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Marcin NOGA
Tomasz MOSKAL

Combustion Engines
Polish Scientific Society of Combustion Engines

Conversion to hydrogen fueling of a range extender SI engine of a 48 V hybrid electric vehicle

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The purpose of the article is to present further development stages of the range extender designed for a 48 V electric vehicle. The initial design of the system consisted of a 160 cm³ single-cylinder carbureted gasoline engine coupled to a synchronous 3-phase AC generator. The conversion of the engine included an adaptation of a port hydrogen injection with a stand-alone engine management system. The research was focused on engine calibration first of all, in order to achieve its stable operation, avoiding abnormal combustion when running on hydrogen. In addition to the basic engine performance indicators, the composition of exhaust gases emitted by the engine was also measured. Initial tests proved the conversion to be stable, and the range extender reaches efficiency slightly higher than achieved when the engine was fueled by gasoline.

Key words: *hydrogen, range extender, electric vehicle, spark-ignition engine, decarbonization*

1. Introduction

In the decarbonization phase of road transport, new technologies are being sought to further facilitate the adoption of battery electric vehicles [5]. One such technology is the use of a range-extender device, which significantly enhances the autonomy of a BEV and allows for both stricter control and relocation of toxic exhaust gas emissions [3, 18]. Range extenders are, in essence, onboard electricity generators, the vast majority of which are fueled by liquid fuels [13]. These generators can be powered by classic combustion engines [2], rotary engines [21], opposed-piston engines [19], or even fuel cells [15]. The emission of toxic exhaust gases can be controlled by selecting the most efficient power source, as well as by using hydrogen as fuel [8, 16, 20].

Research on hydrogen being used as a fuel for combustion engines has been conducted worldwide in numerous institutes, including Poland [10, 14]. One of the well-experienced institutions in this field is Cracow University of Technology, where the first successful attempts with hydrogen-running engines were made at the beginning of the 1980s [7].

In recent years, the development of hydrogen engines has also included special types of engines, advanced methods of variability of engine design parameters, and their specific applications [1]. In the paper of C. Zhang et al, a rotary engine has been used in combination with hydrogen fuel for electricity generation with a peak efficiency of 30% [22]. Research conducted by Seungjae et al. shows that by varying the compression ratio of a single cylinder hydrogen piston engine, peak efficiency can reach as high as 42.3% [6]. The research conducted by Dingel et al. shows a rising potential of applying a range-extender device for battery-powered commercial vehicles operating in urban areas, e.g. garbage collection vehicles [4].

An example of a range-extender device has been developed at Cracow University of Technology [11]. This article describes further development steps for the range-extender device, including electronic hydrogen injection, replacing carbureted gasoline fueling.

The range extender in the current development phase has been prepared for further research concerning the hydrogen combustion control with the use of the indicated pressure readout.

The next chapters of the article describe the test stand used for this research, its development stages, and the methodology used for calculations. Next, results are presented with a focus on engine setpoint parameters, engine load, and exhaust gas composition.

2. Research problem

2.1. Subject of research

The range-extender previously developed at the Cracow University of Technology has been used to conduct the research described in this paper. It has been built for a 48 V light commercial battery electric vehicle and consists of a single cylinder spark ignition engine and a belt-driven three-phase AC synchronous generator with electromagnetic excitation. The generator itself is an adaptation of a commercial vehicle alternator to enable 48 V generation.

In its primary stage, the 163-cc engine was fueled by a float carburetor, and its ignition system was set to a constant ignition advance angle. The carburetor throttle was adjusted by a centrifugal governor.

In further stages, the range extender was equipped with an exhaust aftertreatment system consisting of a three-way catalytic converter and an excess air ratio (λ) control system, which, by adding additional air to the rich mixture, was able to keep the mixture stoichiometric. The range extender performance parameters are listed in Table 1.

The research carried out on the range extender at that stage proved its peak efficiency to be at around 19%. Considering the type of generator and simplicity of the power unit, the result can be evaluated as high.

Table 1. Range-extender technical data before H_2 modifications

Engine model	WEIMA 168FA (Honda GX160-class)
Engine type	four-stroke, SI, single cylinder
Engine displacement	163 cm^3
Engine maximum power	3.8 kW at 3600 rpm
Ignition timing	fixed, 27°CA BTDC
Generator type	Synchronous 3-phase AC
Nominal voltage	48 V
Continuous output power	2200 W
Peak overall efficiency	18.8 %

2.2. Further development of the range extender

In the current stage, the range extender has been adapted for hydrogen fueling. Due to highly specific characteristics of this gas in a combustion engine application [12], it has been decided to tune the engine with the use of an integrated electronic engine management system. Its basic functionality is to control the ignition setpoint and the gas injection timing to the engine intake with excess air ratio closed loop control based on a wide-band oxygen sensor in the exhaust gases.

Such an approach allows for safe and effective operation of a hydrogen-fueled engine. The engine management system used is an ECUmaster Black, which also features a live combustion control interface, making real-time corrections feasible. The adoption of this system required the engine to be equipped with specific actuators (ignition coil, hydrogen injector), as well as a variety of sensors sending the crankshaft position, knock, and temperature sensors. The fitment of camshaft and crankshaft position sensors posed a tremendous challenge, as it required precise mechanical changes in the engine to fit them in a confined space.

Figure 1 illustrates the first part of the main actuators and sensors used in the revised range extender.

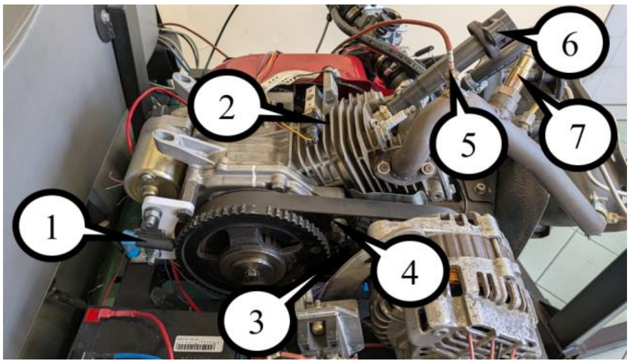

Fig. 1. Range extender equipment: 1 – crankshaft position sensor; 2 – engine temperature sensor; 3 – camshaft position sensor; 4 – knock sensor; 5 – EGT sensor; 6 – ignition coil (active); 7 – wideband oxygen sensor

In Figure 2, the next group of sensors and actuators is shown. The engine has been equipped with a complete set of sensors, which is needed for future research, although the knock sensor was not used in this research, as its efficient use when the engine is running on hydrogen requires fine-tuning of the settings of the ECU with the use of an in-cylinder pressure sensor.

One of the crucial additions to the sensor set was a Bosch LSU 4.9 wideband exhaust oxygen sensor. With the constant feedback signal to the Engine Management Unit, it is feasible to hold stable combustion conditions up to an excess air ratio of 2.

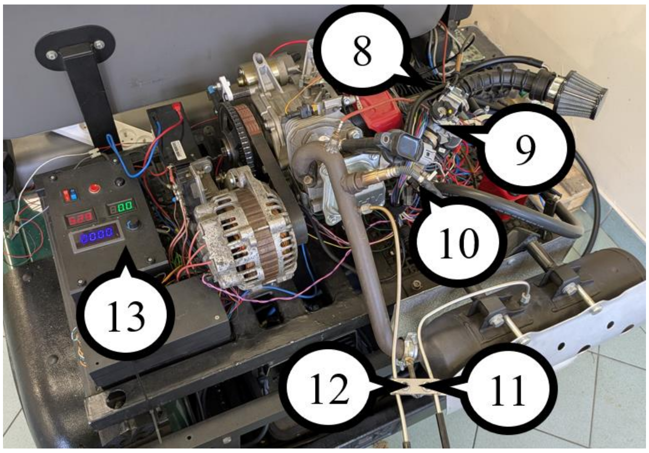

Fig. 2. Range extender equipment, continued: 8 – engine management unit; 9 – throttle body w/ TPS and idle actuator; 10 – H_2 injector; 11 – exhaust gas port after TWC; 12 – exhaust gas port before TWC; 13 – battery charge controller w/ RPM, charge current & voltage readout

The throttle has been fitted with a linear DC actuator, acting on a cable to be able to precisely set the throttle opening.

Hydrogen supply is carried out with a two-stage BRC Zenith CNG reducer with an output pressure of 2 bar. The reducer is equipped with an intake pipe pressure compensation. The elements are illustrated in Fig. 3.

Fig. 3. Range extender equipment, continued: 14 – gas reducer; 15 – combi pressure/temperature sensor for H_2 consumption calculation

The throttle body assembly was adapted with a Bosch NGI-2-K injector (Bosch P/N: 0 280 158 839), dedicated to the application of natural gas. The coil resistance of this injector is 8.9 Ω, and its inductance is 18 mH. When powered directly from a 12 V electrical system, this injector does not require peak and hold control. Instead, it is satisfied with simple saturated control. With this control method, the maximum value of the coil current does not exceed 1.6 A, which is a value far lower than the permissible value of 5 A/output for the used ECU. At the stage of preliminary tests, it was determined that at a supply pressure of 2.0 bar, the injector output is 12 g/min of hydrogen (134.8 SLPM). During the subsequent tests of the hydrogen-powered engine, the injection time of the fuel at high engine load was on average 6–8 ms, depending on the engine speed. This confirms that the injector was selected correctly for this application. The view of the NGI-2-K injector with the fuel supply adapter installed is shown in Fig. 4.

Fig. 4. Injector nozzle view

2.3. Test stand

The mass of consumed hydrogen was calculated based on the gas pressure and temperature readout from a Bosch PST-F 2 sensor, mounted on a CNG reducer inlet attached to a 50 dm^3 high-pressure cylinder. To ensure the most accurate measurement of the hydrogen temperature on the high-pressure side of the cylinder, the sensor is equipped with a heat shield. The sensor parameters are described in Table 2.

Table 2. Pressure/temperature sensor characteristics

Sensor model	Bosch PST-F 2 280 bar
Pressure sensor type	Steel diaphragm
Pressure sensitivity	14.3 mV/bar
Temperature sensor type	NTC thermistor, 10 kΩ @ 25°C

Exhaust gas composition was measured with the use of a Capelec 3201 exhaust gas analyzer.

Exhaust gas temperature was measured with the use of a metal PT100 resistor with its dedicated processor.

Electrical parameters of the generated electrical energy have been recorded with a Racelogic datalogger. The data was acquired at a 10 Hz frequency.

The engine load consists of a synchronous 3-phase AC generator, charging the vehicle's primary energy source – LiFePO4 batteries. The generator is externally excited with a regulated power supply. To avoid an overload of the battery, a 48 V to single-phase 230 VAC inverter is connected to the vehicle's 48 V system, to which a switchable 1/2 kW fan heater is attached.

Figure 5 illustrates the dependencies and energy flow in the revised range extender.

In Figure 6, the entire test stand can be observed, consisting of the light commercial vehicle equipped with the updated range extender, the 50 dm^3 hydrogen tank with reducer, a power supply, a portable computer for data logging, and the exhaust gas analyzer.

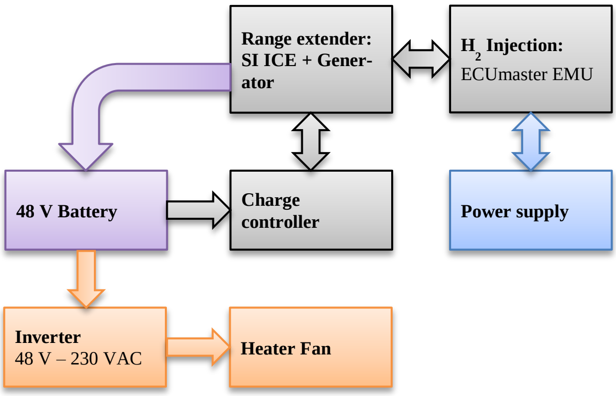

Fig. 5. Test stand diagram

Fig. 6. Range extender test stand

3. Results

The tests were carried out at 5 measurement points, for different values of engine speed and load. The value of the ignition advance angle was reduced to 16°CA BTDC (compared to 27°CA BTDC on the carburetor) due to the specific nature of hydrogen combustion in a piston engine application. After initial testing, the value was set permanently after reaching engine stability in the desired operating range.

The injector opening angle was firmly set to 340°CA BTDC. Estimating the injection time no longer than 10 ms, which results from the parameters of the selected injector and hydrogen pressure, allows for the fuel injection sequence to happen entirely during the opening of the engine intake valve. The engine control algorithm had a lower limit of excess air ratio set to $\lambda = 1.75$. Using a richer mixture when feeding with port hydrogen injection may cause improper engine operation (abnormal combustion, spontaneous ignition of the mixture in the intake system).

In Figure 7, the setpoint data can be observed, with both the throttle position values and manifold absolute pressure values. The setpoint duration was set to maintain a similar level of hydrogen consumption across all test runs.

The operating points were selected in such a way as to indicate high engine load in all cases. This is evidenced by high average absolute pressure values in the intake duct, close to atmospheric pressure, which was 99 kPa during the tests. This allows the engine to achieve high thermal efficiency in these operating conditions.

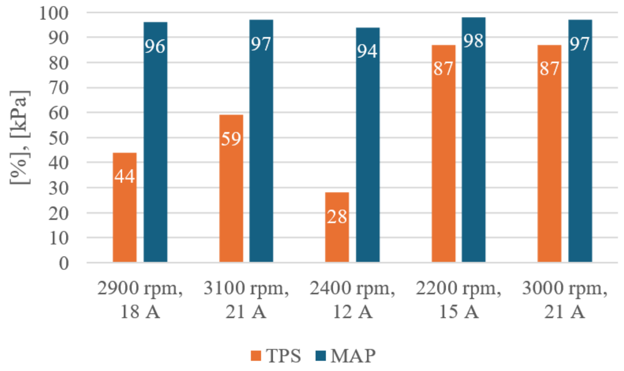

Fig. 7. Range extender setpoint data

Figure 8 shows the excess air ratio across all the set-points. The richest mixture was recorded in the third set-point.

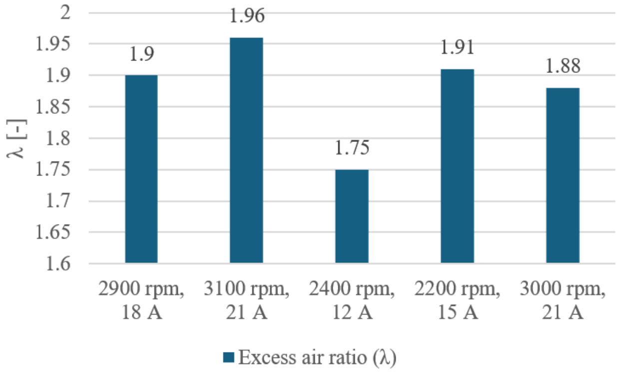

Fig. 8. Range extender excess air ratio (λ)

In the following Table 3, the range extender efficiency is presented. Hydrogen consumption was calculated based on pressure and temperature sensor readouts together with an algorithm developed by Lemmon et al., considering the compressibility factor of hydrogen in relation to temperature and pressure [9].

Table 3. Total RE efficiency on hydrogen fuel

Test run	Electric energy [kJ]	Hydrogen consumption [g]	Hydrogen combustion energy [kJ]	η
2900 rpm, 18 A	292.03	12.94	1552.41	0.188
3100 rpm, 21 A	312.59	13.50	1619.80	0.193
2400 rpm, 12 A	232.82	11.68	1401.78	0.166
2200 rpm, 15 A	305.00	12.61	1513.71	0.201
3000 rpm, 21 A	270.72	11.04	1324.44	0.204

Electrical energy generated by the RE was calculated based on battery voltage and charging current readouts logged by the Racelogic data logger. To calculate the H_2 combustion energy, hydrogen parameters from [17] have been used.

In addition, Fig. 9 shows the calculated specific fuel consumption for hydrogen. The highest value of SFC can be observed for the third run, where the least amount of electrical energy was generated.

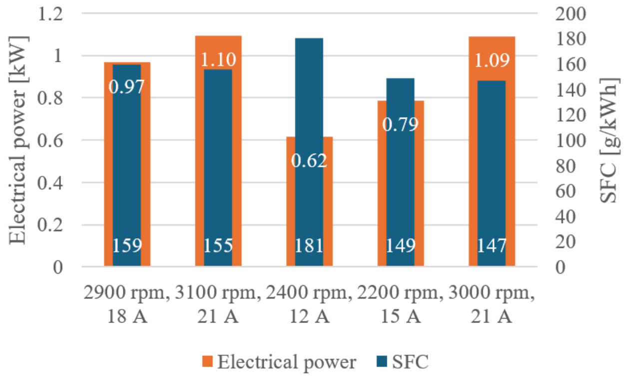

Fig. 9. Range extender performance

The values of the obtained overall genset efficiency are generally relatively high, which can be explained by the engine working with a relatively high load and with a mixture composition favorable due to the efficiency of the engine working on hydrogen. Only for the third point does the efficiency obtained by the range extender have a lower value. On the one hand, this results from the parameters of the engine itself (lower load and richer mixture for this point) and on the other hand from the parameters of the generator (the lowest output power and therefore lower efficiency too) and the ribbed belt transmission (a larger share of parasitic losses at its low load). The specific fuel consumption when powered by hydrogen is significantly lower than when powered by other fuels, which is due to the almost three times higher calorific value of hydrogen in relation to e.g. gasoline.

Table 4. Exhaust gas emission analysis on hydrogen fuel

Test run	NO_x before TWC [ppm vol]	NO_x after TWC [ppm vol]	O_2 before TWC [%vol]	O_2 after TWC [%vol]
2900 rpm, 18 A	67	86	11.8	12.1
3100 rpm, 21 A	19	37	11.9	12
2400 rpm, 12 A	186	218	10.6	10.9
2200 rpm, 15 A	33	58	11.8	11.8
3000 rpm, 21 A	34	49	11.7	11.6

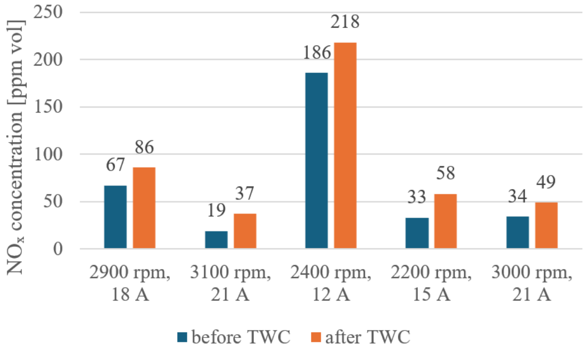

Fig. 10. NO_x concentration in exhaust gases of the hydrogen fueled RE

Table 4 consolidates the results of exhaust gas composition analysis. When it comes to the CO and CO_2, the analyzer readouts equaled in every case 0, and for HCs never exceeded 5 ppm, being just at the threshold sensitivity of the device. Due to this reason, they were skipped in the analysis. Only NO_x emission and O_2 concentration are presented, also visually in Fig. 10 and 11 respectively.

The NO_x concentration values are generally very low, which results from several factors. Primarily from the lean hydrogen-air mixture and the specifics of hydrogen combustion, which occurs significantly faster than gasoline, so the exposure of the cylinder working medium to high temperature is shortened. In addition, it should be remembered that the ignition timing was not set too aggressively, but rather conservatively in the preliminary stage of the engine management unit calibration. Another important observation is the noticeable increase in NO_x concentration in the exhaust system outlet, which results from the process of combining nitrogen with oxygen still present in the exhaust gases (lean mixture) in the hot catalyst integrated in a muffler of the engine. Certainly, the process of oxidation of NO to NO_2 also takes place in TWC.

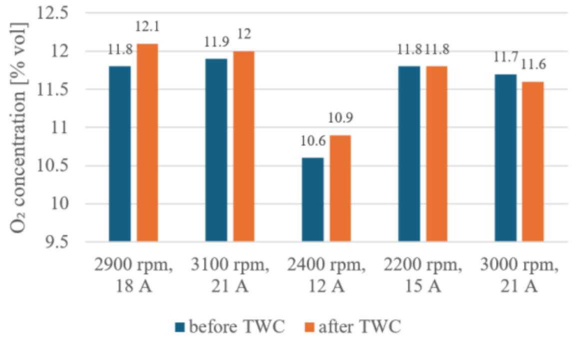

Fig. 11. Range extender O_2 concentration in exhaust gases

The oxygen concentration is high, directly proportional to the adjusted excess air ratio. Small increases in the oxygen concentration measured before and after the TWC may be the result of a certain change in the thermodynamic parameters of the exhaust gases and the specificity of the exhaust gas analyzer used, and to a lesser extent, changes in their composition (see observed NO_x increase).

Values of the temperature of exhaust gases measured upstream of the TWC are presented in Fig. 12.

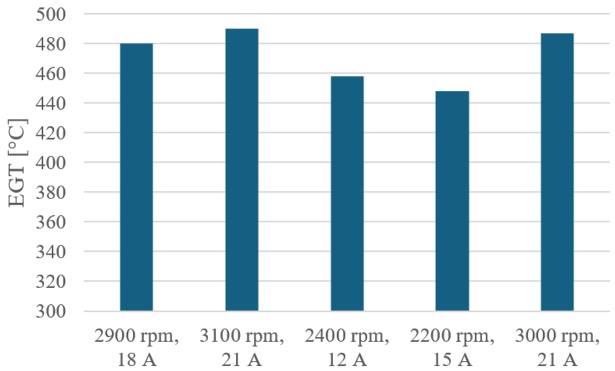

Fig. 12. Exhaust gas temperature of RE fueled by hydrogen

The exhaust gas temperature reaches relatively low values, which was expected in the case of hydrogen fueling and high excess air ratio values. The values for individual points are proportional to the power generated by the range extender engine.

4. Discussion

Compared to the results of previous tests of the range-extender powered by gasoline [11], it is easy to notice a significant reduction in power when powered by hydrogen. This is due to the low calorific value of the hydrogen-air mixture, which in turn is caused by the combustion of a lean mixture ($\lambda = 1.8$) and a reduction in volumetric efficiency, because hydrogen, a gas with very low density, takes up several times more volume in the mixture than gasoline vapors. On the other hand, operation with a lean mixture and a large throttle opening needed to achieve the appropriate power allowed for a noticeably higher (over 1 percentage point) value of the maximum overall efficiency of the range extender. It is expected that more accurate engine calibration will allow for slightly higher range extender power and even better efficiency results. Achieving stable, long-term operation of the hydrogen-powered range extender should certainly be considered a success. This is even more important because the engine used for the tests is a very simple design.

The main goal of using hydrogen as a fuel for the combustion engine is to eliminate any carbon compound emissions. In the case in question, this was fully achieved. The concentration of CO and CO_2 was at a level that was not measurable by the analyzer used. The HC concentration oscillated around the analyzer's sensitivity threshold (5 ppm vol.). In the case of gasoline fueling, these values were approximately ~0.6% CO, ~14.3% CO_2, and ~180 ppm HC in raw exhaust gases. The remaining emissions of the range-extender engine fueled with hydrogen, however, were very low values, usually below 100 ppm, compared to about 3000 ppm when fueling with gasoline.

5. Conclusions

The results of this preliminary research are promising, proving that the stability of such a small piston engine serving the purpose of a range extender can be achieved.

It must be considered that only a few optimization steps have been performed during the construction of the H_2-RE, serving as a small impulse for further research on the matter.

Looking at the exhaust gas analysis data, the benefits of using hydrogen as a fuel can be clearly visible, with CO_2, CO, and HC emissions at a level below the analyzer sensitivity. It can be determined that hydrogen fuel holds a tremendous advantage in lowering carbon emissions further into the atmosphere.

What must be observed is the low NO_x emission, but also the poor performance of the H_2-RE in terms of NO_x aftertreatment. The reason for this fact is that the TWC is unsuitable for lean mixtures required due to the method of hydrogen supply used. For efficient NO_x emission decrease, another aftertreatment method, like Selective Catalytic Reduction, should be considered. Hydrogen, recognized as an effective reductive agent, could be used in this method.

Nomenclature

BEV	battery electric vehicle
BTDC	before top dead center
CNG	compressed natural gas
ECU	engine control unit
H_2-RE	hydrogen range-extender
SI	spark ignition
SLPM	standard cubic decimetre per minute
TPS	throttle opening
TWC	three-way catalytic converter
λ	excess air ratio

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Marcin Noga, DSc., DEng. – Faculty of Mechanical Engineering, Cracow University of Technology, Poland.

e-mail: *noga@pk.edu.pl*

Tomasz Moskal, MEng. – Faculty of Mechanical Engineering, Cracow University of Technology, Poland.

e-mail: *tomasz.andrzej.moskal@gmail.com*