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EFFECT OF THE CONTINUOUS TRAVERSE TRAJECTORY AND DYNAMIC ERROR OF THE VANE ANEMOMETER ON THE ACCURACY OF AVERAGE VELOCITY MEASUREMENTS AT THE CROSS-SECTION OF THE MINE HEADING – MODEL-BASED TESTING

WPŁYW TRAJEKTORII TRAWERSU CIĄGŁEGO ORAZ BŁĘDU DYNAMICZNEGO ANEMOMETRU SKRZYDEŁKOWEGO NA DOKŁADNOŚĆ POMIARU PRĘDKOŚCI ŚREDNIEJ W PRZEKROJU WYROBISKA KOPALNIANEGO – BADANIA MODELOWE

This paper discusses the problem of measuring the average velocity at the cross-section of mine heading with the use of the continuous traverse method. Based on model testing, it has been shown that measurement signals, obtained along the traversing trajectory, belong to the group of non-stationary signals. The methodology of the traversing method measurements, with the aspect of capabilities of measuring instruments used for that purpose, has been analysed. Results of simulation tests concerning the dynamic response of a vane anemometer to the measurement signal for selected trajectories of the continuous traverse have been presented. For this purpose, a velocity profile presenting an expanded stream of undisturbed air flow in the excavation has been used. Attention has been paid to the problem of selecting an adequate trajectory of anemometer movement, as the value of the velocity measured at the cross-section depends on the trajectory.

Keywords: air volume flow, continuous traverse, velocity profile, vane anemometer, dynamic error

W artykule poruszono problem pomiarów prędkości średniej w przekroju wyrobiska kopalnianego z wykorzystaniem metody trawersu ciągłego. Na podstawie badań modelowych wykazano, że sygnały pomiarowe, które uzyskuje się wzdłuż trajektorii trawersowania należą do grupy sygnałów niestacjonarnych. Przeanalizowano metodologię przeprowadzania pomiarów metodą trawersowania w aspekcie możliwości pomiarowych wykorzystywanych w tym celu urządzeń pomiarowych. Przedstawiono wyniki badań symulacyjnych dynamicznej odpowiedzi anemometru skrzydełkowego na sygnał pomiarowy dla wybranych trajektorii trawersu ciągłego. W tym celu wykorzystano profil prędkości przedstawiający rozwiniętą strugę niezakłóconego przepływu powietrza w chodniku. Zwrócono uwagę na problem doboru odpowiedniej trajektorii przemieszczania anemometru, od której zależy wartość mierzonej prędkości średniej w przekroju.

Słowa kluczowe: strumień objętości powietrza, trawers ciągły, profil prędkości, anemometr skrzydełkowy, błąd dynamiczny

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1. Introduction

Measurements of the parameters determining the condition of mine ventilation belong to the group of complex measurements. Based on the results obtained using a series of various sensors, parameters, such as air volume flow and ventilation methane content, are determined. On many occasions, the complexity of such measurements is the cause of error multiplication. Once results of single measurements are converted into complex parameters, it may appear that minor measuring errors considerably disturb the reliability of information on the parameters used to evaluate the safety level of excavation works being in progress. For instance, a measurement error of the average velocity at the cross-section of the mine heading, multiplied by the surface area of such a cross-section, may considerably affect the result of the volume measurement of air flowing through the mine heading.

Basic sources of uncertainty when measuring the average flow velocity using the vane anemometer at the cross-section of the mine heading are listed in (Krach, 2009) they are associated with the properties of the applied measuring instruments and the technique of such measurements as well. Among the sources of uncertainty in question, there are, but are not limited to, continuous traverse trajectories, traversing velocities, and the fluctuation of the velocities measured. All such factors are associated with the concept of dynamics of the measuring instrument used for taking the measurement of the average flow velocity in the mine heading. Inertia of such instruments is the reason why the completion of the measurement before the ambient conditions (represented by the value measured with the response of the measuring instrument) are stable, creates an additional uncertainty component, the so-called dynamic error. The concept of the impact exerted by the dynamic error during air temperature and velocity measurements using hot-wire sensors can be found in (Jamróz et al., 2012; Jamróz, 2011) and (Nabielec, 2011). The investigations concerned instantaneous values of the parameters of a non-stationary gas flow. Extending the concept by adding flow velocity measurements with a vane anemometer allows taking into account dynamic properties of such instruments during the measurements of the average flow velocity in the mine heading.

2. Continuous traverse method

The continuous traverse method is recognised as the fundamental method of measurements of the average flow velocity at the cross-section of the mine heading. This method consists in using anemometers, which allow velocity measurements at time intervals (Roszczynialski et al., 1992). The idea of this measurement method is to provide as precise estimation of the average flow velocity values at the entire selected cross-section of the mine heading as possible. Taking the measurements is associated with traversing by means of the anemometer at a full-time interval (most frequently 60 seconds) along a predefined trajectory determined at the cross-section of the mine heading. While traversing, the anemometer is recording local instantaneous velocity values. Once such traversing is completed, the obtained measurements results are averaged, and as such, the result representing the average value of air flow at the entire cross-section is provided. The method assumes that the flow at the cross-section of the heading is stationary. This means that the velocity should be constant at every point of the cross-section during the entire measuring procedure being performed. The subject literature mentions various types of traverses, where trajectories, along which the anemometers are moved, are different. The trajectories are optimised to obtain the most precise determination of the average flow velocity value as possible (Mbuyi Kamba et al., 1993). For instance, there are parallel, zigzag, and screw-type trajectories (see Fig. 1).

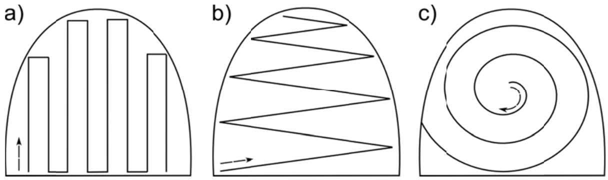


Fig. 1. Continuous traverse trajectories: a) parallel, b) zigzag, and c) screw-type

Due to good metrological properties associated with time stability of the instrument and the resistance to variable measurement conditions, vane anemometers are most frequently used when measuring the average flow velocity according to the continuous traverse method.

3. A mathematical model of the vane anemometer

A single measurement of an instantaneous velocity value using the vane anemometer provides the average velocity of the velocity field limited by vane dimensions. One of the metrological properties of such instruments is their inertia caused by rotor inertia. Completion of the measurement before flow conditions and anemometer response are steady causes the measurement result to be burdened with an additional error, i.e. the dynamic error. New designs of such anemometers are optimised in terms of their dynamic properties. It causes that, the response time of the instrument to the fluctuation of the values measured is shortened. However, due to the physical principle of the measurement, the impact cannot be eliminated completely. When optimising dynamic properties of anemometers, model testing, which allows describing the parameters influencing the dynamics of such instruments, is of great importance. In the publication (Krach, 2004), a dynamic model of the vane anemometer described by means of a differential equation (1) is suggested.

$$c\frac{dv_a(t)}{dt}+\left[a+(1+b)v_a(t)\right]v_f(t)=v_f^2(t) \tag{1}$$

where:

$$c=\frac{J}{\rho S R^2} \tag{2}$$

- v_a — velocity indicated by the anemometer [m/s],
- v_f — actual velocity of the flowing medium [m/s],
- J — moment of inertia of the vane [$kg \cdot m^2$],
- ρ — air density [kg/m^3],
- S — active area of the anemometer [m^2],
- R — vane radius [m],
- a, b — coefficients determining the characteristics of anemometer processing, obtained by calibration.

Assuming an ideal measuring converter, the equation takes the following form (3):

$$c\frac{dv_a(t)}{dt}+v_a(t)v_f(t)=v_f(t)^2 \tag{3}$$

Dynamic properties of the anemometer model are represented by the coefficient c to be located next to the derivative in the equation (3). It is associated both with physical properties of the measuring instrument as well as the flowing medium, the velocity of which is being measured. In the study (Krach, 2009), the value of the coefficient c is estimated within the range of 1.7-1.9 m. The calculations made for one type of the anemometer, i.e. μAS 100, and relevant tests of the device, are presented in (Kruczkowski, 1999).

The functioning of the model was tested against various changes of the velocity value, for the coefficient c = 1.8 m. Instantaneous values of the anemometer model response to the modelled variable input was determined using the function *ode45* that implements the Runge-Kutta's numerical method in the algorithm for solving differential equations. In the simulation case being discussed, instantaneous values of velocity fluctuation of the flowing medium $v_f(t_i)$ were simulated in the form of a sinusoidal wave with an amplitude of 2.3 m/s, the average value of 3 m/s, and a frequency of 0.1 Hz. For the input so described, a dynamic response of the anemometer was simulated in accordance with the relationship (3), and as a result, instantaneous values of the velocity indicated by the anemometer $v_a(t_i)$ were obtained. Results of the simulation testing are presented in Figure 2, where particular dynamic properties of the object, i.e. the vane anemometer, can be noticed. They concern the asymmetry in the dynamic response of the vane anemometer when the velocity measured increases and decreases.

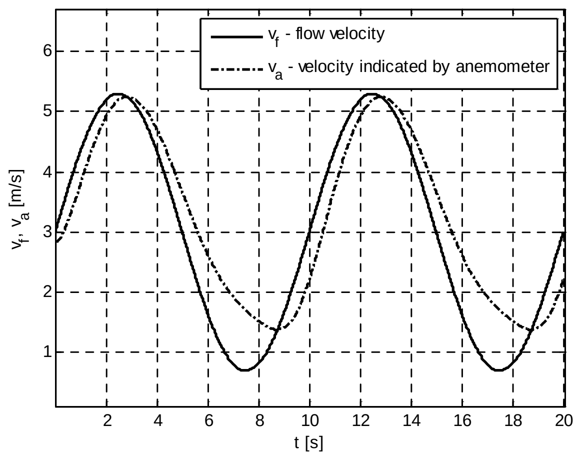


Fig. 2. A response of the vane anemometer model to velocity fluctuations

Whenever the velocity measured decreases, approaching values close to zero, the response time of the model becomes considerably longer. As the velocity having an impact on the anemometer is diminishing, the driving torque of the rotor is diminishing as well. In such case, decreasing of rotational velocity is associated only with the rotor inertia and movement resistance. One may expect that this dynamic property of the vane anemometer can have a strong impact on measurement results, particularly in cases of non-stationary flows, where the velocity fluctuates within values close to 0 m/s.

4. A measurement signal along the path of the continuous traverse

In Fig. 3, there is the velocity profile $v(x, y)$ modelled in the Fluent environment, presenting an expanded stream of undisturbed flow at the cross-section of the mine heading, the dimensions of which are x = 5.5 m and y = 3.8 m. During the simulation, a grid with 250000 points was applied. A local value of the velocity was determined at all such points. A characteristic feature of this profile is the variability of velocity, which assumes minimum values at the floor, roof, and side walls (the layer against the wall), and moving towards the centre of the cross-section, it assumes maximum values, and as such, determining the core area of potential flow (Krawczyk et al., 2011; Janus & Krawczyk, 2013). The traverse method assumes that the velocity field is stationary, meaning that the value of the velocity at the same points of the cross-section is constant during the traverse procedure. The velocity, however, is variable and depends on the point of the cross-section, in which the measurement is being taken.

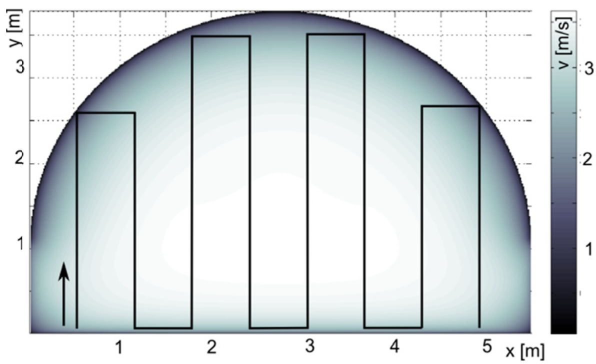


Fig. 3. A velocity profile in the mine heading

In the velocity profile at the example measurement cross-section, the black line marks the continuous traverse trajectory, along which the anemometer is moved. While traversing, the anemometer does not measure the velocity at individual points of the entire velocity profile, but only local velocities along the traversing trajectory. In order to determine the shape of the characteristics of the modelled measurand signal, which should be measured by that anemometer while traversing, subsequent values from the velocity profile corresponding to the velocity values along the traverse trajectory were selected. Based on these values and with the assumption that the traversing was performed by a uniform motion within a period of 60 seconds, it was possible to represent the measurand signal $v_f(t_i)$ as a function of time (see Fig. 4).

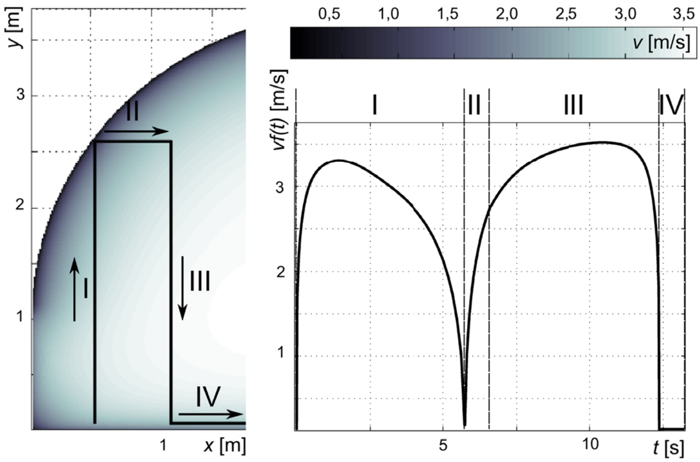


Fig. 4. A traverse section along with the measurand signal

At further stages of traversing, there are considerable dynamic changes of the velocity $v_f(t_i)$. For instance, at the first traverse stage, the measured signal varies from minimum to maximum values, and then it comes back to the minimum value again; the amplitude of the changes is equal to 3.2 m/s. Fluctuation of the signal occurs at very short time intervals. Therefore, one may reasonably ask whether measuring instruments, characterised by some inertia, can follow changes of the signal. It is also necessary to verify the influence of the dynamic error on the measurement result defined as instantaneous differences between values of the velocity measured and the corresponding values indicated by the anemometer. This problem becomes even more relevant if the assumption relating to time minimisation, during which the traverse must be created to ensure a quasi-stationary velocity field at the cross-section, is taken into account.

5. The vane anemometer and its measurement capabilities

The determination of measurement capabilities provided by the vane anemometer with reference to measurements of the average velocity, performed by the continuous traverse method, was carried out using the anemometer dynamics model in accordance with the relationship (3). For this purpose, the velocity profile presented in Figure 3 was used. Based on the profile, three subsequent waveforms of velocity signals $v_{fk}(t_i)$ were selected within discrete times t_i, which should be measured by the anemometer along three different traversing trajectories (k = 1,2,3). The measurand signals $v_{f1}(t_i)$ for the parallel trajectory, $v_{f2}(t_i)$ for the zigzag trajectory, and $v_{f3}(t_i)$ for the screw-type trajectory were selected. Based on these signals and parameters of the anemometer model, with the relationship (3) solved, three signals of the anemometer response $v_{a1}(t_i)$, $v_{a2}(t_i)$, and $v_{a3}(t_i)$ were subsequently modelled for the masurand signals $v_{f1}(t_i)$, $v_{f2}(t_i)$, and $v_{f3}(t_i)$. The results are presented in Figure 5.

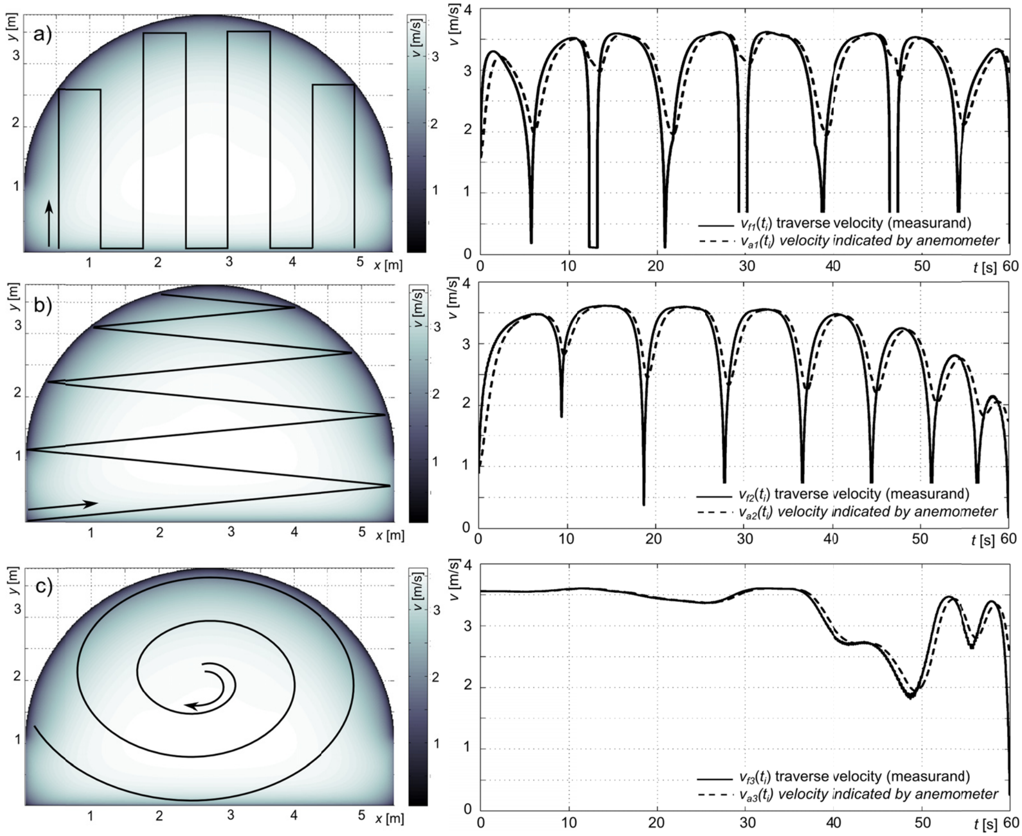


Fig. 5. Traverse trajectories vs. velocity signals

In order to evaluate the magnitude of the dynamic error occurring in individual cases, the criterion Δ (4) was introduced; it describes the average dynamic error, described as the arithmetic mean of instantaneous dynamic error values:

$$\Delta_k = \frac{\sum_{i=1}^{N} \left| v_{fk}(t_i) - v_{ak}(t_i) \right|}{N} \tag{4}$$

where:

k — no. of trajectory type (1 – parallel, 2 – zigzag, 3 – screw-type),
N — number of samples of the signal measured.

For every type of the continuous traverse, there are periods, which are characterised by the occurrence of high velocity gradients of the measuring signal. In such periods, the differences of the indication provided by the anemometer $v_{ak}(t_i)$ and the values of individual measurands $v_{fk}(t_i)$ under dynamic conditions exceed 3 m/s.

For the parallel traverse (Fig. 5a), limitations associated with the dynamic properties of the vane anemometer do not allow for an accurate reconstruction of the measurement signal. The average velocity values of the signals are equal to $\overline{v_{f1}}(t_i)$ = 2.95 m/s in the case of the signal of velocity affecting the anemometer along the traverse trajectory, and $\overline{v_{a1}}(t_i)$ = 3.12 m/s for the signal measured by the anemometer; the average value of the dynamic error Δ_1 is equal to 0.36 m/s.

As far as the zigzag traverse is concerned (Fig. 5b), the difference between the average value of velocity along the traverse trajectory $\overline{v_{f2}}(t_i)$ and the average value of velocity measured by the anemometer $\overline{v_{a2}}(t_i)$ is 0.05 m/s, where the average dynamic error Δ_2 is equal to 0.23 m/s. Decreasing of the measurement error is associated with the fact that there are no time intervals in the measured signal, at which the velocity signal would change abruptly up to the values close to 0 m/s, and then the value would maintain the same level for some time.

The third traverse type allows for the optimisation of the shape of the velocity signal waveform occurring along the traversing path, minimising the number of dynamic states and their rapidity. For this traverse type, the anemometer response $v_{a3}(t_i)$ follows the changes of the signal measured for most of the traverse time; the difference of the values of the average velocities of the measured signal along the traverse trajectory $\overline{v_{f3}}(t_i)$ and the anemometer response $\overline{v_{a3}}(t_i)$ is equal to 0.02 m/s. The average value of the dynamic error Δ_3 is equal to 0.07 m/s. The assessment of the results with regard to the measurement capabilities provided by the anemometer with reference to its dynamics shows that it is possible to optimise the continuous traverse trajectory in a manner that minimises the influence of vane anemometer dynamic properties on the value of the dynamic error made during the measurements. However, a more precise analysis of the results concludes that the average value of the velocity signal occurring along the screw-type traverse trajectory $\overline{v_{f1}}(t_i)$ (3.24 m/s) is considerably different from the average signals of velocity occurring along the parallel $\overline{v_{f2}}(t_i)$ and zigzag traverse paths $\overline{v_{f3}}(t_i)$, i.e. 2.95 m/s and 2.97 m/s respectively.

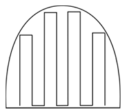
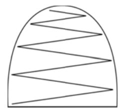
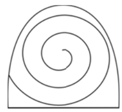
6. Traverse trajectory vs. average velocity

In order to determine the accuracy of estimation of the average velocity values $\overline{v}(x,y)$ within the selected continuous traverse trajectory, the average values of the velocity, determined using all points of the velocity profile (Fig. 3) and points at the trajectory along subsequent continuous traverses $\overline{v_{fk}}(t_i)$, were compared. Results of the comparison are presented in Table 1. They show that the average values of the signal of velocity $\overline{v_{f1}}(t_i)$ for the parallel trajectory and $\overline{v_{f2}}(t_i)$ for the zigzag trajectory are close to the average value of the velocity signal obtained within the entire profile $\overline{v}(x,y)$. The module of the differences between these values is equal to 0.08 m/s for the parallel trajectory and 0.06 m/s for the zigzag trajectory. In the case of these trajectories, the average value determined along the traverse trajectory is smaller with reference to the average value determined using all points at the velocity profile. A similar analysis taking into account the screw-type trajectory concludes that the average value along the traverse trajectory $\overline{v_{f3}}(t_i)$ is greater in relation to the average velocity $\overline{v}(x,y)$ by 0.21 m/s.

Despite the best adjustment of the screw-type trajectory to dynamic capabilities of the vane anemometers in the selected velocity profile, the trajectory does not allow increasing the estimation accuracy of the average velocity determined using all profile points. In the case of the remaining two trajectories, the best measurement results can be obtained when using the zigzag trajectory, where the velocity measured by the vane anemometer $\overline{v_{a2}}(t_i)$ is different from the average velocity value $\overline{v}(x,y)$ only by 0.01 m/s.

TABLE 1

Summary of simulation results

Traverse type			
The average velocity determined using all points of the velocity profile $\overline{v}(x,y)$ [m/s]	3.03		
The average velocity of the measurement signal selected from the velocity profile along the traverse trajectory $\overline{v_{fk}}(t_i)$ [m/s]	2.95	2.97	3.24
The modelled average velocity measured by the anemometer $\overline{v_{ak}}(t_i)$ [m/s]	3.12	3.02	3.26

7. Summary

The development of new measurement methods allows obtaining results, which facilitate the determination of parameters describing the ventilation condition in mines with a higher resolution and accuracy. The creation of a multi-point system for measuring the air velocity in mine headings (Krach et al., 2006) gathers the information to be used as the basis for drawing conclusions relating to actual velocity profiles at predefined measuring cross-sections. Identifying such velocity fields at predefined cross-sections makes it possible to optimise the currently applied measuring methods in terms of measurement errors.

The methodology of measuring the average velocity at the cross-section of the mine heading by means of traversing assumes that one of the trajectories, along which the anemometer is moved, is selected. The analysis of individual trajectories indicated that the shape of the velocity signal form depends on the selected method of anemometer movement. Whenever velocity variability in the velocity profile occurs at the cross-section, traversing with the use of an anemometer results in measuring a non-stationary signal. Results of such a measurement are affected by an additional uncertainty component caused by the dynamic error, the value of which depends on the selected trajectory. Results of the model testing conclude that the value of the error can be minimised by selecting an appropriate path, along which the measuring instrument is to be moved. There is a risk, however, that the selected trajectory of anemometer movement can result in the situation when the average value of velocity measured by the anemometer, despite a great compatibility with the average value of the velocity measured on the basis of the traverse trajectory, can be different from the proper value of the average velocity determined on the basis of all points in the velocity profile. Therefore, having knowledge of existing velocity profiles at the cross-sections of mine headings subject to tests is essential.

The presented model testing shows that carrying out an analysis of the continuous traverse method based on model testing is possible. However, such tests require further investigation in the form of experiments to determine additional properties of the continuous traverse method, such as the variable velocity of anemometer movement or actual traversing trajectories at measurement cross-sections with a variable degree of enclosure.

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