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RETROFITTING ISSUES OF NON-ROAD VEHICLES ON THE EXAMPLE OF A FARM TRACTOR

Summary

It is not possible to meet the current type approval standards for the exhaust emission from internal combustion engines without the use of exhaust aftertreatment systems. An additional problem is in the increased emissions in real driving conditions compared to the values obtained in type approval tests. The current legislative trends are not limited to just lowering the emission limits for new vehicles, but also actions aimed at reducing the impact of vehicles that are already in operation. One of such actions is known as retrofitting, described as retrofitting older structures with modern exhaust aftertreatment systems, without the need for any changes in the engine design. Research has shown that the emission of toxic compounds from agricultural machinery engines can reach values up to 30 times higher than those of an average passenger vehicle. This problem has been noticed by the legislators and regulations concerning operated non-road machines are successively being introduced. Such restrictions are already present in the Berlin city center for example, where all vehicles operated within the given zone must meet the Stage 3b emission limits. Retrofitting is a multi-stage process. The article discusses the issue of performing this process, starting with NRMM (Non-Road Mobile Machinery) emission measurements, through simulation studies of a virtual model of a particulate filter in CFD software (Computational Fluid Dynamics), to verify its operation in an agricultural tractor, i.e. one of the most numerous vehicle types within the non-road vehicle group in Poland.
***Key words**: retrofitting, exhaust emission, particulate matter*

ZAGADNIENIE RETROFITTINGU W POJAZDACH POZADROGOWYCH NA PRZYKŁADZIE CIĄGNIKA ROLNICZEGO

Streszczenie

Nie jest możliwe spełnienie aktualnych norm homologacji typu dla emisji spalin z silników spalinowych bez stosowania układów oczyszczania spalin. Dodatkowym problemem jest zwiększona emisja w rzeczywistych warunkach jazdy w porównaniu z wartościami uzyskanymi w badaniach homologacyjnych. Obecne tendencje legislacyjne nie ograniczają się tylko do obniżenia limitów emisji dla nowych pojazdów, ale także do działań mających na celu ograniczenie wpływu już eksploatowanych pojazdów. Jednym z takich działań jest modernizacja, opisywana jako modernizacja starszych konstrukcji za pomocą nowoczesnych systemów oczyszczania spalin, bez potrzeby wprowadzania jakichkolwiek zmian w projekcie silnika. Badania wykazały, że emisja szkodliwych związków z silników maszyn rolniczych może osiągnąć wartości do 30 razy wyższe niż w przypadku przeciętnego pojazdu pasażerskiego. Problem ten został zauważony przez ustawodawców i sukcesywnie wprowadzane są regulacje dotyczące eksploatowanych maszyn pozadrogowych. Takie ograniczenia są już obecne na przykład w centrum Berlina, gdzie wszystkie pojazdy eksploatowane w ramach danej strefy muszą spełniać limity emisji Stage 3b. Modernizacja jest procesem wieloetapowym. W artykule opisano problem prowadzenia tego procesu, wychodząc z pomiarów emisji NRMM (Non-Road Mobile Machinery), poprzez badania metodą symulacji wirtualnego modelu filtru cząstek w oprogramowaniu CFD (Computational Fluid Dynamics), w celu sprawdzenia jej działania w ciągniku rolniczym, czyli jeden z najliczniejszych rodzajów pojazdów w grupie pojazdów nieporuszających się po drogach w Polsce.
***Słowa kluczowe**: retrofitting, emisja spalin, cząstki stałe*

1. Introduction

Non-road mobile machines (NRMM) cover all types of internal combustion engines, from small stroke engines and spark ignition used in handheld machinery, to engines with a large displacement volume and compression ignition used in the mining industry, as well as railway engines and those intended for floating objects, fueled by liquid or gaseous fuels. In London, construction machinery accounts for 15% of total PM emissions and 12% of NO_x from automotive sources [1]. The share of NO_x emissions is expected to increase in the coming years, as restrictions have been introduced in other transport sectors on the emission of harmful components of exhaust gases by reducing the emission limits. Due to the less restrictive regulations for off-road vehicles compared to even HDV category vehicles, NRMM's share in total NO_x emissions will increase from 15% to 20% in 2005-2020 [1]. Agricultural tractors are covered by a separate directive (EC/167/2013) and must comply with the emission limits from the previous NRMM directive (EC/97/68). Most countries base their legislation on US and EU standards, so it is important that values are set in Europe, which will then be adopted around the world.

Switzerland has stricter rules for construction machinery that require the use of a particulate filter in the exhaust systems of all non-road engines with a capacity of more than 18 kW used throughout the country. Because engines have been working for several decades, the issue of introducing exhaust system components that complement existing solutions has been analyzed to reduce emissions of toxic compounds into the atmosphere. This means that without applying additional requirements for the used engines, modernization devices will be used, affecting the

purity of the emitted exhaust gases (Fig. 1) [2]. This action is referred to as retrofitting.

Source: own study / Źródło: opracowanie własne

Fig. 1. Examples of construction equipment subject to retrofitting
Rys. 1. Przykładowe maszyny budowlane poddane retrofittingowi

2. Emissions regulations for NRMM vehicles in selected European cities

Non-road vehicles are one of the main sources of emission of harmful components of exhaust gases, which is often overlooked. In some cities, they account for 30% of all road pollutants. Construction and agricultural machinery are used for many hours a day during long periods. According to research, NRMM are responsible for 7% of suspended soot and 16% of nitrogen oxides in Europe. The European Union regulation on non-road vehicles regulates emissions from the NRMM to a small extent compared to the regulations for passenger cars and lorries. The table below contains a list of the largest capitals and cities in Europe in terms of the applicable provisions for non-road vehicles (Table 1).

Table 1. Comparison of the advancement level of regulations in selected European cities [3]
Tab. 1. Porównanie stopnia zaawansowania przepisów w wybranych miastach europejskich [3]

Zurich	++	Stockholm	+	Paris	–	Glasgow	–
Vienna	+	Berlin	+	Madrid	–	Prague	– –
London	+	Copenhagen	+	Dublin	– –	Stuttgart	– –
Graz	0	Lyon	0	Rome	– –	Lisbon	– –
Barcelona	0	Dusseldorf	0	Brussels	– –	Luxembourg	– –
Milan	–	Amsterdam	–				

The city with the most developed emissions legislation is Zurich. There is a division into works in urban and private areas within the city. Accordingly, for each case, it is mandatory that machines with engines above 18 kW and 37 kW have a particle filter in the exhaust system [3]. In the case of Vienna, this is the responsibility of engines over 18 kW users. The list also includes cities for which no regulations related to the emission of harmful compounds were adopted, among others Rome and Stuttgart. There are no provisions regarding those cities in which the national and European provisions are introduced. In most cases, EU regulations were adopted, but individual cities did not impose additional recommendations regarding the use of off-road vehicles. In Berlin, a recipe analogous to the well-known vehicle labeling with ecological badges was introduced, which guarantees the possibility of passing through specific areas of the city. In this city, since 2014, construction machinery used on construction sites must comply with the IIIB/IIIA emission standard (IIIA for machines <37KW). This corresponds to the current EU standard set for new machines. Older construction machinery must be equipped with a particulate filter to be legally usable [4]. There is currently no legislation in Poland regarding this aspect.

3. The problem of the apparatus fixing

Due to the completely separate nature of off-road vehicles, their tests constitute a separate challenge required for the retrofitting process. In connection with the introduction of new regulations on emissions, there is a need to study non-road machinery in order to determine the degree of their negative impact on the environment and to verify the applied elements of the exhaust gas treatment system as part of retrieval. Road vehicles, both passenger cars and lorries, are equipped with recesses, luggage racks, storage compartments and holders dedicated to fix positions, which make it possible to mount the test equipment inside them. Despite the large size of non-road machines and the miniaturization of test equipment and the reduction of the number of personnel required to operate, the design of machines very often makes testing impossible [5].

Agricultural tractors are the most popular machines from the NRMM group operated in the country. The weight of the test equipment is a problem when the tractor body shell is made of plastic, which has insufficient bearing capacity. This material is often used to cover the roof, which is the only place where the apparatus can be placed [6]. Due to this, special frames or trailers are designed to allow the analyzers to be placed outside the vehicle. This is not a universal solution, because agricultural machines are adapted to perform various works, which often prevent interference in the vehicle's geometry. In addition, the mass often hinders agricultural work and increases the center of gravity. An example is the weight mounted in the front of the tractors to ensure improved stability and efficiency of work (Fig. 2). Often their shape makes it impossible to mount the frames in a stable manner, which especially applies to smaller units.

Source: own study / Źródło: opracowanie własne

Fig. 2. View of the weight used in the front of the vehicle
Rys. 2. Widok obciążnika stosowanego w przedniej części pojazdu

Source: own study / Źródło: opracowanie własne

Fig. 3. A view of the movable part of harvester that prevents installation of the test equipment
Rys. 3. Widok części ruchomej kombajnu uniemożliwiającej montaż aparatury badawczej

In the case where the vehicle sheathing is made of metal materials, the reason for the inability to attach the test apparatus may be in the nature of the work that the machine performs. An example is a combine harvester whose some elements must remain movable, which prevents the analyzers from being placed on its roof (Fig. 3), close to the end of the outlet system.

4. Apparatus operating conditions

The PEMS (*Portable Emission Measurement Systems*) apparatus is adapted for use outside the laboratory, however, the conditions of use of vehicles with off-road use significantly differ from PC class vehicles. The larger internal combustion engine dissipates more heat, which, if you try to investigate field work carried out at the turn of July and August, can increase the operating temperature of the analyzers to as much as 60-70°C, which may lead to their destruction. The cooling the exhaust sample is then problematic. Before it goes to the NDUV and NDIR analyzer it should be cooled to less than 5 Celsius degrees. Possible discrepancies cause incorrect results of concentration of carbon monoxide and nitrogen oxides. Additional cooling beside the air circulation inside the devices is not possible due to the already mentioned amount of space On the other hand, too low temperature will not allow keeping the temperature of the heating path at the level of about 193 ˚C, which will cause hydrocarbons to condense. Air cooling also causes problems with the settling of pollutants inside the analyzers, which is typical during field tests in dry conditions (Fig. 4a). It is also impossible to use the apparatus in rain and snow (Fig. 4b). A number of problems also occurs during tests carried out on water vehicles, because of salt in seawater additionally acting in a highly corrosive way to the electronics used in the analyzers.

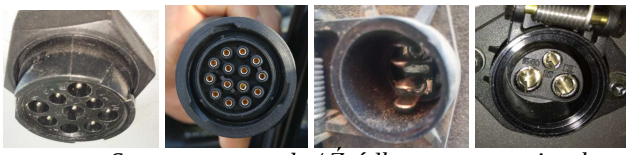
a)

b)

Source: own study / Źródło: opracowanie własne

Fig. 4. Examples of operation conditions of agricultural tractors a) summer, b) winter
Rys. 4. Przykładowe warunki pracy ciągników rolniczych, a) lato, b) zima

The emission unit for vehicles with non-road use is g/kWh. In order to determine it, information about the instantaneous power generated by the engine is required. These data are collected by the engine controller in order to select the parameters of diesel injection. This information is transmitted via the CAN network of the vehicle. This value should be read by PEMS apparatus in order to determine the unitary emission of toxic compounds. The diagnostic connectors in NRMM vehicles are usually separate for vehicles and for the engine. There is no standardization present in PC-class vehicles where DTC connectors are present. Examples of NRMM vehicle class connectors for the diagnostic system are shown in Fig. 5.



Source: own study / Źródło: opracowanie własne

Fig. 5. CAN plugs used in non-road vehicles
Rys. 5. Wtyczki CAN stosowane w pojazdach pozadrogowych

The connectors provided by manufacturers are limited to the most popular solutions, but despite having a proper plug-in, often the data transfer protocol is impossible to read by the apparatus, i.e. the vehicle transmits on several channels at the same time, and the apparatus cannot interpret such results and as a results and thus no signal is read [6]. This results in the necessity of using producer solutions and only at the stage of processing the results, the combination of mass emission with instantaneous motor power, which causes many difficulties with proper start of measurements at the same moment and with the same sampling frequency.

5. Particle filters simulation testing

In order to verify the legitimacy of using diesel particulate filters in the outflow systems of non-road vehicles, a series of virtual filter simulations were performed in the AVL Fire Aftertreatment software, carried out in specific temperature and pressure ranges, with a set of different internal filter structures, i.e. number of cells per front filter surface (CPSI - *Cells Per Square Inch*), as well as the dimensions of the external media and the diameter of the inlet channel (Fig. 6b). These numbers affect the filtering capability of the carrier, thereby increasing the pressure and, consequently, increasing the resistance of the exhaust gas flow. The new design of the filter should have the least possible effect on the exhaust flow resistance, because this value is directly related to fuel consumption and thus carbon dioxide emission (Fig. 6a).

The second problem consists in the construction of the carrier itself. The simulation program only allows filter simulations of the ceramic housing (Fig. 7a), operating on the principle of flow through a porous wall, whereas retrofitting is based on metal supports arising from the coiling of a catalytically thin, corrugated sheet metal that is characterized by a flow structure. This causes a number of problems in the simulation due to changes in the real geometry during the flow of heated exhaust gases (Fig. 7b). The simulations themselves are also burdened with certain approximations related to the wave phenomena occurring in the motor out-

let systems. Virtually all self-ignition engines are equipped with a turbocharging system, combined with control systems, i.e. variable geometry of the turbine steering wheel blades or exhaust vent (wastegate valve). This causes a series of flow disturbances in the channel, which is also shaped depending on the particular engine.

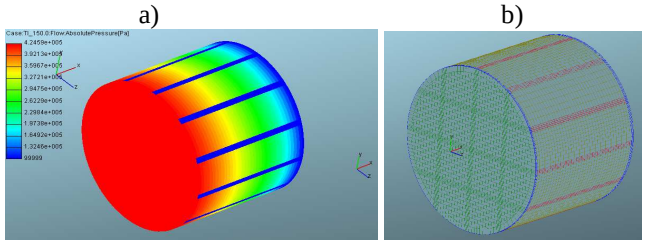


Fig. 6. a) the result of simulation of the absolute flow pressure, b) filter mesh prepared for simulation [7]
Rys. 6. a) wynik symulacji absolutnego ciśnienia przepływu, b) siatka filtra przygotowanego do symulacji [7]

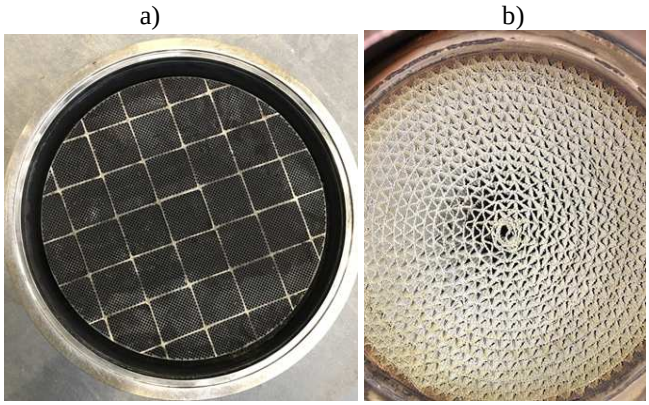


Fig. 7. View of the particulate filter carrier: a) ceramic, b) metal [8]
Rys. 7. Widok nośnika filtra cząstek stałych: a) ceramicznego, b) metalowego [8]

6. Conclusions

Numerous NRMM tests have proved their over-emissivity in real operating conditions compared to the limits contained in the approval standards. Their considerable number and age, as well as the increasing number over the years, mean that their use has a significant impact on the surrounding environment, especially in the field of nitrogen oxides and particulate matter, which are the biggest problems of today's diesel engines. Retrofitting used in HDV vehicles brought the expected results and confirmed that such actions bring a positive effect in the form of reducing emissions by modern exhaust gas treatment systems in used vehicles. The working conditions of NRMM are separate and require separate solutions. The issues described in the article indicate difficulties in carrying out the retrofitting process for NRMM, but these activities will be needed in the future, due to the introduction of restrictions for such machines in various countries and cities.

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