Article citation info:
NOGA, M., GORCZYCA, P. Development of the range extender for a 48 V electric vehicle. *Combustion Engines*. 2019, **177**(2), 113-121. DOI: 10.19206/CE-2019-220

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CE-2019-220

Development of the range extender for a 48 V electric vehicle

The article deals with the concept, development and results of preliminary tests of a range extender for an electric light commercial vehicle Melex with a 48 V electrical system. The purpose of the project is to build a prototype of the range extender powered by an internal combustion engine that will increase the range of the vehicle with electric drive, and at the same time will be characterized by a high efficiency and low exhaust emissions. The developed range extender is a combination of a 163cc single-cylinder combustion engine with a generator joined through a ribbed belt transmission. The 3-phase generator from a heavy-duty vehicle was used. In order to match the output voltage of the generator to the system voltage of the electric vehicle, an external adjustable regulator and a rectifier bridge with an increased operating voltage were used. The range extender was attached to a body of the electric vehicle by means of a welded frame made of thin-walled steel profiles. Initial tests of the developed range extender showed its proper interaction with both the lead-acid battery of the vehicle as well as with the nickel-metal hydride battery (NiMH) adapted to 48 V voltage from a hybrid electric vehicle. A maximum output power exceeding 2 kW was obtained. Maximum value of the overall efficiency of the range extender reaches up to 18.8%, which is a high value considering the small size of the used engine and the type of generator. The directions for further development of the range extender were also revealed in this paper.

Key words: *electric vehicle, range extender, spark ignition engine, overall efficiency, three-way catalyst*

1. Introduction

Nowadays, the emphasis is on the ecology of transport, with a special place for reducing carbon dioxide emissions. It is one of the ways to fight the greenhouse effect as well as environmental pollution. For this reason, hybrid- or all-electric vehicles are becoming more and more popular. In hybrid vehicles, part of the electrical energy needed to drive a vehicle is obtained from an electric machine that recovers energy while braking the vehicle [11]. It allows for a significant reduction of fuel consumption by a combustion engine [17]. In pure electric vehicles, all the energy needed to drive the vehicle is drawn from the batteries in the vehicle. In highly developed countries, where renewable sources or nuclear energy are used to produce electricity, it allows significant reducing greenhouse gas emissions. In Poland, electricity which is used to charge electric vehicle batteries, is mostly obtained at power plants or combined heat and power plants fired with coal or lignite. In countries producing electric energy in similar way, the use of electric vehicles as a way of fighting against carbon dioxide emissions is not very well justified until now. It is true that an electric vehicle does not emit pollutants and this is itself very beneficial, but its use does not eliminate emissions in a wider context. Emissions are moved from the place where the vehicle is used to a place where the power plant is. For example, in Poland, CO_2 emissions for each kWh of energy drawn from the electric grid currently amount to over 800 g [16], which is one of the highest values in Europe. With the energy demand of about 0.15–0.20 kWh per 1 km driving for an average passenger car [21], this gives CO_2 emissions related to the use of an electric vehicle equal to about 120–160 g for each kilometer driven. Additionally, the above estimation does not take into account battery and charger efficiencies, which are significantly lower than 1 [15]. Modern vehicles with hybrid drive achieve in road tests a fuel consumptions, which give results of CO_2 emissions of around 100 g/km [20].

One of the most serious disadvantages in the fast extending the use of electric vehicles, even in highly developed countries, is the limited range of these vehicles [8]. This limitation results from the relatively low energy density for currently available batteries [5]. In order to mitigate this inconvenience for end-users, some manufacturers of electric vehicles provide, as additional equipment, a so-called range extender [10, 14]. The device is essentially an auxiliary power unit that usually consists of an electric generator powered by an internal combustion engine with a power up to about 30 kilowatts. Such device is automatically activated when the battery state of charge drops below the limit [19]. It is possible to continue driving, usually at a limited speed. The most famous electric car with a range extender optionally available is BMW i3.

Based on the facts provided above in an outline, in the Students Club of Combustion Engines operating in the Institute of Automobiles and Internal Combustion Engines of the Cracow University of Technology, an idea appeared to create the range extender for an electric vehicle with a 48 V electric system. The concept of the range extender was adopted, consisting of a single-cylinder spark-ignition internal combustion engine driving a three-phase alternating current generator. The main objective of the project is to obtain the highest possible efficiency and the lowest possible CO_2 emission of the auxiliary power unit by selecting the optimal operating conditions, modifications of the engine and its additional systems, and then through the use of alternative fuels. In addition, the development of the range extender allows Students to use knowledge achieved in the course of their studies in many fields: design and operation of machines, combustion engines, electrical engineering, electronics, control engineering, programming, etc.

In the first phase of development, the use of a gasoline-powered engine has been proposed, but in the future the possibility of using more environmentally friendly fuels, such as bioethanol, natural gas or even hydrogen, is foreseen. Compared to conventional fuels the use of bioethanol or natural gas would significantly reduce CO_2 emissions in a process of electricity production for the vehicle [22]. The use of hydrogen would practically eliminate the carbon compounds from the exhaust gases emitted by the engine [2, 6].

2. Range extender for an electric light commercial vehicle

2.1. Vehicle

The prototype range extender described in the next section has been designed for the light commercial vehicle Melex 945DS. A general view of the vehicle that is in the equipment of the Laboratory of Mechatronics of the Cracow University of Technology is presented in Fig. 1.

Fig. 1. Electric light commercial vehicle Melex 945DS

Vehicles of this type in many varieties has widespread use for transporting goods inside industrial plants, warehouses, or as golf carts. They can be also found at airports and in many Polish city-centers as a transport mean for tourists. The model used for research purposes is a two-person vehicle (driver + passenger). The vehicle can also carry loads up to 150 kg in a cargo space located over a rear axle. The nominal voltage of the electric system is 48 V. The energy storage system consists of eight 6V-lead-acid batteries in series with a capacity of 221 Ah (10 h). The batteries are located under the driver's and passenger's seat. The propulsion source is an electronically controlled separately-excited DC motor with a rated power of 3.9 kW at 4300 rpm. The power is transmitted from the motor to the rear wheels through a two-stage gear reducer. The vehicle in this configuration achieves a top speed of around 30 km/h. The nominal amount of energy stored in the batteries equal to approx. 10.6 kWh, what allows to drive the distance of 60 km. The described vehicle has a curb weight of 620 kg (with batteries). The vehicle is equipped with a lighting system necessary to use in public roads [15].

2.2. Adopted concept of the range extender

The concept of the student project of range extender foresaw the use of generally available, inexpensive and easy to control devices. A three-phase alternating current generator with electromagnetic excitation was used. Alternator propulsion using a single-cylinder spark-ignition combustion engine through a ribbed-belt transmission was used, and rectification of the electric current generated in the alternator was carried out using a 6-diode rectifier bridge. A diagram of the concept of the range extender is shown in a Fig. 2.

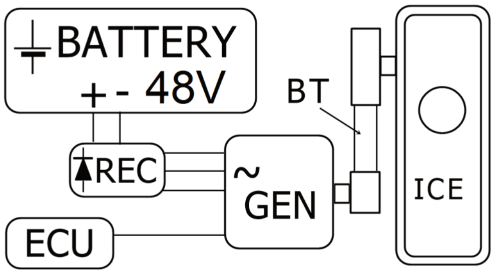

Fig. 2. Adopted concept of the range extender; ICE – Internal Combustion Engine, BT – Belt Transmission, GEN – Generator, REC – Rectifier Bridge, ECU – Electronic Control Unit

The estimated nominal output power of the power unit is about 2 kW. According to this value and the nominal voltage of the vehicle electrical system, individual components have been selected, which will be described in detail below.

2.3. Engine of the range extender

After estimating the power required to drive the generator, it was determined that it would be most reasonable to use a low power industrial four-stroke engine. A single-cylinder, forced air-cooled WEIMA 168FA engine with a displacement of 163 cm^3 and a maximum power of 3.8 kW obtained at 3600 rpm was chosen. This is the license version of the Honda GX 160 engine, which is popular all over the world.

The basic engine specifications are summarized in Table 1.

Table 1. Technical specifications of the engine used in the project

Parameter	Value
Engine type	four-stroke, SI, single-cylinder, OHV, forced air cooling
Displacement	163 cm^3
Bore x Stroke	68 × 45 mm
Compression ratio	8.5
Maximum power	3.8 kW at 3600 rpm
Maximum torque	10 Nm at 2500 rpm
Length x Width x Height	304 × 362 × 335 mm
Fuel system	float carburetor
Ignition system	transistorized magneto
Lubrication system	splash-type
Shaft rotation	counterclockwise
Net weight	15.0 kg

The engine is equipped with a centrifugal speed governor, which is very convenient for a propulsion of a generator. In order to be able to automatically start the engine of the range extender, apart from a recoil starter, an electric starter was also used. The float-type, horizontal carburetor of the engine is equipped with a manually controlled choke valve. Because of the use of a splash lubrication, the engine crankshaft is supported in ball bearings. The engine has a forced air-cooling system. The fan made of plastic is mounted on the flywheel. As an ignition system a transistorized magneto was used. The ignition timing is fixed at 25°CA BTDC.

Currently, in industrial engines with an output power of about 3.5 kW, a side-valve arrangement is still relatively often used, which gives a simple cylinder head design and low price of the engine, but does not allow to achieve high performance, thermal efficiency and low exhaust emissions [4]. The chosen engine is an OHV-type. Two valves are driven by rocker arms and pushrods from the camshaft located in a cylinder block. A location of the valves in the cylinder head allowed a favorable shape of the combustion chamber, hence the minimum brake specific fuel consumption of the engine at the factory carburetor settings is around 330 g/kWh. For an engine of this size this can be considered a beneficial result. The mentioned BSFC results were obtained by the authors of the work as part of research conducted in another project.

2.4. Generator and other electrical components

In the project the three-phase AC generator from a heavy-duty vehicle was used. The used alternator with the symbol A004TA0592 was produced by Mitsubishi. The general view of the used generator is shown in Fig. 3.

Fig. 3. General view of a generator used the project [24]

The generator's rated voltage is 28 V, while the nominal charging current is equal to 90 A and can be obtained starting from a rotational speed of 6000 rpm. The generator is excited electromagnetically by a rotor with 6 pole pairs. Stator windings are connected in a star. The weight of the alternator is equal to 7 kg. In the factory version, the alternator was equipped with an integrated rectifier bridge and an electronic voltage regulator.

In order to match the generator's output voltage to the battery of the electric vehicle, both the rectifier bridge and the voltage regulator were removed. Due to a need to obtain a significantly increased output voltage of the generator, the connection of the stator's windings in the star was retained. The original rectifier bridge was made of Zener diodes with a breakdown voltage of approx. 50 V. This value was too low due to the voltage needed to fully charge the Melex vehicle batteries, which exceeds 60 V. The range extender design uses an external six-diode bridge with a maximum reverse voltage of 1200 V and a continuous output current of 60 A. After attaching the aluminium heat sink to the rectifier, it was placed on the support frame bracket in such a way that it was cooled by air outflowing from the alternator ventilation gaps. The generator's excitation circuit uses an adjusted electronic current stabilizer. The regulator allows to maintain the set value of the battery charging current under given operating conditions. In a final form of the range extender, it will be replaced by an automatic regulator of the generator's output parameters that implements a predetermined battery charging strategy.

2.5. Power transmission

As mentioned earlier, the range extender concept adopted simple solutions, hence transmission with a ribbed belt was used to transmit the drive from the engine to the generator. A belt of 6PK-type for automotive applications was used. Transmissions with a ribbed belt are characterized by simple construction, low price, they are quiet and do not require lubrication. The efficiency of such a transmission reaches up to 97% at rated load, with a load equal to half the rated load, the efficiency is slightly lower and amounts to approximately 95% [23]. These can be considered a high values, especially taking into account average values of efficiency obtained by internal combustion engines.

The maximum regulated engine speed is 3600 rpm. At 28 V, the generator requires a speed of at least 6000 rpm to obtain a nominal output current. The characteristics of the used generator at the output voltage increased to above 50 V were not known. However, from the fundamentals of electric machines, it is known that at the same load and the same excitation magnetic field, obtaining an increased output voltage requires approximately proportional increase of the generator's rotational speed [1]. For this reason, it was decided to use a multiplier transmission with a gear ratio of approximately 0.5. Finally, the original 69 mm diameter pulley was left in the generator, while a 126 mm diameter wheel was used on the motor shaft, which gives a gear ratio of about 0.55. The generator pulley width has been reduced to the width of the 6PK belt by turning method.

The internal combustion engine of range extender has a counterclockwise rotation direction, while the generator rotates in a clockwise direction in a powertrain which it originates. It is true that due to the generation of alternating current, the direction of rotation of the generator is irrelevant, however, both the fan and the excitation circuit brushes are adapted (optimized) to work in only one direction. As a result, the internal combustion engine and generator had to be placed on opposite sides of the belt transmission. On the one hand, this increases the transverse dimension of the engine-transmission-generator assembly, but on the other hand it allows the use of a small-length belt, which does not require additional tensioning pulleys. In addition, the longitudinal dimension of the engine-transmission-generator assembly is clearly smaller in this case.

2.6. Support frame

As part of the project, it was planned to mount the prototype range extender in a rear part of the electric vehicle in a place intended for the cargo space.

In order to be able to mount the system on the vehicle, it was necessary to design and make a special support frame. The developed 3D model of the designed item is shown in Fig. 4.

The support frame is made of thin-walled steel square pipes. The object has dimensions of 850 mm × 500 mm. The frame is attached to the vehicle body through rubber-metal elements in four points. The purpose of the dampers is to diminish vibrations caused by the single-cylinder engine of range extender. Unfortunately, the engine has no balancing shaft, so the role of rubber-metal elements is the more important. The dampers are attached to the vehicle via special brackets. Direct mounting of the damping elements to the vehicle was not possible due to a fact that the body of the vehicle is made of a plastic of a relatively low mechanical strength.

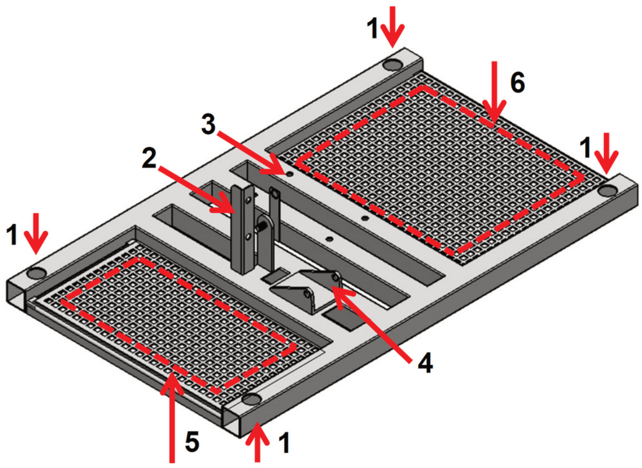

Fig. 4. Support frame of the range extender: 1 – hole for mounting of damping elements, 2 – bracket of a rectifier bridge, 3 – hole for mounting an engine, 4 – bracket of a generator, 5 – area for mounting control devices, 6 – area for mounting an engine management system (in future)

The support frame has a bracket that holds the generator and a bracket that allows to adjust the belt tension of the transmission by turning the alternator. The frame is also equipped with mounting brackets for the rectifier bridge with heatsink and engine speed sensor. Two shelves were made in the free spaces of the frame, thanks to which it was possible to mount the range extender control systems. Perforated steel sheets were used to make shelves. Frame elements were joined together by MAG-method welding. After finishing the construction works, the frame was cleaned and covered with two layers of anticorrosive coating.

2.7. Developed prototype of the range extender

After making the support frame, the range extender components were mounted on it. Then the ready auxiliary power unit was mounted on the Melex electric vehicle. The view of the developed range extender mounted on the electric vehicle at the place for the cargo space of is shown in Fig. 5.

The electrical leads of the rectifier bridge have been connected to the poles of the vehicle battery. Connections were made using cables with a 6 mm^2 cross-section. For safety reasons, double-insulated wires and over-current protection in the form of fuses were used.

The generator control system has been equipped with devices for measurements the battery voltage, charging current and rotational speed of the internal combustion engine. The generator excitation circuit switch, engine off switch and starter button are located both on the control panel of the generator control unit and on the dashboard of the vehicle so that the range extender can be started and stopped while the vehicle is being driven. A potentiometer for adjusting the charging current was placed on the generator control panel.

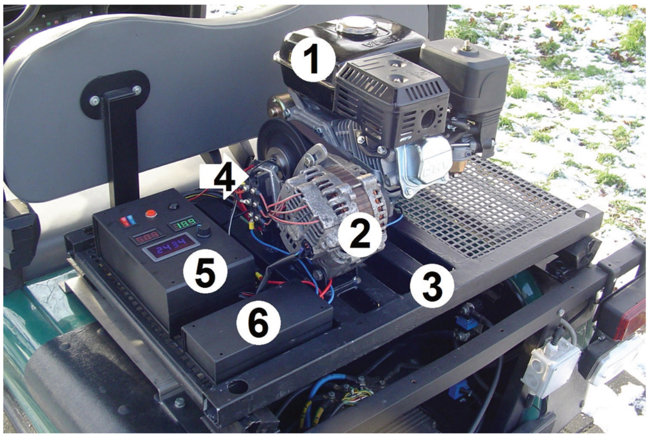

Fig. 5. View of the developed 48 V range extender: 1 – engine, 2 – generator, 3 – support frame, 4 – rectifier bridge, 5 – generator control unit, 6 – relays and voltage converter for a starter motor

The used engine electric starter is intended for operation at 12 V. To avoid the need to use an additional battery with this voltage, the starter is supplied from 48 V vehicle batteries via a DC-DC voltage converter.

3. Stationary research of the range extender

3.1. Preliminary tests of an efficiency of the range extender

Preliminary tests of the developed range extender were carried out when the engine with the generator was mounted on the test frame, and the electric vehicle was equipped with a nickel-metal hydride (NiMH) battery instead of a lead-acid battery. These batteries were adapted to an electric vehicle from a hybrid car. The main issue of the adaptation was the proper connection of the modules so that the output voltage of the pack match the system voltage of the Melex vehicle. Finally, a package with a nominal voltage of 50.8 V and a capacity of 32.5 Ah was obtained. The aim of the work was to develop a lightweight battery pack allowing for increasing the payload of an electric vehicle. More information for readers interested in this topic can be found in [16].

The carried out preliminary research was aimed at verifying the feasibility of the range extender project built according to the adopted concept and using the chosen components.

Already the first tests have confirmed that the adapted generator powered by the chosen combustion engine enables effective charging of the battery of the electric vehicle. A NiMH battery pack charging current exceeding 35 A was obtained.

A quantitative assessment of the range extender's operation consisted in examining the overall efficiency of the power unit at selected operating points (engine rotational speed–battery charging current). The overall efficiency means that this is considered as an energy delivered to the battery pack referred to an amount of used fuel. In particular, the overall efficiency of the range extender was calculated using formula (1):

$$\eta_{RE} = 100 \cdot \frac{E_{RE}}{m_f \cdot LHV} \quad (1)$$

where: η_{RE} – overall efficiency of the range extender, %, E_{RE} – energy delivered by the range extender, kJ, m_f – mass of a gasoline consumed in the test, kg, LHV – lower heating value of the gasoline, kJ/kg.

A denominator of the formula (1) represents the amount of chemical energy of fuel consumed by the engine during each test. The petrol LHV value of 43,000 kJ/kg was used for calculations [13].

The energy delivered to the battery by the range extender E_{RE} was calculated using the following general formula:

$$E_{RE} = \int_{t_0}^{t_1} V_{bat} \cdot I_{RE}\, dt \quad (2)$$

where: V_{bat} – battery voltage, V, I_{RE} – current delivered by the range extender, A, t – time, s, 0/1 – start/end of the measurement.

The registration of measurement results was carried out using a digital data acquisition card, thus finally the formula for calculating the energy delivered to the battery has the form:

$$E_{RE} = \sum_{t=t_0}^{t_1} V_{bat} \cdot I_{RE} \cdot \Delta t \quad (3)$$

The measurement frequency was 10 Hz, so the time step Δt was 0.1s in the formula. The measurement of fuel consumption was carried out using a laboratory digital scale. Due to the measuring range of the data acquisition card for measuring the battery voltage, a resistive divider with 1: 6 attenuation was used. The charging current was measured with a contactless transducer using the Hall effect. The measuring range of the transducer was 70 A, while its sensitivity was 33 mV/A.

The efficiency measurements were carried out at three operating points. In each of the tests, the consumption time of 100 g of fuel was measured. As the system was assembled in the test version, it was decided to perform measurements at a charging current not exceeding the safe value of 20 A. The first test was carried out at a speed of 2,900 rpm and an adopted load of 20 A. The second measurement was made for the same lever position of the engine speed governor, but with a reduced load value – 9 A. Due to the reduced engine load, the rotational speed in this test was slightly higher – around 3000 rpm. The last, third experiment was made at a set speed reduced to 2550 rpm. In the third test, the load was adopted to be the same as in the first measurement, i.e. 20 A.

Figure 6 shows exemplary graphs of the range extender operating parameters at 20 A load and an engine speed set to 2550 rpm (Test No. 3).

The value of the excitation current allowing to obtain the desired value of the charging current was set at the beginning of the test, and then it was not corrected anymore. Because of this, the current delivered by the range extender decreased slightly during the test. This was the result of a gradual increase in the battery voltage. During the test no. 3 the range extender delivered about 585 kJ of electric energy to the battery.

Results of the overall efficiency tests of the range extender for the three measurement points are summarized in Table 2.

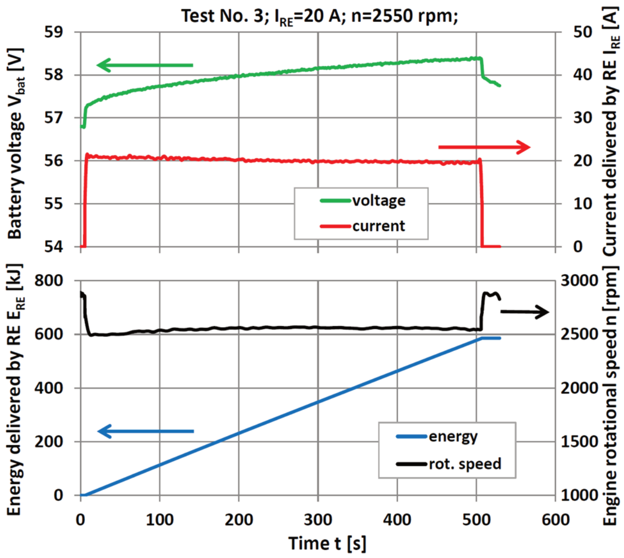

Fig. 6. Range extender operating parameters in the function of a charging time at 2550 rpm and $I_{RE} \approx 20$ A

Table 2. Summary of the results of measurements of an overall efficiency of the range extender

Parameter		Test No. 1	Test No. 2	Test No. 3
Current delivered by RE, I_{RE} [A]	setpoint	20	9	20
	average in the test	18.9	8.6	20.1
Engine rotational speed, n [rpm]		2900	3000	2550
Charging time, t [s]		505	688.2	501.6
Fuel consumption, m_F [kg]		0.1	0.1	0.1001
Energy delivered by RE, E_{RE} [kJ]		523.31	335.83	584.95
Overall efficiency of RE, η_{RE}		**12.2**	**7.8**	**13.6**

Due to slight variability of the range extender output current during the test, the table lists both current setpoints as well as averaged values from the actual measurement. Figure 7 presents a comparison the overall efficiency of the range extender.

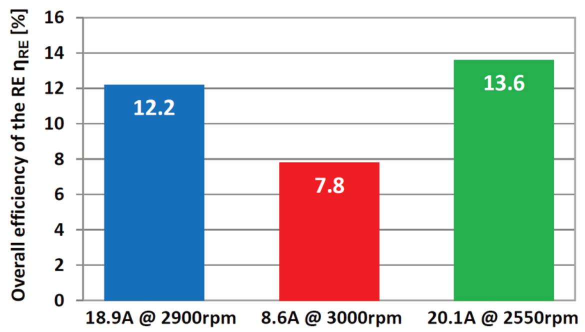

Fig. 7. Comparison of the overall efficiency of the range extender in different operating points

The maximum efficiency of the range extender in the preliminary experiments was 13.6% and was obtained at the load 20 A and at the engine rotational speed 2550 rpm.

This can be explained by the fact that under the given conditions the engine load was the highest. Similarly, due to the properties of the used generator, it is advantageous that the desired current value is obtained at the lowest possible rotor speed, i.e. at the lowest frequency of the generated alternating current [1]. The result obtained in the second test confirms that the operation of the power unit at the low load is inefficient. For this reason, the operation of the range extender in the low load region should be avoided.

3.2. Overall efficiency and exhaust gas toxicity of the range extender with air-fuel ratio correction

After installation the range extender assembly on the electric vehicle, further research and development work was carried out. One of the directions of further development of the design was the adaptation of a motorcycle exhaust system with an integrated three-way catalytic converter. These actions were taken to reduce the noise emitted by the power unit [7], but also to reduce concentrations of toxic exhaust compounds in the future. The used silencer comes from a Yamaha Majesty S XC125R motorcycle with a 125 cm^3 displacement engine and a maximum power of 8.8 kW at 7500 rpm. A view of the range extender with the adapted motorcycle exhaust system is presented in Fig. 8.

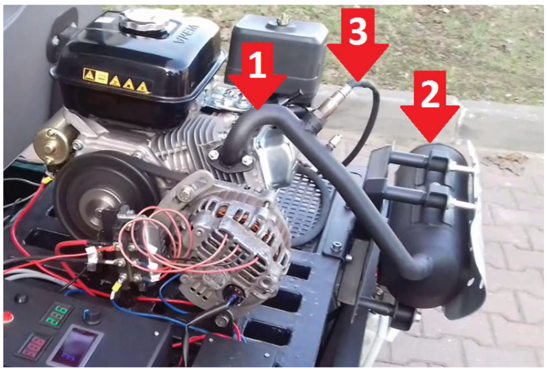

Fig. 8. An adapted exhaust system mounted to the range extender: 1 – exhaust pipe, 2 – muffler with TWC, 3 – wideband oxygen sensor

Adaptation of the exhaust system for mounting to the range extender required the use of a new pipe connecting the cylinder head exhaust port to the muffler. An oxygen sensor was installed in the new exhaust pipe to allow a regulation of the air-fuel ratio in a closed loop. In the next stage of development of the range-extender, a system for maintaining the stoichiometric air-fuel ratio of the mixture will be prepared so that the catalytic converter integrated in the exhaust system can operate effectively [12]. The research of the range extender equipped with a new exhaust system was aimed at verifying the considered method of the maintaining stoichiometric AFR, as well as an evaluation of the operation of the catalytic converter under these conditions. As the result of previous activities, it was revealed that with the carburetor factory settings, the engine is fed with a rich mixture. The value of relative AFR (λ) is variable between 0.8 and 0.9, depending on the engine load and rotational speed. This makes, that it is possible to supply additional air downstream from the carburetor in order to dilute the mixture so as to obtain a stoichiometric air-fuel ratio.

In addition, as part of the carried out work, the overall efficiencies of the range extender fed with the mixture without modifying its air-fuel ratio, and after obtaining the stoichiometric AFR were compared.

In order to supply an air stream after the carburetor, a stub pipe was added to the intake port of the cylinder head, which was connected to an additional throttle valve via a rubber hose. The purpose of the valve was to regulate the air flow that dilutes the air-fuel mixture formed in the carburetor. The concept of modification of the intake system is shown in Fig. 9.

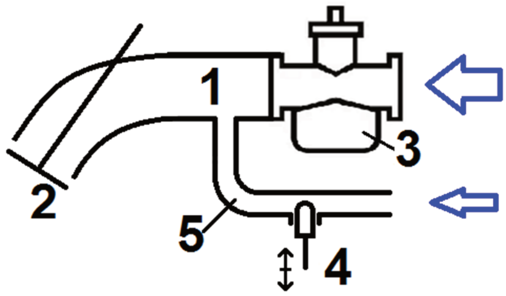

Fig. 9. Scheme of a modification of the air intake system: 1– intake port, 2 – intake valve, 3 – carburetor, 4 – additional-air valve, 5 – additional-air port

Comparative tests using the mixture composition regulation were carried out at a rotational speed of approximately 3400 rpm and a load of about 42 A. With a battery voltage of 52–53V, this gives the output power of the range extender within 2.2 kW, which is significantly higher than that obtained in the previous tests. This was possible because the range extender was already mounted in the vehicle on the support frame made in a target form. The methodology of the conducted research was analogous to that described in subsection 3.1. The only difference was that the range extender was mounted in the space previously occupied by the NiMH battery, hence the load for the range extender was this time lead-acid batteries. However, this fact did not affect the results. As before, the period of registration of the operating parameters of the range extender was determined until the engine consumed 100 g of fuel. Arcon Oliver K-4500 gas analyzer was used to determine the exhaust composition and conversion efficiency of the catalyst. The analyzer allows the measurement of CO, CO_2, HC, NO_x and O_2 concentrations in dry exhaust gas. The relative air-fuel ratio is calculated by the analyzer based on the exhaust gas composition. In order to measure the composition of the exhaust gas, two exhaust gas intake points were made, one in the pipe in upstream from the catalyst, and the other in the muffler downstream from the reactor support.

During the first measurement the engine operated with a closed additional-air valve. As the second, a test was carried out in which the mixture formed by the carburetor was diluted by additional air supplied downstream from the throttle. The opening degree of the additional air valve was adjusted so as to obtain a stoichiometric AFR.

Figure 10 presents graphs of energies delivered to the battery and overall efficiencies of the range extender obtained in the both measurements.

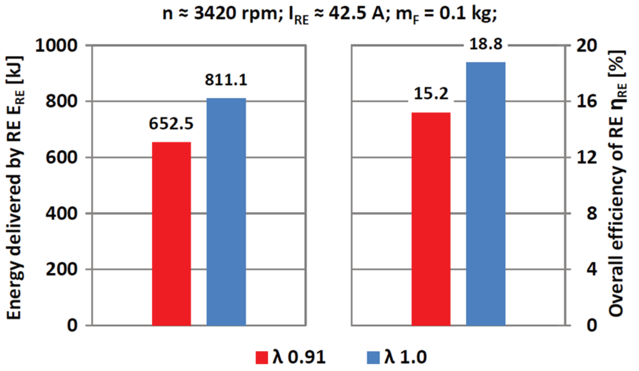

Fig. 10. Comparison of energies delivered to battery and efficiencies of the range extender working with factory settings (λ 0.91) and with a modified relative AFR (λ 1.0) by the supplying of additional air

When the engine was running without additional air, the mixture composition oscillated around the value of relative air-fuel ratio of 0.91. When using the dilution of the mixture with additional air, the fuel consumption of the engine decreased, hence the time of consumption of 100 g of fuel increased. For this reason, in the second test, the generator delivered a significantly larger amount of electricity to the battery, and this gave a significant increase in the overall efficiency of the range-extender when fed with a mixture of stoichiometric air-fuel ratio.

Figure 11 shows the results of the exhaust composition measurement in the both experiments. In the first measurement, with the unmodified air-fuel ratio of the mixture, the composition of the exhaust gases upstream from the catalytic converter (λ 0.91) was recorded. During the second measurement, the compositions of exhaust gas both upstream from (λ 1.0 upstr. TWC) and downstream from the catalytic reactor (λ 1.0 dwnstr. TWC) were recorded. This made it possible to evaluate the conversion efficiency of the reactor being part of the new exhaust system.

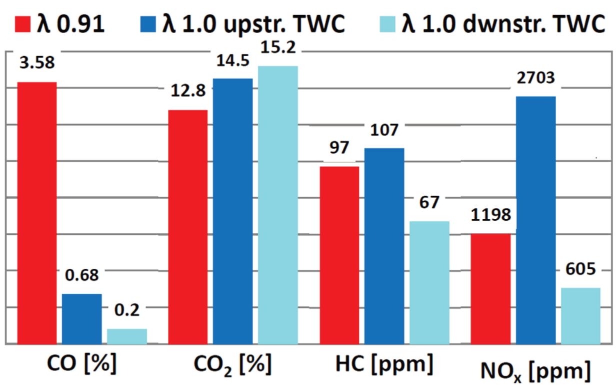

Fig. 11. Comparison of CO, CO_2, HC and NO_x concentrations in exhaust of the RE engine working with factory settings (λ 0.91), as well as with AFR modification (λ 1.0)

During operation without adding air downstream from the carburetor, the engine was fed with a rich mixture, hence a high CO concentration and a relatively low NO_x concentration in the exhaust. The correction to the stoichiometric AFR resulted in a significant decrease in the concentration of carbon monoxide, but also in an increase in the concentration of NO_x upstream from the catalytic converter. This was expected when shifting from a rich to stoichiometric mixture. It was also observed, that the concentration of hydrocarbons upstream from the catalytic converter was higher by 10 ppm in relation to the result for the composition of the mixture λ = 0.91. This may be due to the deterioration of the fuel atomization conditions associated with the reduction of the air flow rate through the carburetor when additional air is supplied. However, this was not a particularly large increase. It should also be noted that particularly for a low-power engine fed by a carburetor, a very favorable proportions of CO to CO_2 upstream from the catalytic converter was observed when the engine was fed with a stoichiometric mixture. This indicates that the mixture was correctly prepared, as well as combustion process occurred properly.

Figure 12 shows the results of conversion efficiency when engine was fed with a stoichiometric mixture. Efficiencies were calculated from exhaust gas compositions upstream from and downstream from the catalytic converter that were presented above.

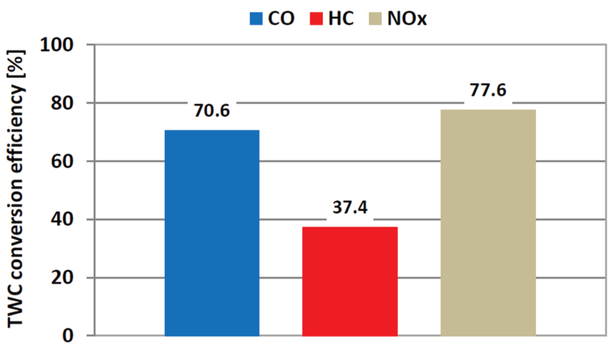

Fig. 12. Conversion efficiency of TWC during operation of the engine with stoichiometric air-fuel ratio

The use of modification of the air-fuel ratio by dilution with additional air caused that the catalytic reactor integrated in the new exhaust system started to work. The conversion efficiency for CO and NO_x obtained relatively high values. In the case of hydrocarbons, a lower efficiency was obtained. This is usually observed for reactors, that were aged in a some extent, like the one used. In any case, the concentrations of toxic compounds downstream from the catalytic converter, when the engine is running with the stoichiometric mixture are clearly lower than those recorded when working with the unmodified AFR (λ = 0.91). This confirms the correctness of the adopted concept of the air-fuel ratio adjustment in order to enable decreasing of toxic components emissions of the developed range extender.

4. Road tests of the vehicle equipped with RE

In order to determine the impact of the range extender implementation on the traction parameters of the electric vehicle, road tests were carried out. During the tests the vehicle behavior was compared at an acceleration from v = 0 to v = v_{max} with RE off, and then with RE turned on. In tests, the vehicle load was the driver and passenger, which together with a weight of the range extender gives the total vehicle weight of 820 kg. The engine rotational speed was set at 3450 rpm, while the current delivered to the battery was approximately 40A. During the tests, the vehicle batteries remained charged at around 70%. With a higher state of charge, turning on the range extender could adversely affect the life of the batteries.

Figure 13 presents a comparison of waveforms of the battery voltage, the battery current and the vehicle speed in acceleration tests with the range extender switched off and then running.

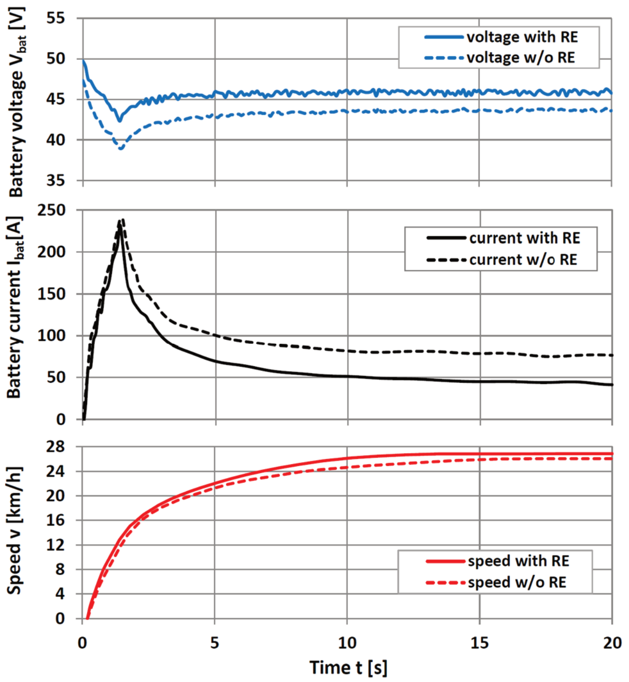

Fig. 13. Comparisons of battery parameters and vehicle speed during acceleration with the range extender off (dashed) and running (solid)

The use of the range extender causes a significant decrease in the current drawn from the batteries while driving at a speed close to maximum. The decrease of the current drawn from the battery causes that proportionally smaller decrease in battery voltage under load are observed. The increase in the voltage of the battery operating under load by about 2 V, caused by the decrease of the voltage drop on the internal resistance of the batteries [9], resulted that the maximum speed of the vehicle with the range extender running increased by approx. 1 km/h. The use of the auxiliary power unit also had an impact on reducing the acceleration time of the vehicle from 0 to 24 km/h. With the range extender off, it was 8.4 s, and when driving with the RE turned on, this time has been shortened to 6.8 s.

5. Conclusions and further development

The first stage of the project development was completed. The developed range extender works correctly both in stationary conditions and when driving a vehicle. At several selected measurement points, the overall efficiency tests were carried out, during which promising results were obtained. In the further part of the work, the engine exhaust system was modified by using a muffler with a three-way catalytic converter. The use of a simple method of regulating the air-fuel ratio of the mixture allowed to verify the efficiency of the engine's cooperation with the exhaust gas aftertreatment system. The use of a three-way catalytic reactor, when the engine is running a stoichiometric mixture, significantly reduces the emission of toxic exhaust components. In addition, the leaning the mixture formed by the carburetor up to stoichiometric ratio in the last of the analyzed measurement points resulted in obtaining the most favorable, so far, result of the overall efficiency of the developed RE amounting to 18.8%. Taking into account the low output power of the auxiliary power unit, the efficiency can be considered very beneficial. A positive result of the verification of the method of regulation the stoichiometric mixture, confirms the desirability of developing the AFR automatic correction system.

The results of the carried out work allowed also to determine the area and extent of further work on the developed range extender. In the next step, these activities will be focused on the development of an automatic control system of the range extender. The next research of the efficiency of the power unit at various points of its operation map will allow to determine the effective algorithm for controlling the engine speed depending on the demand for electrical power. As mentioned in the introduction, it is also planned to introduce modifications to the engine and fuel system oriented at increasing the overall efficiency and the use of alternative fuels, what will allow for a significant reduction of CO_2 emissions. To accomplish these goals it will be necessary to equip the engine with an integrated injection-ignition system [3]. Among engine modifications, an application of a strategy of the late intake valve closing allowing the implementation of a work cycle with increased expansion (Miller–Atkinson) is considered [18].

Acknowledgements

This research was conducted in the framework of task No. M-04/406/2018/DS, which was a subsidy for research granted by the Ministry of Science and Higher Education of the Republic of Poland.

Nomenclature

η_{RE}	overall efficiency of the range extender, %
λ	relative air-fuel ratio
AFR	air-fuel ratio
APU	auxiliary power unit
BSFC	brake specific fuel consumption, g/kWh
BT	belt transmission
BTDC	before top dead center
CA	crank angle, degrees
dwnstr.	downstream from
ECU	electronic control unit
E_{RE}	energy delivered by the range extender, kJ
GEN	generator
I_{bat}	battery current, A
I_{RE}	current delivered by the range extender, A

ICE	internal combustion engine
LHV	lower heating value, kJ/kg
m_f	mass of a gasoline consumed in the test, kg
MAG	metal active gas
n	engine rotational speed, rpm
OHV	overhead valve
RE	range extender
REC	rectifier bridge
SI	spark ignition
t	time, s
TWC	three-way catalyst
upstr.	upstream from
v	vehicle speed, km/h
V_{bat}	battery voltage, V
w/o	without

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