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EDWARD PIECZORA
PIOTR DOBRZANIECKI

About requirements for diesel drives used in hard coal mine underground workings

Due to the rapid increase of using transportation machines with diesel drives in hard coal mine underground workings, the technical and operational requirements for these drives are analyzed. The ambiguity of the European Union requirements regarding the emission of exhaust gases is indicated. The planned scope of work to meet the requirements given in the Diesel Engine Directive for drives intended to be installed in mobile machines operating in mine workings in atmospheres potentially threatened by methane and/or flammable dust explosion hazards is given.

Key words: *mine workings, diesel drive, explosion hazard, exhaust gases, requirements regarding exhaust gases emission*

1. INTRODUCTION

The transportation of materials and run-of-mine as well as the transportation of people all play a very important role in mining plant operation. Underground transportation systems in Polish coal mines are based on the following transportation systems:

- underground railways, used on the main transportation routes,
- suspended monorails or floor-mounted-railways in transportation between different divisions,
- conveyor belts.

An underground mining railway is the main system for the transportation of machines, equipment, materials, personnel, and waste rock. The transportation of run-of-mine in cars has been almost completely replaced by conveyor belts.

On-floor transportation has been used since the very beginning of the coal mining industry – the first rails in a coal mine appeared in the 17th century. The beginning of suspended mine transportation dates back as far as the mid-20th century. Due to the development of cable winches in Polish mines, the use of suspended railways and then cable-driven on-floor railways became widespread.

However, they have some limitations:

- they can only move along a set route;
- the train operator has no visual contact with the transportation set,
- the possibility of the uncontrolled breaking of a cable poses a hazard,
- constant maintenance of the cable and guide rollers is needed.

The above limitations were the main reason for introducing the suspended monorails with diesel drives after 1990. Their advantages and created infrastructure (depots, fuel filling stations) contributed to the use of diesel locomotives in underground railways.

2. REQUIREMENTS FOR DIESEL DRIVES USED IN WORKINGS WITH POTENTIALLY EXPLOSIVE ATMOSPHERES

In accordance with the Act of April 15, 2016, on the conformity assessment and market surveillance [1], “Products placed on the market or put into service must meet the requirements”. It shall be presumed that the product meets the requirements if it

complies with the provisions of the harmonized standards with the directives. The basic directives related to diesel drives intended for use in underground workings endangered by firedamp and/or combustible dust are as follows:

- Directive 2006/42/EC of the European Parliament and of the Council of May 17, 2006, on machinery and amending Directive 95/16/EC;
- Directive 2014/34/EU of the European Parliament and of the Council of February 26, 2014, on the harmonization of the laws of the member states relating to equipment and protective systems intended for use in potentially explosive atmospheres;
- Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016, on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013 and amending and repealing Directive 97/68/EC;
- Directive 2014/30/EU of the European Parliament and of the Council of February 26, 2014, on the harmonization of the laws of the member states relating to electromagnetic compatibility.

In Annex IV to the Machinery Directive (MD) – categories of the machines to which one of the procedure specified in Paragraph 12, Items 3 and 4 of the directive are mentioned. These are the machines intended for underground operation of the following types:

- locomotives and brake vans;
- hydraulic powered roof supports.

Regarding underground transportation machines, only locomotives for underground railways and braking trolleys for suspended monorails and floor-mounted railways are covered by the strictly specified procedures for conformity assessment described in the Machinery Directive.

There are the following standards harmonized with the Machinery Directive:

- PN-EN 1889-1:2011 Machines for underground mines – Mobile machines working underground – Safety – Part 1: Rubber-tyred vehicles;
- PN-EN 1889-2+A1:2010 Machines for underground mines – Mobile machines working underground – Safety – Part 2: Rail locomotives;
- PN-EN 1679-1+A1:2011 Reciprocating combustion engines – Safety – Part 1: Compression ignition engines.

Most important standards harmonized with the ATEX Directive associated with the discussed problem are as follows:

- PN-EN 1834-1:2002 Reciprocating combustion engines – safety requirements for the design and construction of engines for use in potentially explosive atmospheres. Group II engines for use in flammable gas and vapour atmospheres;
- PN-EN1834-2:2002 Reciprocating combustion engines – safety requirements for the design and construction of engines for use in potentially explosive atmospheres. Group II engines for use in underground workings susceptible to firedamp and/or combustible gas.

It is worth mentioning that, in the list of Polish standards, the following standards are still in force:

- PN-G-02150:1997 Mining railway – Division and terminology;
- PN-G-36000:1997 Diesel drives for underground mine's vehicles – Requirements,
- PN-G-36001:1999 Diesel drives for underground mine's vehicles – Tests;
- PN-G-46865:2002 – Underground mine's vehicles – Diesel suspended monorail locomotives – Requirements.

The standards were developed in KOMAG within the former Standardization Committee No. 148 (at present, Technical Committee No. 285 of the Polish Standardization Committee).

According to Art. 113 of the Act of June 9, 2011, "Geological and Mining Law" [2], the products are used in mining plants, which:

1) meet the requirements regarding the conformity assessment specified in the separate regulations;
2) were specified in the regulations issued on the basis of Item 15, meet the technical requirements included in those regulations referred hereinafter as "technical requirements", received approval for operation in mining plants as well as those that are marked in the way that is specified in those regulations… Thus, it should be stated that, according to the above-mentioned act, "putting into operation in the mining plant the facilities, machines, equipment, and longwalls as well as making their significant design changes or significant changes to the operational conditions requires the permission of the mining plant manager".

It should also be mentioned that, according to the Regulation of Council of Ministers of April 30, 2004, on approval for products to be used in mining plants [3] (which is still in force), the following machines are mentioned in Annex 1:

– machines for rope transportation, suspended monorails, and their subassemblies;
– cars for personnel transportation as well as special transportation cars and vehicles with diesel drives.

These require the approval of the State Mining Authority.

2.1. Requirements for safe operation of diesel drive in workings threatened by explosion hazard

The PN-EN 1834-1:2002 standard includes four main configurations of diesel systems for potentially explosive atmospheres (Fig. 1). They were classified according to area from which the air is sucked and the area to which the exhaust gases are emitted.

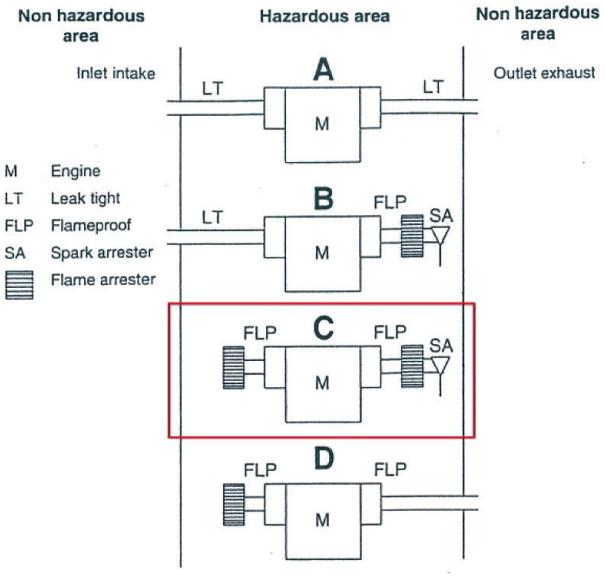


Fig. 1. Main configuration of diesel systems for potentially explosive atmospheres [4]

According to the PN-EN 1834-2:2002 standard, configuration "C" (Fig. 1) presents a diagram of a diesel drive intended for areas threatened by methane and/or flammable dust explosion hazard. In this configuration, air is sucked from and combustion products are emitted to the potentially explosive atmosphere. Air inlets and exhaust gas outlets should be protected by flame arresters, and part of the drive between them should be of anti-explosion manufacture that meets the requirements for Group I of the PN-EN 60079-0:2013-03 standard (Explosive atmospheres – Part 0: Equipment – General Requirements).

It is necessary to equip the driving system with the automated stopping (switching off) of the diesel engine when the permissible value of rotary speed is exceeded as well as the automated stopping or self-protection of the engine should occur in the case of the following hazards [4]:

– exceeding the permissible temperature of the liquid in a diesel engine cooling system;
– insufficient pressure of lubricating oil;
– not enough liquid in the cooling system;
– exceeding the permissible temperature of the exhaust gases;
– exceeding the permissible temperature of the engine oil;
– exceeding the permissible temperature of the hydraulic oil.

Additionally, in the case of one of the above-mentioned hazards, the control system should signalize the emergency state. A fuel cut-off from the system supplying the engine should be the method for the automated stopping of the engine (both normal and emergency), and moreover, each engine should be equipped with a valve cutting off the air supply [4].

The requirements regarding the permissible temperature of the external surface of the components of the whole driving system is one of the most important conditions that are necessary to be met when diesel engines are used in mining diesel drives operated in coal mines. According to the requirements of PN-EN 1834-2:2002, the temperature of the external surfaces of all engine components and the temperature of the exhaust gases emitted to the atmosphere after the flame arrestor cannot exceed 150°C. This refers to the operational conditions of the engine under full load [4]. The full scope of the requirements and the method for their verification are included in the PN-EN 1834-2:2002 standard as well as other related standards.

2.2. Requirements regarding quality of exhaust gases

The permissible emissions of toxic substances in the exhaust gases from the engines installed in machines designed for operation in mine undergrounds are given in Table 1. They are identical to the values included in the PN-EN 1679-1+A1:2011 standard harmonized with the Machinery Directive. They refer to diesel engines featuring power from 37 to 560 kW.

Table 1

Emission limits of toxic substances according to PN-EN 1679-1+A1:2011[4]

Power	Carbon monoxide CO	Hydrocarbons HC	Nitrogen oxides NO_x	Particulate matter PM
[kW]	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]
37–75	6.5	1.3	9.2	0.85
75–130	5.0	1.3	9.2	0.70
130–560	5.0	1.3	9.2	0.54

In Table 2, the permissible emissions of toxic substances in exhaust gases specified in repealed Diesel Engine Directive (Directive No. 97/68/EC).

Transition to Stage IIIB requirements; i.e., a reduction of emissions of particulate matters (PM) by about 90% as well as a reduction of emissions of nitrogen oxides (NO_x) by 50% was the most significant change in the requirements for the emission of exhaust gases. Stage IV requirements further reduced the emissions of nitrogen oxides (NO_x) to even a level of zero. Regarding the emission of exhaust gases from non-road mobile machines, Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016, repealing the Diesel Engine Directive and introducing the Stage V requirements (Tab. 3) became in force starting on January 1, 2016. The requirements significantly reduced the level of particulate pollutants as related to the Stage IV requirements of the repealed Diesel Engine Directive.

The determination of emission limits for exhaust gases from engines intended to be installed in non-road mobile machinery operating in a potentially

Table 2

Emission limits of toxic substances according to Diesel Engine Directive [5, 6]

Power	Date of incorporation	Carbon monoxide CO	Hydrocarbons HC	Nitrogen oxides NO_x	Particulate matter PM
[kW]	–	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]
Stage I					
37–75	04.1999	6.5	1.3	9.2	0.85
75–130	01.1999	5.0	1.3	9.2	0.70
130–560	01.1999	5.0	1.3	9.2	0.54
Stage II					
19–37	01.2001	5.5	1.5	8.0	0.8
37–75	01.2004	5.0	1.3	7.0	0.4
75–130	01.2003	5.0	1.0	6.0	0.3
130–560	01.2002	3.5	1.0	6.0	0.2
Stage IIIA					
19–37	01.2007	5.5	NO_x + HC – 7.5		0.6
37–75	01.2008	5.0	NO_x + HC – 4.7		0.4
75–130	01.2007	5.0	NO_x + HC – 4.0		0.3
130–560	01.2006	3.5	NO_x + HC – 4.0		0.2
Stage IIIB					
37–56	01.2013	5.0	NO_x + HC – 4.7		0.025
56–75	01.2012	5.0	0.19	3.3	0.025
75–130	01.2012	5.0	0.19	3.3	0.025
130–560	01.2011	3.5	0.19	2.0	0.025
Stage IV					
56–130	10.2014	3.5	0.19	0.4	0.025
130–560	01.2014	5.0	0.19	0.4	0.025

explosive atmosphere in Annex VI of Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016 (Tab. 4), is an important novelty as related to the previous regulations.

Table 3

Emission limits of toxic substances according to the Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016

Power	Date of incorporation	Carbon monoxide CO	Hydrocarbons HC	Nitrogen oxides NO_x	Particulate matter PM
[kW]	–	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]
Stage V					
37–56	01.2019	5.0	NO_x + HC – 4.7		0.015
56–130	01.2020	5.0	0.19	0.4	0.015
130–560	01.2019	3.5	0.19	0.4	0.015

Source: based on data included in above-mentioned regulation

As related to the PN-EN 1679-1+A1:2011 standard, the current regulations are significantly tightened up regarding hydrocarbon (HC) limits and especially for nitrogen oxides (NO_x) and particulate matters (PM), leaving the carbon monoxide (CO) limit at nearly the same level. From a comparison of the data given in Tables 1 and 2, it results in the fact that engines meeting the requirements of the PN-EN 1679-1+A1:2011 standard refer to those engines that meet the Stage I requirements included in the repealed Diesel Engine Directive. Thus, we can see some discrepancies in the European Union requirements. In the scope of the quality of exhaust gases, new commercialized mobile machines with diesel drives intended to be used in underground workings not threatened by explosion hazard (e.g., tire vehicles) should meet the Stage V requirements given in Table 3. Mobile machines (including underground locomotives for mine railways) intended to be used in atmospheres threatened by methane and/or flammable dust explosion hazard should meet the requirements given in Table 4 referring to the Stage IIIA requirements of the repealed Diesel Engine Directive. Other machines operating underground can meet the exhaust gases emission requirements given in Table 1.

One's attention should be drawn to the Regulation of Ministry of Energy of November 23, 2016, on the detailed requirements for mine underground transportation [7] that have been in force since July 1, 2017, where the following entries are in §635:

1. In diesel vehicles and machines, compression-ignition engines are used.
2. The content of carbon monoxide in the gases emitted from an engine exhaust system should not be higher than the following:
   - 500 ppm – in mines not threatened by methane explosion hazard;
   - 500 ppm – in mines threatened by methane explosion hazard, in the case when the methane concentration in the sucked air is 0.0%;
   - 1200 ppm – in mines threatened by methane explosion hazard, in the case when the methane concentration in the sucked air is 1.0%;
   - 1800 ppm – in mines threatened by methane explosion hazard, in the case when the methane concentration in the sucked air is 1.5%.
3. The number of diesel vehicles and machines operating at the same time in a working is set in such way as to not exceed the concentration limits of the harmful exhaust gases mentioned in §142, Item 2 (i.e., carbon dioxide – max. 1%; carbon monoxide – max. 0.0026%; nitrogen oxides – max. 0.00026%; sulphur dioxide – max. 0.000075%; hydrogen sulphide – max. 0.0007%; and oxygen concentration – min. 19%).

Table 4

Emission limits of toxic substances according to the Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016, for the engines intended to be installed in non-road mobile machinery operating in potentially explosive atmospheres

Power	Date of incorporation	Carbon monoxide CO	Hydrocarbons HC	Nitrogen oxides NO_x	Particulate matter PM
[kW]	–	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]
37–56	01.2017	5.0	NO_x + HC – 4.7		0.4
56–130	01.2017	5.0	NO_x + HC – 4.0		0.3
130–560	01.2017	3.5	NO_x + HC – 4.0		0.2

Source: table compiled on basis of data included in above-mentioned regulation

Thus, we can observe differences in the above-mentioned European regulations (e.g., a lack of requirements for nitrogen oxides, hydrocarbons, and particulate pollutant emission limits), and the ventilation conditions in the working are the criterial factor when deciding about the approval of using a diesel machine in a given underground working. The control requirements for diesel drives during their operation were not specified, assuming that the manufacturer of each machine determines the requirements for periodical control (the method and frequency of the control as well as the criteria for further operation) in the technical manual (technical-and-operational documentation).

3. TECHNICAL POSSIBILITIES OF REALIZATION OF REQUIRE-MENTS FOR DIESEL DRIVES OPERATING IN WORKINGS THREATENED BY EXPLOSIVE HAZARDS

Bearing in mind the requirements of the so-called Diesel Engine Directive, the engines' manufacturers developed adequate solutions in their products for use in non-road machinery operating on the surface. An example of a solution of one of the manufacturers is given in Table 5.

Table 5

Development of diesel engine solutions for non-road vehicles [8]

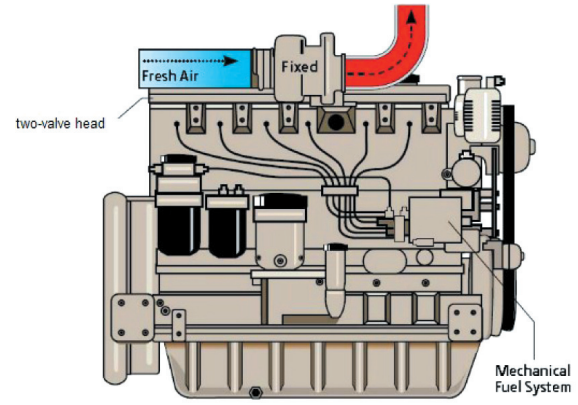
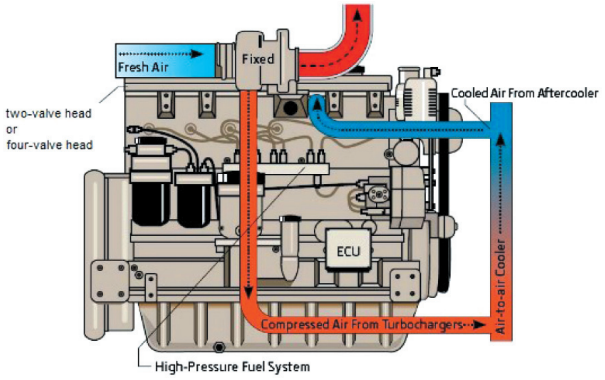
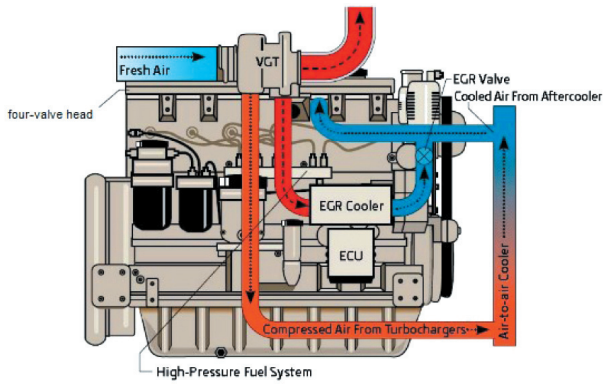
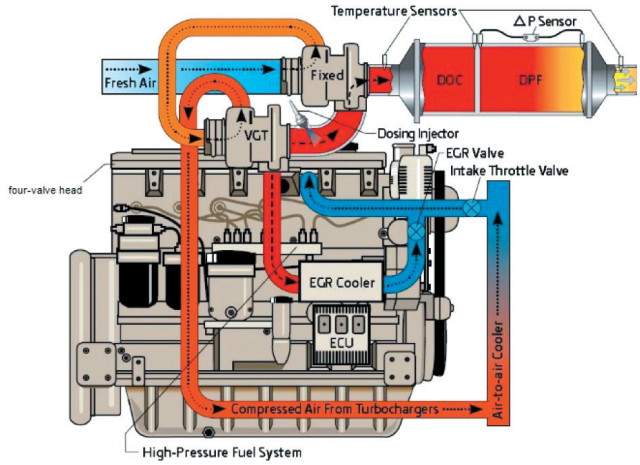
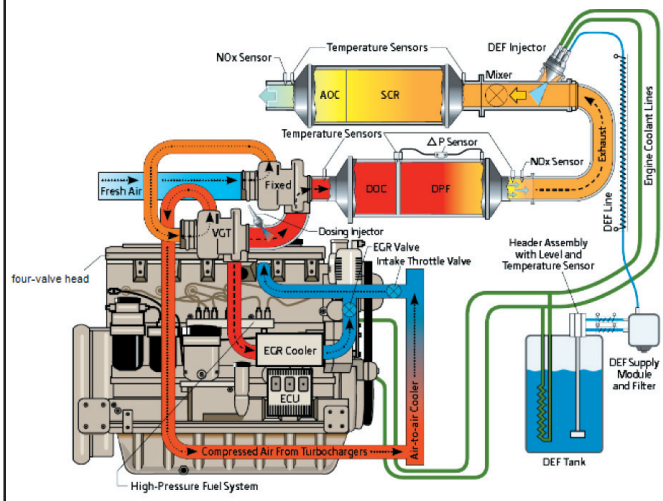
Stage	Diagram	Description
I		Presented system is simplest solution with mechanically controlled inline diesel injection pump and distributor diesel injection pump [9]. Engine is equipped with two-valve head, typical turbocharger with fixed geometry of guide's blades, simple intake system with air filter, and exhaust system.
II		Equipping engine with high-pressure fuel feeding system (e.g., electronically controlled common rail [9], two- or four-valve cylinder head, and cooler of compressed air intake [so-called intercooler] is improving modification of previous system. Engine is usually fitted with turbocharger of guide's blade fixed geometry. Use of intercooler allows for increasing engine power, while electronically controlled fuel injection system decreases emission of hazardous substances with exhaust gases.
IIIA		Another step, is use of EGR system with its own cooler and turbocharger of blade variable geometry. Use of cooled stream of exhaust gases lowers temperature of combustion process, limiting emission of nitrogen oxides (NO_x). Turbocharger of variable guide's blade geometry improves engine operational characteristics (e.g., reduces so-called turbo lag effect at low outlet speed of exhaust gases).

Table 5 cont.

IIIB		Further improvement consisted in using the out-of-the-system exhaust gases processing. Presented example shows oxidation catalytic reactor and a particulate matter filter. It allows to reduce the content of such substances as carbon monoxide, hydro-carbons, and particulate matter.
IV		Most advanced system connecting all previous systems and adding SCR system (selective catalytic reduction). Due to feeding reductive substance (i.e., UAN water solution), further reduction of nitrogen oxides in exhaust gases is observed.

Basing on information included in Table 5, we can conclude that:

- the requirements for exhaust gases quality at Stages I, II, and IIIA were met due to the improvement of the engine feeding system, especially the control of the time and number of fuel injection stages;
- the emission level of each substance according to the requirements of Stages IIIB and IV can be satisfied only by using the so-called off exhaust gases processing system (consisting of a catalytic reactor, particulate matter filter, and other components).

It should be mentioned that none of the diesel engine manufacturers adapts the already-made engines for operation in underground workings threatened by methane and/or flammable dust explosion hazard, leaving the problem to be solved by the manufacturers of underground mining machines with diesel drives.

A sample design of the anti-explosion manufacture of a diesel drive system for transportation machines used in underground workings threatened by methane and/or flammable dust explosion hazards is presented in Figure 2.

The engine was equipped with a liquid-cooled exhaust manifold and turbocharger as well as an exhaust gases outlet hose with a water jacket. In place of an exhaust gas water washer, a “dry” heat exchanger can be used. In the case of a water washer, the exhaust gases flow through its chambers and are cooled down by contacting the cooling water, and the soot is washed out. Periodic replacement of the water is required (after each working shift). The evaporation of water and its frequent splashing out have an adverse impact during operation. In a “dry” heat exchanger, exhaust gases do not directly contact the cooling water, so the soot is not removed from the exhaust gases

An additional water cooling system is requited (pump, cooler). Electronic supervising systems controlling the parameters deciding about safe operation are installed. In Figure 3, a sample design of a diesel engine meeting the Stage I requirements equipped with a water system cooling the turbocharger and an outlet exhaust gases collector is shown.

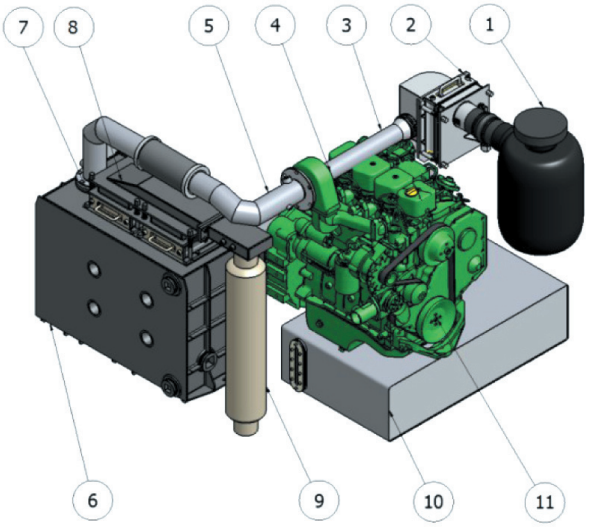


Fig. 2. Sample design of engine unit intended to operate in atmosphere threatened by methane and/or flammable dust explosion hazard meeting Stage I/II requirements: 1 – air filter, 2 – flame arrester in inlet system, 3 – inlet hose, 4 – turbocharger, 5 – exhaust gases outlet hose, 6 – water exhaust gases washer, 7 – flame arrester in exhaust system, 8 – exhaust manifold, 9 – spark arrester, 10 – fuel tank, 11 – diesel engine [5]

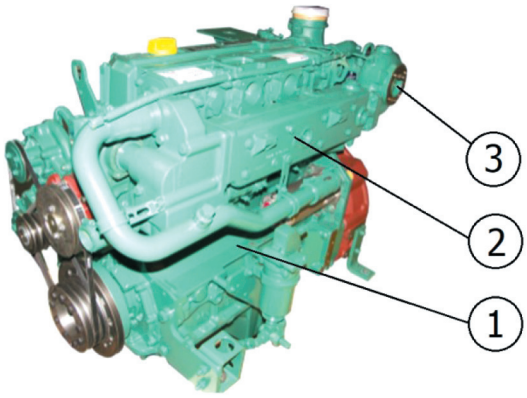


Fig. 3. Sample design of engine unit intended to operate in atmosphere threatened by methane and/or flammable dust explosion hazard meeting Stage I/II requirements: 1 – diesel engine, 2 – liquid-cooled outlet exhaust gases collector, 3 – liquid-cooled turbocharger [5]

The diesel engines used so far by the Polish manufacturers of transportation machines to be used in underground workings threatened by methane and/or flammable gas explosion hazards meet the requirements of the Diesel Engine Directive – Stage II, and incidentally Stage IIIA. The use of engines meeting current requirements needs further research work. A testing infrastructure, an experienced staff, and testing facilities enable us to conduct such research work at KOMAG. Figure 4 shows a sample design of an industrial diesel engine meeting Stage IV/V requirements.

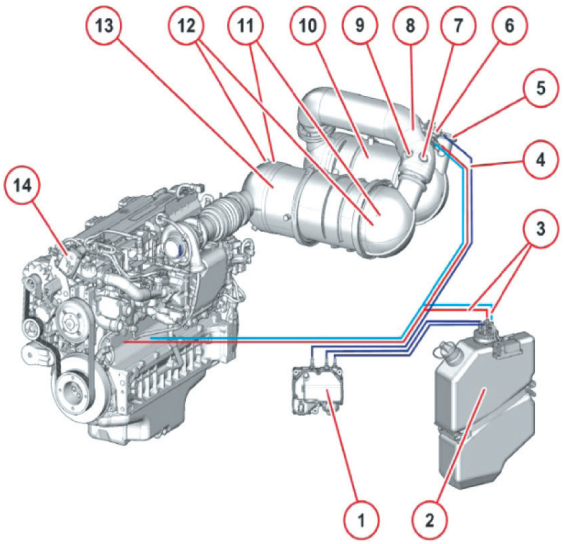


Fig. 4. Sample design of industrial diesel engine meeting Stage IV/V requirements: 1 – SCR supply pump, 2 – SCR tank, 3 – coolant line for preheating SCR tank for cooling metering unit, 4 – SCR hose, 5 – NO_x sensor, 6 – metering unit, 7 – NO_x sensor, 8 – temperature sensor, 9 – pressure sensor, 10 – SCR catalytic reactor, 11 – differential pressure sensor, 12 – temperature sensor, 13 – diesel particle filter (DPF) for diesel engines, 14 – throttle valve [11]

The adaptation of engines for operations in areas threatened by methane and/or flammable dust explosion hazards according to the requirements of the ATEX Directive as well as the Diesel Engine Directive include the following [10]:

- protection of exhaust gases collector and turbocharged surfaces against excessive temperatures,
- anti-explosion protection of intake-outtake system of flame arrester,
- anti-explosion protection of engine's electrical equipment – injectors, sensors, engine controller, alternator, and starter.

The adaptation of a factory-made engine meeting Stage IIIA level requirements requires the design of a diesel drive for operation in areas threatened by methane and/or flammable dust explosion hazards

and requires undergoing research and development work related to the following:

– development of water-cooled outtake exhaust gases collector and turbocharger in anti-explosion (flameproof) manufacture,
– adapting the existing control system (controller, sensors) to explosive atmospheres.

It is essential to adapt the injectors to operate in a potentially explosive atmosphere. Due to the need for the precise positioning of the injectors in pockets, stable fixation, and high operating temperature, their adaptation to meet the ATEX Directive requirements is a complex technological issue. Close cooperation with the engine's supplier is necessary.

4. SUMMARY

The transportation of materials and run-of mine as well as the transportation of personnel are important parts of the mining processes. In the beginning of the 1990s, trains with diesel drives started to be used in place of the widely used cable driven transportation machines in coal mines due to the latter's limitations. The created infrastructure (depots, refueling chambers) contributed to the use of underground diesel locomotives. The implemented diesel drives should meet the safe operation requirements in workings threatened by explosion hazards as well as EU exhaust gases quality requirements. Discrepancies in these requirements were indicated. The standards harmonized with the Machinery Directive indicate that rubber-tired vehicles as well as mobile machines (including underground locomotives) are intended for use in atmospheres potentially threatened by methane and/or flammable dust explosion hazards need to meet the much more restrictive requirements of Regulation (EU) 2016/1628 of the European Parliament and of the Council of September 14, 2016 (Stage V and Stage IIIA) than the requirements for other machines, included in PN-EN 1679-1+A1:2011 standard.

Engine manufacturers offer engine designs meeting Stage V exhaust gases emission regulations for non-road vehicles but do not offer engines for mobile machines intended for use in atmospheres potentially threatened by methane and/or flammable dust explosion hazards. To adapt the engine to the requirements of the ATEX Directive, it is necessary to conduct R&D work, including the following:

– protection against excessive surface temperature of outlet exhaust gases collector and turbocharger,
– anti-explosion protection of intake-outtake flame arrester system,
– anti-explosion protection of engine's electrical equipment – injectors, sensors, engine controller, alternator, and starter.

The above-mentioned work can be realized by KOMAG in close cooperation with the engine manufacturer.

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EDWARD PIECZORA, Ph.D., Eng.
PIOTR DOBRZANIECKI, Ph.D., Eng.
KOMAG Institute of Mining Technology
ul. Pszczyńska 37, 44-101 Gliwice
{epieczora, pdobrzaniecki}@komag.eu