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Characteristics and Diminishing of Gaseous Emission from Diesel Engine*

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Abstract

Operation of compression-ignition engines (6C107), used as propulsion of mining locomotives, was analysed in respect of toxic substances emission. To this end, relative emission indices, defined in relation to fuel consumption and to power output, were taken into consideration. These indices are appropriate quantities because they take also engine operation parameters into account. The experiments were aimed at verifying if the engines meet very strict mining emission standards. The emission was investigated before and after the catalyst. Thus, changes of the indices within the catalyst and conversion rate of the toxic substances were evaluated. The analysis and obtained results were used to:

- determination of the most appropriate running conditions of the tested engines,
- deduction of the methods of gaseous emission reduction at the most unfavourable operation ranges of the engines.

Proposed conception and presented method of considerable gaseous substances emission reduction in the whole operation range of the Diesel engine consists in using oxidation catalyst and cutting-off fuel supply to selected cylinders of the engine.

Key words: *diesel engine, emission reduction, catalytic converter, fuel supply cut-off technique.*

1. Introduction

Potentially toxic constituents of the exhaust gas have come to be widely known as exhaust emissions. The exhaust gases from internal combustion engines contain chemical substances and compounds which have an adverse impact on our environment in the form of acidification, ozone formation, carcinogenic emissions, etc. Therefore, legislation has been introduced imposing limits on what levels of such substances are acceptable in exhaust gases.

The standards are especially stringent for engines used in mining locomotives because exhaust fumes result in poor air. However, the Diesel engines 6C107 in these locomotives were not designed specifically for the mining use. So, reduction of the exhaust emissions from the engines was required to meet the strict limits. These reductions can be achieved by various, carefully designed measures dealing with the engine and catalytic exhaust gas aftertreatment system.

The catalytic converters have undergone remarkable evolution and have widely spreaded during the last 20 years. The first catalytic converters did no more than burn carbon monoxide (CO) and hydrocarbons (HC) that had escaped from the combustion process inside the engine. Now, there is a range of advanced technologies available based on three-way catalysis, adsorption, storage and filtration processes. This enables the treatment of carbon monoxide, hydrocarbons, nitrogen oxides (NO_x) and particulate emissions that cannot be dealt with inside the gasoline or diesel engine, to meet the demands of current and future exhaust emission regulations.

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The USA introduced catalytic converters in 1975, and the first catalyst-equipped cars appeared on European roads in 1985. In 1993 the European Union introduced new car emission standards that effectively mandated the use of catalyst. Now more than 250 million of the word's 500 million cars are fitted with catalyst. Catalytic converters are also increasingly fitted on heavy duty vehicles and off-road engines and vehicles (Searles 1998).

Advanced technology of the catalysts and their substrates ensures high conversion efficiency. Cell density of ceramic substrates has increased from 200cpsi of cross-section to as high as 900cpsi. Wall thickness has reduced from 0.3mm to almost 0.05mm. Metallic substrates also allow high cell density to be achieved. Complex internal structures can be developed with a wall thickness of 0.04mm and cell density of 800cpsi. This progress is extremely beneficial. A larger catalyst surface area allows better conversion efficiency and durability. Thin walls reduce thermal capacity and pressure losses (Searles 1998).

Diminishing of gaseous toxic substances emission from compression-ignition engines can be realized e.g. by application of oxidation catalysts. Diesel-engined cars sold in Europe are now fitted with oxidation catalyst. A few heavy duty and off-road vehicles also use them.

Oxidation catalysts lower particulate mass by up to 50%. This is done by destroying the organic fraction of the particulate and making significant reductions in CO, HC and the characteristic diesel odour. Unfortunately, efficiency of the catalyst is sufficiently high only above boundary value (minimal) of engine load. This is conditioned by suitable temperature level of the catalyst (so-called temperature threshold). During Diesel engine operation at low loads and idling, the temperature of exhaust gas leaving cylinders is considerably lower than during nominal load. As a result, temperature of the catalyst also decreases. This causes reduction of the toxic constituents conversion efficiency within the catalyst.

Therefore additionally, in the indicated operation range of the engine (idling and low load), the selected cylinders disconnection technique is proposed.

2. Selection And Operating Characteristic of Oxidation Catalyst

2.1 Relative emission indices of toxic substances

For the evaluation of the internal combustion engines with regard to the content of toxic substances in the exhaust gas, the use of the relative indices of emission of toxic substances is proposed (Postrzednik and Zmudka 1993). These are defined as follows:

- based on the mass flux of consumed fuel m_f:

$$\varphi_{p,i} = \frac{\dot{n}_{txc,i}}{\dot{m}_f}, \quad \frac{\text{kmol i}}{\text{kg f}}. \tag{1}$$

- or based on the power output N_e:

$$\varphi_{e,i} = \frac{\dot{n}_{txc,i}}{N_e}, \quad \frac{\text{kmol i}}{\text{kJ}} \tag{2}$$

where: $\dot{n}_{txc,i}$, kmol/s - flux of i-th toxic constituent in the exhaust gas: (CO, NO_x, HC, ...).

Index $\varphi_{p,i}$ can be applied in the whole operation range of internal combustion engine, from idling to full load. Index $\varphi_{e,i}$ is less suitable for the evaluation of engine at idling and small loads; for as $N_e \to 0$ the value of $\varphi_{e,i} \to \infty$.

Using the definition of efficiency:

$$\eta_e = \frac{N_e}{\dot{m}_f W_d} \tag{3}$$

where: W_d , kJ/kg - calorific value of fuel, one can give the relation between these mentioned indices:

$$\varphi_{e,i} = \frac{\varphi_{p,i}}{\eta_e W_d} \tag{4}$$

$$\varphi_{e,i} = \frac{\dot{m}_f}{N_e} \varphi_{p,i} \tag{5}$$

From the calculated individual indices of emission for each toxic substance, the corresponding general indices of the exhaust gas toxicity, which represent degree of the gas toxicity, can be obtained:

$$\Phi_p = \sum_{i=1}^{k} w_i \varphi_{p,i} \tag{6}$$

$$\Phi_e = \sum_{i=1}^{k} w_i \varphi_{e,i} \tag{7}$$

where: w_i - equivalency coefficient of i-th substance.

For this purpose, the array of the coefficients w_i, as for example given in (Instructions... 1983) and shown on TABLE I, can be used, which indicates the equivalency of toxicity (to the environment) of each constituent relative to the harmful effect of sulfur dioxide SO_2

TABLE I. EQUIVALENCY COEFFICIENTS w_i

Toxic substance	w_i
acrolein	25.6
aliphatic hydrocarbons	0.1
aromatic hydrocarbons	1.5
benzopyrene	6253.4
carbon monoxide	0.5
leadtetraethyl, TEL	625.3
nitrogen oxide	2.9
soot	8.1
sulfur dioxide	1.0

2.2 Calculation of the indices of toxic substances emission

The flux of the i-th toxic substance can be calculated as:

$$\dot{n}_{txc,i} = \dot{n}_{de} [txc]_i \qquad (8)$$

where: $\dot{n}_{de}$, kmol/s - molar flux of dry exhaust gas,

$[txc]_i$ - molar fraction of toxic constituent in dry exhaust gas, e.g. [CO], $[NO_x]$, [HC].

From (1) and (8) one obtains:

$$\varphi_{p,i} = \frac{\dot{n}_{de}}{\dot{m}_f} [txc]_i \qquad (9)$$

where

$$\frac{\dot{n}_{de}}{\dot{m}_f} = n_{de}'' \qquad (10)$$

is the specific quantity of dry exhaust gas, then:

$$\varphi_{p,i} = n_{de}'' [txc]_i \qquad (11)$$

and

$$\varphi_{e,i} = \frac{n_{de}'' \dot{m}_f}{N_e} [txc]_i \qquad (12)$$

The specific quantity of dry exhaust gas $\dot{n}_{de}$ $_e$ can be calculated from the balances of the elements taking part in the combustion process (Szargut 1985). In this case, previous knowledge of the elementary fuel composition is required. Then, the molar flux of the dry exhaust n_{de} can be computed using the specific quantity of the dry exhaust and mass flux of fuel consumed.

2.3 Experimental results of toxic substances emission

The diesel engine 6C107 used as a propulsion of mining locomotives was an object of the research carried out. The general data of the engine tested are given in TABLE II and its other specifications are the following:

- four stroke,
- six cylinders in-line,
- direct injection,
- naturally aspirated,
- toroidal combustion chamber in a piston.

Different variations of the 6C107 engine allow it to be also applied to drive:

- trucks of gross mass up to 12 metric ton,
- medium capacity buses,
- self-propelled vehicles and machines,
- agricultural machinery.

TABLE II. GENERAL DATA OF THE 6C107 DIESEL ENGINE TESTED

Parameter	Value
maximum power	98 kW (2400 r.p.m.)
maximum torque	380 Nm (1600 r.p.m.)
cubic capacity	6540 cm^3
cylinder bore	107.19 mm
piston stroke	120.65 mm
compression ratio	16
minimum specific fuel consumption	250 g/kWh

The relative indices of emission were investigated at the whole operation range of the diesel engine tested, which was equipped with prototypical oxidation catalyst. They were calculated:

- for carbon monoxide

$$\varphi_{p,CO} = n_{de}'' [CO] \qquad (13)$$

$$\varphi_{e,CO} = \frac{\dot{m}_f}{N_e} n_{de}'' [CO] \qquad (14)$$

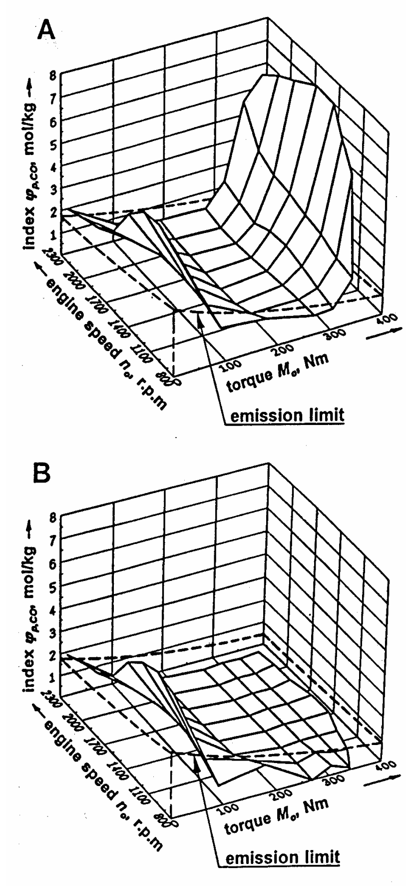

Figure 1. Relative index of emission of carbon monoxide, $\varphi_{p,CO}$; diesel engine - 6C107, ***A*** *- before catalyst,* ***B*** *- after catalyst.*

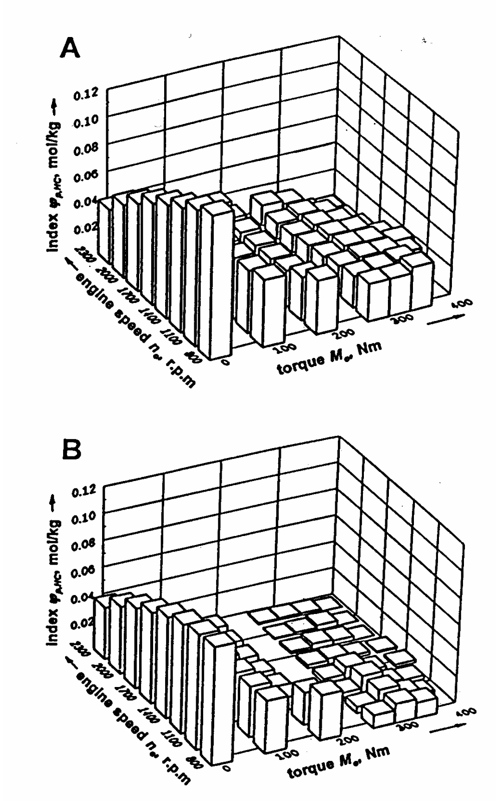

Figure 2. Relative index of total emission of hydrocarbons $\varphi_{p,HC}$; diesel engine - 6C107,
***A** - before catalyst,* ***B** - after catalyst.*

- for hydrocarbons

$$\varphi_{p,HC} = n_{de}''[HC] \qquad (15)$$

$$\varphi_{e,HC} = \frac{\dot{m}_f}{N_e} n_{de}''[HC] \qquad (16)$$

Characteristics of the index $\varphi_{p,CO}$ of the carbon monoxide emission before and after catalyst are presented in the *Figure 1*. The values of the index $\varphi_{p,CO}$ before catalyst are unacceptable under high as well as low loads and idling (*Figure. 1A*). The most appropriate running conditions of the tested engine, on the basis of the index $\varphi_{p,CO}$, exists at medium engine load over the whole speed range.

The use of the catalytic converter improves situation decidedly at the greater part of the operation range of the engine (*Figure 1B*). First of all for high and mean loads. Here, conversion rate of the CO exceeds 90%. Efficiency of the catalyst is considerably smaller at low loads.

A trend of the index $\varphi_{p,HC}$ of the hydrocarbons emission is presented in *Figure 2*. The highest values occur at low loads and the idle running, especially for small engine speed. However the highest efficiency of the converter exists at high and mean loads.

3. Selected Cylinders Fuel Supply Cut-off Technique

High conversion rate of the measured toxic constituents was stated at mean and high load. Thus, at this range, the tested catalyst can be used for the diesel engines 6C107 as an equipment effectively reducing the level of carbon monoxide and hydrocarbons emission. But conversion efficiency of the catalyst is small at idling and low load. So, at this range of engine operation the other methods of emission decrease should be applied. It can be e.g. selected cylinders fuel supply cut-off method (*Figure 3*).

The applied method is based on suitable correction of edges of injection pump plungers (Postrzednik and Ciesiokiewicz, 1993). The following effects are achieved:

- fuel injection cut-off in some sections of the pump which leads automatically to disconnection of some cylinders of work at idling and low load (reduction of carbon monoxide emission); number of operating cylinders is adapted to instantaneous engine load (the minimal number is at the idling),
- adaptation of the injection advance angle dependence on the engine load and fuel charge (reduction of nitrogen oxides emission).

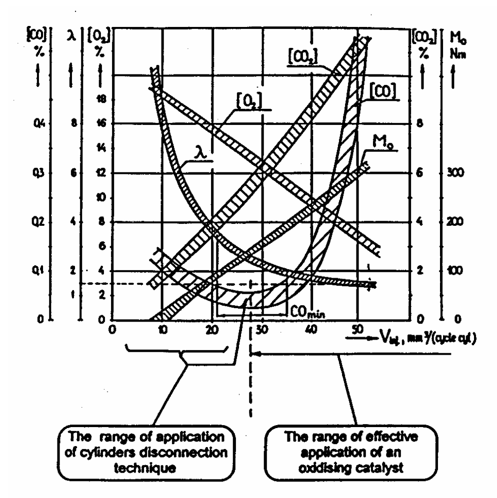

Figure 3. Main ranges of engine work. Effect of specific fuel charge on selected engine parameters.

4. Effect of Specific Fuel Charge on Engine Parameters

The specific fuel charge m_{inj} (V_{inj}) is defined as amount of fuel, which is injected into one cylinder, during one working cycle of engine. It can be calculated for four-stroke engine from the following formulas:

$$m_{inj} = \frac{2\,\dot{m}_f}{n_o\,z}, \quad \frac{kg}{cylinder, cycle} \qquad (17)$$

$$V_{inj} = \frac{m_{inj}}{\rho_f}, \quad \frac{m^3}{cylinder, cycle} \qquad (18)$$

For the tested diesel engine, effect of the specific fuel charge V_{inj} on torque M_o, excess air number λ and selected constituents of exhaust gas was determined. Ranges of obtained values of these parameters are presented in the *Figure 3*. All values of measured parameters for different engine speeds are situated within the narrow bands. It follows that rotational speed n_o of an engine crankshaft is of small importance.

Realized research revealed that molar fraction of the carbon monoxide (and the other constituents) in exhaust gas depends on current fuel charge injected, thereby on current value of excess air number λ. Carbon monoxide concentration attains the minimum value at mean load (*Figure 3*).

From this fact it appears that volume of the fuel charge injected into working cylinders should be controlled so as the amount of the noxious substance (CO) emitted to be minimum. This can be secured by cutting-off fuel supply to selected cylinders of engine.

5. Realization of Sequence Cutting-off Fuel Supply to Cylinders

The basic purpose of the method is suitable operating system of respective cylinders so as parameters of working cylinders fulfil the conditions of minimum carbon monoxide emission (*Figure 3*) at every situation. Working cycle does not occur in the remaining cylinders (disconnected cylinders).

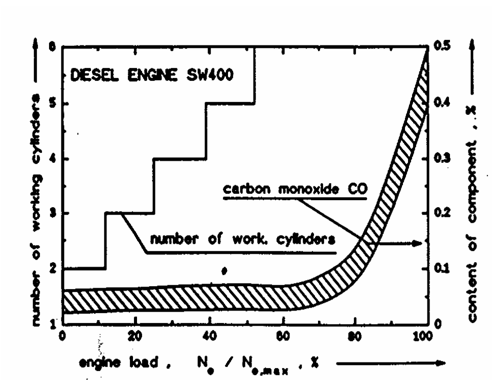

Figure 4. Number of working cylinders and effect of cylinders disconnection on carbon monoxide emission.

The essence of the method is that the fuel is not injected into selected cylinders (in which the working cycle is not realized) of the engine whereas accordingly the remaining cylinders operate under increased load (the fuel charge is subjected to increase respectively) that is to say the load at which the smallest carbon monoxide emission exists. Thus, through partially disconnection of some cylinders (at idle running and low load) the working cylinders are more loaded as normal, so the total CO emission from these cylinders is lower. Number of operating cylinders is adapted to instantaneous, current engine load (the minimal number is at the idling) - *Figure 4.*

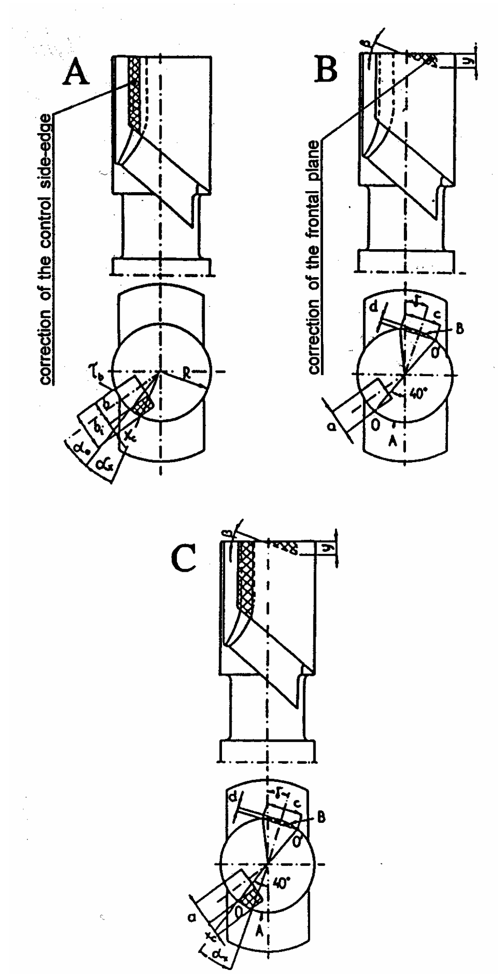

Figure 5. Technical realization of sequence cutting-off fuel supply to cylinders:
***A** - correction of control side-edge,*
***B** - correction of frontal plane,*
***C** - complete correction of plunger.*

Technical realization of this conception consists in special correction of the control side-edge of injection pump plungers (see *Figure 5A*). The correction relies on the proper grind off of the control side-edge what causes that the fuel is not injected into the adequate cylinder. The injection starts later, according to the engine load.

Separate problem is necessity of decrease of nitrogen oxides (NO_x) emission. Reduction of NO_x emission can be achieved e.g. by proper control of the fuel injection advance angle. One proposes to solve this problem also by suitable correction of injection pump plungers but in this case correction of frontal plane. The procedure is presented in the *Figure 5B*. This correction relies on the grind off of the frontal plane what affords possibilities for adaptation of the injection angle to the load at which the NO_x emission is the lowest.

By this means, the complex solution of the problem of toxic substances emission can be attained (*Figure 5C*).

Full of promise results were obtained during realization of the above idea of sequence disconnection of cylinders for compression-ignition engine 6C107. Thus, cylinders disconnection technique is the good method to reduce noxious substances emission, especially at the idling and low load.

6. Conclusion

Considerable reduction of noxious substances emission can be achieved in the whole operation range of the compression-ignition engine by the use of oxidation catalyst and selected cylinders disconnection technique. Results of experiments performed with diesel engines (type 6C107) showed positive effects of the applied methods and constructional solutions. So, the tested engines with the corrected injection pumps and catalysts can be used to the underground mining transport as well as to city bus service.

Nomenclature

N_e	power output, kW ,
V_{inj}	specific fuel charge, m^3/(cylinder, cycle),
W_d	calorific value of fuel, kJ/kg,
m_{inj}	specific fuel charge, kg/(cylinder, cycle),
m_f	mass flux of fuel, kg/s,
n_o	engine speed, r.p.m.,
n_{de}	molar flux of dry exhaust gas, kmol/s,
n_e	specific quantity of dry exhaust gas, kmol/kg fuel,
$n_{txc,i}$	molar flux of i-th toxic constituent, kmol/s,
$[txc]_i$	molar fraction of toxic constituent in dry exhaust, e.g. [CO], [NO_x], [HC], ...,
z	number of cylinders,
η_e	efficiency of engine,
λ	excess air number,
ρ_f	fuel density, kg/m^3,
φ	relative index of emission of toxic substance,
Φ	general index of toxicity.

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