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TEST STAND FOR A COMBINED HEAT AND POWER UNIT FED WITH ALTERNATIVE GAS FUELS

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Abstract

This paper presents the reasons for the development of gas-combined power and heat units and justification for testing the effect of the used gas fuel on the performance of such units. A PBCHP10VB CHP unit driven by a liquid-cooled piston combustion engine adapted for feeding with gas fuels is described. The concept is presented for testing the effect of different gas fuel mixtures, including biogas, on this unit's operation, mainly on the obtained electric power from the current generator and the temperature of the liquid cooling the driving engine heating up output water and on the composition of exhaust gas from this engine. A simple device for obtaining gas fuels containing different combustible gas mixtures is presented. The instruments used to check the composition of the obtained gas fuel and check exhaust gas from the engine are briefly described.

The paper describes a test stand for testing the effect of different gas fuels on the operation of a PBCHP10VB gas CHP unit manufactured by Power Blessed Co., Ltd registered in Shanghai, constructed at the Department of Mechatronics and Technical and Information Technology Education of the Faculty of Technical Sciences at the University of Warmia and Mazury in Olsztyn.

Keywords: *power and heat cogeneration, piston combustion engine, gas fuel, biogas*

1. Introduction

In this era of electrification, of all areas of life for basically all societies, there is a universal demand for electrical energy. This demand can be met only in part with transmission networks drawing electrical energy from commercial suppliers from power plants using current methods, i.e. nuclear, coal, hydroelectric, wind and solar power plants and from recently built power stations burning gases (natural gas, petroleum gas, landfill gas, gas from biomass fermentation etc.). As noted, "in part", means only where this network is fed and energy is transmitted without disturbances caused, for example, by overloads or interruptions caused by climatic situations, natural disasters or sabotage.

Regarding the availability and operational reliability of power transmission networks, power generators are the electrical energy source for specific individual isolated consumers. They are, as a rule, driven by heat engines, most often piston combustion engines, for which petroleum-derived liquid fuels are typically the heat source, although solutions with Stirling engines with any heat source are also possible.

All power plant heat resources in use today involve environmental hazards, which the general public is becoming increasingly sensitive. Nuclear power plants generate radioactive waste and their failures are particularly dangerous. Power plants (including power generators) based on the burning of minerals (coal and petroleum) and their processing products emit substantial quantities of carbon, nitrogen and sulphur oxides to the atmosphere. Hydroelectric power plants prevent fish migration and involve the flooding of large areas when damming water. Wind and solar power plants also cover large areas, spoil the landscape and depend on weather conditions – wind and insolation. Generally, there is no ideal electrical energy source. For this reason, ideas for energy acquisition from sources, which have not been used before and could, serve as potential sources started to appear towards the end of the 20th century. For example, all parts of plants produced in agriculture, which are waste and are composted in the "open atmosphere" can be composted in specific processes and systems to obtain gases such as methane or carbon monoxide, which can then be burnt to obtain the heat needed to generate electrical energy.

In areas where there is also demand for heat itself, e.g. for heating buildings or tap water, the striving is observed for simultaneous combined power and heat production – their so-called "cogeneration". Power and heat cogeneration significantly increases the efficiency of using the combustion energy of all fuels. In areas with a simultaneous demand for power and heat (e.g. in urban agglomerations in the temperate zone) combined heat and power plants are therefore widely used – high capacity systems for such cogeneration, in which the current generator is driven by a steam turbine and hot steam itself is the heat source for the heat distribution medium. Unfortunately, because of high heat losses during its long-distance transmission, the range of this transmission is limited to a few dozen kilometres around a CHP plant.

Taking the above facts into account, it seems that for areas distant from urban agglomerations and industrial centres, where there is demand for power and heat and feeding transmission networks to them is economically unjustified, it is most appropriate to use individual CHP units, for which the energy source are fuels which easy to deliver or, even better, produced and available nearby. In most such solutions, a piston combustion engine drives the current generator and the heat source is exhaust gas from this engine (high-temperature source) and sometimes also the engine's cooling and lubrication systems (low-temperature sources). If there is no demand for heat, these units work as ordinary power generators – the whole heat energy from the engine's exhaust, cooling and lubrication systems is lost to the environment.

An example of such units are gas CHP units adapted for burning fossil gases, distributed by oil corporations and companies (i.e. natural gas – NG, compressed natural gas – CNG, liquefied natural gas – LNG, whose main component is methane, and liquefied petroleum gas – LPG, a mixture of mainly propane and butanes) and gases which can be produced at local coking plants, biogas plants, wastewater treatment plants or waste disposal sites and in mining areas also from mine demethanization, which are mixtures in different proportions of mainly hydrogen, hydrocarbons (methane, ethane, propane, butane...), carbon monoxide and dioxide, oxygen and nitrogen. It is clear that engines burning gas fuels used in CHP units are required to have high flexibility regarding the parameters of these fuels, i.e. their volumetric and mass composition, heating value, resistance to knocking combustion (~ methane number), Wobbe index (~ the amount of energy contained in gas fuel fed to the engine's combustion chamber), density under normal conditions, flammability limits when mixed with air, the values of the air excess factor for these flammability limits, etc. Biogas, obtained in the process of anaerobic fermentation of diverse organic materials with varied moisture contents carried out even at the same biogas plant at different temperatures, can have particularly varied compositions and properties.

This paper describes a test stand for testing the effect of different gas fuels on the operation of a PBCHP10VB gas CHP unit manufactured by Power Blessed Co., Ltd registered in Shanghai, constructed at the Department of Mechatronics and Technical and Information Technology Education of the Faculty of Technical Sciences at the University of Warmia and Mazury in Olsztyn.

2. PBCHP10VB gas CHP unit

The tested CHP unit has the capacity to generate 10 kW of three-phase electrical power (18 A, 400 V), which allows to feed loads with a combined power up to this value, and 11.7 kWh of heat energy, which allows to heat up output water to a temperature of ca. 50-70 °C with its flow through the operating heat exchanger with a volumetric flow rate of ca. 0.5 dm^3/s.

The source of mechanical and heat energy for the unit is a Toyota 4Y266562 engine. This is a four-cylinder, four-stroke, in-line spark ignition engine, cooled indirectly with liquid with its forced circulation through the coolant pump driven by the V-belt from the engine crankshaft, originally adapted for being fed with two different fossil gas fuels, i.e. either with natural gas (NG), available in transmission networks, or liquefied petroleum gas (LPG), available in cylinders in stores which sell it. Gas fuel with pressure existing in the feeding system (the transmission network for NG or behind the reducer/evaporator for an LPG cylinder), in the order of 1-3.5 kPa overpressure over the atmospheric pressure, is fed to the unit's connection stub pipe, behind which there are the starting valves and the reducer. The unit's reducer sets the pressure of the gas fuel fed to the mixer (which is a part of the pipe feeding air to the engine and in which the fuel-air mixture is produced) which is sucked in by the engine cylinders through an electronically-controlled throttle valve, depending on the negative pressure set in the mixer for a given position of this throttle valve.

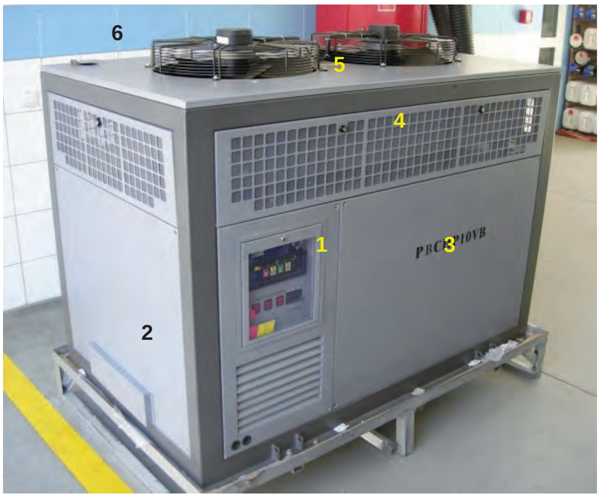

Fig. 1. PBCHP10VB CHP unit: 1 – control panel, 2 – power connection, 3 – main unit chamber with engine, current generator and operating heat exchanger, 4 – upper unit chamber with radiator, equalizing tank, air filter and exhaust silencer, 5 – engine radiator fans, 6 – exhaust gas outlet

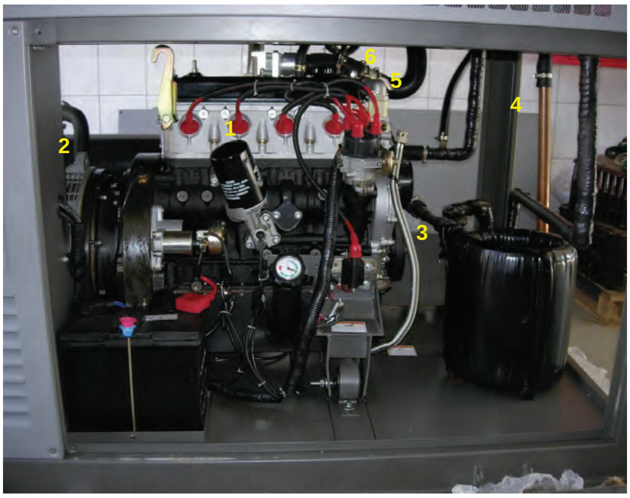

Fig. 2. Interior of the main unit chamber 1 – engine, 2 – current generator, 3 – operating heat exchanger, 4 and 5 – conduits to and from engine radiator, 6 – pipe feeding air to the engine

The current generator is driven from the engine crankshaft. For the frequency of the generated alternating current to be as close as possible to 50 Hz, the combustion engine should work at a fairly constant speed of 1500 rpm. This speed is maintained automatically independently of the engine load (of electric power received from the unit) by a system consisting of an electronic controller, an engine crankshaft rotational speed sensor cooperating with the toothed ring at the engine flywheel and a system changing the composition (change in the unit reducer flow rate) and quantity (change in the throttle valve's position) of the fuel-air mixture sucked in by the engine cylinders. Due to the constant engine speed, the ignition advance angle is constant and can be changed only by rotation of the whole distributor in relation to the engine block.

The system of heat generation by the described CHP unit takes heat from the combustion engine's cooling and exhaust systems. For this purpose, the circulation of the engine coolant was specially designed after the engine is warmed up to temperatures causing thermostat opening and coolant direction from ducts in the engine block (in the block and head) outside towards the radiator, where this liquid is first directed to a specially-designed engine exhaust manifold. This manifold has double walls, between which the coolant flows, heated up by hot exhaust gas flowing out of the cylinders. The coolant is led from the exhaust manifold water jacket to two more heaters, located on the arms of the U-bent initial part of the exhaust pipe, bent to obtain a compact unit structure while maximizing the surface of heat transfer to the coolant. The heated coolant (in the engine block, on the exhaust manifold and around the exhaust pipe) is directed to the operating heat exchanger for the external system receiving heat from the unit. This exchanger is two

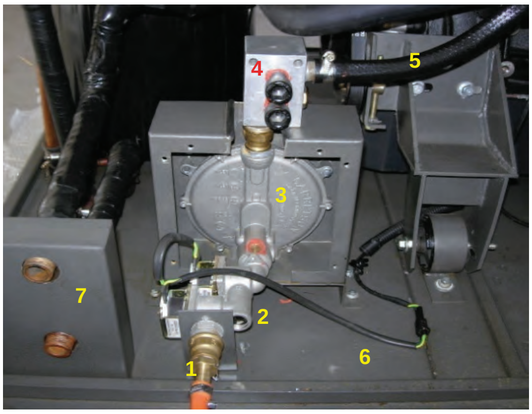

Fig. 3. *Gas fuel feed system components 1 – gas connection stub pipe, 2 – solenoid valves, 3 – reducer, 4 – gas flow rate controller, 5 – conduit feeding gas to the mixer, 6 – conduit controlling solenoid starting valves, 7 – heated water connection*

Fig. 4. *Gas fuel and air feed system components: 1 – air feed pipe, 2 – conduit feeding gas from the reducer, 3 – gas and air mixer, 4 – electronic throttle valve unit, 5 – suction manifold, 6 – exhaust manifold*

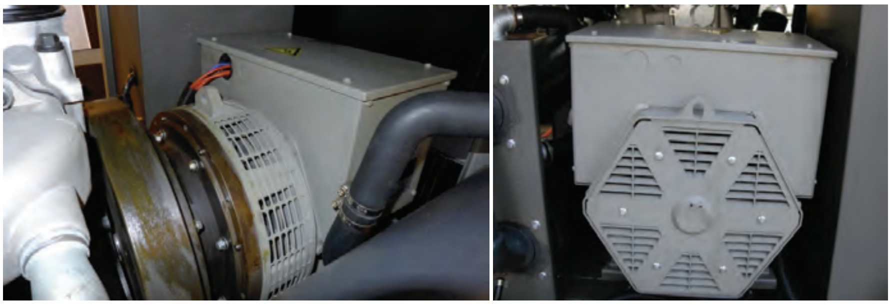

Fig. 5. CHP unit current generator (view from and towards the engine)

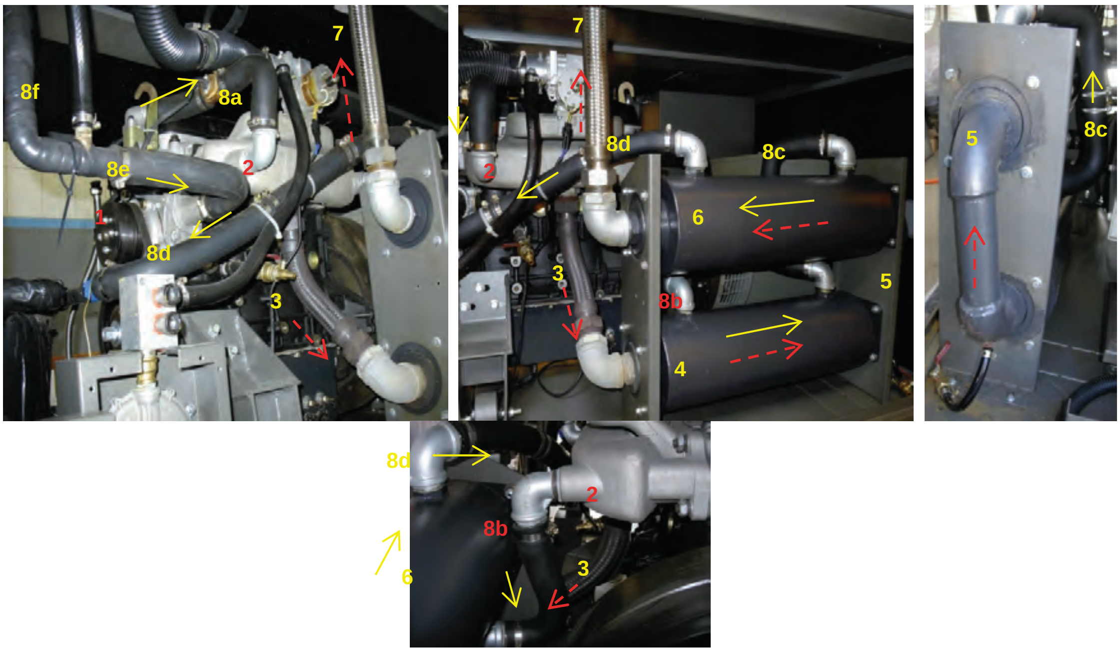

Fig. 6. *Coolant heating system 1 – thermostat and coolant pump unit, 2 – exhaust manifold with heater, 3 – exhaust pipe from exhaust manifold to the first heater, 4 – first heater on the exhaust pipe, 5 – exhaust pipe between heaters, 6 – second heater on the exhaust pipe, 7 – exhaust pipe from the second heater to exhaust silencer, 8 – coolant pipes: a – from engine block to heater on exhaust manifold, b – from heater on exhaust manifold to first heater on the exhaust pipe, c – from first to second heater on the exhaust pipe, d – from second heater on the exhaust pipe to operating heat exchanger for external system, e – from radiator to engine block, f – from equalizing tank, continuous arrows – coolant circulation, dash arrows – exhaust gas flow*

spirally shaped pipes near each other – hot coolant flows through one of them, output water from the unit being heated up through the other. After partial cooling in this exchanger, the coolant is directed to the radiator with fans, where it is finally cooled to the temperature required for engine cooling. The coolant is directed from the radiator back to the engine block. Because the CHP unit can operate in the mode of power generation alone, for the case of heat not being given up by the coolant to water in the operating heat exchanger, the radiator with the fan system is appropriately larger and more efficient than ordinary car radiators or radiators from power-only generators with an ordinary driving engine cooling system – it occupies the whole unit roof.

Fig. 7. Operating heat exchanger for heated water external system 1 – heat exchanger, 2 – coolant pipe from second heater on the exhaust pipe, 3 and 4 – start and end of parallel pipe system of engine cooling system (heat source) and external system (heat receiver), 5 – coolant pipe to engine radiator, 6 – valve for emptying engine cooling system, 7 – pipe with water to heat from external system, 8 – pipe with heated water to external system, 9 – overflow pipe carrying off water from the upper unit chamber, arrows – coolant and heated water circulation

3. Feed system – gas mixer

As already mentioned, the engine of the tested CHP unit is adapted according to the user manual for burning fossil gases available in the worldwide NG and LPG trading network, with the composition standardized globally. However, in accordance with the ideas presented in the introduction and concerning the use of locally-produced combustible gases for power and heat cogeneration, the idea emerged to test (based on the example of the available CHP unit) the possibility of its operation and the obtained parameters when fed with different combustible gas mixtures.

A very simple mixer was constructed to obtain different gas mixtures. A metal pipe section 1 m long and 15 cm in diameter was blanked off on both sides. Several connections with volumetric flow rates controlled by throttle valves for the connection of different gases making up the used mixtures were executed at one base of the so-created cylindrical tight tank. One connection for connecting the obtained mixture to the feed input of the CHP unit was executed at the second base of this tank. A connection for the intake of a small part of the formed mixture by its composition analyser was also executed in this connection. It was assumed that the adopted mixer dimensions and the path travelled inside it by gases released into it in a predetermined manner (set with valves) and the outflow also in a predetermined manner was defined by a constant demand for fuel by the engine of the unit in stationary operation and, after some time, it produced a homogeneous mixture with a specific composition. The desired composition was obtained by proper adjustment of the quantity of given gases fed to the mixer.

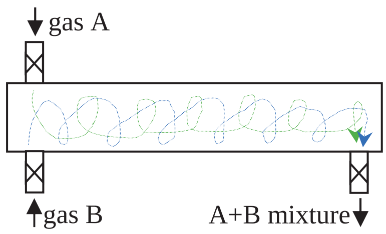

Fig. 8. Diagram of the mixer for gases feeding the tested CHP unit

4. Test-stand measuring components

The operating parameters of the tested CHP unit for the set electrical load level obtainable for a given gas fuel fed to the unit will be recorded during the conducted tests.

The composition of the gas mixture will be recorded (as obtained in the manner described in the previous point and fed to the unit as gas fuel). A Gas Data GFM410 portable analyser (designed for monitoring and analysis of the composition of landfill gas, biogas and even air in polluted areas) will be used for this purpose. The analyser measures the percentage contents of methane (CH_4), carbon dioxide (CO_2) and oxygen (O_2) in the tested gas and the number of carbon monoxide (CO) and hydrogen sulfide (H_2S) molecules per one million gas molecules. The CH_4 and CO_2 contents are determined by measuring the degree of absorption of specific wavelength infrared light by the tested gas and the contents of the other three gases with electrochemical sensors. The CH_4 content determination error varies from 3% of the indicated value at high concentrations (~ 100%) to 4% of the indicated value at low concentrations (~ 5%). The CO_2 content determination error varies from 1% of the indicated value at low concentrations (~ 10%), through the maximum error of 7.5% of the indicated value at concentrations in the order of 40% to 3% of the indicated value at high concentrations (~ 100%). The O2 content determination error is 0.5%. The CO and H_2S content determination errors are 5% of their measuring ranges (2000 ppm for CO and 500 ppm for H_2S). This analyser will also be used to check the pressure of gas fed to the feed stub pipe of the CHP unit – as already mentioned, it must be maintained in the range of 1–3.5 kPa (10-35 mbar) overpressure over the atmospheric pressure, with the resolution of manometer indications at 0.1 kPa (1 mbar).

The second tested gas will be exhaust gas from the CHP unit's engine. A Bacharach ECA 450 analyser, designed for analysis of combustion efficiency, will be used to determine the exhaust gas composition. The analyser measures the percentage contents of oxygen (O2) and combustible gases (hydrocarbons [HC], the so-called unburned fraction) in the tested gas and the levels of carbon monoxide (CO), nitric oxide and nitrogen dioxide (NO and NO2) and sulphur dioxide (SO2) molecules per one million gas molecules and, on this basis, computes for the defined fuels (e.g. NG or LGP) the value of the air excess factor, the percentage carbon dioxide (CO2) content and the number of nitrogen oxide (NOx) molecules per one million gas molecules and the numbers of NO, NO_2, NO_x, CO and SO_2 molecules per one million O_2 molecules. The determination error for the measured O2 contents is 0.3%. The determination errors for the measured HC, CO, NO, NO_2 and SO_2 contents are 5% of the indicated values.

As noted in the description of the tested CHP unit, its automatic adjustment system selects the quantity and composition of the fuel-air mixture according to the current generator's electrical load, i.e. for operation as only a power generator. Because a combined power and heat unit is being tested, the temperature obtained by the coolant flowing into the operating heat exchanger for different electrical loads (quantities of the combusted gas fuel) and different gas fuel compositions is also important. A UNI-T UT53 multimeter with a thermocouple as an equipment component will be used to measure the temperature of this liquid. The thermocouple contact will be fastened on the pipe with coolant just near its entrance to the operating heat exchanger.

Fig. 9. GFM410 gas fuel (e.g. biogas) analyser

Fig. 10. ECA 450 combustion efficiency analyser

5. Conclusions

In this era of widespread use of electrical equipment, there is an increasing demand for electrical energy, also in areas distant from power transmission networks. The solution to this problem is the use of individual power generators driven by e.g. combustion engines fed with different fuels, as well as non-conventional sources available directly at the generator's place of operation. If, apart from demand for electrical energy, there is also demand for heat, the use of CHP units for simultaneous generation of both kinds of energy is most appropriate.

There is a need to determine the possibility of such units' operation under conditions of their feeding with diverse gas fuels produced in local biogas plants or waste treatment plants with regard to both the obtained electrical and thermal power and environmental hazards caused by the exhaust gas. This paper presents a certain concept for a stand on which such a test can be carried out.

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Z BIOMASY, ODPADÓW ROLNICZYCH I INNYCH**