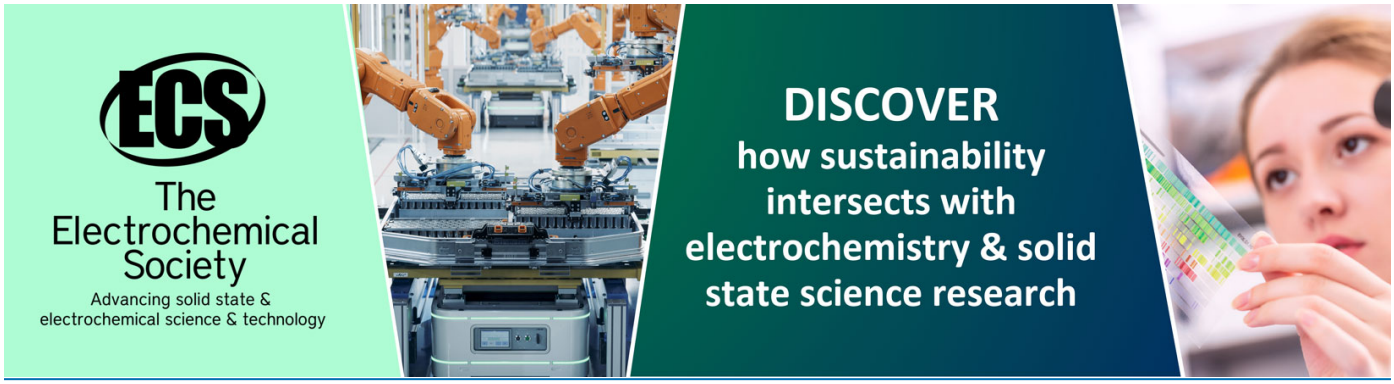
Application of gaseous fuels with variable chemical composition for energy purposes



Application of gaseous fuels with variable chemical composition for energy purposes

M Brzeżański W Marek M Mareczek and T Papuga

Cracow University of Technology, Krakow, Poland

E-mail:mbrzez@pk.edu.pl

Abstract. The article presents the concepts of power systems with combustion engines fed with gaseous fuels of variable chemical composition. These are usually waste gases from the chemical industry or low-calorific gaseous fuels that require the addition of another fuel. Preliminary results of exploitation tests of power generators equipped with engines fuelled with this type of gas are presented.

1. Introduction

In some technological processes conducted in the chemical industry, various types of gases are used on a large scale, a significant part of which, after use in various types of processes, is a post-production waste. In many cases, waste gases have a changing chemical composition which usually does not allow their further use, including application as fuel in standard combustion systems for heating devices. For these reasons, waste post-production gases are usually subject to utilization by burning them on torches, which is connected to energy losses, as well as fees for environmental protection for heat and exhaust emissions. Some of these gases are characterized by unfavorable properties, and their use is possible by mixing and co-burning of these gaseous wastes, e.g. with natural gas. A team of scientists from the Institute of Automobiles and Combustion Engines of Cracow University of Technology has developed innovative concepts that enable the use of various types of waste gases as fuel for stationary piston combustion engines, applicable to the drive of power generators.

This is a very difficult task, because in conventional piston engine fuel systems, a sudden change of the chemical composition of the fuel usually means the loss of control over the rotational speed stabilization system and triggers the shutdown procedure of the aggregate. For these reasons, industrial engine manufacturers do not foresee the possibility of using fuels whose chemical composition changes significantly over a short period of time. The problem is also with gaseous fuels with low calorific value, whose use in engines is usually unprofitable.

Other problems that condition the possibility of fueling the engine with gaseous fuel include thermodynamic parameters, such as pressure, temperature, humidity, as well as the content of chemically aggressive components and resistance to knocking combustion. This applies in particular to gases originating from certain technological processes in which there are quite large changes in the pressure and temperature of reactants, which have a significant effect on the thermodynamic state of waste gases, some of which may, for example, be condensed. All mentioned features of waste gaseous fuels are a significant barrier to their use as fuel for piston combustion engines and many recognized producers of engines fueled by gaseous fuels exclude the possibility of their use on such fuels. For this

reason, the developed concepts of post-production waste fuel systems that have been tested in laboratory and industrial applications can be considered as innovative.

2. Concepts of feeding systems of internal combustion engines, by use of post-processing gases

The concepts of feeding systems of combustion engines with waste gaseous fuels developed at the Cracow University of Technology open up a new area of using of these fuels for energy purposes. They take into account all the aforementioned features of these fuels, mainly the variability of their parameters, in particular chemical composition in short time intervals, thermodynamic state and resistance to knocking combustion.

The first system was created as part of a research project for the SKOTAN SA company, executed and deployed at Zaklady Azotowe ZAK Kedzierzyn - Kozle chemical industrial plant. The system has been developed for industrial post-processing gases from chemical installations that are available at pressure greater than 3 bar. For this type of cases, an injection gas fuel system was developed. It consists of an innovative system of controlling the power supply system and the ignition system, which takes into account both the type of fuel and the variability of its basic parameters. The above system was created and subjected to laboratory tests at the Cracow University of Technology and was subsequently verified in industrial research carried out in a pilot energy installation, located in Zaklady Azotowe ZAK Kedzierzyn - Kozle chemical industrial plant. The developed system has been patented under the name: "The method of controlling of regulatory parameters in a spark-ignition internal combustion engine", Patent: PL 222462 B1 - WUP 07/16, dated 29/07/2016. Industrial research of this system, carried out while powering engines with waste gases from chemical processes containing a high proportion of hydrogen, was started in March 2014 and is still being carried out on a continuous mode.

The second type of the system still in the phase of laboratory testing, was developed for the HORUS-Energia company, specializing in the production of power generators. It is an electronically controlled mixer feeding system, designed for gaseous fuels, which are available at a pressure close to ambient pressure. This group includes a number of flammable gases coming from industrial processes or biological decomposition processes of organic substances. These include, for example, biogas, fermentation gases, carbon monoxide, mine gases, blast furnace gas, or coke oven gas. The developed system can be adapted to supply one of the fuels or a mixture of several gases, composed in any proportions. Both systems have been adapted to the engines cooperating with electric generators, where extremely important parameters are maintaining constant rotational speed and fast response of the system to load change. These parameters are included in the relevant industry standards, and their fulfillment is a condition for the admission of power generators for use. The developed control systems meet the above requirements, also in case of significant changes in the parameters of the fuel supplied, including such as chemical composition, calorific value, or resistance to knocking combustion. In this area, the developed systems are innovative solutions that have not been used yet in the products of reputable companies producing power generators.

3. Research object

A 6-cylinder, supercharged MAN E2876 LE302 type engine with displacement (volume) of 12,82 dm^3, factory-adapted for natural gas supply, was selected as the object of laboratory tests. In the factory configuration, it is fed with natural gas by means of a mixer, develops an effective power of 200 kW and is designed to drive a power generator. The choice of this unit was done mainly to the fact that MAN offered a 12-cylinder engine with the same cylinder geometrical dimensions. Because the assumptions of the research program provided for the development of the concept of a single-cylinder energy conversion system, with the possibility of its duplication, the modular construction of the 6th and 12th cylinder engines fulfilled the condition. HORUS-Energia was the supplier of engines, electrical machines and housing of the units, while all elements of the developed concept of the gas fuel injection system and the electronic control system were made at the Cracow University of Technology. This is also where the power generators, supplied by Horus-Energia company were

equipped with all the developed and made components, of the power supply and control system. After these operations, the aggregates were transported to a specially built facility at the Zaklady Azotowe ZAK in Kedzierzyn - Kozle industrial plant.

4. Design assumptions of the injection system

The first task carried out to supply combustion engines with post-production gases with variable physical-chemical parameters was to develop a system that allows the use of various types of gaseous combustible substances that are waste products from chemical processes carried out in the butanol, isooctane and aldehyde installations at Zaklady Azotowe ZAK Kedzierzyn – Kozle industrial plant. According to the factory specification, the main combustible component in the offered gases, was industrial hydrogen, whose volume fraction was on average 60 to 90% and volatile hydrocarbons, carbon monoxide and methane. In practice, the chemical composition of the offered gases, was subject of rapid and significant changes, and the volume fraction of hydrogen often exceeded 90%.

The purpose of the research was to develop a power and control system for the engine using this type of fuel and to adapt it to the requirements resulting from the regulations allowing power generators to be operated and to provide them with the most favorable working conditions. It became necessary to identify new problems related to the cooperation of the engine with the power generator, as well as to achieve the best possible working and ecological parameters of the engine in the research. The research concerned an engine performance at a constant rotational speed of 1500 1/min and a changing load, because such conditions correspond to the operation of the internal combustion engine in the generator set. Among the control parameters of the tested engine, which had to be adapted to the type of tested fuel, were primarily the ignition advance angle and the coefficient of air excess. Both of these parameters have a very significant impact on the combustion process in the cylinder of the engine, which determines the value of the energy parameters obtained and the emission of toxic exhaust components.

Significantly also affect the temperature of the exhaust, which in the case of conducted tests is of key importance due to the engine's criterion, according to which the maximum temperature of exhaust gases cannot exceed 700 ^{o}C, due to thermal resistance of the turbocharger. Additionally, both the value - the coefficient of air excess and especially the value of the ignition advance angle are closely related to the occurrence of knocking phenomenon. For this reason, for the tested fuel and for each working point of the engine, both of these control parameters were set individually. In the carried out analyzes, three criteria for the selection of engine control parameters were adopted, for which the engine load value was selected with the specified fuel supply:

- max. engine exhaust temperature may not exceed 700 ^{o}C,
- there must not be anomalous combustion in the form of knocking,
- the backflow of the flame to the intake manifold must not occur.

During the laboratory tests, the concentration of: carbon monoxide CO, THC hydrocarbons, nitrous oxide NO and carbon dioxide CO_2 and oxygen O_2 was tested and registered. In addition, the effect of the tested fuel on other engine parameters, such as: torque and power, fuel consumption, total efficiency, coefficient of excess air and exhaust gas temperature were examined and registered.

5. Control system of post-processing gases injection

The implementation of the set tasks required in practice to design and build a gas fuel installation with a modular configuration, similar to a Common Rail type fuel supply system. In this case, the fuel rail has been divided into separate segments supporting each of the engine cylinders. A single segment has been equipped with two electromagnetically controlled injectors, which facilitates precise control of the fuel dose depending on the engine load. Natural gas injectors were used, commercially available, which after the modification consisting in increasing the quantity of gaseous fuel, were properly calibrated. Each of the injectors was individually controlled by a signal from the control system, which resulted in the possibility of individual adjustment of the excess air ratio in each of the cylinders. The ignition system has been significantly modified, introducing the possibility of individually adjusting the ignition timing and ignition energy in each of the engine cylinders. The value of the ignition advance angle was dependent on the signals coming from the knock sensors, in which each of the cylinders was also equipped. On the basis of experimental tests, spark plugs were selected in which the spark channel was advanced into the combustion chamber. This change has brought about a significant improvement in ignition initiation of the tested fuel mixtures, especially when the engine is supplied with a very lean mixture.

A special, programmable engine controller developed in the LabView environment was designed and made at the Cracow University of Technology. Its task was to control the most important engine control parameters, such as the value of the gaseous fuel dose, the value of the ignition angle, the degree of the throttle opening and the value of the air excess coefficient. The modular nature of the feeding and ignition systems made it possible to supervise the combustion process in each of the cylinders. It was carried out on the basis of the exhaust temperature measurement, measured individually by thermocouples, placed in the exhaust duct of each cylinder, directly at the exhaust outlet from the head.

The exhaust gases temperature, which was measured individually, uniquely determined the amount of heat released in each cylinder, and was also a diagnostic tool, informing about disturbances in the combustion process, such as, for example, extended combustion caused by poor mixture or misfiring. In addition, the controller, in the adaptive mode, constantly cooperated with the knock sensors, thanks to which it uniquely determined the limit of the knock for each of the cylinders, in all analyzed engine operation conditions. This type of supervision and regulation made it possible to achieve high efficiency of energy conversion in each of the engine cylinders.

6. Operational tests

The concept of the engines fuel injecting (with waste gas fuels), developed at the Cracow University of Technology was applied in three engines - one 6-cylinder with a nominal power of 200 kW and two 12-cylinder engines with a nominal power of 400 kW. The total nominal power of three engines prepared for operational tests was 1 MW assuming that natural gas was supplied, while when supplying gases of a different chemical composition, the obtained performance was respectively lower.

During the project implementation, the system components were made and three engines were equipped with them. Engines, after equipping with designed and made elements of the power supply system, have been connected with power generators and placed in the building arrangement prepared by the HORUS-Energia company. In this form, the aggregates have been put into operation in a facility located on the premises of Zaklady Azotowe Kedzierzyn-Kozle industrial plant, where they have been working in a continuous mode, dependent on the supply of post-processing gas, producing electricity. During the operation a number of tests were carried out, the effects of which confirmed the initial assumptions of the developed concept.

Measurements made during the operation tests of the aggregate with a 6-cylinder engine have shown that in the case of feeding with waste gas fuel with a hydrogen content of approx. 60%, 167 kW apparent power can be obtained. In relation to the internal combustion engine of this aggregate, a predicted cylinder power of approx. 30 kW was obtained. The specific fuel consumption corresponding to this load was about 1 Nm^3 / kWh. However, in standard continuous operation conditions, this unit could be safely operated with a load of 140 kW due to the limitations of peripheral equipment. In the case of aggregates with 12-cylinder engines, in comparable operating conditions, 260 kW of apparent power was obtained, while under standard continuous operation conditions, this aggregate could be safely loaded up to a value of approximately 230 kW due to the limitations of peripheral devices. In tab. 1 work balance of aggregates during initial exploitation tests conducted over a period of selected 8 months, has been presented.

Table 1 presents the aggregates performance balance during the preliminary in-service tests conducted over a period of selected 8 months

Aggregate name	Working time	Generated energy	Average load
No. 1 - 12 cyl.	3992 h	816 MWh	204 kW
No. 2 - 12 cyl.	3490 h	668 MWh	191 kW
No. 3 - 6 cyl.	3938 h	470 MWh	119 kW

An important effect of using waste gas fuel with a high hydrogen content was to obtain practically zero emission of toxic exhaust components. Control measurements made during operation of the unit with a 6-cylinder engine, in a variable load field, fully confirmed the pro-ecological suitability of this type of waste fuels. At the engine operating point, which corresponded to the operating conditions for the maximum value of 167 kW, only 0,3% v / v CO_2 and 59 ppm NO_x were disclosed in the exhaust. The chemical characteristics of the deployed fuel and the method of regulating the mixture composition and engine power have contributed to the achievement of such a result. The nominal power (1 MW) of three aggregates was determined with the use of natural gas, i.e. a fuel with high resistance to knocking combustion and a calorific value of approx. 36 MJ / Nm^3. The operating parameters achieved by the engine depend clearly on the properties of the fuel to which the engine is fed. Gas fuel with a hydrogen content by about 94% (according to chromatographic analysis) has a calorific value of about 11 MJ/Nm^3. The calculated average total efficiency of electricity generation was approx. 0,33.

When powering the engines with waste fuel with a high share of hydrogen, the obvious effect is an extremely low CO_2 emission value per unit of energy generated. On average, during the period of supervised use of aggregates, a value of just over 25 kg CO_2 was obtained per 1 MWh of generated energy, which is incomparably lower emission value in relation to electricity generation in coal-fired power plants, where this indicator can be from 800 to up 1000 kg of CO_2, per 1 MWh.

Obtained engine working parameters should be considered a great achievement on the scientific, technical and economic scale, taking into account the properties of fuel. This system has so far been working correctly with very high variability of fuel composition and does not create operational problems, which allows a positive prognosis for its further industrial applications.

7. Operational tests during coke gas supply

An additional verification of the developed concept of supplying the engines with gaseous fuels, in which the engine parameters adapt to the properties of the fuel, was to carry out tests during the coke-oven gas supply. In the conducted research, coke oven gas was drawn from the industrial network, and before being fed into the engine it was dried and purified from solid substances. The measurements were made on a aggregate equipped with a 6-cylinder engine. While supplying the engine with coke-oven gas with a hydrogen content of 50 - 60% it was possible to obtain complex power up to 202 kVA, which corresponded to the designed power from the cylinder at 35 kW. The specific fuel

consumption corresponding to this load was about 0,6 Nm^3 / kWh, which corresponds to the efficiency of electricity generation of 33%.

Operational tests were carried out in a 100-hour period, while during continuous operation the aggregate was loaded in approx. 50% of the maximum value obtained in the measurements, which resulted from the limitations of the systems cooperating with the engine. Based on the measurements carried out and the results of previous work, it can be predicted that under standard continuous operation conditions, this aggregate can be safely loaded up to a value of approx. 140 kW due to the limitations of peripheral devices. An important effect of the use of coke oven gas is very low emission of toxic exhaust components (table 2).

Table 2. Selected values of concentration of exhaust components during engine feeding with coke gas

O.n.	Complex power [kVA]	Real power [kW]	CO [%]	CO_2 [%]	HC [ppm]	O_2 [%]	NO_x [ppm]	Coefficient of air excess
1.	200	196	0,02	4,4	6	9,2	139	1,70
2.	183	181	0,02	4,4	6	9,0	137	1,70
3.	162	160	0,02	4,4	7	9,1	130	1,70
4.	145	142	0,02	4,4	7	9,1	123	1,70
5.	124	122	0,02	4,4	7	9,1	138	1,70
6.	103	102	0,03	4,3	8	9,2	134	1,70

Control measurements made during operation of the aggregate in a variable load field fully confirmed the pro-ecological usefulness of this type of fuel. At the engine operating point, which corresponded to the maximum operating conditions of 200 kW in the given operating conditions, only 0,02% v/v CO, 4,4% v/v CO_2, 6 ppm HC and 139 ppm NO_x were disclosed in the exhaust gasses. Similar results were recorded while the engine was running in a 100 hour operating cycle. The chemical characteristics of the applied fuel and the method of regulating the mixture composition and engine power have contributed to the achievement of such a result. The conducted research has also shown that the use of coke oven gas as a fuel for generating electricity brings very good results in the reduction of CO_2 emission per unit of energy generated. In this case, the value of 677 kg of CO_2, per 1 MWh of generated energy was obtained, which is significantly lower than the value obtained in coal-fired power plants (see above).

The carried out verification tests fully confirmed the design and operational features of the developed power supply and control concept, especially considering the issue of "fuel elasticity" of the generator set, which can be successfully supplied with natural gas, coke gas and waste gas with variable chemical composition. The obtained parameters for the analyzed aggregate fed with coke-oven gas should be considered a significant achievement.

8. The concept of a fuel mixing feeding system, for post-processing gasses

Injection system of gas fuel supply requires pressure of about 3 bar, while in the industry there is a large number of combustible gases, available at pressure close to ambient pressure. Compression of this type of fuels is not profitable and rationally justified, therefore at the Cracow University of Technology in cooperation with the HORUS-Energia company, an innovative, electronically controlled system of mixer feeding of combustion gas engines of various types with gaseous fuels was developed. This system is currently in the phase of laboratory tests, carried out on the same type of 6-cylinder engine, which has undergone extensive research in the development of the injection power

concept. This gives the opportunity to compare both power system concepts and control important engine parameters.

The developed system of electronically controlled mixer has similar functional advantages and has a similar control system as the mentioned injection power system. In addition, it has a modular structure that allows the engine to be fed with fuels of different physicochemical and chemical properties from different sources. It is very important to be able to connect another module to the fuel system with different properties without having to turn off the engine. The developed concept has been adapted to the motors cooperating with electric current generators, in which the condition of maintaining constant rotational speed should be kept as well as the adequately fast reaction of the system to load change. These parameters are included in the relevant industry standards, and their fulfillment is a condition for the release of power generators for use.

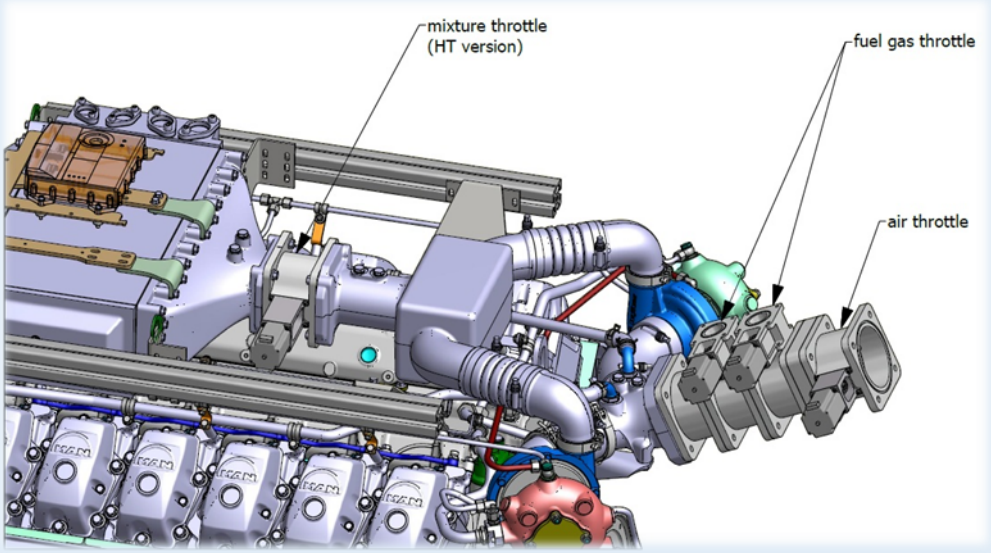


Fig. 1. Concept of electronically controlled system for gas fuelled engines

Some of the available gaseous fuels are characterized by low calorific value or low resistance to knocking combustion. Their use as fuel for reciprocating engines is often unjustified due to the inability to achieve cost-effective total efficiency of the entire energy system. The developed concept of the power system solves this problem, creating the possibility of supplying additional gas with better properties and flexible creation of the mixture with the desired parameters. In this field, a study was carried out on the developed concept to examine the extreme caloric values of the feed gas, where the generator engine is able to work properly.

In the laboratory tests, the following gas fuel mixtures were used with very different, often extreme properties, from the point of view of the operation of the internal combustion engine:

- natural gas with carbon dioxide,
- natural gas with nitrogen,
- natural gas with propane,
- propane with acetylene.

In the first phase of the laboratory tests, the minimum calorific value of the gas was determined, which guarantees stable operation of the engine. The tests were carried out for mixtures of natural gas with carbon dioxide with different share of the aforementioned components, thanks to which different

fuel heating values were obtained. The control system's ability to adjust its control parameters to varying calorific value during the engine operation was tested.

The research also concerned the use of so-called high calorific gases, composed for research purposes in various proportions of natural gas and propane. This part of the research was aimed at examining the limitations related to the heat load of engine components, mainly turbochargers. The aggregate reaction to the supply of gaseous fuels with different tendency to knock combustion was also examined. In this stage of the research, a mixture of technical propane with acetylene, i.e. an unsaturated hydrocarbon with a very high tendency to knock combustion was used. In this case, the tests were carried out while feeding the engine with a mixture of these gases with different acetylene content in order to determine the response of the developed control system to the octane (methane) number of applied fuel. The main purpose of the laboratory tests was described to determine the limit values of parameters of applied fuel, which will be accepted by the developed electronic control system, and also meet all conditions allowing for the fuel to be admitted to feed of the internal combustion engine.

To determine the dynamic characteristics of the aggregate at load change, which is one of the main parameters of the quality assessment of the fuel supply system, the generator voltage waveform was recorded when the combustion engine was fed with methane. During the rapid increase of the generator load in the short time after the load change occurrence, the basic electrical parameters of the aggregate have returned to their nominal values (fig. 2). Therefore, it can be assessed that the developed concept meets the requirements set for this type of power generators. Many such characteristics were made, also during the change (increase or decrease) of the load (fig. 3), as well as during the change of such fuel parameters as: calorific value, octane (methane) number or change of thermodynamic parameters.

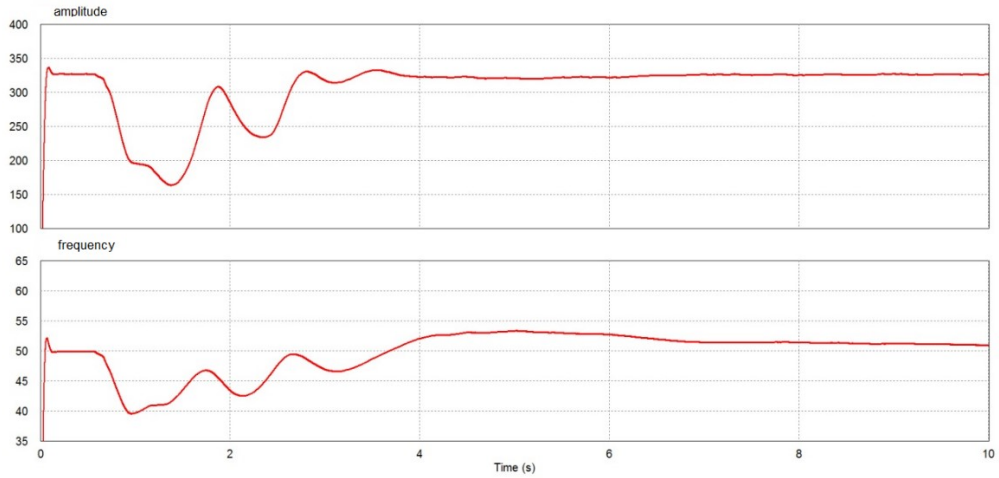


Fig. 2. Characteristics of changes in generator current parameters when the load increases in the range: 10 -150 [kW]

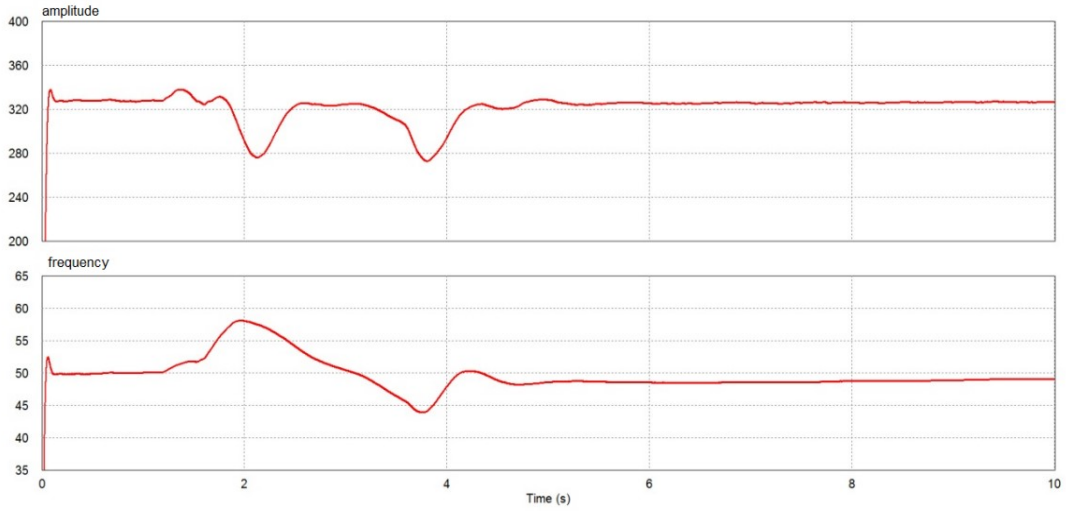


Figure 3. Characteristics of the generator current parameters changes when the load is reduced in the range: 180-50 [kW]

The results of this type of measurements fully confirmed the usefulness of the developed concept of an electronically controlled mixing system for feeding piston combustion engines of various types with gaseous fuels. As mentioned in the introduction, the developed concept of an electronically controlled mixer system can be designed to supply piston combustion engines with all types of gaseous fuels that are available at pressures close to ambient pressure. In practice, this group includes numerous flammable gases from biological decomposition processes of organic substances or some industrial processes. These include, for example, biogas, fermentation gases, carbon monoxide, mine gases, blast furnace gas, or coke oven gas. An important advantage of the developed concept is also the possibility of feeding the engine with one of the listed fuels or a mixture of gases, composed in any proportions. The practical effect is a significant extension of the range of gaseous fuels, which can be successfully used to supply power generators.

9. Conclusions

The experience gained during laboratory tests and verification of industrial research of these concepts allow to formulate the following most important conclusions:

1. Carried out laboratory and industrial verification tests have demonstrated the usefulness of the developed concepts of power supply and control systems for reciprocating internal combustion engines designed to work on various types of gas fuels for the needs of the power industry.
2. The developed concepts are characterized by high flexibility in relation to the applied fuels, and at the same time guarantee their best energy use, thanks to the system of ongoing analysis and optimization of the most important engine parameters.
3. The modern technical and software tools used in the studied prototypes create a new quality in the discipline related to the design and operation of internal combustion engines.
4. The obtained effects of work of piston engines during the supply of various types of gaseous fuels result from the adoption and use of technical solutions that are generally much more modern than the power and control systems used so far.
5. The analysis of the results of laboratory tests has shown that it is possible to significantly extend the kinds and types of gaseous fuels that can be successfully used to supply piston combustion engines.
6. A lot of attention has been devoted to the selection of control parameters, including such as the ignition timing and the composition ratio of the mixture, resulting in a favorable operational and ecological performance of the engine when feeding with different fuels.

7. The results of the research allowed to determine the strategy of power supply and control of the engine parameters, determining the limit values of physical-chemical properties of the applied fuels, which may be accepted from the point of view of the correctness of the engine operation and the values of ecological parameters.
8. The obtained scientific and cognitive effects as well as the positive effects of industrial verification studies indicate the existing development potential and the necessity to look for new concepts of development works in the field of power engineering. This type of work meets the demands of applying sustainable development, which in the power engineering sector mainly concerns the rationalization of energy consumption by reducing losses. In the case of the most important works, the effect is the energetic use of various types of energy sources, in the form of gaseous post-processing fuels, which until now have been largely unproductively lost.
9. Developed at the Cracow University of Technology and at HORUS-Energia company, concepts of innovative power and control systems for reciprocating internal combustion engines designed for operation on various types of gas fuels are suitable for direct implementation into operation.

References

[1] Brzeżanski M, Mareczek M, Marek W, Papuga T, Zastosowanie odpadowych produktów przemysłu chemicznego w energetyce, *III Konferencja Naukowo-Techniczna, Współczesne Technologie i Urządzenia Energetyczne*, Kraków 2013
[2] Brzeżanski M, Mareczek M, Marek W, Papuga T, Określanie parametrów ekologicznych stacjonarnego silnika spalinowego zasilanego różnymi paliwami , *Zeszyty Naukowe Instytutu Pojazdów*, Warszawa 2014.
[3] Brzeżanski M, Mareczek M, Marek W, Papuga T, Determination of operating parameters of industrial engine fuelled with post processing gases with high hydrogen content, *IOP Conference Series, KONMOT 2016*, Kraków 2016
[4] Brzeżanski M, Mareczek M, Marek W, Papuga T, Sposób sterowania parametrów regulacyjnych w silniku spalinowym o zapłonie iskrowym, *Opis Patentowy nr PL 222 462 B1.* WUP 07/16
[5] Brzeżanski M, Mareczek M, Papuga T,, Sutkowski M, Smuga W, A 4-stroke spark-ignition engine fueled with low quality gas*, Combustion Engines* – 2017, No. 1 (168), s. 122-124
[6] Brzeżanski M, Mareczek M, Marek W, Papuga T, Sutkowski M, The realized concept of variable chemical composition fuel gas supply systems, for internal combustion engines - *Combustion Engines* – 2017, No. 3 (170), s. 108-114
[7] Brzezanski M, Koncepcje wykorzystania odpadowych gazów poprodukcyjnych do celów energetycznych, *Nowa Energia* – 2017, Nr 5-6 (59-60), s. 18-27
[8] Factory and advertising materials of the HORUS-Energia company