable size spectrum. This AG satisfies the above requirements in many respects.[27] The general view of an AG used in the experiments is shown in Fig. 1, and its specifications are given below.

1. The generator is installed on a ZIL-131 high-flotation truck.

2. AG has two aerosol generation modes:

a) thermocondensation mode, in which submicron-sized particles ($d < 1$ μm) are generated;

b) pneumomechanic mode, in which particles of different sizes ($5 < d_m < 30$ μm) are generated.

Both of the modes can be employed simultaneously.

3. The AG can be used for creation of sources of different geometry: point source, linear source with different spatial orientation; pulsed, continuous, static, mobile sources.

4. The AG is capable of changing the initial temperature of the aerosol cloud.

5. With this AG, it is possible to change the chemical composition of aerosol particles, including generation of fluorescing particles of different size, which allows the use of high-sensitivity detection methods.

The use of the AG allows us to implement, under field conditions, the whole set of the existing experimental methods for investigation of smoke jets.

The significant advance in the technique of field investigations consists in application of digital photogrammetry, which provides for 3D models of the objects under study. These models are formed from stereoscopic pairs of images of the objects. The process of computer processing of the images consists in formation of the stereo image and the mathematical model of the studied object based on realization of the conditions of collinearity and complanarity of the projecting rays.[34–36] The model is reduced to its true scale and oriented about the external coordinate system using the reference points, whose spatial coordinates are known or measured in the coordinate system chosen for solution of the problem. The result is a 3D metric image of an object studied, the spatial coordinates of the points in which can be determined with the given discreteness and stored in files in the digital and graphical formats.

The specific characteristics of an object studied determine the features of the particular technological processes. Thus, stereophotography for studying the dynamics of aerosol clouds generated by an AG should ensure the high degree of synchronization between two digital cameras in order to achieve the stereo effect.

Fig. 1. Example of a digital photo with AG, smoke jet, and reference points.

An important aspect is the choice of the zones for location of the reference points. This is a problem, because the trajectory of spreading of the aerosol clouds depends on many factors and is difficult to be predicted.

The technology proposed for determination of the geometry of smoke plumes includes the following procedures:

1. Preparatory work (calculation of optimal shooting parameters).
2. Selection of the positions for points of the reference grid and their marking with the allowance made for the AG position and the wind rose at the time of shooting.
3. Geodesic work on determination of the coordinates of the reference points.
4. Synchronous stereo shooting of generated aerosol clouds by digital cameras.
5. Digital processing of recorded stereopairs:
– internal orientation of the left and right photos;
– construction of the photogrammetric model using the measured points of the left and right photos;
– external orientation of the model using the measured coordinates of the reference points;
– identification of the boundaries of the aerosol clouds spreading in the stereo mode (finally, we obtain the set of spatial coordinates X, Y, Z).
6. Calculation of the parameters characterizing the dynamics of the aerosol cloud spread and visualization of the results.

The stage of the preparatory work involves calculation of the optimal shooting parameters ensuring the maximum accuracy in determination of the spatial coordinates of the points determining the configuration of a cloud studied. For this purpose, we have developed a MathLab application for modeling the process of shooting under the preset conditions, in particular, taking into account the camera characteristics and the supposed dimensions of the object, from which the distance to the object, shooting basis, and the other needed parameters are calculated.

An essential parameter determining the accuracy of determination of the spatial coordinates is the basis, whose values are found by use of the equations:

$$B_{X\max} = \frac{m_x p^2}{x_{\max} m_p}, \quad B_{Y\max} = \frac{m_y p^2}{f m_p}, \quad B_{Z\max} = \frac{m_x p^2}{z_{\max} m_p},$$

where m_x, m_y, m_z are the root-mean-square (rms) errors in determination of the coordinates X, Y, Z; $x_{\max}$, $z_{\max}$ are the maximum dimensions along the coordinates X, Z (determined by the frame parameters); p is the mean value of the X-parallax, in mm; m_p is the rms error in determination of the X-parallax, in mm; f is the focal length of the camera's objective, in mm.

The mean value of the basis B_s satisfying the accuracy in determination of all the three coordinates is taken as a final one.

The distance from the cameras to the mean object plane $Y_{\max}$, at which the preset coverage is ensured, is determined as

$$Y_{\max} = \frac{f B_s}{l_x (1 - p_x)},$$

where l_x is the maximum dimension in the image plane (frame size); p_x is the preset longitudinal coverage, in %.

The object length in the mean plane in the zone of longitudinal coverage is

$$L_x = mp,$$

where m is the scale of the images.

The maximum acceptable object height in the mean plane is

$$L_{z\max} = h_i + Y_{\max} \tan(b_z + w),$$

where h_i is the height of the camera; w is the transverse camera angle; b_z is the half of the vertical field of view.

At the next stage, the reference points are chosen with the allowance for the calculated shooting parameters and the AG location. Then the points are marked with the specially made images of black crosses on a white background, whose size depends on the scale of shooting. The points are chosen at different distances from the cameras so that their images fall within the coverage zone. The spatial coordinates of the marked points are determined by the geodesic method.

The digital cameras are synchronized with a computer through a special adapter for simultaneous connection of the cameras, which ensures the synchronization accuracy of 0.002 to 0.004 s.

The photogrammetric processing of stereopairs outputs the files of the coordinates of the spatial points of the object under study, which can be exported into programs for 3D graphics for visual presentation of the results.

The technology developed was tested in suburbs of Novosibirsk on a grassed ground. Before shooting, we have specified the grid of marked reference points in the conditional coordinate system (see Fig. 1, points marked by "a").

The dynamics of spreading of the generated cloud was tracked using two ground-based synchronized Casio QV-3000EX digital cameras. The cameras were arranged so that the basis was parallel to the direction of spreading of the aerosol cloud. The shooting parameters are summarized in the Table, and the arrangement of the equipment during the shooting is demonstrated in Fig. 2.

Parameter	Value
Distance to the object, m	70
Basis, m	16
Scale of shooting	1:10000
Pixel size in the object space, m	0.033
Number of reference points	8
Accuracy of geodesic determination, mm	1
A priori accuracy in determination of coordinates, m	0.26

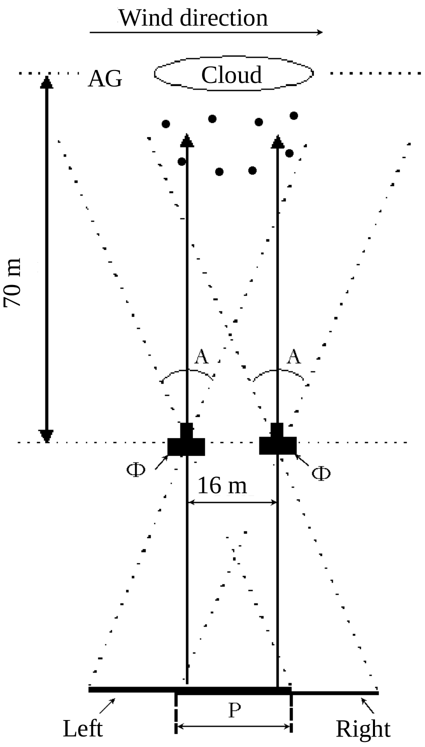

Fig. 2. Diagram of shooting and arrangement of the equipment: reference points (•); left image (Left); right image (Right); longitudinal coverage (P); camera's field of view (A); digital cameras (Φ).

The experiment has yielded six stereopairs with the images of the aerosol cloud at different time; the interval between the stereopairs was 2 s.

The digital processing formed photogrammetric models from the obtained stereopairs, and then the models were used to measure the coordinates of the points corresponding to the top and bottom edges of the smoke plume, as well as the coordinates of the set of points directly on the cloud image that characterized its spatial configuration in the horizontal direction.[13]

Finally, we have calculated the parameters characterizing the jet shape in the vertical and horizontal directions.

Figure 3 depicts the projections of the AG smoke plume onto the vertical plane at two moments in time as obtained from the images in the first and third stereopairs. It can be seen that, under shooting conditions chosen, the maximum distance from the nozzle section, at which the dimensions of the aerosol cloud have been measured, was about 40 m.

The results obtained have allowed us to follow the variation of the jet shape with the distance from the nozzle (Fig. 4). Every curve in the plot characterizes the shape of the smoke plume fixed at one of the six stereopairs. It can be seen from the figure that at the distance up to 10 m the jet profile is practically rectilinear, from which it can be concluded that at this part the jet geometry is determined by the velocity of the jet outflow from the nozzle. This conclusion is

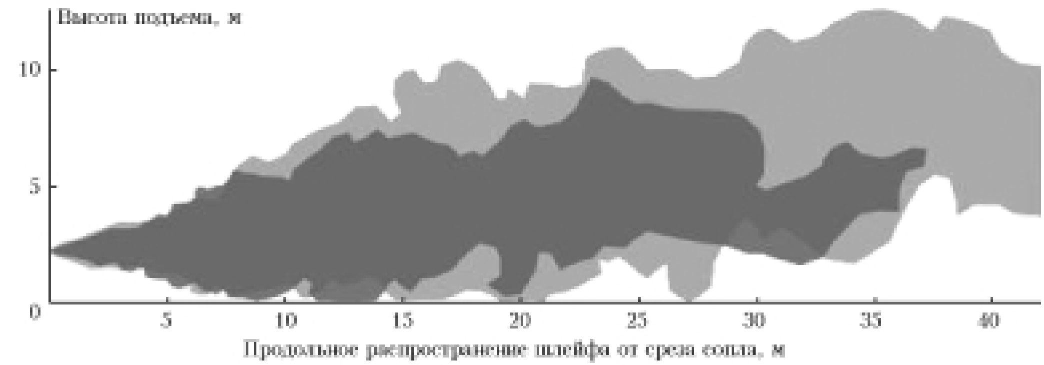

Fig. 3. Projections of the aerosol cloud onto the vertical plane.

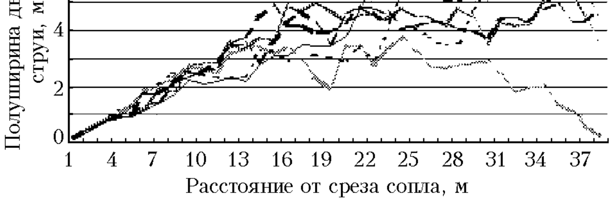

Fig. 4. Variation of the jet shape: first series (..........), second series (-------), third series (——), and fourth series (- - - - -).

in a close agreement with the theoretical calculations in Ref. 37. To describe the behavior of the aerosol cloud far from the nozzle, it is necessary to take into account the effect of atmospheric turbulence.

The spatial model of the cloud was retrieved by the Delone triangulation method using the MathLab tools; one of the possible versions of its visualization is shown in Fig. 5.

The analysis of the obtained data has shown that the proposed technology is capable of measuring the evolution of a 3D geometry of an aerosol cloud. Therefore, unlike previous techniques, the application of digital stereophotography opens new possibilities of studying the dispersal of gaseous and aerosol pollutants under real conditions of atmospheric turbulence with the allowance made for the nonuniform surface.

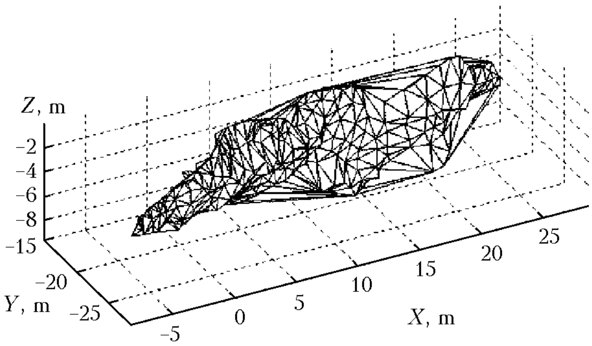

Fig. 5. Digital model of the cloud.

Conclusions

1. The new method has been proposed for studying the evolution of a 3D geometry of an aerosol cloud under natural conditions. This method allows investigating the behavior of gaseous and aerosol pollutants in a turbulent atmosphere with regard for the dynamic and thermal inhomogeneities of the surface.

2. The techniques of field experiments and processing of experimental data have been described.

3. The results of the field experiments have been presented along with the theoretical estimates of the capabilities and the accuracy of measurements of the aerosol cloud dimensions.

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