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Thermal oil biomass boiler dynamics as a part of the micro-CHP ORC plant

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Abstract

The aim of the paper is to present the results of experimental research conducted on two helical coil biomass boilers with oil heating agent, which are a central units of co generative micro power-plant designed and built in IFFM in Gdańsk. Experimental data served as a source for defining the interdependencies governing the dynamics of the micro-CHP as a whole. Furthermore, during the research the authors came across a few possible modifications to the construction that may yet improve the device.

Nomenclature

P_{boiler}	–	heating power of the boiler, kW
$P_{turbine}$	–	electrical power of the turbine, kW
$\dot{m}_{oil}$	–	oil flow rate, kg/h
T_{oil_in}	–	oil temperature at the inlet to the coil exchanger, °C
T_{mean}	–	mean temperature of oil inside the coil heat exchanger, °C
T_{oil_out}	–	oil temperature at the coil exchanger outlet, °C
ΔT	–	temperature difference, °C
η	–	thermal efficiency of the boiler, %
λ	–	air excess number

Keywords: CHP; Boiler; Dynamics; ORC; Micro-turbine; Thermal oil

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1 Introduction

In a modern day world, reasonable energy management is of utmost importance. Therefore it is necessary to implement new, improved methods of energy conversion, especially from bio-fuels. Biomass, among other renewable fuels, is a very specific and troublesome source of energy. It's high nonhomogeneity, diverse heating values, bulk densities, water contents and varied composition makes designing a device for thermal utilization of such fuel a challenge. Many issues render classical approaches to boilers to be not as accurate as they used to be for coal or gas-burning large scale units. Therefore an experimental research was performed, whose aim was to design a small scale biomass boiler unit characterized by high efficiency and output parameters. It can also act as a heat source for co generative micro CHP (Combined Heat and Power) plant based on Organic Rankine Cycle (ORC) and a custom-made vapour turbine combined with the generator. In this section, the heating agent is a low-boiling HFE7100, which evaporates while receiving heat from the oil and powers the turbine, producing heat and electricity in micro-scale for small households or farms. Both the ORC section and helical coil boiler are unique constructions in their field. Knowledge of the key parameters affecting the dynamics of the operation of such system is of great importance in view of the development of automatic control system for the entire installation of micro CHP plant.

2 Construction

Two similar boiler units were used in the experiment. The first one (37 kW in heat) served as a power source for a large experimental ORC section that was built for the purpose of testing heat exchangers, pumps and turbine prototypes. The second one (30 kW in heat) was a part of miniaturized complete micro-CHP plant. Both boiler units consist of a coaxial, double helical coil as the heat exchanger and a fixed grate pellet burner located at the bottom of the unit and connected with a small biomass reservoir. In these installations thermal oil is used as the heating agent due to high output parameters required by the ORC section. The hot flue gas from the burner flow up through the smaller coil, then change direction at the top of the boiler and flow downward between both coils and finally flow up to the stack. On the other hand, the thermal oil inlet is located at the bottom of the outer helical coil. The oil travels up to the inner coil and then down to the outflow. This configuration is basically a counter current exchanger with counter/co current section between both coils. Spiral tube heat exchanger prevents thermal oil from overheating, which could have taken place for instance in a shell-type exchanger. The flue gases flow diagram, as well as boiler construction and micro CHP section layout was presented in Fig. 1.

This construction is quite unusual if compared to typical coil heat exchangers [1,2,3,9]. Conventional coil exchangers are being used with gas burners in a horizontal position. In this case the coils are placed in a vertical manner in order to decrease the impact of deposits accumulating on the surface of the exchanger, which could affect its efficiency.

The real ORC system is more complex than shown in Fig. 1. It consists of three heat exchangers (evaporator, regenerator and condenser), the reservoir of working fluid and the set of valves. The oil-free vapour microturbine is used as an expander [8]. It is a 4-stage radial microturbine containing two centripetal and two centrifugal stages. Inside the common casing, between two radial-axial gas bearings, a high-speed electric generator is mounted. The bearings are lubricated with the vapour of working fluid HFE-7100. The micro-CHP power plant is equipped with the regulation and the electricity conditioning systems.

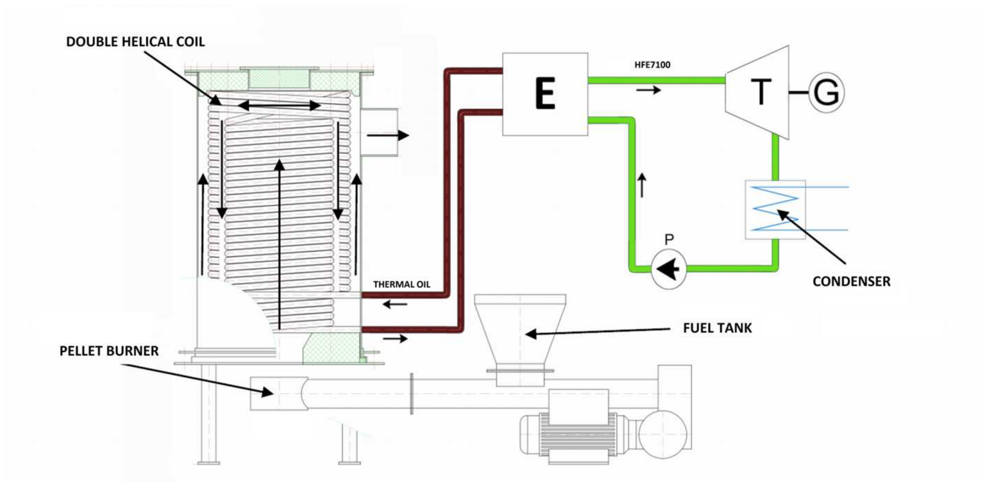

Figure 1: Boiler and ORC conceptual layout with flue gas flow diagram. E – plate heat exchanger, T – turbine, G – generator, P – pump.

3 Measurement system

In the case of the 37 kW boiler, the dedicated measurement system does not include the ORC section, nevertheless the ORC section has its own independent measurement system. The 30 kW boiler is fully integrated with the ORC section and in this case the measurement and operating system is the same for both devices. In presented herein experimental research the heat from thermal oil was transferred to a low boiling HFE7100 in a custom plate exchanger and used to power a steam turbine. In this configuration it is possible to measure thermal balance between both sections of the installations.

In this type of a burner both, air and fuel, are being transported to the boiler separately and then mixed at the grate inside the combustion chamber. In this situation the effects of air flow degradation while passing through a thick fuel bed similar to that observed in previous research [1] were also noticed. Inlet air flow was not measured directly, but was calibrated in such a way that the overall air excess number λ would be between 1.1 and 1.3. The air excess number λ (–) represents the ratio of the air actually supplied to the amount of air theoretically needed for a stoichiometric combustion process. Since the air flow is not measured directly during the experiment, the value of λ is being calculated from the amount of oxygen, carbon oxide and carbon dioxide present in the flue gases. In this study it was impossible to unequivocally determine actual fuel flow, thus, the results are qualitative mainly.

The mass flow of thermal oil is being measured in both cases at the outlet of the boiler using a turbine flow meter. It is commonly known that these types of flow meters are very sensitive to viscosity so the oil type heating agent will cause problems. However, while the temperatures are moderate and high, the oil viscosity drops significantly and the turbine can work properly. This flow meter is powered via a 24 V power supply. Electromagnetic sensor generates a pulse signal (Hz) which is later converted to 4–20 mA signal.

In case of the 37 kW boiler the temperatures of flue gases were measured in four points. The first one was located in the main stream right above the burner. In this case a corundum coated S-type fireproof thermocouple was used to ensure stable measurement in aggressive environment. The second and third points of measurement were located at the inlet to the exchanger and on the bottom of the second draught (two thermocouples type K), respectively. Flue gas temperature was measured on top of the third draught and at the outlet inside the stack. In case of the 30 kW boiler only the temperature inside the stack was registered. Moreover, in both cases the temperatures of the thermal oil at the inlet and at the outlet were also measured. A measurement set schematic for the experiment is presented in Fig. 2.

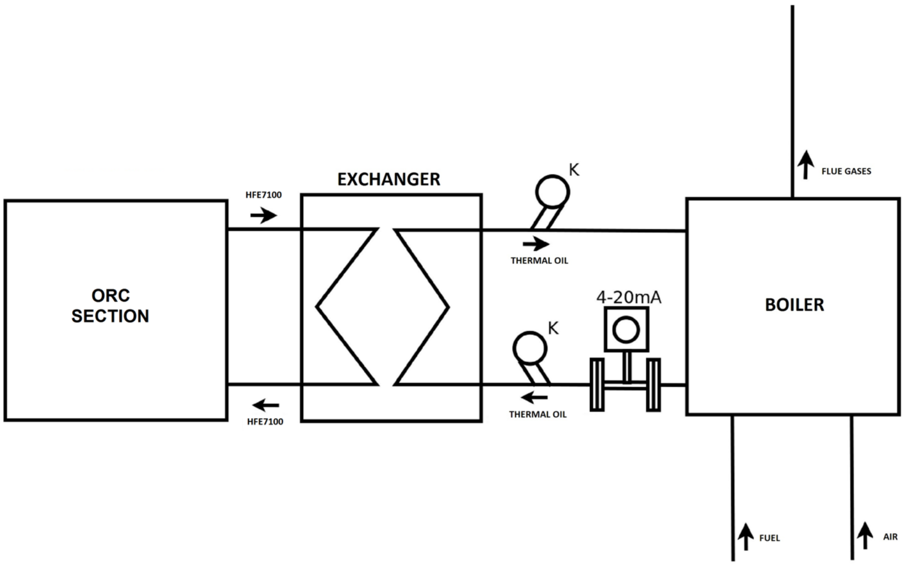

Figure 2: Schematic of measurement set for balancing coil type biomass boiler unit. K stands for K-type thermocouple, 4-20mA represents signal type from flow meter.

4 Results

Unfortunately no similar analysis could be found in the available literature, basically because the combination of a fired boiler with a small scale ORC system is a very unusual setup. Many analyses can be found that cover an ORC system powered by e.g. photovoltaic/fuel cells [4] or Stirling engines [5] but the dynamics of such systems are vastly different. The experimental research focused mainly on the ORC section of the discussed CHP plant, was presented in [6,10].

In addition to previous research [1,2,7], the main aim of the experiment was to study the interaction between the parameters of the boiler and the turbine section. All of the previous research was performed using a forced-draught cooling tower as a receiver of the heat from the thermal oil. Current research focuses on the micro CHP plant as a whole.

The 37 kW unit was tested for the influence of oil mass flow on the outlet temperature. The results are shown in Fig. 3. The turbine flow meter starts to rotate if the mass flow is above 450 kg/h which can be seen on the upper graph, after that, when the flow rate is set on a higher level, a significant decrease of the flow value can be observed. This effect is caused by high temperature oil mixing with cool oil outside the boiler itself. This effect makes a significant impact on the dynamics of the start-up of the whole installation; the higher the amount of thermal oil in the piping, the longer it takes to balance the boiler. With rising temperature of the thermal oil, the mass flow rate decreases (especially during preheating), therefore it is necessary to further increase the flow after the initial start-up (this can be seen near 5000 s). The moment when the turbine starts can be observed after 7000 s. Subsequently, after that moment, the temperature of the oil drops, rises and drops again as the turbine is being tested. Around the 11000 s it was even necessary to reduce the mass flow rate of the oil to increase the outlet temperature of the oil.

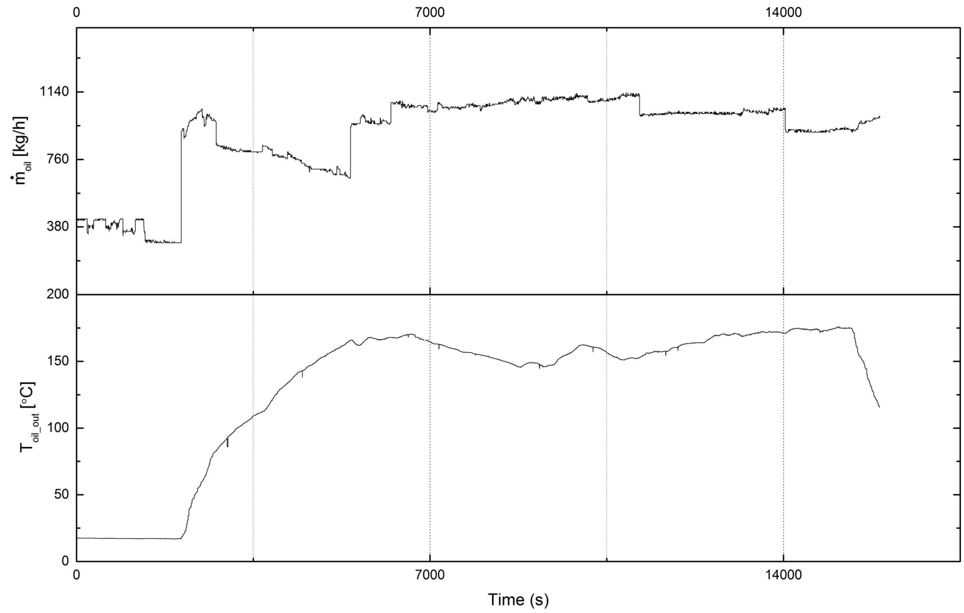

Figure 3: Start-up, work and shutdown of the micro CHP plant with 37 kW boiler.

The last phase represents the cooling mode, when the boiler is being prepared for a shut down. The process of turning off the device is quite quick (about 15 min) compared to the heating up process, which can last even up to 1h30min due to the large volume of oil in the installation. The start-up process can be significantly shortened by reducing the overall amount of the working heating fluid in the piping.

The 30 kW boiler is a part of a miniaturised ORC section, which is very similar to the one connected to the 37 kW boiler. The main difference is the amount of working fluids inside the devices (both thermal oil and HFE7100), which improves significantly the dynamics of the plant as a whole. Figure 4 presents the comparison of the inlet temperature of the thermal oil and the overall efficiency of the boiler. It can be concluded that the inlet temperature of the thermal oil directly influences its efficiency. The lower is the temperature, the higher is the thermal efficiency of the device.

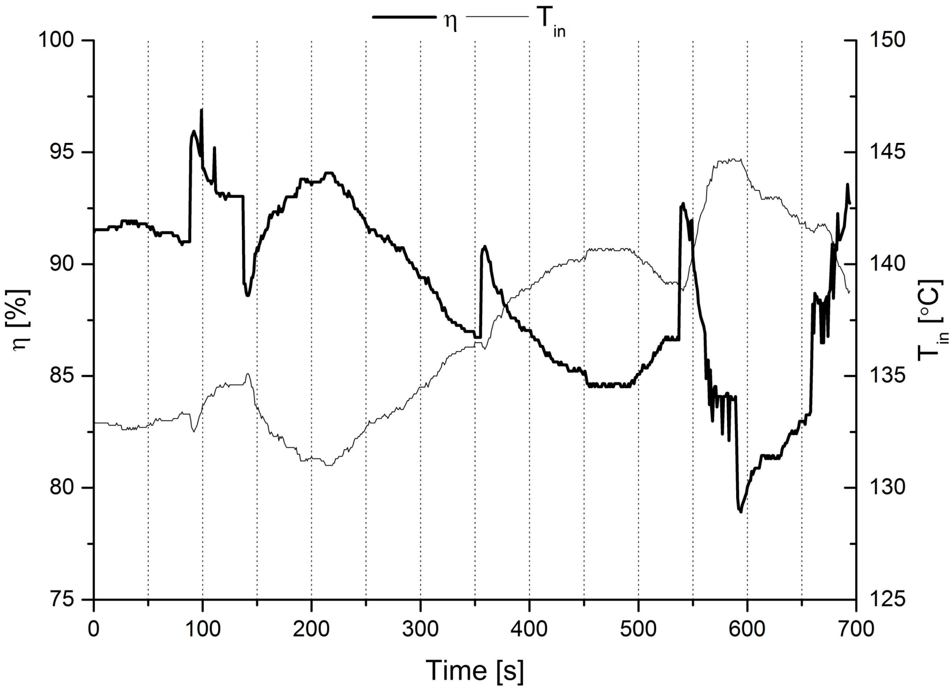

Figure 4: Correlation between the inlet temperature of the thermal oil and the thermal efficiency of the 37 kW boiler.

Moreover, the power of the turbine directly represents the power of the boiler (Fig. 5). Interestingly, the change in electrical power of the turbine in most cases slightly advances over the power of the boiler. This effect can be explained by reviewing the nature of the measurement and moment of inertia of the rotating system. The rotational speed of the microturbine rotor (having a weight of approx. 2 kg) during the test was changing from 18000 rpm up to 23000 rpm. Since the electric power of generator depends mainly on the rotational speed, it should change more slowly than the thermal power of the boiler. The measurement of the electrical power of the generator is strictly analogue, while the corresponding

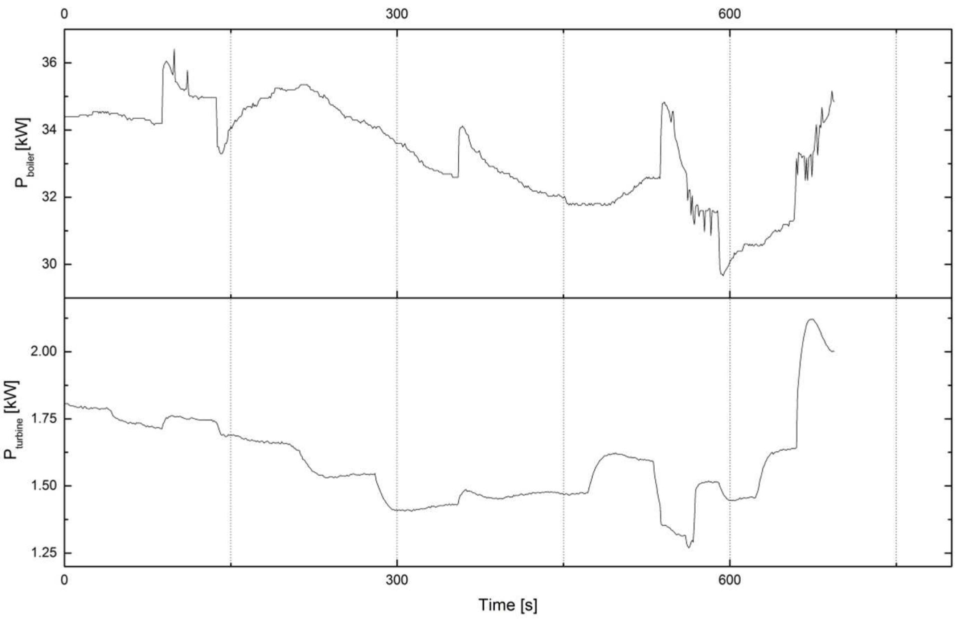

Figure 5: Comparison of the net power of the 30 kW boiler and the electrical power of the turbine during the experiment.

measurement of the boiler power utilizes three devices – two thermocouples and a turbine flow meter, each with its own time of reaction. Nevertheless, the exact correlation of these two parameters is definitely noticeable considering all other parameters that can be, and were, changed in this set during the experiment. Also, the influence of the minor but sudden change of turbine power does not influence the power of the boiler, and produces a smooth transition line.

5 Conclusion

Research shows that the key factor influencing the rate of start-up, operation and shut-down of the system is the amount of thermal oil in the piping – the larger is the oil capacity, the greater is the inertia of the system. In addition, there was an almost proportional relationship between the oil inlet temperature and the heat output of the boiler. Generally, the lower is the oil inlet temperature, the higher is the gross efficiency of the boiler. This parameter can be used as a key for proper control of the process, but this entails the need to control the amount of heat transferred to the central heating system in the condenser, which is not easy to achieve in a commercial application. In the case of a 30 kW boiler, during the entire test period, the electric power generated on the turbine corresponded with the thermal power supplied by the boiler. It should be noted that small, abrupt changes in power turbines do not affect significantly the power of the boiler, which passed smoothly from one state to another.

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