Experimental tests of the prototypical micro-cogeneration system with a 100 kW biomass-fired boiler

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Abstract. Renewable energy based micro cogeneration systems are an interesting option for domestic, agricultural and commercial sectors. In this paper, a dedicated system with a 100 kW_{th} biomass-fired boiler was proposed. Developed system works according to modified Rankine Cycle operation. Steam generated in two shell and tube heat exchangers is used to power steam engine (connected with power generator) and then flows via condenser to degasifier. During the presented tests, the selected parameters of the boiler, oil circuit and steam/condensate circuit were analyzed. As was shown, the maximum thermal power taken from the oil circuit to evaporate condensate and superheat steam was ~105 kW_{th} (it was ~91% of thermal power generated in the boiler). The value steam pressure varied from 2 to 5 bars during operation of the steam engine. Steam mass flow was then equal to ~105 kg/h, what allowed to generate electric power at a level of ~1.05 kW_{el}. Such a low value resulted e.g. from limitations in the oil temperature, limitations in the steam temperature, steam pressure and steam flow, limitations caused by power generator's construction, as well as other construction and operating parameters.

1 Introduction

Among different renewable energy sources, biomass is one of the most promising options in Polish conditions. It is characterized by a wide availability, high caloric value, low prices and ability to decrease the dependency on fossil fuels. From this standpoint, biomass (wood, straw, chips, etc.) may be used as a fuel in micro scale combined heat and power generation systems (µCHP). Depending on heat source parameters and expected amount of generated power, there are different technologies dedicated to biomass utilization, including internal combustion piston engines, cogeneration plants with a steam/vapour turbine working on a Rankine Cycle (RC) or Organic Rankine Cycle (ORC), Stirling engines (SE) and thermoelectric generators (TEG) [1,2].

Analysing the current state of art it can be concluded, that many studies on µCHP systems using renewable energy source have been conducted, but there are not many studies on RC/ORC-based µCHPs using a biomass heat source [3]. One of the examples of the ORC system using a biomass boiler as a heat source was shown in [4]. Presented system was characterized by an electricity output of 2 kW_{el}, and electrical efficiency 7.5-13.5% (depending on the hot water temperature from the boiler and the condenser cooling water temperature). Another example was presented in [5], where an experimental ORC system based on a 50 kW pellet-fired boiler was tested and a maximum electrical power was obtained at a level of 860 W. On the other hand, three variants of the CHP plant based on the Organic Rankine Cycle and fuelled with sawmill waste have been analysed in [6]. In this case, a 250 kW_{th} boiler was used as a heat source and generated power varied from ~25 kW_{el} to ~70 kW_{el} (respectively octamethyltrisiloxane, methylcyclohexane, methanol and water were used as a working fluid).

Besides performance analysis of µCHP systems powered by different fuels and based on the use different working fluids, many other studies have been performed, including e.g. analysis of the dedicated constructions of turbines [7] and heat exchangers [8]. Moreover, an economical and environmental conditions of using biomass-fired heating and CHP systems, were presented in [9,10]. Carried out analysis confirmed the possibility of introducing environmentally friendly units, characterized by a relatively short pay-back period. From the standpoint of clean energy production, biomass-fired CHP systems can be expanded e.g. by implementation of solar energy based units. An example of such solution was presented in [11], where an integrated system for sewage sludge drying through solar energy and a combined heat and power unit fueled by biogas was analyzed.

Worldwide literature contains not only experimental works, but also investigations based on performed simulations. For example, in [12] two types of simulations have been performed: the first one aimed at selecting a design optimization criterion of geometrical parameters of the shell and tube heat exchangers, while the second one evaluated the off-design performance of the ORC power plant.

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This paper shows the experimental tests of the prototypical µCHP system with a 100 kW biomass-fired batch boiler. Unlike above listed solutions, this system is based on modified Rankine Cycle operation. Previously conducted tests of the new boiler's construction shown the high potential of its usage as a high-temperature heat source for combined heat and power generation. The heat taken from oil by the evaporator and superheater reached a level of ~50 kW during combustion of single fuel input [13]. This paper is a continuation of these studies. On the other hand, it is the second approach to extend the functionality of a batch boiler with a power generation system (the first one, based on the use of a 180 kW$_{th}$ straw-fired batch boiler equipped with additional heat exchanger located after the second combustion chamber was described in [14]).

2 Experimental unit

An experimental unit is equipped with a 100 kW$_{th}$ biomass-fired batch boiler, oil circuit, steam/condensate circuit and water circuit. The boiler has an oil jacket and is equipped with a dedicated fuel feeder. Steam is generated and superheated in two connected in series shell and tube heat exchangers, operating respectively as an evaporator and a superheater. Generated steam is conditioned using a moisture separator and a reducing valve, and then powers a 2-cylinder, double-acting, 20-horsepower steam engine. Electricity is generated in a 2 kW$_{el}$ generator connected through the V-belt with the steam engine. Steam removed from the engine is condensed in a condenser and pumped to a degasser. In the last phase, condensate is pumped to the evaporator and the whole process starts again.

The main elements of the developed µCHP system are shown in Fig. 1.

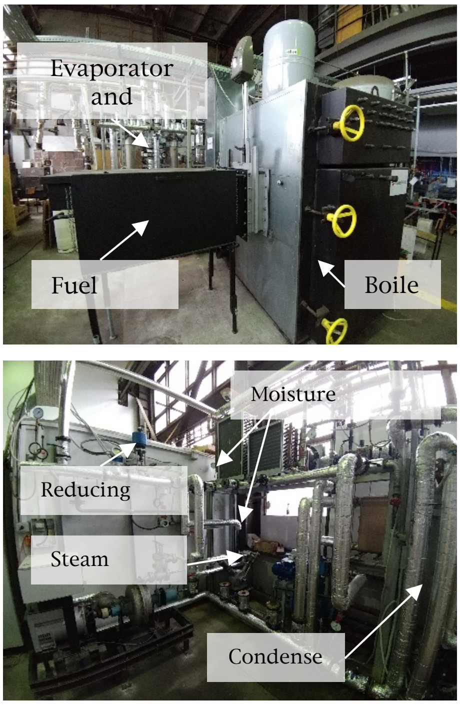

Fig. 1. The main elements of the developed µCHP system.

The operation of the whole system is controlled by dedicated automation system with WAGO PFC200 PLC controller. The following parameters were controlled: inlet air flow, flue gas flow, thermal oil flow, condensate flow and cooling water flow (via inverters connected with fans and pumps). On the other hand, among the control signals, there were recorded: temperature, pressure and flow of the inlet air, flue gas, oil, steam, condensate and cooling water as well as rotate speed of the steam engine and current and voltage generated in the generator.

3 Results and discussion

During tests ~100 kg of straw was burned. Straw was formed in rectangular bales with mass varied from 7.1 to 8.7 kg and average moisture content lower than 10%. Straw was loaded to the combustion chamber in portions by the fuel feeder. Below presented results show the most important operation parameters of the boiler, oil circuit and steam/condensate circuit.

3.1 Boiler's operation

The boiler's operation was realized using oil temperature and flue gas temperature as a control signals. Temperature of the thermal oil was assumed at a level of 190-200°C (while maximum achieved value was temporarily ~210°C) and it resulted mainly from actual parameters of combustion process. Variations in the oil temperature were relatively low, what is really important from the standpoint of steam generation process. On the other hand, the temperature of flue gas was assumed at a level of 320-340°C. It was controlled via the inlet air fan and the flue gas fan setting. The variations in the flue gas temperature were significant, so continuous control was required (both fans operated with relative power varied from 30 to 100%). As was shown in Fig. 2, temporarily achieved value of flue gas temperature was ~400°C.

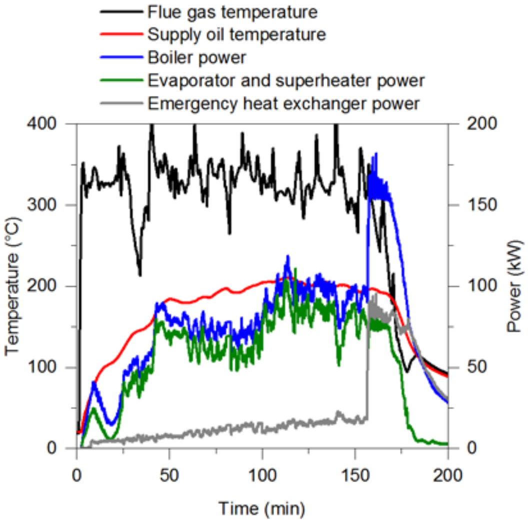

Fig. 2. The variations of the main parameters connected with the boiler operation during analysed process.

Heat generated in the boiler was transferred by the oil circuit to steam/condensate circuit (via evaporator and superheater) and emergency water cooling circuit (via emergency heat exchanger). As was shown in Fig. 2, the maximum thermal power taken from the oil circuit to evaporate condensate and superheat steam was at a level of ~105 kW_{th} in 112 minute of combustion process (it was ~91% of thermal power generated in the boiler). On the other hand, the maximum thermal power reached in the boiler was ~180 kW_{th} during the time when the emergency heat exchanger was switched on.

3.2 Evaporator and superheater

From the standpoint of a power generation system, it was important to provide proper temperature, pressure and flow of the steam. During analyzed combustion process, the maximum value of steam temperature at the outlet from superheater was ~198°C (in a time, when oil temperature at the inlet to evaporator was ~208°C). Oil was cooled by ~30-50°C, depending on the actual phase of the process (except the initial and afterburning phases). Temperature of the condensate pumped to the evaporator varied only a bit (~18-22°C). The maximum observed steam pressure was ~5.8 bars (before steam engine was run) and varied from 2 to 5 bars (during steam engine operation). The variations in steam pressure were caused mainly by variations in the oil temperature and set of the steam regulating valve. The variations in the oil, steam and condensate temperature and steam pressure were shown in Fig. 3.

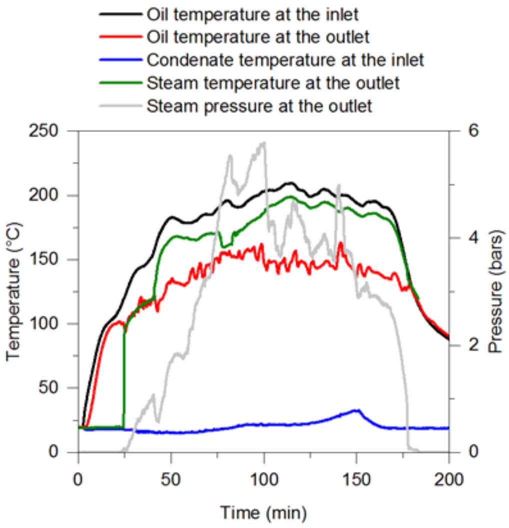

Fig. 3. The variations in oil, steam and condensate temperature as well as steam pressure during analysed process.

3.3 Steam circuit

As was given before, the value steam pressure varied from 2 to 5 bars during operation of the steam engine. In time, when generated electric power (in generator connected with steam engine) reached the highest value, steam pressure dropped to 4.3 bars. Steam mass flow was then equal to ~105 kg/h, what allowed to generate electric power at a level of ~1.05 kW_{el}. The variations in the steam pressure (measured before and after steam engine) and rotation speed of the steam engine are shown in Fig. 4.

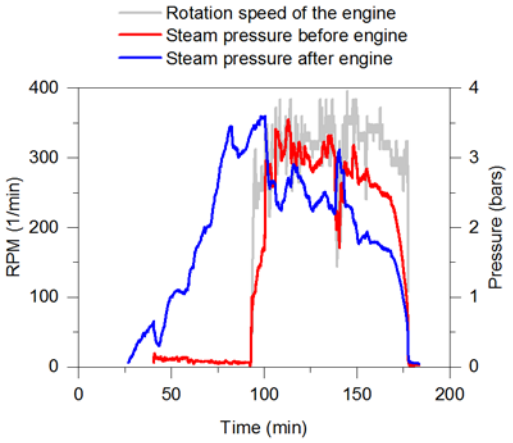

Fig. 4. The variations in the steam pressure (before and after engine) and rotation speed of the steam engine.

The variations in the rotation speed of the steam engine, shown in Fig. 4, resulted from variations in steam flow and steam pressure as well as from variations in electric power taken from the generator (power taken from the generator was adjusted via the electrical load).

3.4 Steam engine and generator

The current-voltage (I-V) and power-voltage (P-V) characteristics were determined using the electrical load, equipped with 20 bulbs with total power of 2 kW_{el}. The maximum power (~1.05 kW) was reached for voltage ~278 V and current ~3.65 A. This is only ~10.7% of the nominal power of the steam engine (its nominal power, given by manufacturer) is ca. 14 kW, when pressure is 13.8 bars and rotation speed is 700 RPM. I-V and P-V characteristic were shown respectively in Fig. 5 an Fig. 6.

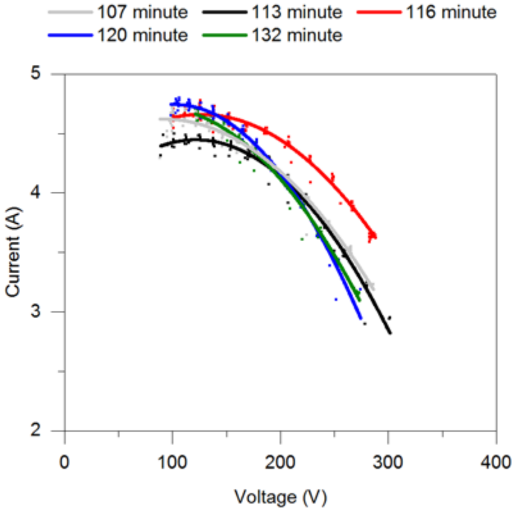

Fig. 5. Current-voltage (I-V) characteristics of the power generator.

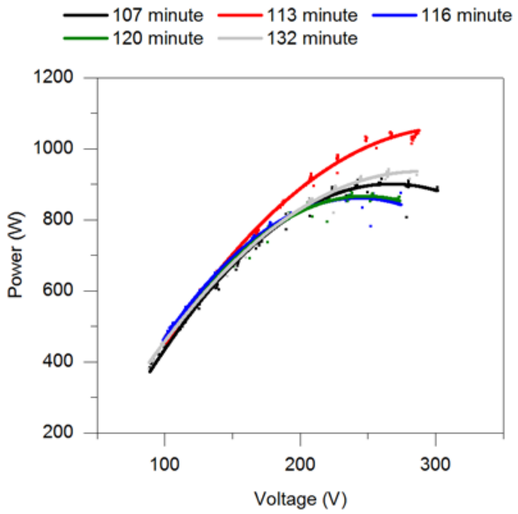

Fig. 6. Power-voltage (P-V) characteristics of the power generator.

The power ~1.05 kW$_{\mathrm{el}}$ was achieved in a time, when thermal power generated in boiler was at a level of ~110 kW$_{\mathrm{th}}$. Consequently, the efficiency of power generation was very low (~0.95%). Such a low value resulted e.g. from limitations in the oil temperature, limitations in the steam temperature, steam pressure and steam flow, limitations caused by power generator's construction, as well as other construction and operating parameters.

4 Conclusion

Results of the initial tests of the developed μCHP system confirm the possibility of increased functionality of straw-fired boiler with a power generation. On the other hand, many further tests and improvements are still required to provide higher efficiency and reliability of the developed system. At this time, maximum power generated in the system was ~1.05 kW$_{\mathrm{el}}$ (what gives efficiency of power generation ~0.95%).

Detailed analysis of the results allowed to conclude e.g. that:

- stable over the time, high temperature of the oil is one of the key factors determining steam parameters and consequently – the amount of the power generation;
- straw combustion is very dynamic process, which requires continuous regulation and proper fuel supply – this problem should be further studied;
- steam pressure higher than 4 bars and steam flow at a level of 100 kg/h are required to generate electric power at a level of 1 kW$_{\mathrm{el}}$;
- to provide higher power generation it is required to increase oil and steam temperature, what is connected with the use of use of more expensive components (valves and other armature, flowmeters, pumps, etc.);
- condensate should be pre-heated, before it is pumped to evaporator (one more heat exchanger – regenerator – should be installed).

Above listed positions represent only a part of conclusions resulting from the conducted studies. Improvements, which are planned to introduce in the near future (both in the field of system configuration and its operation), should allow to significant increase a level of generated power.

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