EFFECT OF STEAM INJECTION ON PERFORMANCE AND EMISSIONS OF AGRICULTURAL DIESEL ENGINE

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Abstract. The need to reduce vehicle emissions has encouraged the development of various solutions. One of them is the steam injection method, which proved to be an effective option of reducing NOx emissions. In order to evaluate the effectiveness of the steam injection method on an agricultural engine, appropriate tests were carried out at the Alternative Fuels Research Laboratory of the Latvia University of Life Sciences and Technologies. The engine KDI 1903M and a self-made steam device ensuring steam injection in the intake manifold were used in the tests. The research engine was connected to the SIERRA CP-Engineering engine test bench. Additionally, emissions were recorded by the AVL SESAM FTIR exhaust gas analytical system. Testing was performed without steam supply and with steam supply at constant speeds, as well as in different load modes - 10 kW and 20 kW. The results showed that the largest reduction of nitrogen oxide (NOx) emissions was obtained at idling (7.5%), while in case of all load modes the results were very similar (reduction by 4.1-5.0%). At the same time, increase of carbon monoxide (CO) emissions was observed in all testing modes by 3.0-5.6%, while carbon dioxide (CO_2) changes were negligible. The studies confirmed an insignificant increase in the power and torque. The results prove that further research should increase the volume of steam supply by improving the given device.

Keywords: diesel engine, steam, testing, emissions, power.

Introduction

Compliance with environmental regulations has required a lot of effort for internal combustion engine manufacturers in the last decade. Over time, the engine design was supplemented with various technological solutions, which not only complicated the overall design of the engine, but also paved the way for new types of fuels. In search of a common solution for reducing greenhouse gases, liquid and gaseous fuels of various origins, including biofuels, appeared on the market. Despite the fact that the simplest of them, for example, vegetable oils, did not gain wide popularity in city transport and were not available for purchase at filling stations, various types of research proved the possibility of their use even at low ambient temperatures [1]. Although biodiesel fuel was more widely available to consumers, the main problem of its application was its negligible effect on NOx emissions and compatibility with industrially produced, older car spare parts using in high level blends [2]. Similar studies were also related to gaseous fuels, which had been more widely known for many years. It was established that the impact of a self-equipped and inadequately adjusted gas system on ecology was not the same as it could be in case of factory equipped vehicles [3], as also ecological input stays behind the other fuels. Therefore, the need for new, more efficient types of fuel, as well as various types of additives, stimulated researchers to look for other options including both hydrogen and water injection.

Initially, water injection was considered a suitable solution to improve the engine performance as a consequence of improved atomization explained by a very low interfacial tension between fuel and water during the compression process, and a better mixing process of the air and fuel due to a higher contact area [4], as also the combustion in the cylinder is greatly suppressed [5]. This leaves an effect on several emissions like carbon monoxide, soot, particulate matter, and also nitrogen oxides [4], which are reduced based on the decrease in the peak flame temperature. Different strategies have been proposed for water injection, like injection in the engine inlet, directly in the combustion chamber with a fuel injector or separate injection system, and all of them have been detailly investigated [6].

Further studies showed that the process of steam injection is very similar to that of water injection, but only with different effects [7]. The main methods for steam injection include pre-turbine steam injection (PTSI), intake manifold steam injection (IMSI), and in-cylinder steam injection (ICSI) [8]. The pre-turbine steam injection method allows to improve the turbine power and engine fuel economy in almost all operating conditions [9], while intake the manifold steam injection can improve the engine brake thermal efficiency, reduce the fuel consumption and NOx. ICSI method could be divided into the compression stroke ICSI and power stroke ICSI based on steam injection timing [8], and it leaves an impact on reduction of the fuel consumption, performance of the turbocompound engine and the engine emission characteristics.

The number of studies conducted in this area is limited and mostly connected with different simulation models, especially in case of diesel engines while there are also some other very interesting studies. Parlak [10] studied electronically controlled water steam injection system with the aim to reduce NOx emissions, and in full load condition diesel engine tests observed reduction of NOx emission by 33%, increase of power till 3% and decrease of specific fuel consumption up to 5%. In similar research Kökkülünk [11], comparing experimental and theoretical data obtained on a single cylinder, naturally aspirated, four-stroke direct injection diesel engine, concluded that steam injection yields a positive effect on performance and NO emissions at all speeds while it does not affect CO_2, HC and CO emissions considerably. Cesur [12] observed that steam injection into the engine using B10 (90% diesel + 10% biodiesel) fuel improved both the engine performance and the exhaust emission parameters injecting steam into the intake manifold at different ratios at the time of the induction stroke using an electronically controlled system. At the same time, Gonca [13] developed the steam injection method determining optimum temperatures and mass ratios based on thermo dynamical analyses.

There still is limited knowledge on the effect of steam on the engine power, torque, fuel consumption and emissions directly from agricultural engines at different testing conditions. Considering the growing demand for more environmentally friendly vehicles in the nearest future, steam usage in engines should be investigated more deeply to provide an overall picture of the changes of all the most important emissions in different regimes. In that case the IMSI method was chosen as the most simplified option to achieve optimal results creating a self-made steam device for steam production.

Materials and methods

Research was carried out with the engine KDI 1903M at the Alternative Fuels Research Laboratory of the Latvia University of Life Sciences and Technologies in April 2023. Commercially available diesel fuel complied with standard EN 590 was used for the tests, where a renewable component of 7% is added to diesel fuel. KDI 1903M is a highly versatile 3-cylinder in line liquid cooled engine, used as an agricultural engine, as well as the engine for the generator set, compressor and pressure washer; the main specifications of it are listed in Table 1 [14].

The research engine was connected to the SIERRA CP-Engineering engine test bench, which consists of an AC dynamometer and is controlled by the CADET control system responsible for the correct operation of the loading equipment. The engine parameters during tests are given in Figure 1. Emissions were recorded by the AVL SESAM FTIR exhaust gas analytical system where the composition of exhaust gases is determined by an infra-red spectrometer.

Table 1

Basic engine parameters

Parameter	Value
Engine type	CI engine
Cylinders	3
Bore, mm	88
Top power, kW at rpm	31 at 2600
Maximum torque, Nm at rpm	133 at 1500
Stroke, mm	102
Compression ratio	17

A self-made steam device was used for the experiments, for which a battery was used as the necessary power source. The two glow plugs were connected in string closure, consuming 18 A, and connected to the existing engine battery. By turning on the steam device by a switch and connecting it to the engine with a pipe, experiments could be carried out. The productivity of the steam generator was 15 $g \cdot min^{-1}$ constant in all modes.

Research was performed without steam supply and with steam supply at constant speeds (930, 1500 and 2000 rpm), as well as in different load modes - 10 kW and 20 kW. Overall, 5-10 measurement repetitions (5 times for tests without load and 10 times for tests with added load) were performed in each test condition, from which the average values of the measurements were calculated and presented after mathematical processing.

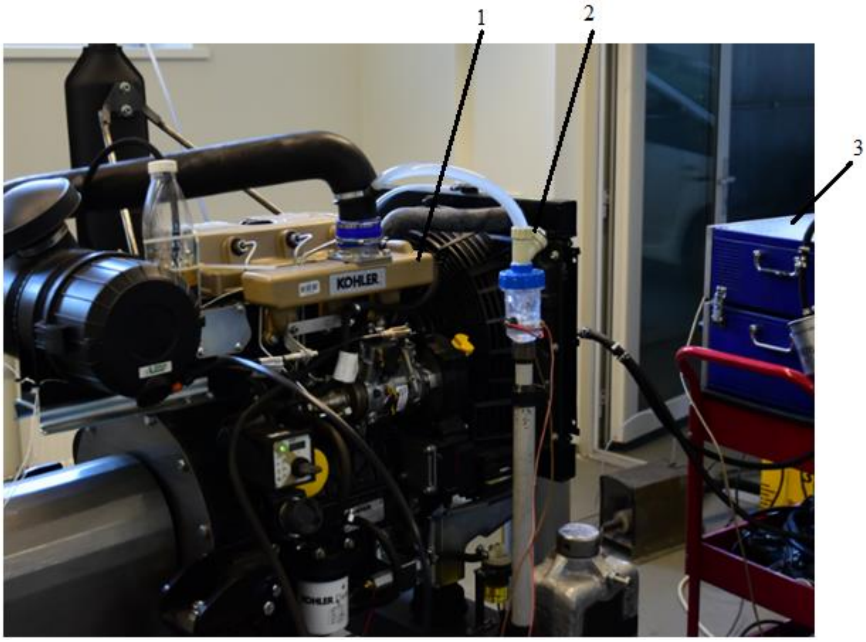

Fig. 1. **Test engine:** 1 – engine; 2 – steam generator;
3 – fuel consumption measuring equipment

The average values from each type of test have been displayed in the graphs. The accuracy of measurements in the graphs is displayed using statistical analysis with the assumption that 95% of results should be within 2 standard deviations of the result. Therefore, the accuracy displayed in the graphs represents $\pm 2\sigma$.

Results and discussion

The effect of steam addition on the engine dynamical, economic and ecological parameters is observed and analysed in this section. Fig. 2 shows that the injection of water steam reduces NOx in all modes of the diesel engine. It is known that steam injection during the combustion process can dilute the concentration of other combustion products such as nitrogen oxides (NOx) or particulate matter. Also, steam can absorb a significant amount of heat during the combustion process, which can lower the maximum combustion temperature. As it is known, high combustion temperature is the main factor of NOx formation. By reducing this temperature, water steam can help reduce NOx emissions. This was also confirmed by modelling results of the thermodynamic analysis on steam injection in the intake manifold of the engine [14].

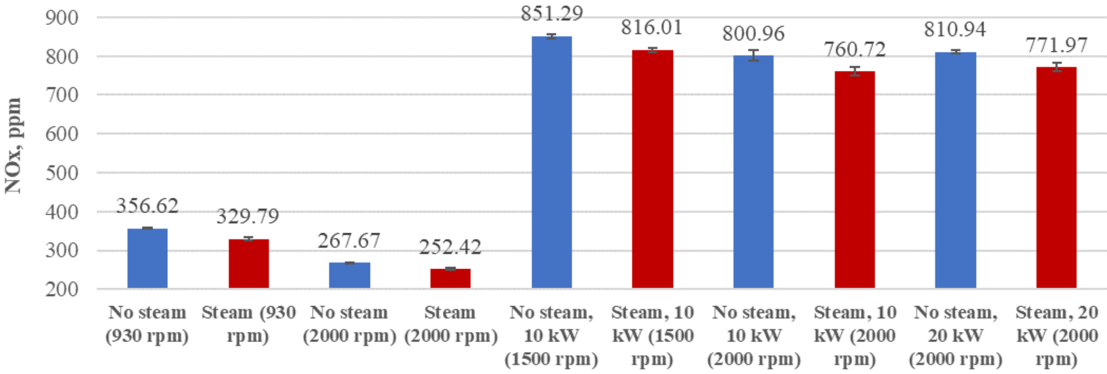

Fig. 2. **NOx at different testing conditions with and without steam addition**

The content of CO_2 in the exhaust gases of an internal combustion engine mainly depends on the efficiency of the combustion process, air-fuel ratio, engine efficiency, operating conditions and the presence of exhaust after-treatment systems. CO_2 emissions from engines can be reduced when these factors are optimized. Water steam, on the other hand, can react with CO at high temperatures, which usually occurs in combustion processes. The reaction between water steam and CO produces carbon dioxide (CO_2). This is an oxidation process, and the addition of water steam can help convert CO into less harmful CO_2. From Fig. 3 it can be seen that the change in CO_2 is insignificant (max. increase is 1.4% at 2000 rpm and 20 kW using steam) because none of the above factors were changed in this experiment and also the purpose of this experiment was more focused on reducing NOx only.

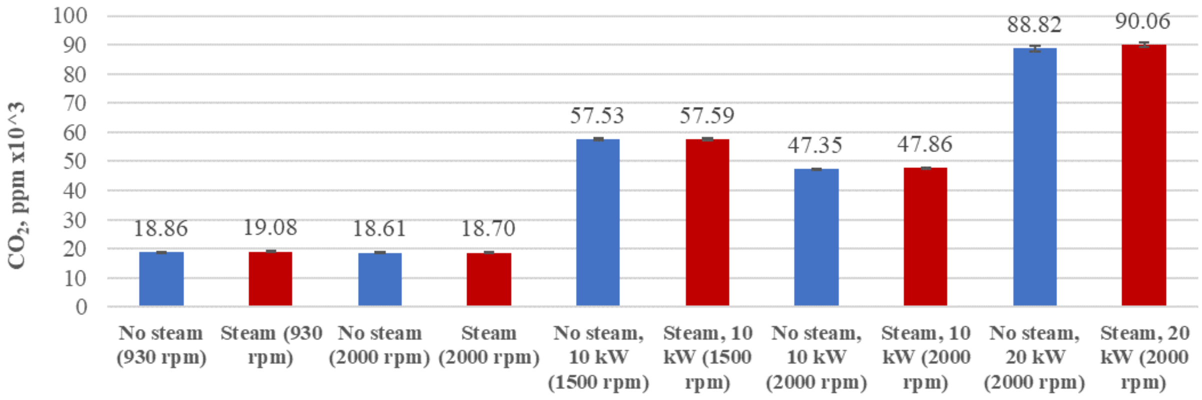

Fig. 3. **CO_2 at different testing conditions with and without steam addition**

The actual effect of water steam on CO emissions depends on various factors, including the specific combustion conditions, the amount of water steam injected, and the design of the combustion system. Increase in CO emissions in these tests probably could be explained by formation at high combustion temperatures as a result of incomplete combustion. This increase was about 3.0-5.6% and no effect of load and rpm was observed. Water steam can contribute to a more complete and efficient combustion of diesel fuel, but since the experiment was not intended to control the combustion temperature in the engine cylinder, CO has increased slightly (see Fig. 4).

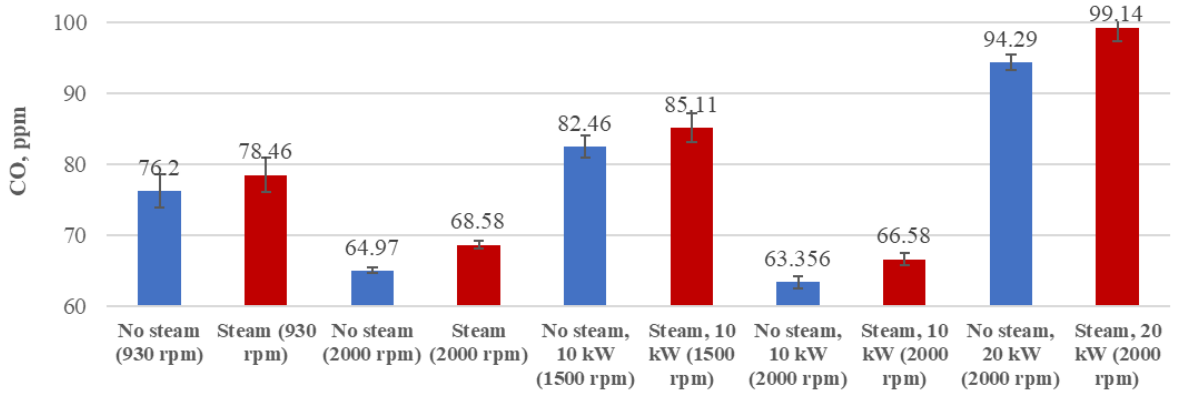

Fig. 4. **CO at different testing conditions with and without steam addition**

Water steam injection into an engine can have both positive and negative effects on the engine power and torque, depending on how the process occurs and the design of the particular engine. By making optimal use of water steam, it can improve combustion efficiency by ensuring more complete combustion of the fuel – steam injection contributes to decreased fuel droplet diameters, which steamize rapidly in such way absorbing the heat of the cylinder charge owing to the high heat capacity and partial pressure of oxygen increases [14]. Additionally, the introduction of water steam into the combustion process can improve mixing in such way also resulting in more efficient combustion. This improved combustion efficiency can increase the power for a given amount of fuel. In this experiment, the introduction of water steam during the combustion process produced a slight cooling effect on the engine, thereby reducing the production of NOx. In case of extreme cooling, it could hinder the combustion process and reduce the power, but as it can be seen in Fig. 5-6, the power and torque have not decreased.

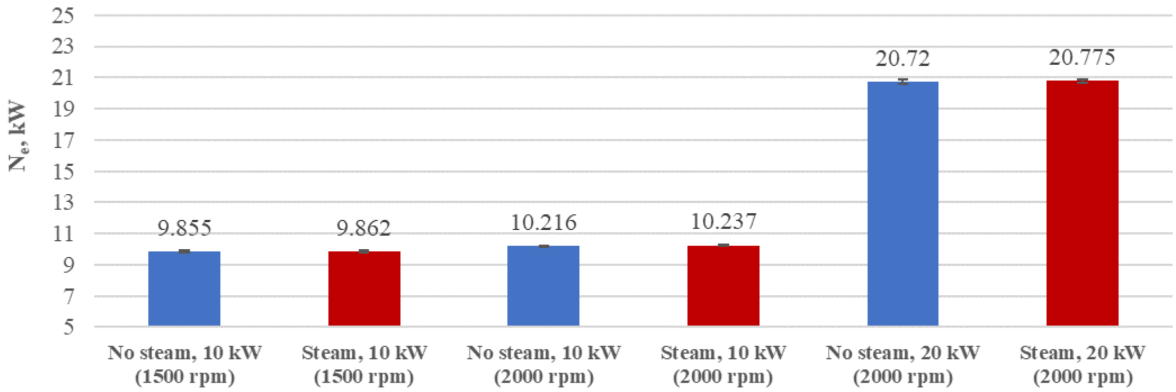

Fig. 5. **Power at different testing conditions with and without steam addition**

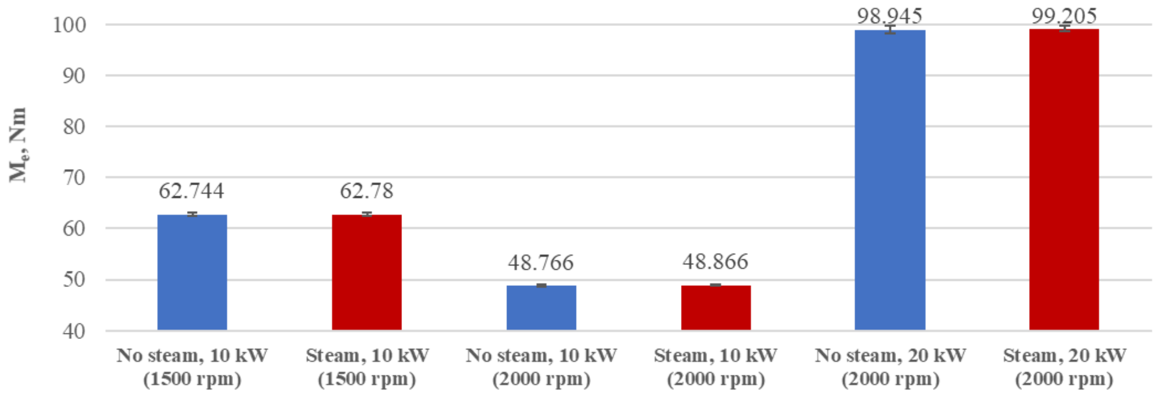

Fig. 6. **Torque at different testing conditions with and without steam addition**

The use of steam in small quantities could be a suitable solution for increasing the engine efficiency and reducing emissions in diesel engines, although the overall benefit is not very noticeable. Although the study shows not only the benefits, but also the shortcomings of the following solution, which still needs to be worked on, it could be concluded that water steam injection is optimal for specific engine operating conditions.

Conclusions

1. Changes in the engine power and torque were negligible in different testing modes and loads.
2. In idle mode, NOx decreased by 7.5%, but CO_2 increased by 1.2% and CO by 3.0%, while at high revs (2000 rpm) NOx decreased by 5.7%, CO increased by 5.5% and CO_2 did not change.
3. The load did not significantly affect the NOx changes compared to the idling mode, because at a 10kW load the NOx reduction was 4.1% (1500 rpm), and at a 20 kW load – 4.8% (2000 rpm).
4. Load had a negative effect on CO_2 emissions - it increased by 1.1% (10 kW, 2000 rpm) and 5.1% (20 kW, 2000 rpm).

Author contributions

Conceptualization, K.A.; methodology, K.A. and A.B.; software, K.A.; validation, K.A. and A.B; formal analysis, K.A. and A.B.; investigation, K.A. and A.B.; data curation, K.A.; writing – original draft preparation, K.A.; writing – review and editing, K.A. and A.B.; visualization, K.A. All authors have read and agreed to the published version of the manuscript.

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