Development of research work in the air-water spraying area for reduction of methane and coal dust explosion hazard as well as for dust control in the Polish mining industry

D Prostański
KOMAG Institute of Mining Technology, Gliwice, Poland
dprostanski@komag.eu

Abstract. The article presents a method for equipment designing and techniques to reduce methane ignition hazard, excessive dust in the place of operation and in conveyor transportation lines as well as methods to eliminate the risk of coal dust explosion. It describes technical solutions, the effects of these solutions and tests’ results related to effectiveness of the described air-water solutions as well as water spraying devices. The spraying systems used in longwall shearsers and roadheaders, on conveyor belt transfer points as well as the spraying curtains in the roadways are described. A new approach to the assessment of the safety level in the zones protecting against coal dust explosion hazard is also given. Intensity of dust accretion along the explosion protecting zones is analyzed. The spraying device is suggested, the operation of which depends on dust concentration in the ventilation air. The article presents the results of tests on the effectiveness in dust reduction and suppression of methane ignition. The tests were carried out in the laboratory, on testing facilities and in-situ.

1. Introduction
Methane and coal dust ignition hazards are the reason of many mining disasters. Within dozen or so years, five disasters, which killed 64 people took place [1, 3]. Presence of methane and coal dust at the place of mining and its ignition by sparks generated by tools contacting with mined rock or by other ignition sources are the main reason of the said disasters. Contamination of mine air by coal dust generated in the result of rock cutting and grinding or in transportation processes is another serious hazard. Airborne dust in mine is the reason of about 500 cases per year of pneumoconiosis among workers [1, 2].

Finding the possibilities of elimination or reduction of methane and/or coal dust explosion hazard as well as improvement of air quality by air-water spraying systems and development of other design solutions, eliminating such hazards, was the objective of KOMAG Institute research projects. The practical character of the developed solutions was kept in the research work.

2. Assumptions for the method of designing the air-water spraying installations
Innovative approach to reduction of impact of methane ignition and explosion hazard as well as reduction of dust concentration by using the air-water aerosols were suggested as result of the research work.
Available research results indicated that use of air-water spraying system can be efficient method for reduction of methane and/or coal dust ignition hazard due to high energy of ejecting the water drops evenly atomized in a stream of compressed air.

The scope of research and design work, enabled to develop the method for designing the air-water spraying installation for longwall shearers. Its general description is presented in figure 1. The method combines computer modelling, virtual prototyping, functionality tests on mock-ups, laboratory stand tests as well as verification of the installation in real mine conditions.

The developed method is of general character, what was confirmed by the results of further design and research work for other mining machines. According to this method, air-water spraying installation for roadheaders as well as the installations reducing dust concentration in roadway were developed and tested.

The method was developed to obtain smart solutions. For this purpose the models for determination of dust settlement intensity in a function of dust concentration were elaborated. The models were the basis for development of stationary and mobile spraying installations. The applied predictive algorithms allow to control the spraying process in changing dust generation intensity in mine roadways. These solutions enabled a creation of zones protecting against propagation of coal dust explosion and increased work safety in mining faces. Also the spraying installation acting selectively at the place of the dust generating mining machine operation, was included in this group of solutions.

![Figure 1. General description of the method for designing air-water spraying installations.](image)

Each solution of the spraying installation, irrespectively of its application undergoes designing and testing. After application of solution, it is further modified as the result of in-situ observations and tests. Continuous development of air-water spraying installations is associated with solving the problems and meeting the requirements of increasing operational safety in mines as well as with improvement of work safety in underground mines. In the consequence of this development, the original technical solutions, improving functionality and automation level, are also elaborated.

3. Control of methane ignition possibility and reduction of dust concentration in a longwall panel

First projects on air-water spraying installations were undertaken in the result of many accidents including mining disasters caused by methane ignition during coal cutting by shearers and roadheaders [1, 3]. The disasters in the longwall face may be influenced by the type of cutting knives [24, 25] and by the effectiveness of spraying systems for the suppression of methane ignition. The concept of spraying installation, intended for a longwall shearer in a form of 3D model, was developed under projects. It was used in the simulation tests. The expected parameters of spraying streams were specified: range and the stream angle as well as arrangement and number of spraying nozzles, which enable a creation of water curtain around the shearer’s cutting drum. The shape of the stream aims at preventing...
against propagation of methane explosion out of the contact zone of cutting drum with cut rock. An analysis of available designs of two-media spraying nozzles with the stream parameters, flow rate and pressure of spraying media, was performed. Then the laboratory tests of two-media spraying nozzles were carried out. Basing on this research methodology, the tests schedule was planned and the test stand was constructed. Within these tests degree of stream atomization, its range and shape were assessed. The designs of two-media nozzles of even distribution and properly atomized spraying stream and a range of the stream not less than 2 meters were selected. The assumption was that nozzles should have flow rate not less than 1 dm³/min and pressure not exceeding 0.6 MPa and air flow rate 150 dm³/min at pressure below 0.45 MPa. Further step included a development of original solutions with increased mechanical strength. The laboratory tests, conducted with use of Sprytec drops analyzer, showed that median drops diameter does not exceed 25 µm [6]. The spraying installation put on wooden mock-up of shearer’s arm with the cutting drum was designed and tested. It enabled to assess the functionality of air-water spraying installation. According to the assumptions the atomized water ejected in a form of stream from nozzles, deployed on the cutting drum, made a tight water curtain around it. It prevented propagation of methane flame out of the cutting zone [4]. The installation of nozzles dipped in a longwall shearer’s arm with determined directions of spraying streams was suggested and ratio of water and compressed air flow rate as well as supply and mixing of water and air in external spraying system were determined. After completion of tests and development of the technical documentation, an air-water spraying installation for arms R-200N of KSW-460NE shearer was designed [4]. After completing the installation, the testing stand was designed and methodology was developed for testing the installation regarding assessment of its effectiveness in extinguishing the methane flames and in controlling its ignition. During the tests, the gas ignition was initiated at the same time by two sparks of energy 10 MJ each (figure 2a). The tests were conducted in Barbara Experimental Colliery (GIG). After the tests full effectiveness of the designed installation for the assumed scope of its use was proven [4]. After certification procedures realized by the manufacturer, the pilot shearer with the spraying installation was tested in-situ in Pniówek mine in longwall W-9 [4]. During tests the functionality of air-water spraying installation in underground conditions, assessment of its reliability and effectiveness in dust control was evaluated. After the tests full functionality of air-water spraying installation was assessed and proven (figure 2b). [5]. Next tests of the shearers showed full usability in reduction of methane ignition hazard as well as in efficient dust control especially, regarding the respirable fraction [5].

![Image](image_url)

**Figure 2.** KSW-880EU longwall shearer a) extinguishing of flames by air-water spraying installation, b) efficiency of dust control with air-water and water spraying system [5].

Validity of selection of this problem for research work as well as realization of research projects were confirmed by successful implementation of the spraying installation, especially that it was the first such application in the longwall shearer in the world.
Positive effects of the implementation of air-water spraying systems in the KSW-460NE longwall shearer caused the producers’ interest in applying this solution in other types of longwall shearsers.

Process of implementation the air-water spraying installation in longwall shearsers caused undertaking the research work on increasing the automation level of operation of these installations. In longwall shearsers with air-water spraying installation there is a separate high-pressure water installation, which is an alternative solution. Change of spraying type requires restarting the shearer and causes breakdowns, which reduce shearer’s availability and coal production losses. As a part of the design work another solution was suggested, in which pressure of compressed air decreases, water supply to air-water nozzles on the shearer’s arm is cut off. Such a solution limits water flow rate, which increases by tens dm$^3$/min if there is no compressed air. Also original solution was suggested, which enabled automatic selection of spraying variant operation mode depending on compressed air presence or absence, by switching the check valves incorporated with pressure sensors. The research work on development of compact set of check valves opening alternately depending on pressure of compressed air, was started. This solution was used in KSW-880EU shearer.

Within the next steps research and design work, associated with air-water spraying installation in KSW-800NE longwall shearer was realized. The project included the research work oriented onto development of new design of air-water spraying installation installed not only in the shearer’s arms, but also in the cutting drum. Preparation of air and water mixture before feeding it to the cutting drum, where its rotational movement caused mixing water with air was the solution idea. The research work showed full effectiveness of the spraying installation in extinguishing methane flames [7]. Then tests were carried out in the underground mine in the scope of assessment of dust control efficiency with the applied solution of the spraying installation [7]. To provide stability of spraying installation parameters irrespective to the stability of feeding parameters, a device balancing media pressure on output irrespectively to the media pressure on input was designed. Balancing water pressure and compressed air pressure is mechanical by using the pressure scale.

Together with application of other types of longwall shearsers with air-water spraying installation in-situ tests were conducted in coal longwalls in scope of effectiveness of dust control. The measurements were taken at longwall outlet and at the miner’s work-place using the CIP-10 gravimetric dust meters. Analysis of test results indicated that in each case degree of dust reduction in the case of using the air-water spraying was up to 77% of total dust and respirable fraction up to 93%, in comparison with a typical water spraying system [5, 9].

4. Systems for reduction of methane ignition in roadheaders

Recognizing the problem of exceeding the dust concentration and methane ignition hazard in roadway faces, it was suggested to transfer developed designing method for using air-water spraying installations in roadheaders. In roadheaders there are many solutions of the systems protecting against methane ignition, where internal sectoral behind-tool spraying systems, installed in cutter heads, are highly efficient in reduction of methane ignition hazard [10, 23]. However, these solutions are complicated and damage prone devices supplied by pumps with pressure in the range from 5 MPa to 10 MPa and water flow rate from 100 to 180 dm$^3$/min. Efficient air-water spraying system, suggested by other producers [11], requires dozen or so cubic meters of compressed air per minute, what often exceeds possibility of delivery of such volume of air in the conditions of the Polish mines.

Conceptual, designing and research projects concerned external air-water spraying installations in roadheaders. In this solution experience gained from the installations designed longwall shearsers was used, what significantly simplified and shortened the designing process. The assumption was to supply this installation with water and compressed air of pressure from 0.35 MPa to 0.5 MPa, water flow rate about 30 dm$^3$/min and air from 1.5 to 3.0 m$^3$/min. In the result of tests it was suggested to apply spraying pack and spraying nozzles in a shape of reversed letter C, placed just after the cutter head on connection of a gear with a motor, enabling covering entire cutting zone by the spraying curtain. Each type of roadheader requires individual approach due to design differences. Spraying pack was assumed to be of universal character. After manufacturing the spraying installation and mounting it on the roadheader as
well as checking its operation, it was tested on the test stand and tests confirmed proper effectiveness of extinguishing the gas flames (figure 3) [12]. The tested installations were installed in different types of roadheaders. First air-water spraying installations for roadheaders were implemented in Murcki, Jas-Mos and Borynia coal mines.

![Figure 3. Air and water spraying installation in the roadheader [12].](image)

Despite a very good extinguishing characteristics, mining regulations do not allow using the external spraying installations as the main spraying system in the atmosphere where methane concentration exceeds 0.5%. Within the concentration ranging from 0.5% to 1.0% only roadheaders equipped with internal sectoral spraying system can operate. Through elimination of main disadvantages of known designs of sectoral spraying and replacing them with new approach solutions without these disadvantages, the internal sectoral spraying installation was suggested, where water is delivered out of the cutter head gear under pressure not exceeding 1 MPa with flow rate below 30 dm$^3$/min. Variant of this installation is also provided for air-water version. After development of internal sectoral spraying system (figure 4a) and simulation tests carried out as well as design work, a sectoral spraying installation for KPD roadheader was made (figure 4b). The stand tests of operational safety in relation to methane ignition hazard confirmed the effectiveness of this installation.

![Figure 4. Installation of internal sector spraying system before trying to prevent ignition of methane [13].](image)

KPD roadheader equipped with internal and external spraying installations was used in Jas-Mos mine and next in Marcel mine.

5. Application of air-water spraying in reduction of airborne dust concentration in roadways

Experience gained in realization of research and design projects on spraying installations intended for longwall shearsers and roadheaders was used in development of air-water spraying installations to be
applied in other places in the mine as dust concentration is one of the important problems that so far have not been solved comprehensively. Dust problem in roadways, besides mining operations and faces is important as dust is almost everywhere in coal mines. The problem is most important in roadways with the stream of used air and in the area of conveyors.

Undertaking design work on air-water spraying installation CZP BRYZA for dust control in mine roadways was one of the projects. The work assumed that airborne dust would be captured by water atomized by compressed air and after its watering, the dust particles would settle on louvre-type grate of special design (figure 5) [6]. The flow rate of the sprayed water does not exceed 3 dm³/min. Such inclination of louvres (crossbars) was suggested not to obstruct free flow of air and to collect as much of wetted dust as possible.

![Figure 5. CZP BRYZA roadway dust barrier [6].](image)

Spraying installation in operation should not negatively affect the working personnel, what was realized with the method for switching on/off the curtain on both sides. After manufacturing the first unit of CZP BRYZA the tests were conducted in Budryk mine in the scope of dust control efficiency in the zone protecting against propagation of coal dust explosion. The test results showed a double reduction of dust concentration in air flowing out of the longwall panel (figure 6). During observation it was noticed that CZP BRYZA device removed dust settled on entire circumference of the working on a distance of 100 m. Dust settled on the floor increased its water content, extending time of protecting against dust explosion by 50% [6].

![Figure 6. Efficiency of reducing the airborne dust concentration behind CZP BRYZA roadway dust barrier measured along the working width [6].](image)

Positive test results of the device were installed increased work safety in this working. Ten CZP BRYZA anti-dust barriers were installed in eight coal mines. Regularly dust control effectiveness of newly implemented devices was tested, which showed a double reduction of total dust as well as of its
respirable fraction irrespectively of the place of device installation. The roadway anti-dust barriers were also manufactured only in a water version.

6. Reduction of dust on coal haulage equipment

Transfer points of coal haulage conveyors are another field, where the air-water spraying devices were applied. Adaptation of this method seemed to be easy and natural. Conveyor transfer points required installation of spraying devices just over these points, however, the most important issue was to direct precisely the spraying stream towards the places of most intensive dust generation during loading the coal from one conveyor to another. It was noticed that dust starts generation on external surface of coal at the area of contact with the receiving conveyor. Propagation of dust during its transfer between conveyors was another problem. These problems were reduced by directing the air-water streams spraying installation to the edge of transferred run-of-mine and placing the drainage grate over the conveyor, which enabled catching the watered dust. After required conceptual work, simulation tests and designing the spraying installation VIRGA was installed in the underground workings of Brzeszcze mine. This solution consisted of a frame with nozzles evenly installed in two rows along entire frame width. In-situ tests, which were conducted, covered measurements of dust concentration at the area of conveyor operation, behind the transfer point, about 7 meters from the sprinkler and 7 meters ahead of the transfer point. The conducted measurements in the selected measuring points for the case without spraying, with water and with air-water spraying installations showed that efficiency of dust control for water spraying was 50% for total dust and only 4,4% for removal of respirable dust fraction. When using the air-water spraying installation, efficiency of dust control was 80% for total dust and even 90% for respirable dust fraction [6]. In the result of test, four VIRGA spraying installations implemented in Brzeszcze mine, and they were installed on the transportation route from the longwall panel. Water flow rate was reduced to 2 dm$^3$/min. The tests confirmed high efficiency of dust reduction up to 80% (figure 7) [14].

![Figure 7](image_url)

**Figure 7.** Measurement of respirable dust concentration and efficiency in reducing the respirable dust fraction using the VIRGA air-and-water spraying system [5].

Application of drainage grate cooperating with BRYZA-1200 spraying device was planned in another concept, where it was assumed that the water flow rate would not exceed 0.5 dm$^3$/min (figure 8a). Such a result was obtained by changing the design of spraying nozzles i.e. by reduction of inlet and outlet opening diameter. After designing and manufacturing of BRYZA-1200 prototype, it was tested in in-situ
The analysis of these results showed that almost 83% of dust control effectiveness was achieved (figure 8b) [5]. Tests of BRYZA-1200 transfer points’ spraying installations in other mines showed at least 70% efficiency of dust removal from mine air.

Both types of conveyor sprinklers were initially designed as manually started devices. It was suggested to start up the spraying installation by belt movement aided by mechanical roller water distributor with the roller coupled with the conveyor belt and in another application using an optical dust sensor. In one of spraying installations it was suggested to start-up with proximity sensor detecting height of feed on the conveyor. These solutions enabled to increase the automation level of spraying installations, additionally limiting water consumption. Mine water used for spraying systems, not always has parameters that favour its combination with coal or rock dust particles. That is why a device, dosing the liquid agents reducing the water surface tension driven by flow of spraying water, was developed. Connection of intrinsically safe pilot electro-valve with check valve was the solution increasing the automation level of spraying installation. It enabled failure-free start-up of spraying installation by any electric impulse. In more complicated systems of spraying installations, which required protection against flow in wrong direction, the solution was suggested, which was a combination of solenoid valve with a pilot operated check valve as well as with check valve operating in the opposite direction. At the places, where installation of greater number of spraying systems is planned, a solution of the control valve of high water flow intensity was developed. All these devices found practical applications and contributed to increasing efficient dust control in coal mine air as well as in improving work safety and comfort.

7. Longwall system for dust control

The method for designing the air-water spraying installation was developed within the spraying installation working selectively at the place of mining machine generating dust during operation in longwall panels. This idea consists of installation of a single pack of spraying installations on the selected powered roof supports along the longwall and production of air-water mixture in the spraying packs in the area of generated airborne dust [8]. It was suggested to start only those spraying installations fixed to powered roof supports which are between the operating shearer and longwall end at the side of stream of used dust-laden air (figure 9). Additionally, it was assumed that each sprinkler should have a possibility of periodical switching off to enable passing the personnel through the spraying zone or in the case of required work in this spraying zone. The observations and measurements taken in the longwall showed that the highest dust concentration was in the shearer’s mining path (over the AFC) and significantly lower concentration in the zone of personnel movement. In this zone dust concentration increased proportionally to a distance from the longwall shearer and was increased due to mixing of the ventilation stream and taking the dust from above of AFC to other parts of the working cross-section.
It was observed that the highest efficiency of dust removal from the longwall face can be achieved by directing the spraying streams towards the mining path to the zone between the longwall shearer and the ventilation roadway, which takes off airborne dust from the longwall. Such an approach enabled efficient reduction of dust by tens percent with water consumption of the whole system from 0.5 to 3.0 dm³/min depending on the shearer position in the longwall face. To increase efficiency of dust control in low longwalls, below 2 m, sprinklers were developed, which had a function of articulating spraying streams (figure 10a). The tests of spraying system in Budryk mine longwall panel, with use of two sprinklers in the entire longwall, confirmed 80% efficiency in dust reduction in the distance up to 27 m from the sprinkler and about 63% in the distance of 72 m from the sprinkler (figure 10b). Similar tests were conducted in Sośnica mine, where one sprinkler was installed in the entire longwall and pressure of compressed air was 0.05 MPa. Despite the significantly lower spraying parameters, use of the sprinkler enabled dust reduction by over 92% in the distance of 6 m from the sprinkler and over 63% in the distance of 12 m from the sprinkler [15]. Positive test results of the longwall spraying system contributed to industrial implementation of this solution in longwall panels in other coal mines.

Figure 10. a) KOMAG-n spraying system in the longwall of Budryk mine, efficiency in dust reduction in the distance up to 72 m [15].

8. Improvement of safety in the zones protecting against coal dust explosion
During research work on air-water spraying systems, it was found that the zones protecting against propagation of coal dust explosion were made using the methods which did not enable their
Automation. Arrangement of such zones involves manual application of rock dust or watering it in such an amount to eliminate flammability and volatility of coal dust. Preparation of these zones is governed by the relevant regulations [16] and national standards [17, 18]. Effectiveness of the protecting zones preparation is controlled by tests conducted, among others, by Barbara Experimental Colliery. Proper quality of the protecting zone is usually assured by adding surplus amount of agent neutralizing the explosive coal dust. The project provided possibilities process automation of protecting zones preparation with proper quality of neutralizing the explosive coal dust as well as with limitation of penetration of coal dust to the protecting zone by use of air-water spraying systems. There has not been any such research work suggesting such an approach before. This subject was proposed in the framework of cooperation between the KOMAG, GIG (KD Barbara) and Brzeszcze mine as a part of the MEZAP research project [19].

The project included the following two variants of supporting the preparation of protecting zones:
- installation of air-water spraying system on a suspended rail (figure 11a),
- stationary installation of air-water spraying installation coupled with dust meter and the control device (figure 11b).

**Fig. 11.** Air-water sprinkling installation a) mobile installation b) stationary installation [19].

Only after detailed in-situ tests on measuring dust concentration in the zones protecting against coal dust explosion, which were planned in a few mine workings, it was possible to use the suggested solutions in mines. The following measurements were taken within the tests: rate of dust settlement and presence of the settled dust, moisture, dust concentration with division into the fractions from nanometers to 1 millimeter as well as measurements of air flow rate, its temperature and water content. Empirical models of relationship between intensity of dust settlement and changes in its concentration were developed [20]. The results showed that while walking away from dust source, rate of dust sedimentation and its concentration decreased what can be described by the exponential functions (figure 12). Depending on type of the roadway, its character, airflow direction and its rate, slope of the function is different [20, 21]. The developed mathematical models of dust sedimentation rate enabled a development of algorithm for intelligent control module coupled with an optical dust meter, controlling stationary air-water spraying installation. Controlling the spraying process in the function of dust concentration in mine workings was possible due an installation of predictive algorithm [22]. The solution paved the way to aiding a preparation protecting zones against propagation of coal dust explosion. In-situ tests of the stationary protective zone showed an extension of the protecting zone life between its consecutive renewals [20].
Fig. 12. Equivalent characteristics of dust deposition depending on dust concentration in the air in paths under analysis [20].

The second version of aiding the preparation of protecting zones was based on the solution of mobile protecting zone. The design of spraying device was developed and its testing was planned, which predicted assessment of dust sedimentation and dust transient moisture as well as a movement assessment of dust settled on the floor to other parts of the working [20].

Both variants of aiding the preparation of protecting zones showed positive results with lower sedimentation rate and also higher content of transient water. Variant with a stationary protective zone is technically easier in implementation and common use as it does not require movement along the protective zone as well as dust concentration control with use of optical dust meter and adaptive control of spraying efficiency, depending on change in dust concentration such a solution gave a better image of safety conditions in the protective zone as one of defending barriers against propagation of coal dust explosion.

Research work, related to maintaining the protecting zones against propagation of coal dust explosion, is continued within ROCD European project. It is planned to develop a system for prediction of dust propagation and its concentration in the selected part of the mine, basing on developed empirical models and sensors installed in the key places of ventilation system.

9. Summary
The proposed method for designing air-water spraying installations enabled a development of effective solutions to reduce dust concentration and methane ignition risk as well as coal dust explosion. The solutions are widely used in the coal mining industry. Development of a simple, reliable in operation and effective solutions allowed to extend installations’ scope of use in almost all the areas of mines. Other implementations that are not the subject of this article have been applied in preparation plants and aggregate mines. Up-grading of spraying installations has led to an increase in the level of automation, improving the safety and optimizing operation of these installations. In the design and implementation process, particular attention was paid to improvement of miners’ work comfort in the area of operation of these installations. During an operation of cutting drums, when machines were equipped with air-water spraying systems no methane ignition event occurred and all the air-water spraying installations contributed significantly to the reduction of coal dust in mines.
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