

Concept of the exhaust system for diesel engines used in underground mining

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Abstract. The article presents the selected problems resulting from operation of diesel engines in the mining industry, resulting from necessity of meeting the current regulations. These regulations regarding the engines working in underground workings include: new emission limits of each toxic substance in exhaust gases, issues related to anti-explosion protection and limitations associated with the maximum temperature of the external surfaces of the drive unit and the emitted gases. The article shows own concept of the exhaust system that improves the quality of exhaust gases which meet safety requirements. The concept of a heat exchanger, which reduces temperature of exhaust gases, in which the heat pipes are suggested to be used for heat transport, is also given. Project assumptions and the anticipated research process were discussed.

1. Introduction

Reciprocating combustion engine (ZS) is one of the drive systems used in transport, during operations in underground mine workings.

Among many hazards occurring in underground mine workings (especially in hard coal mines), the presence of potentially explosive atmospheres can be mentioned, which is associated with the presence of coal dust and methane.

In connection with the above, the safe use of diesel engines requires meeting many technical requirements, both for the engine and the accompanying accessories. One of the problems is to keep the temperature of the external surfaces and exhaust gases from the engine exhaust system, below 150 °C. The fulfillment of this criterion entails the necessity of using additional cooling systems, which increase the dimensions and mass of the final devices, and often their use is associated with the necessity of frequent water refilling (e.g. in wet heat exchangers). An additional problem, especially important in closed spaces, such as underground mine workings, is the reduction of emissions of exhaust gases toxic components emitted by diesel engines.

Therefore, there is an urgent need to modify the currently used solutions, in order to get easier service, reduce the size and weight of the exhaust system elements and reduce toxic components emissions .

2. Legal conditions



Safety requirements related to the use of diesel engines in potentially explosive atmospheres are described in a series of Standards PN-EN 1834. When using diesel engines for underground work in zones threatened by occurrence of methane and / or combustible dust where both the air required for the combustion process as well as its by-products (exhaust gases) are taken from and emitted to the area of potentially explosive atmospheres. Due to the presence of combustible coal dust in underground hard coal mine workings, one of the requirements is to limit the maximum temperature to 150 °C. This restriction applies to the external surfaces of the engine as well as to all its components, the charged air and the exhaust gases emitted to the atmosphere. The main requirement put to air intake and exhaust systems is a necessity of equipping them with the flame arrester, and additionally equipping the exhaust system with spark arrester.

Aspect that is particularly important in underground mine workings is the quality of emitted exhaust gases. Specific requirements in this regard depend on engine power and they are described in the Standard EN 1679-1:1998+A1:2011 [1], being the standard harmonized with the Machinery Directive [2]. Requirements of the emission limit by diesel engines operating in underground mine workings are also defined in the Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery [3]. This regulation repealing the Commission Directive 2012/46/EU of 6 December 2012 amending Directive 97/68/EC of the European Parliament and of the Council on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery [4] (i.e. combustion directive), in terms of gaseous and particulate pollutants from internal combustion engines, and at the same time is a superior document in relation to the requirements of Standard.

In opposition to the previous combustion directive [4], which in terms of acceptable pollutants, equally treated engines operating in potentially explosive atmospheres and besides it, Regulation 2016/1628 [3] define different (milder) requirements for engines used in explosive atmospheres in relation to engines operating besides this atmosphere. In practice, for the engine power range of 37 to 560 kW, the requirements of Regulation 2016/1628 [3] coincide with the requirements of STAGE IIIA of the so far in force combustion directive [4].

3. Currently used drive systems

Diesel engines currently used in the underground mines were adapted by their end manufacturers. The currently used drive systems meet the requirements of STAGE II, and in the incidental cases the requirements of Stage III A [5].

The reason that until now the engines complying with STAGE IIIA and higher haven't been successfully introduced in the hazardous areas, is a relatively low demand for such engines. Therefore, there is no interest from engine manufacturers to adapt engines to meet the demanding explosion-proof requirements of the ATEX Directive [6]. At the same time, it is difficult to adapt the existing engines by end device manufacturers due to technological reasons.

Adaptation of the engine to the requirements of the ATEX Directive includes [7]:

- temperature protection of the exhaust manifold surface and compressor - available in current solutions,
- anti-explosion protection of the intake/exhaust system with flame arresters - available in current solutions,
- anti-explosion protection of the electric equipment of the engine - injectors, sensors, engine controller - not available in the current solutions,
- application of the aftertreatment system and its thermal and explosion protection - partly available in current solutions.

The problem in adaptation of the non-ATEX version engines, meeting the requirements higher than STAGE II to the ATEX requirements, is a need to modify the injection systems and their controllers. However, this is difficult because there are no injectors available in the explosion-proof version.

Meeting the requirements of STAGE IIIB and higher in the scope of emissions of individual substances in exhaust gases, can only be met by means of the so-called aftertreatment, consisting of catalysts, particulate filter and others.

The currently used exhaust gases cooling systems as well as flame arresters are presented, for example, in [8].

4. Concept of exhaust gas systems and flame arresters

4.1. Exhaust gases system

Due to difficulties in adapting the engines meeting the requirements of STAGE IIIA (described above) for work in potentially explosive atmospheres, this research work focused on reducing the harmful substances emitted by diesel engine by using the aftertreatment system. For this purpose, the concept of an engine exhaust system equipped with a DOC (diesel oxidate catalyst) and a DPF (diesel particulate filter) was developed. Thanks to the use of the DOC reactor, a significant reduction of CO and HC concentrations in exhaust gases is expected (> 90%) [9].

In order to meet the safety requirements related to the meeting the surface temperature limit of 150 °C, it is necessary to equip the reactor with a water jacket. On the other hand, cooling the reactor surface can reduce the efficiency of the DOC reactor. For this reason, it is suggested to apply additional air insulation between the surface of the reactor and the water jacket (figure 1).

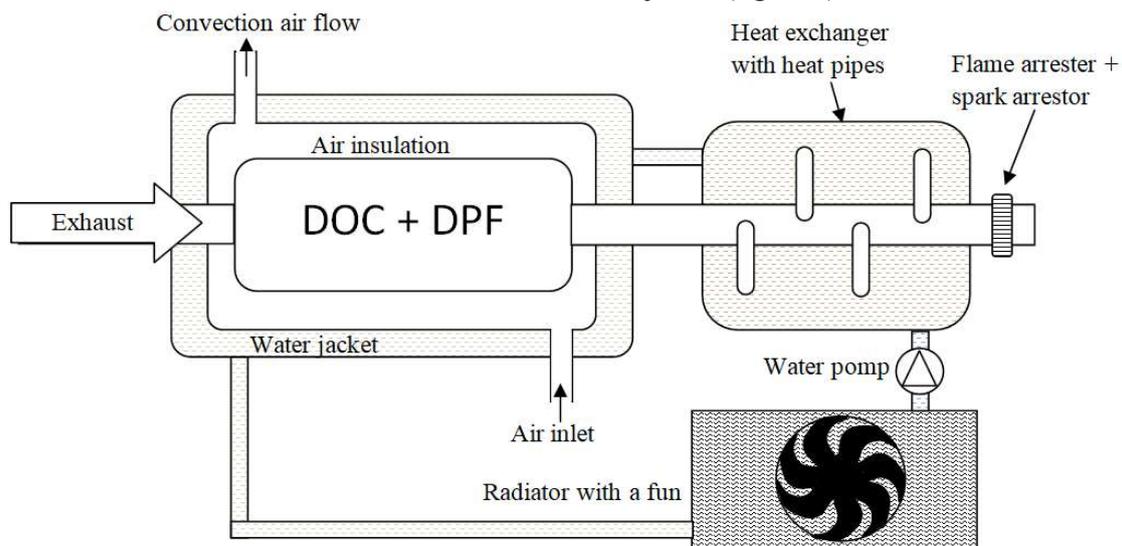


Figure 1. Exhaust system concept with aftertreatment system, adapted to work in potentially explosive atmospheres

An increase of temperature of exhaust gases is expected, due to the use of a DOC reactor. Therefore it is necessary to provide a more efficient cooling system for exhaust gases in relation to current solutions that are not equipped with aftertreatment system. The suggested concept of a heat exchanger assumes the separation of exhaust gases from refrigerant. In order to reduce the exhaust gas temperature more effectively, below the permissible value of 150 °C, it is suggested to use heat pipes, which when transporting heat, use a two-phase, closed cycle of evaporation and then condensation of the working fluid partially filling its interior [10]. The benefits of using heat pipes are related to the smaller dimensions of the heat exchanger and the lower thermal inertia of the system.

In its conventional form, the heat pipe is a two-sided closed thin-walled pipe that can be made of copper or aluminum and covered with an anti-corrosive coating, e.g. chromium. Table 1 shows the operating temperature of the heat pipes depending on the working fluid used.

Table 1. Examples of working fluids and the operating temperature of heat pipes resulting from their use [11]

Working fluid	Operating temperature [°C]	Working fluid	Operating temperature [°C]
Helium	-271 ÷ -269	Mercury	250 ÷ 650
Ammonia	-60 ÷ 100	Sulfur	257 ÷ 674
Acetone	0 ÷ 120	Cesium	450 ÷ 900
Methanol	10 ÷ 130	Rubid	527 ÷ 1002
Water	30 ÷ 277	Calcium	1127 ÷ 1827
Naphthalene	135 ÷ 350	Lead	1397 ÷ 1927

A characteristic feature of a heat pipes is that they can transport high-density heat flux, many times larger than in the case of bars of similar size and made even of the best heat conductors [10].

Use of heat pipes instead of homogeneous heat conductors (rods), allows to limit the dimensions and mass of manufactured heat exchangers. The sample heat pipe with a diameter of 0.6 cm, a length of 30 cm, with a temperature difference of 3 °C, has heat dissipation power of 180 W. To obtain the same parameters using a homogeneous copper cylinder of the same length, its diameter would have to be 24.4 cm and the mass would be about 125 kg [12].

Due to high efficiency of heat transport through the heat pipes, it will be possible to take it faster from the exhaust gases. From the considerations it follows that the heat pipe reaches the best parameters, the operating temperature range and the maximum heat removal rate, for the vertical operation at the at the top condensation zone and the evaporation zone being at the bottom. Due to the fact that heat pipes can be shaped, it is possible to place them in other zones of the heat exchanger than the top.

Figure 2 presents three proposals for a heat exchanger, with heat pipes in a direct contact with exhaust gases, which do not have direct contact with the exhaust gases, as well as those cooled with liquid or air.

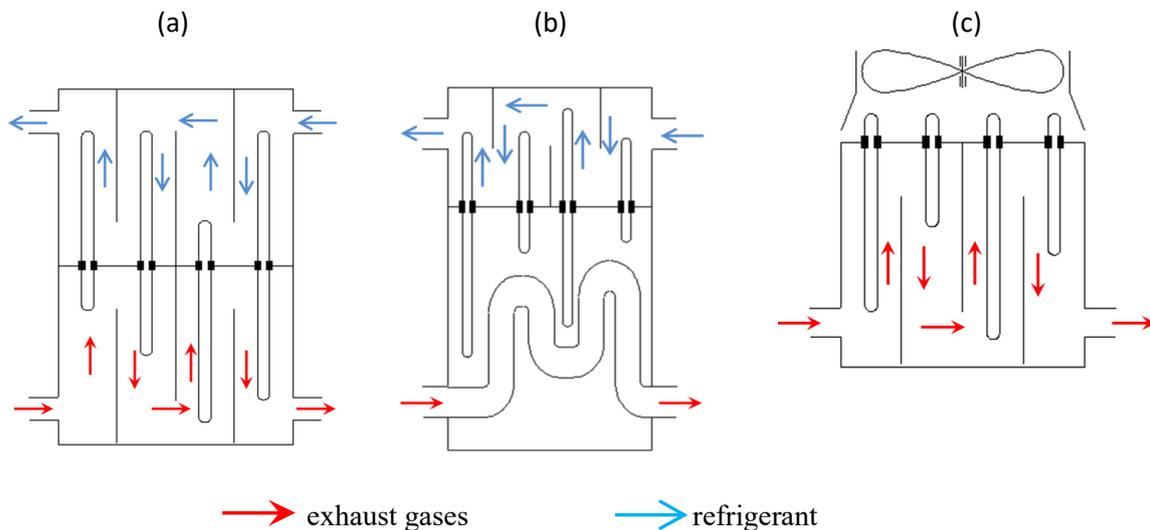


Figure 2. Concept of heat exchanger (a)two-section with pipes having direct contact with the exhaust gases (b)double-section with an additional tube and pipes not in direct contact with the exhaust gases (c)single section, with pipes in a direct contact with exhaust gases and additional air cooling

4.2. Flame arrester

After analyses, it has been suggested to build a flame arrester based on a ceramic core used in catalytic reactors, but without a catalytic coating. Theoretical considerations show that a catalytic core with a cell density of 100 cpsi meets the requirements regarding the gap width for the first explosive group.

The material from which flame arresters is made should meet the requirements of PN-EN 1834-2:2002 [13] Standard. Therefore, prior to designing the flame arrester based on such a core, it is planned to carry out tests on the abrasion resistance of the ceramic core.

Flame arresters used in the mining industry usually come from low-volume production and are often subjected to manufacturing errors. Use of the reactor core will ensure repeatability of the most important flame arrester component.

5. Summary

The article presents the current legal requirements for diesel engines operating in underground mine workings. The issues related to the protection of drive systems used in potentially explosive atmospheres were discussed. Attention was paid to threats resulting from high temperature and flame propagation. The analysis of the legal status shows that the legislators have noticed a problem in adapting drive systems for work in potentially explosive areas. The consequence of this is the relaxation of exhaust gas quality requirements for this type of drive systems.

The article presents the concept of exhaust gas outlet system. The expected benefits of the presented concept include:

- significant reduction of CO, HC in exhaust gases (> 90%),
- smaller dimensions of the exchanger between the exhaust gases and the refrigerant,
- lower weight of the entire exhaust system.

Within the concept development, computational analyses are planned to select the technical parameters for the heat exchanger. As part of the research work on the possibility of using ceramic monoliths, first, it is planned to test the abrasion resistance of ceramic material, which according to the requirements of the Standard PN-EN 1834-2:2002 must be not less than this for stainless steel 14404 or 14435

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