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New Acoustic Anemometers for the Mining Industry

S.Z.Shkundin & V.V.Stuchilin
Moscow State Mining University. Moscow, Russia

ABSTRACT: The selection of the measurement base for the control of ventilation regimes in underground mines involves the choice of devices for measuring velocities and air/gas flow rates. The resolution of this task is rather difficult. Tachometric sensors (the great Leonardo's invention) traditionally used in many countries have a variety of disadvantages: low sensitivity, high inertia, inability to cover necessary measurement ranges with one device, presence of movable accumulating error parts, vulnerability to the effects of dust, etc. For about a hundred years, attempts to create thermoanemometers have continued, successfully in some areas, but not so in mining. The present report deals with a number of new acoustic devices developed in Moscow State Mining University. Acoustic anemometers are free of all the disadvantages listed above: they have unsurpassed sensitivity, time lag freedom and a wide range for velocity and flow rate measurements. They do not contain movable parts, are sensitive to the direction of the stream and are not sensitive to coal dust

I INTRODUCTION

The solution of mine safety delivery problems necessitates the creation of modem and reliable technical methods and tools for ventilation control in mine workings. The increasing demand for monitoring of the quality of the air/gas dynamics process means that more and more advanced devices must be used for air/gas flow and velocity measurement.

Anemometers which are used now for occasional measurements of air/gas flow characteristics, as well as anemometer sensors involved in systems of mine ventilation monitoring and metrology support, are not capable of ensuring modern safety and metrology demands or regulations, or of providing an appropriate level of mine atmosphere control.

The main way of measuring air/gas velocity in coal mines İn Russia is still the use of tachometric anemometers, some of which were developed more than 40 years ago, the ASO-3 and MS-13, and some of which are the latest developments, the AP-1 and APR-2.

As mentioned above, tachometric devices such as the ASO-3 wind-wheeled anemometer, the MS-I3 cup anemometer and the new APR-1 tachometer (all Russian) are the most widely used devices for measurement of gas and air consumption at mining enterprises. They operate on the principle of turbine-type anemometers (with a small rotating turbine). Under the dynamic thrust of the flow, the small turbine develops torque, the quantity of which is a function of the speed of flow. The value of the rotation frequency of the small turbine can be used as a basis for assessing the speed of the monitored flow. The ASO-3 anemometer is used to measure the speed of air flow ranging from 0.3 to 5 m per sec.

The air flow acts on the blades, causing rotation through the stringed axis. In the MS-13 cup anemometer, unlike the ASO-3 anemometer, speedy air flow puts pressure on the inside surface of four hemispheric cups placed symmetrically in a circle. A cup anemometer is used to measure the speed of the air flow ranging from 1 to 20 m per sec.

A stopwatch is needed to time the number of rotations of the impeller and then, in order to calculate the frequency value, the speed of the air flow is determined through grade characteristics (data) given in the anemometer manual. The period of measurement required, using the ASO-3 anemometer, to identify the average speed of the air flow in a mine working must not be less than 100 sec. with no less than three measurements taken. Thus, one measurement, including preparation, takes about 8-10 minutes. Tachometric anemometers have their disadvantages, which affect measurement error. On the one hand, the impeller has to be as light as possible so as to make sure that the friction threshold and its sensitivity are adequate; on the other hand, it has to be as rigid as possible so that it is not deformed by turbulence flow. The axis has to have the smallest possible diameter, yet this axis wears more quickly, accumulates error and is subjected to dust. The impeller axis deviation from a vector parallel or perpendicular to the flow is also caused by the occurrence of a turbulent inlet vortex. Sensitive mechanical parts in the devices are subjected to unfavorable mining environments, particularly in terms of dust subsidence and penetration. At the same time, for a number of reasons, the metrological support is not adequate (in fact, of all anemometers used in mines, not more than 15% are tested annually).

Most mining anemometers designed and produced today are devices with a small movable turbine, the rotation speed of which İs measured not by mechanical meters but with the help of inductive AE-2, optic AFA-1, electromagnetic ESNV-1, and capacitive and other means. They have the same disadvantages in that they have an impeller and movable axis. Apart from that, the level of error for induction converters of the rotation speed of the impeller increases due to the permanent magnet on the blades creating antitorque. Mine dust with magnetic properties that exists in the flow monitored also contributes to the increase in measurement error. One disadvantage of the photoelectric converter is an increase in error as a result of less detectable light flow in dusty mine environments. Turbine-type anemometers, because of their design characteristics, are more suitable for measurement of high speeds and as far as low speeds are concerned, these devices have nonlinear characteristics determined by the considerable influence of force moments of viscous and mechanical friction as compared to the torque.

In order to reduce the friction threshold (friction between the axis of the impeller and the bearings), special devices are used. For instance, the ESNV-1 employs an impeller mounted on a special vibrating frame. The APR uses axes fixed by means of hard stones. However, this complicates the design and makes it more costly. Modern designs of portable turbine-type anemometers allow for temporary automatic averaging of measurement results. They also allow for digital indicators and for the sensor element to be fixed to a telescopic rod. However, neither this anemometer nor any other tachometric devices that have been developed recently, including those built with the modern technology of watchmaking factories, can meet the challenge of measuring speeds starting at 0.05 m per. sec. This has been confirmed by aerodynamic tube tests performed at Moscow Mining University.

Another method of measuring the speed of the air (low is the thermo type. Here, two main varieties exist: thermoanemometric and thermocatalytic. Devices where the signal to be measured is a function of tlie heat dissipated throughout the monitored environment by the electrically heated body as the source of energy are known as thermoanemometers. There are two methods of measuring the speed of flow by thermoanemometers. The first is based on maintaining a constant current heating thermoelement, and the measurement of the speed of the flow is associated with the measurement of the temperature of the thermoelement.

The other method presupposes that the heating current keeps the temperature of the filament constant; as a result, the measurement of the speed of flow is associated with the measurement of the compensating electric current. Most thermoanemometers operate on the principle that the filament heated by an electric current is contained in a Whetstone bridge circuit. The passing flow cools the filament, its temperature decreases, and as a result, its electrical resistance also decreases. This causes an imbalance of the bridge and it is monitored by an electric device. The TA-8 thermoanemometer of the same type measures the speed of flow in the range of 0.1-5 m per sec. The advantages of thermoanemometers include their capacity to measure low speeds (0.1-0.5 m per sec), while their main disadvantage is thermal lag. However, unstable graduation results, dependence of the readings on temperature flow. construction fragility and the influence of subsiding coal dust during the taking of readings limit their range of application. Thermoanemometers have not found any widespread application in mines. Devices in which heat is transferred from a heater to a measuring-converting element with the aid of controlled gas flow belong to the constant-type colorimetric anemometers. The greater the speed of the controlled flow, the lower the sensitivity of the devices become, which is why they are suitable for speed measurement. The ATA-2 thermoelectric anemometer ensures the desired accuracy of measurement with a flow speed of 0.5 m per sec. As the air within the thermoelectric anemometer moves, the heat from the thermofilament is transferred to a number of thermocouples, which is registered by a millivollmeter. In this way, the speed and direction of the flow are determined. The sensitivity of the thermofilament to environmental temperature and pressure is a disadvantage in any thermoanemometer. The sensitive element of a thermoanemometer is made of platinum or sometimes nickel filament with a diameter of several micrometers and a length of 2-10 mm. The smaller the diameter of the thermofilament, the less durable and more susceptible to wear it becomes. The thermofilament is also subject to aerodynamic stress. As a result of pulsation while measurements are taken İn turbulent flows, vibrations occur in the thermofilament, and Üıese can either cause damage to it or cause fluctuations of resistance, which bring about considerable error in measurements. One disadvantage of colorimetric flow meters is the negative influence of moisture and corrosive admixtures of gassy environments on the work of the thermoconverter and the heater, which are in immediate contact with the environment.

The way to widen the upper limit of the speed measurement range in colorimetric anemometers is to slow down part of the flow so that its speed does not exceed the maximum speed for the given thermoconverter. The colorimetric sensor of the speed of the DBT air flow meter as part of the complex system for continuous automatic air monitoring in mine workings provides measurement in the ranges of 0-2.5, 0-5, and 0-10 m per sec. The change from one range limit to another is carried out by changing diaphragms placed in conical extensions of the sensor. At this point, it should be mentioned that the noted range beginning from zero is nonsense - no meter can measure zero due to quite definite sensitivity.

There is a tendency outside Russia to combine a colorimetric converter and a pressure mechanism, creating a pressure differential depending on the dynamic pressure of the flow. Ventor, made by the Maichak company (Germany), is a mechanism for monitoring the speed of flow in mine workings. It has a speed sensor consisting of a differential Pitot tube and colorimetric speed converter. Within the sensor, the flow passing through the channels of the colorimetric converter is formed as a result of the impact and static pressure difference at various points of the monitored flow. The sensor is capable of measurements ranging from 0.15-0.75, 0.5-2.5, and 1.5-7.5 m per sec.; the sensitivity of the mechanism to speed can be regulated in the range of 15% of the upper measurement limit.

The difference in the range of speeds measured by turbine-type anemometers and thermoanemometers suggests the idea of combining the two sensors based on different principles into a single device. The UBM-1 is a domestic device designed for methane concentration and aiT flow measurements during mine air and gas dynamics research, and İn solving engineering problems of coal mine ventilation with dust and gas hazards, it has a unit responsible for speed of flow measurements which combines thermoanemometric and tachometric primary converters. The thermoanemometer is responsible for measurements of low speeds of flow ranging from 0.05-0.5 m per sec., while with speeds of flow which are within the range of 0.5-10 m per sec., measurements are taken by the tachometric sensor. However, such an engineering solution is apparently possible only for laboratory research instruments as devices combining two different sensors are twice as expensive, bulky and the whole structure turns out to be too complicated.

From all the facts mentioned above, one can conclude mat mining enterprises in Russia have no anemometers based on principles other than those employed in turbine-type and thermo-type anemometers.

However, as we can see, commercially available turbine-type and thermoanemometers and sensors for controling the speed of gas and air flows in mine workings have a host of disadvantages as mentioned above. In particular, they cannot ensure the speed range defined by safety regulations, they are bulky, and they are neither reliable nor cheap. As things stand now, there İs no hope that further improvements of engineering solutions based on traditional principles of thermo and tachometric anemometry used to measure speeds of flow in mines will lead to the creation of a device with the desired characteristics. As the analysis of modem anemometric sensors shows, further improvement in the quality *of* measurements is related to the application of more expensive materials and more complex technologies. One can say that thermo- and turbine-type methods for the measurement of flow speed have reached their limit in as far as being a basis for the creation of mine speed monitoring devices. Moreover, they still cannot meet the needs of mining anemometry.

Evidently, the solution to this problem should be found not by improving traditional principles used in these constructions, but by employing new methods of anemometry.

Complicated modern mining technology comprises the use of appropriate means of automation, hardware and software for mine ventilation control. Such apparatus and software would make it possible to increase the permissible level of methane concentration, i.e., to increase mining. The effectiveness of the operation of such systems depends very much on the reliability and quality of the anemometers involved, and on their sensitivity, precision and inertia.

2 ACOUSTIC METHOD OF FLOW RATE MEASUREMENT

Careful analysis of published work and preliminary laboratory investigations has shown that on the one hand, acoustic methods in flow measurement have not realized their potential, and on the other hand, none of the existing acoustic methods of flow measurement allows the creation of an anemometer able to:

- measure speeds of flow in the range of 0.05-30 m/s;
- be free of moving parts;
- measure high frequency pulsations;
- measure average flow speed in the working cross-section;
- have stabile characteristics, making it possible to decrease error.

The suggested measurement method satisfies all the requirements mentioned here (Shkundin et. al., 1991). The method is based on air-acoustics interaction and involves excitation of vibrations in the cylindrical wave guide air duct, reception of these at some distance from the excitation point, and a comparative analysis of radiated and received vibrations as a result of which an informative signal (e.g., vibration phase or time difference) is singled out and serves as a flow rate measure. It differs from other known methods in that definite mode waves are radiated and received by excitement of the air conduit elements acoustically isolated from each other. This method provides accuracy and exception of the air conduit effect upon the aerodynamic field of air/gas flow.

A description of the wave propagation process in tubes without flow was given by Scuchic (1976) From this description, we concluded which waves can spread in the round channel of the given diameter. The spread rate of the zero mode wave fronts of these vibrations is equal to that of sound velocity in open space with the same medium

For an analytic description of air-acoustic interaction, which is the basis of acoustic anernometry, it is necessary to solve the boundary problem for the equation with partial derivatives. For the first approach, the anemometer channel may be realised for unlimited length. For better correspondence with real physical phenomena, in the mathematics model it Is necessary to take into consideration die error caused by acoustic wave reflection from the open ends of the anemometer (Kremleva & Shkundin, 1998).

The method of correction determination corresponding to the reflected waves field by means of normal mode reflection coefficient calculation is proposed. The analytic dependencies of the velocities upon the dimensions, channel "wall material and air/gas medium characteristics were obtained using the work of Gohnson and Ogimoto (1980).

3 OPERATING THE ANEMOMETER

The measuring channel of the anemometer constitutes a cylindrical air conduit containing two semi-channels (Figure 1).

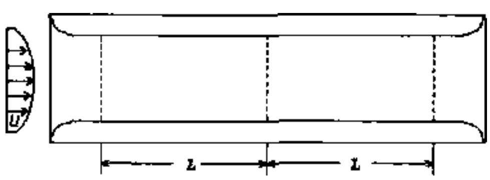

Figure 1. Scheme of anemometnc channel

There is a radiating element in the center of the air conduit, on each side of which receiving elements are found at a distance L. The difference of phases m the right semi-channel $\Delta\varphi_1$

(down the flow) is expressed:

$$\Delta\varphi_1 = \frac{2\pi f L}{C+U} + \varphi_1 \qquad (1)$$

where:

C = sound velocity;

U = flow velocity;

φ_1 = initial phase difference;

Analogous for the second, left semi-channel (against the flow):

$$\Delta\varphi_2 = \frac{2\pi f L}{C-U} + \varphi_2 \qquad (2)$$

where:

φ_2 = initial phase difference in the second semi-channel.

The anemometer has to operate in accordance with technical tasks at temperatures of 5 to 25°C that correspond to the regime of metrological tests. In this range of temperature changes, as it is easy to see, the sound speed does not exceed 345 m/s.

In the right semi-channel, the minimum value of the phase difference corresponds to the maximum of (C + U), i.e., C = 345 m/s and U = 20 m/s, that is, assuming $\varphi_1 = 0$:

$$\Delta\varphi_{1min} = {}^{2\pi f L}\!/_{365} \qquad (3)$$

In the left semi-channel, $\Delta\varphi_{2\,mm}$ corresponds to the case when C = 345 m/s and U = 0. That is, assuming φ_2=0:

$$\Delta\varphi_{2min} = {}^{2\pi f L}\!/_{345} \qquad (4)$$

Now formulas (2) and (3) will give the following:

$$\Delta\varphi_1 - \Delta\varphi_{1min} = 2\pi f L\left(\frac{1}{C+U} - \frac{1}{365}\right) \qquad (5)$$

$$\Delta\varphi_2 - \Delta\varphi_{2min} = 2\pi f L\left(\frac{1}{C-U} - \frac{1}{345}\right) \qquad (6)$$

Before measurement, phase zero in the right semi-channel is adjusted to C + U = 365 m/s; in the left semi-channel, phase zero corresponds to C - U = 345 m/s. Phase zero may be schematically fixed precisely, and, therefore, anemometer phasing does not generate measurement error. We can describe different basic phases of the measurement algorithm from the formulas above as follows:

1. Automatic amplification and adjustment of the received vibrations.
2. Transformation of sinusoidal vibrations into meander.
3. Correcting phase change.
4. Forming of binary codes of the analog signals in each semi-channel.
5. Time averaging of binary codes.
6. Calculation of binary codes corresponding to the flow speed.

4 ANEMOMETER ELECTRO-ACOUSTIC CONVERTERS

For the implementation of different variants of the anemometric control studied, cylindrical channels with piezoceramic rings of different standard sizes were utilized. The material of the rings CTP-19, CTP-23, CTBP (CTP - circonate-titanate of plumbum; CTBP - circonate-titanate of barium and plumbum), a wide spectrum of imported piezoelectric ceramics, was also produced by such companies as: PI Ceramic (PIC131 … 163), Sensor Technology (BM400 type I, BM300 … 940), TRS Ceramics (TRS100… 600), etc.

Table 1. Piezoceramic rings ofdifferent standard sizes used in anemometric converters.

Geometrical characteristics, mm		2	3		
Externa] diameter	27.5	30	17 J	173	112
Internal diameter	22	27	15.8	15.8	100
Height	8	4	5	3	26
Wall thickness	2	1.8	0.75	0.75	6

The piezoceramic ring represents the cylinder, on each surface (external and internal) of which the silver covering as electrodes is fixed. With supply to the electrodes of an alternating voltage, the return piezoeffect causes alternately, in phase with the applied stress, compression and relaxation of the piezoceramic cylinder, in the direction of its imaginary axis and from it. These oscillations happen near die non-movable imaginary average surface driving through average at the end faces of the cylinder lengths of circles. These oscillations are also accompanied by oscillations lengthwise of the cylinder, which are not used. From the influence of the circumscribed radial oscillations, the acoustic waves spread along the cylindrical channel. These waves come to the receiving ring, in which the piezoeffect causes a polarization of charges, and the potential difference emerges on the ring facing. The basic characteristics of acousto-electric piezoceramic converters are:

1. Acoustic power.
2. Electro-acoustic efficiency.
3. Electrical impedance.
4. Resonance frequency.

The electro-acoustic converter can be represented by the equivalent circuit, which contains two parts - electrical and mechanical. The electrical part contains units representing generating properties in a radiation mode, resistance, as a resistance of dielectric losses and capacity, connected in parallel. The mechanical part of the equivalent circuit contains a resistance of mechanical losses, the reactance of the converter and load. With the growth of frequency, the resistance of a converter diminishes (because of the capacity presence İn the equivalent circuit) and on the resonance frequency it reaches a minimum value. Furthermore, with the frequency increase, the resistance rises again and reaches a maximum at the sc-called anti-resonance frequency.

Because of this, the source has a resonance-frequency behavior, with a particular radius; usually it is reasonable to work only in a rather narrow frequency band close to the resonance. The resonance frequency strongly depends on the radius of the ring: the smaller the radius is, the greater the resonance frequency.

In practice, the radiated frequency and diameter of the channel are completely determined by the resonance-frequency behavior of the piezoceramic rings used as the sources and receivers of a sound. The amplitude-frequency curve (AFC) of the anemometric channel is a superposition of the AFC of the rings and the AFC of the appropriate wave guide at a stationary value of the radiation amplitude.

Experiments were conducted on the analysis of AFC converters. On this basis, it is possible to conclude that the resonance frequencies of the one type ring are essentially varied (within limits of 10 %). From the facts mentioned above, it is possible to conclude that to maximize the transferred power in the anemometric channel, it is necessary to use a couple of similar rings. At the same time, amplitude-frequency research has made it possible to state the AFC stability under a feed voltage not increasing 10 V, and also recurrence of the characteristics with repeated turning on and off. The schemes for obtaining AFCs separately for the converter and for the whole channel are represented in Figure 2.

As the experimental data and theoretical calculations have shown that the pressure on receiving rings depends on a radiated frequency, the radius of the channel, the height of the radiating ring, the length of the sound through base, and also upon the sound speed in the media. The dependence of the acoustic pressure on the height of the radiating ring is particularly interesting to us.

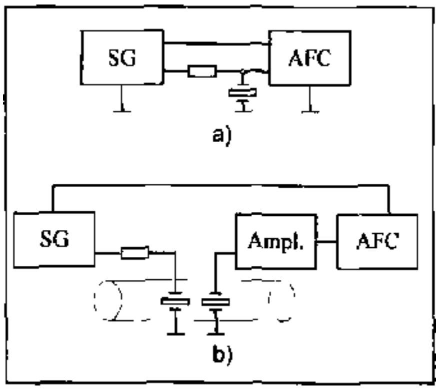

Figure 2. Block diagram for obtaining amplitude frequency characteristics', (a) tar piezoceramic rings, (b) for anemometric channel.

One of the particular features of mine anemometry is the variation in temperature over a wide range, and though the Curie temperature (temperature at which piezoelectric loss in properties occurs) for ceramics is much higher, the change of temperature strongly affects the characteristics of piezoelectric converters and the whole system. Thus, it was necessary to determine the dependences of the most important characteristics of piezoelectric ceramics on temperature.

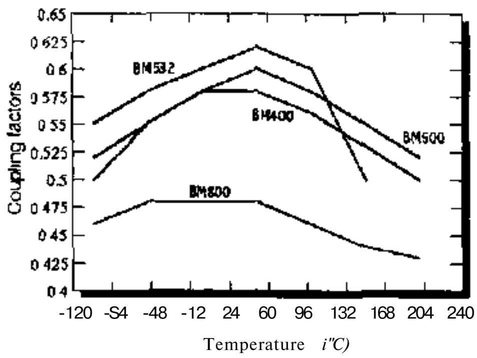

Figure 3. Dependence of coupling factors on lemperature.

It can be seen that even at small changes of temperature, the resonance frequency varies, inevitably reducing the acoustic power, which should be compensated for by certain means. The electro-acoustic efficiency factor, one of the most important indicators, depends upon the electromechanical bound factor, which depends on temperature.

Thus, it is possible 10 conclude that the particular service conditions of mine anemometers strongly influence both the characteristics of primary converters and the choice of the type of ceramics.

In addition, the choice of a certain type of piezoelectric transducer is determined by the dielectric penetration, dielectric loss angle, piezoelectric modulus, and also such important parameters as the O-factor, and, as already noted, the electromechanical bound factor.

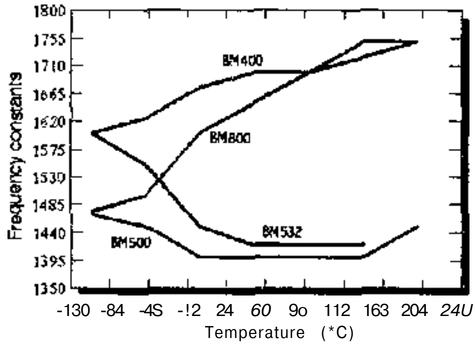

Figure 4. Dependence of frequency constants on lemperature.

5 CONCLUSIONS

Acoustics is the most probable way for progress in the area of mine ventilation control devices.

As has been proved at Moscow State Mining University, on the basis of acoustics, İt is possible to develop different types of acoustic control hardware: portable anemometers for episodic control, stationary devices for permanent monitoring and also methods of metrology support for ventilation measurements. The Plant of Measurement Apparatus, a partner of MSMU, is ready to meet any request.

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