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Impact of flameproof exhaust system on efficiency of selective catalytic reduction

Ecological problems associated with operation of diesel engine in underground workings are discussed. Characteristic features of diesel drives operating in workings threatened by explosion hazard, including technical problems with use of selective catalytic reduction, are presented. The results of stand tests of flameproof diesel drive, in which selective catalytic reduction of nitrogen oxides (NO_X) was used, are given.

Key words: *flameproof exhaust system, NO_x emission, selective catalytic reduction*

Wpływ ognioszczelnego układu wylotowego na sprawność metody selektywnej redukcji katalitycznej

W artykule omówiono problemy ekologiczne związanie z pracą silnika z zapłonem samoczynnym w wyrobiskach podziemnych. Przedstawione zostały cechy charakterystyczne spalinowych układów napędowych pracującym w wyrobiskach zagrożonych wybuchem, uwzględniając problemy techniczne związane z zastosowaniem metody selektywnej redukcji katalitycznej. Zaprezentowano wyniki przeprowadzonych badań stanowiskowych ognioszczelnego, spalinowego układu napędowego, w którym zastosowano metodę selektywnej redukcji katalitycznej tlenków azotu.

Słowa kluczowe: *ognioszczelny układ wylotowy, emisja tlenków azotu, selektywna redukcja katalityczna*

1. Introduction

Emission of gaseous pollutants to the atmosphere is a significant hazard to the natural environment. Diesel engines emit the following basic toxic substances: carbon oxide (CO), hydrocarbons (CH), nitrogen oxides (NO_X), aldehydes (RCHO), sulfur dioxide (SO_2) and particulate matter (PM). Diesel engines used in mining plants emit a lot of nitrogen oxides, due to operation at high load [0]. Distribution of NO_X emission from different sources is presented in fig. 1 [0]. From the diagram it results that diesel engines used in road and off-road vehicles are responsible for over 43% of total emission of nitrogen oxides.

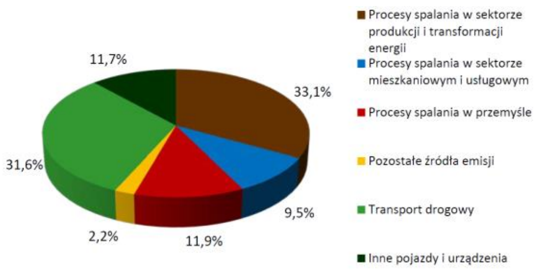

Fig. 1. Distribution of nitrogen oxides emission in Poland in 2009 [0]

At present selective catalytic reduction (SCR) is the most effective method for reduction of nitrogen oxides in exhaust gases from diesel engines. Depending on used reducing agent, the following two variants of this method can be distinguished:

- CH-SCR, reduction of NO_X with use of hydrocarbons as the reducing agent, NO_X reduction efficiency up to 80%,
- NH_3-SCR, reduction of NO_X with use of ammonia as reducing agent, NO_X reduction efficiency up to 95%.

Selective reduction of nitrogen oxides with use of ammonia is commonly used in the automotive industry due to its efficiency and costs. In the automotive industry 32.5% urea water solution, under trade name AdBlue is used, as ammonia is a toxic gas [0]. NO and NO_2 are reduced on the surface of catalytic reactor according to the following reactions [0, 0]:

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (1)$$

$$4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O \quad (2)$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O \quad (3)$$

Reactors with vanadium – tungsten oxides catalyst on titanium oxide as the carrier ($V_2O_5/WO_3/TiO_2$) are most popular. Moreover, reactors with catalytic zeolite surface with copper ions Cu-ZSM-5 or iron Fe-ZSM-5 are more widely used at present. Reducing agent is injected in front of catalytic reactor, most often just behind the turbocharger outlet, i.e. at the place of highest temperature in the exhaust system. Example of the system for dosing the urea water solution is presented in fig. 1. In this system, the spraying nozzle is installed in the exhaust pipe at some distance from the valve dosing the agent. In such case, spraying is assisted by compressed air.

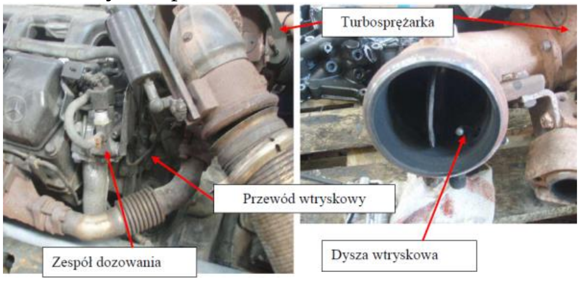

Fig. 2. System for dosing the urea water solution on the example of truck engine [0]

Water evaporates at first after injection of urea water solution to the stream of exhaust gases. Then, during flow of the stream through the exhaust system, the following thermolysis and hydrolysis reactions take place:

$$(NH_2)_2CO \rightarrow NH_3 + HNCO \qquad (4)$$

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \qquad (5)$$

The amount of reducing agent is strictly determined by the control module depending on operational parameters of diesel engine. A possibility of emission of ammonia that does not take part in reactions (ammonia slip) from exhaust system is a disadvantage of using the ammonia as reagent. According to the regulations, the permissible ammonia concentration is 25 ppm [13].

2. Design of mine diesel drive in the aspect of conversion of nitrogen oxides

Example of drive system of transportation machines and equipment used in hard coal mining industry, where diesel engines are used, is presented in **Błąd! Nie można odnaleźć źródła odwołania.**.

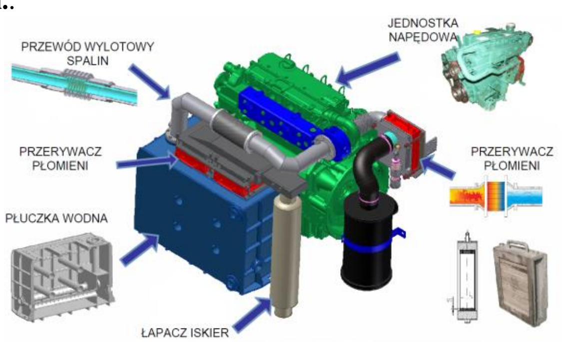

Fig. 3. Diesel engine for operation in potentially explosive atmospheres [0]

Extended inlet and outlet systems, which meet the mining requirements, are beside diesel engine the parts of drive system. The limit of maximum temperature of external surfaces of drive equal to 150ºC is the most important requirement for diesel engines to drive the mining machines. It refers to the case, when flammable dust is present. In the case, when the drive is used in underground workings, where there is no flammable dust, maximum temperature of the surface and exhaust gases should not exceed 450ºC. This condition refers to all engine components, which are in direct contact with surrounding atmosphere. This condition is especially important for the catalytic reactors in the systems for reduction of nitrogen oxides, which reach the temperature exceeding this permissible value during operation. Their use requires development of temperature protection for external surfaces, which at the same time will not affect the processes on the surface of the reactor core. All the components included in the exhaust system designed for operation in conditions of gas and coal dust explosion hazard, are presented in 0.

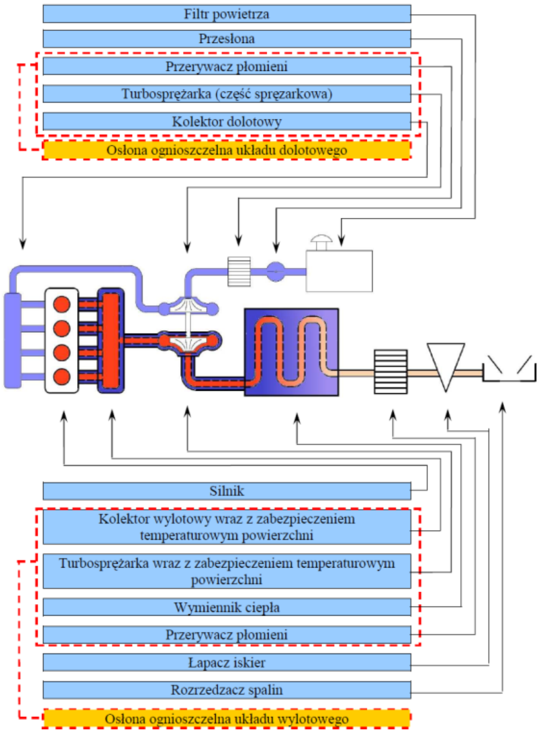

Fig. 4. Diagram of inlet-outlet system of drive unit used in the mining industry [0]

Assemblies of exhaust system are important from the point of view of the system for conversion of nitrogen oxides. Exhaust system of mine diesel drive should be equipped with flame trap and spark arrester. The flame trap has to protect against propagation of flames from flameproof section of exhaust system to the surrounding explosive atmosphere (0). Requirement as regards maximum temperature refers also to exhaust gases, which are just behind the flame trap. Part of exhaust system between flame trap and engine should additionally meet the requirements referring to the flameproof casing and be designed according to the requirements for gases of group I.

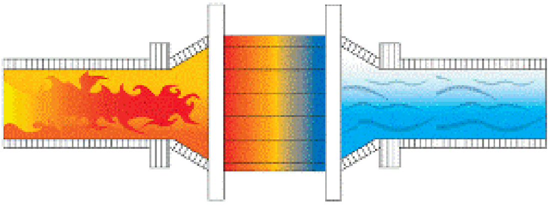

Fig. 5. Principle of operation of flame trap[0]

According to the requirements the flameproof casing should guarantee as follows [0]:

- resistance to pressure of internal explosion during test of most severe explosion that can be expected in a flameproof casing;
- resistance to pressure during the test with the controlled pressure exceeding the highest pressure recorded during the tests at worst conditions of explosion, with maintenance of flameproof casing properties;
- preventing against propagation of internal explosion during the test of most hazardous explosion that can happen inside the flameproof casing. In such conditions the explosion should be stopped in the flameproof casing and not transferred to the surrounding atmosphere.

The highest efficiency of conversion of nitrogen oxides is observed in temperature above 300ºC [0, 0]. Thus, the catalytic reactor can not be installed out of flameproof zone, because too low temperature of exhaust gases can not ensure proper reduction of nitrogen oxides. Additionally it should be taken into account that modules of catalytic reactors consist in the first part of oxidation reactor, which ensures proper ratio between NO and NO_2 and enables decrease of effective temperature of NO_X conversion (0) [0].

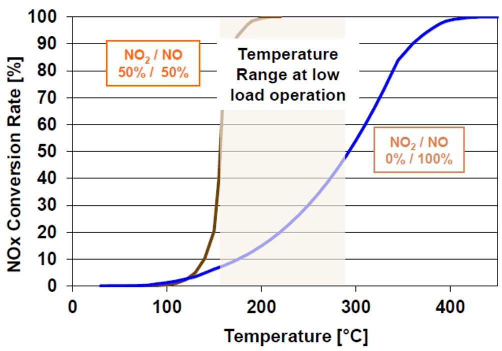

Fig. 6. Degree of NO_X reduction depending on temperature and NO_2/NO ration[0]

Egzotermic oxidation reactions can increase temperature of exhaust gases above the permissible temperature of 150ºC. Due to this, the system of catalytic reactor has to meet the same requirements as the flameproof part of exhaust system.

Injection of urea water solution to the exhaust system is required in the system for selective catalytic reduction (SCR) in front of catalytic reactor. Impact of exhaust system on hydrolysis and thermolysis reactions, in the result of which NH_3 particles are formed to reduce NO_X on the catalytic surface of reactor, was identified during the tests within the project [7]. Urea is highly prone to settle on the internal surface of exhaust pipe in a result of its dosing directly to the flameproof exhaust system. It can result from the design in which the pipe is cooled by water jacket.
Freezing of urea solution in the temperature below zero is one of significant problems in the automotive industry associated with use of urea solution for reduction of nitrogen oxides. Additional heating is required in such cases. There is no such a problem in the case of using the SCR system in underground workings, what simplifies the design of the system.

3. Testing the impact of features of flameproof diesel drive on efficiency of conversion of nitrogen oxides by selective catalytic reduction

Mine drive equipped with BF4M1013M Deutz diesel engine of displacement 4.5 dm^3, was used in the tests. According to the manufacturer's data it reaches maximum power 81kW at rotary speed 2300 rpm. Special design of exhaust manifold and turbo compressor meeting the requirements for the engines used in the mining industry, is its characteristic feature. External surfaces of exhaust manifold and turbo compressor are protected against excessive warming by water cooling from engine cooling system. This engine is used in Lds-100K-EMA locomotive, SKZ-81 drivetrain and drivetrain of PIOMA CSP suspended monorail. Test stand for mine diesel drive is presented in 0.

Fig. 7. General view of test stand [0]

Test stand was extended by assemblies of the system for selective catalytic reduction for mine diesel drives. The following main sub-systems are part of the stand:

- SCR reactor system with water jacket,
- system for preparation of agent,
- system for injection of agent with control.

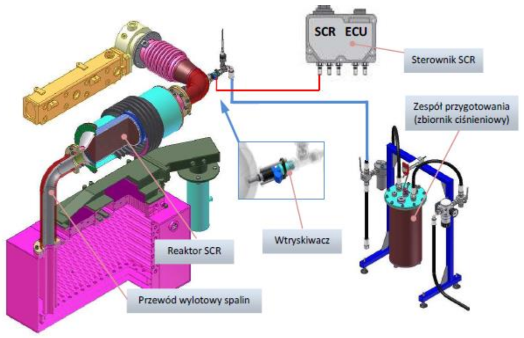

Fig. 8. Sub-systems of exhaust system with selective catalytic reduction unit

Concentration of nitrogen oxides measured in exhaust system in front of catalytic reactor and behind catalytic reactor during the tests according to variant A, in which cooling of exhaust system by water jacket were not planned, is presented in Fig. 9. In most points of the test, the reduction of nitrogen oxides was above 50%. Comparing the results it can be concluded that increase of rotary speed and load to engine results in more effective operation of catalytic reactor.

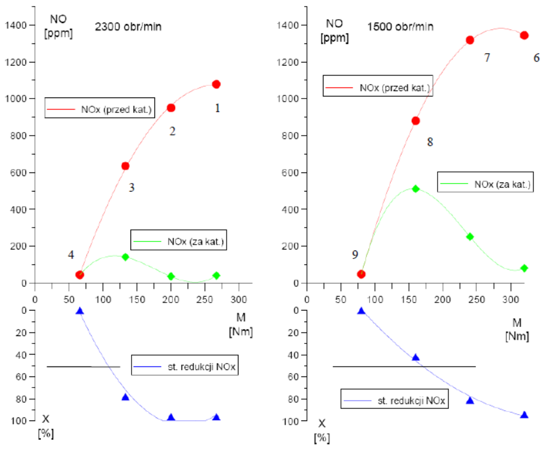

Fig. 9. Concentration of nitrogen oxides and level of their reduction for exhaust system without water jacket (variant A) [0]

Exhaust system was disassembled after completion of tests. It was observed that internal wall of the pipe at the section between reagent injector and catalytic reactor was covered with powder deposits, which could be easily removed.

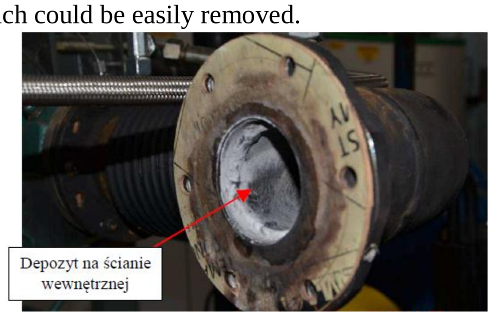

Fig. 10. Internal wall after tests without water jacket [0]

Concentration of nitrogen oxides in front of catalytic reactor and behind catalytic reactor during the tests according to variant Bs, in which exhaust system was cooled by agent from engine cooling system, is presented in Fig. 11. Reduction of NO_X above 50% (69%-91%) was obtained only for points 1 and 2. In the case of rotary speed equal to 1500 rpm the reduction of NO_X in points 6 and 7 was in the range 28-36%. Dosing the AdBlue in points 4 and 8 did not change readings of analyzer of exhaust gases. The results confirm the possibility of required reduction only during operation of engine at high load, when the concentration of nitrogen oxides in exhaust gases is high and the temperature of exhaust gases is enough for proper reduction.

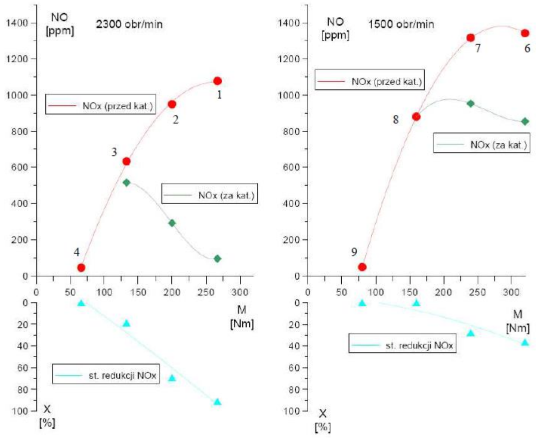

Fig. 11. Concentration of nitrogen oxides and level of their reduction for exhaust system with exhaust pipe cooled by the agent from engine cooling system (variant Bs) [0]

The components of exhaust system were disassembled after the tests. Internal wall of the pipe between injector and catalytic reactor was covered with a layer of deposits of glassy surface of thickness from 1 to 2 mm. The structure of deposit on the surface was shaped by a stream of exhaust gases. Grooves and infiltrations were clearly visible (0, 0).

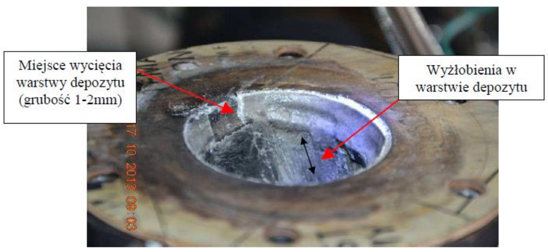

Fig. 12. Internal wall after the tests with cooled exhaust pipe (pipe) [0]

The deposits were settling on the pipe walls mainly during operation of engine at low load, when both flow of exhaust gases and temperature of exhaust gases were low. A layer of deposits disappeared during operation of engine at high load.

Fig. 13. Internal wall after the tests with cooled exhaust pipe (entry to the pipe) [0]

Collective results of testing the conversion of nitrogen oxides in exhaust system of tested engine for variants A and Bs are given in 0.

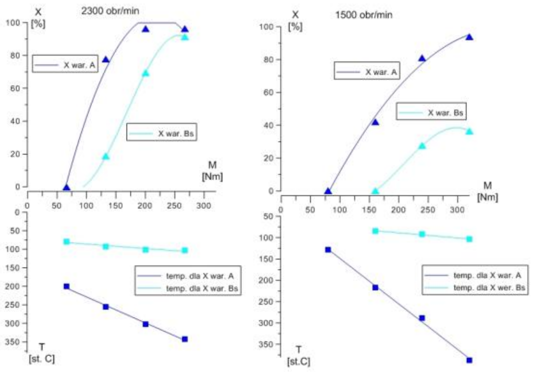

Fig. 14. Comparison of efficiency of the system for reduction of nitrogen oxides depending on configuration of exhaust system [0]

Lower part of the diagram refers to the temperature of internal surface of exhaust pipe in the first part of exhaust system. In variant A this is the temperature of external surface of exhaust pipe, and in variant Bs this is the temperature of cooling agent at the outlet of exhaust system. Significant reduction of efficiency of the system for reduction of nitrogen oxides was observed in the case, when there was a water jacket. High temperature of internal surface of the pipe favours evaporation of water and urea thermolysis, what took place during testing in variant A. In Bs variant, where exhaust channels were intensively cooled, reduction of nitrogen oxides was lower and solid deposits settled on the walls of the system. Such phenomena did not occur at high flow intensity and high speed of exhaust gases, when sprayed agent is better mixed with the main stream of exhaust gases. Smaller amount of agent reaches the “cool” wall, where it can settle.

3. Summary

Underground mine workings are the special places of diesel engines operation, where diesel machines operate in confined space. Mining teams in these workings are exposed to exhaust gases, especially to nitrogen oxides, which are most hazardous among all components of exhaust gases from diesel engines. While intensive actions aiming at minimization of this problem are noticeable on the market of the surface machines, there are no proper designs and methods for conversion of nitrogen oxides for the machines operating in underground workings with explosive atmosphere. Design of mine drive system for operation in workings with explosive atmosphere was analyzed, taking into account technical problems associated with use of the system for selective catalytic reduction of nitrogen oxides in exhaust gases. Significant impact of cooling the mine exhaust system on efficiency of conversion of nitrogen oxides, and especially on the amount of deposit settled on the internal wall of exhaust pipe, was indicated. Elimination of these unwanted effects requires development of a new design of exhaust pipe section between injector and reactor for selective catalytic reduction.

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