Reducing NOx emissions from diesel engines supercharged with pressure wave compressor driven by the electric motor

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Abstract. The overwhelming parts of the modern Diesel engines for vehicles are supercharged. However, the supercharging process lead to generating a significant amount of NOx emissions. Therefore, the supercharging intensity may be intentionally limited in order to avoid increasing NOx emissions excessively, as these emissions are drastically limited by the Euro 6 pollution standard. By moving from Euro 5 to Euro 6, the NOx emission's permissible limits have been reduced by up to 80%. These reductions of NOx emissions were made possible mainly due to the utilization of the some conventional equipment and procedures presented in the paper. Diesel engine's supercharging could be realized efficiently also with pressure wave compressor (PWC). The paper highlights the possibility of realizing the EGR process directly through the PWC. The concept of supercharging with PWC leads to a significant reduction of NOx, for a significant increase of both the pressure and temperature of the intake air.

1. The current context of reducing NOx emissions

1.1. Supercharged diesel engines

The overwhelming parts of the modern Diesel engines for vehicles are supercharged. More and more often, the concept of downsizing is applied (Figure 1). Thus, by increasing the supercharging pressure, the engine's specific power also increases [1].

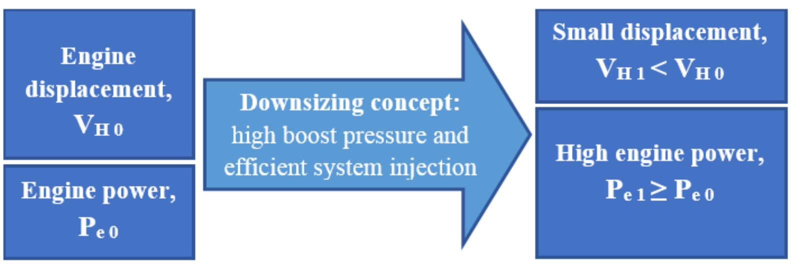

Figure 1. Downsizing concept.

A downsizing example is presented in Table 1, according with [2]. However, the supercharging process increases the level of pressure and temperature of the engine cycles [3]. That means that a poor air-fuel mixture (with oxygen in excess) it is formed in cylinders, which burns at high temperature.

These two conditions lead to generating a significant amount of NOx emissions – which makes more difficult to meet the Euro 6 pollution standard [4,5,6].

Table 1. Downsized diesel engine example.

Parameter	Before downsizing	After downsizing	Difference
Engine displacement	2000 cmc	1600 cmc	-20 %
Supercharger pressure	2.5 bar	3 bar	20 %
Maximum cylinder pressure	170 bar	200 bar	18 %
Specific power	64 kW/l	80 kW/l	25 %

1.2. The Euro 6 emissions standard

NOx emissions of the exhaust gas for Euro 6 Diesel engines must not exceed the concentration levels from Table 2. The values are valid for the vehicle's operating conditions according with the cycle specified in table: New European Driving Cycle (NEDC), World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC).

Table 2. Euro 6 standard emissions – NOx limit values.

Type vehicles	Cycle	NOx emissions limit values, g/km	Reduction from Euro 5 standard, %
Passenger cars	NEDC	0.08	56
Light vehicles	NEDC	Class I: 0.08	56
	NEDC	Class II: 0.105	64
	NEDC	Class III: 0.125	55
Heavy duty vehicles	WHSC	0.40	77
	WHTC	0.46	80

It could be noticed that by passing from the pollution standard Euro 5 to Euro 6 one, the NOx emissions have been significantly reduced, the differences between the two standards reaching values up to 80%. These reductions of NOx emissions were made possible mainly due to the utilization of the following equipment and procedures: exhaust gas recirculation (EGR), Diesel Oxidation Catalyst (DOC), Lean NOx Trap (LNT) and Selective Catalytic Reduction Technology (SCRT) [5,7,8].

Regarding NOx emission, the Euro 5 standard could be attained largely through utilizing the EGR system alone. In case of Euro 6 standard, depending on the engine displacement, a LNT or SCRT usage is supplementary needed - beside that of EGR.

2. Another section of your paper

The EGR procedure consists in introducing of 6 to 10% of the exhaust gases back into the cylinders. Essentially, exhaust gas replace a part of the intake air, which reduces the oxygen quantity within the combustion chamber. In addition, by introducing triatomic molecules that have high specific temperature – such as CO_2 or H_2O – the maximum temperature of the cycle is also reduced [7].

Three types of EGR systems can equip the supercharged engines: low pressure EGR, high pressure EGR or both of them (depending on engine's speed, LP EGR or HP EGR is used). At low speeds, LP EGR is used to avoid affecting the turbocharger's performance. At low-medium speeds (when there is sufficient exhaust gas flow rate), HP EGR is used – having a faster response, while not affecting the reliability of intake air‘s systems. At medium-high speeds, the EGR system does not work.

Generally conventional EGR contains the components from Table 3 [7,8]. There are two main disadvantages of using an EGR system: the increase of complexity of the engine due to the amount of additional equipment used exclusively for recirculating the exhaust gas and the decrease of engine's reliability due to the frequent obstruction of EGR's valve and throttle.

Table 3. The role of the main components of the conventional exhaust gas recirculation.

EGR components	The components role
EGR valve	Control of the volume of recirculated exhaust gas
EGR cooler and temperature sensor	Reducing the temperature of the recirculated exhaust gas and finally the cycle temperature.
EGR throttle	Adjust intake air or exhaust gas to supercharged engines.
EGR valve and throttle control unit	On the basis of information on sensor (temperature, pressure, flow, speed, position and gas composition) controlling the EGR adjusting

The main advantages of recirculation the exhaust gas when using PWS are: increasing the reliability of the engine and reducing its cost because it eliminates the components of the conventional EGR that are used exclusively for the recirculation and improving the air filling of the cylinders by reducing pumping losses - as the intake or exhaust manifold throttle are removed.

The previously described internal EGR can be successfully used thanks to the innovative PWC driving system. This system consists in driving PWC with an electric motor having a variable or sequential speed. On the other hand, the classic solution involves driving the PWC at a speed proportional to the engine's one. Due to the fixed ratio between the engine speed and the PWC, it is difficult to provide simultaneously high supercharging pressures and a satisfactory flow rate of EGR [3,10]. According to the new PWC driving solution, its speed is independent of that of the internal combustion engine (Figure 3). The experimental research can identify the optimal speed with which PWS should be driven for each of the engine operating conditions.

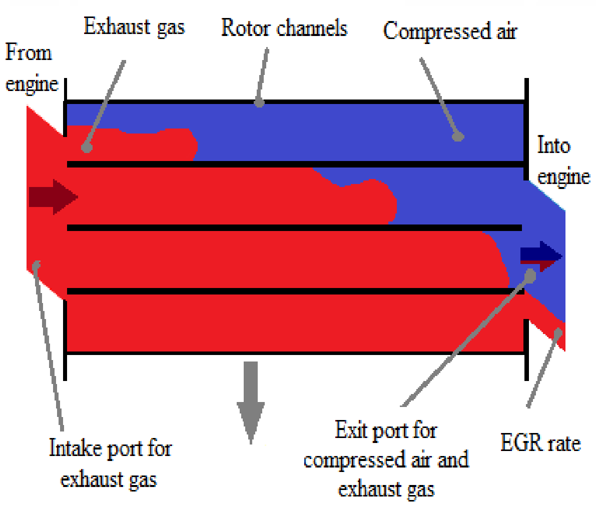

Figure 2. Scheme of the internal EGR trough PWC.

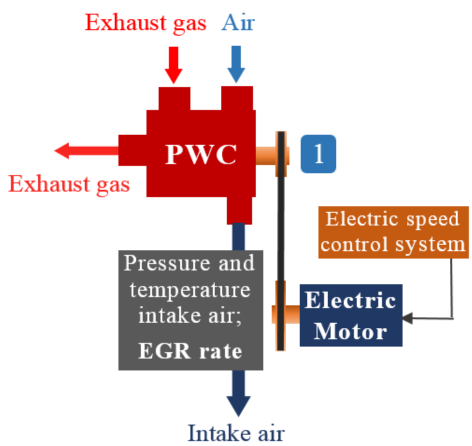

Figure 3. Supercharging system with PWC driven by the electric motor.

When choosing the PWC optimal speed could be taken into account of engine performances or more precisely of specific fuel consumption and emissions pollutants including EGR rate.

2. Interpretation of experimental results

Experimental researches were performed on a supercharging Diesel engine. During experimental research the engine was equipped with a turbocharger (original variant) and Comprex type PWC, model CX-93 (modified variant). The PWC was driven by a variable speed from an electric motor. As a result of research show the efficiency of the PWC in comparison with turbocharger (TC).

The experimental results presented in Figures 4, 5 and 6 were obtained for the engine supercharged with TC and PWC. The evolution of the parameters varies with the engine speed. Engine load and PWC speed have been kept at the same values throughout this research. Figure 4 shows that the fuel consumption is reduced if the engine is supercharged with PWC. At the same time, the air consumption increases due to the higher pressure of the supercharging. Figure 5 shows that the supercharging pressure generated by PWC is greater than the one achieved by the TC. The increase of the supercharging pressure takes place along with a significant increase of the intake air temperature.

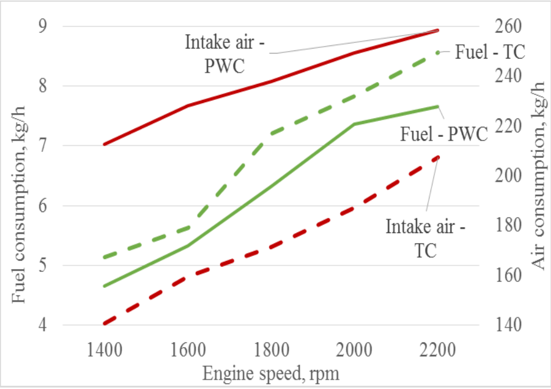

Figure 4. Comparing the fuel and intake air consumption obtained during supercharged with TC and PWC.

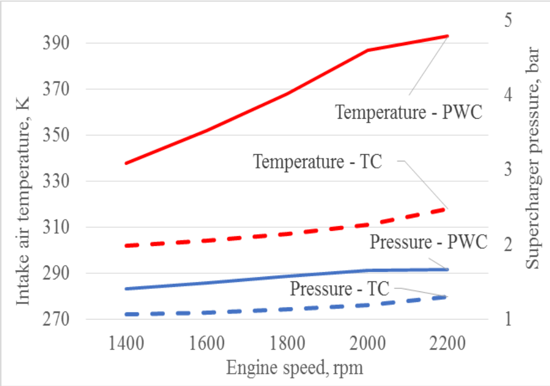

Figure 5. Comparing temperature and pressure intake air obtained during supercharger with TC and PWC.

The supercharging with PWC led to a reduced amount of diesel fuel injected per cycle, an increased amount of air entering the cylinders and a significant raise of the intake air temperature. These aspects normally lead to an increase in NOx emissions. However, as shown in Figure 6, an increase in NOx emissions is only observed at 1600 rpm. At 1800 rpm, the NOx emission is almost unchanged, while for the speeds of 1400, 2000 and 2200 rpm, the NOx emission is, against the expectations, lower. This situation could be explained by the internal EGR of the PWC.

According to [3], the time when the exhaust gas reaches the end of the channel depends on the PWC speed, on the exhaust gas pressure and on the pressure wave speed. Therefore, considering Figures 4-6, for a constant PWC speed, it can be stated that the rate of EGR depends on the last two factors mentioned above. Figure 7 shows the results of the experiments for a constant engine speed. PWC was driven with 3 different speeds (S1pwc, S2pwc and S3pwc).

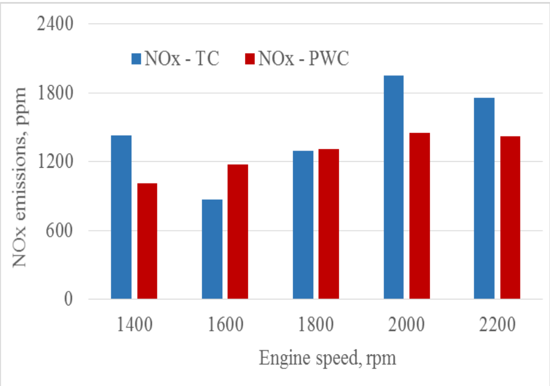

Figure 6. Comparing NOx emissions from exhaust gases obtained during supercharged with TC and PWC.

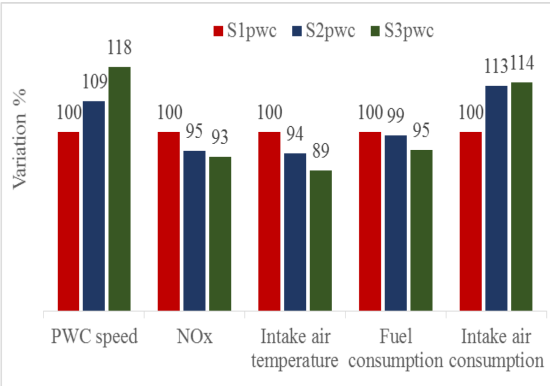

Figure 7. Comparing parameters obtained with the PWC driven at different speeds - at the same speed and engine load.

The reference values (100%) are the ones measured during driving PWC with the S1pwc speed. By consecutively increasing the PWC speed by 9% (S2pwc) and 18% (S3pwc), NOx emissions decreased by 5% and 7%, respectively. After analyzing the chart, it can be seen that NOx have been reduced due to a 6% (11%) decrease of the intake air temperature and to a 1% (5%) decrease of the fuel consumption.

3. Conclusions

When comparing the measured values for NOx emissions during PWC supercharging with those measured during turbocharging, the emission reduction is a substantial one.

The concept of supercharging with PWC (i.e. direct contact between exhaust gas and intake air) leads to a significant reduction of NOx, for a significant increase of both the pressure and temperature of the intake air.

The recirculation of exhaust gases through PWC represents another advantage of this compressor that justifies supercharging Diesel engines with it. In addition the driving with variable or sequential speed successfully enables the internal EGR process.

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