Study of the operation of straw-fired boiler dedicated to steam generation for micro-cogeneration system

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Abstract. The combined heat and power generation (CHP), based on the use of renewable energy sources, is an essential aspect of currently developing energy systems. Among the other renewable sources, biomass is characterized by high caloric value, wide availability, and low prices. This paper is focused on the study of the operation of a straw-fired boiler, as a part of developing a micro scale CHP system based on the modified Rankine Cycle operation. Based on the previously conducted studies, a dedicated construction of a 100-kWth straw-fired batch boiler was designed and implemented. Thermal oil heated in the boiler was transferred respectively to the evaporator, superheater, and oil/water emergency heat exchanger. The control of the system operation was realized using a dedicated automation system based on the programmable logic controller (PLC). Presented results include the impact of various fuel inputs and the boiler’s control scenario on the oil heating process. The power received by the evaporator and superheater (the first phase of combustion process) reached a level of 48 kW temporarily. The ratio of heat taken from evaporator and superheater to the theoretical amount of chemical energy accumulated in the fuel ranged from 16.8% to 21.4%. Moreover, also observed were differences in carbon monoxide emission from the boiler. Based on the results, some outlines for controlling the operation of the boiler were obtained.

1. Introduction
Straw-fired batch boilers, due to their simple structure and low operating costs, are an excellent source of heat for a wide range of applications, including heating systems for residential houses, farms, housing estates, industrial facilities, as well as schools and other public buildings. The power output of typical straw-fired batch boilers ranges between 40 and 700 kW. Besides the typical boilers, air heaters using thermal oil as a working medium are also available on the market. These devices allow the boiler to heat thermal oil up to 150-200°C. The possibility of generating high-temperature heat justifies the attempts to use straw-fired devices (including batch boilers) as the source of heat supplied to micro cogeneration systems [1].

In general, two main combined heat and power generation technologies are considered in the view of biomass utilization: the internal combustion piston engines and turbine-based cogeneration plants with a steam/vapour turbine working on a simple Rankine Cycle (RC) or Organic Rankine Cycle (ORC). An Organic Rankine Cycle is a commonly used Rankine Cycle due to its numerous advantages, including lower costs and maintenance requirements. Other combined heat and power (CHP) technologies, such as those based on gas turbines, Stirling engines, and fuel cells, are still in the development phase. Additionally, thermoelectric generators are currently slowly being introduced for domestic heating appliances, such as stoves [2,3].
There are many worldwide studies in the field on the use of biomass-based technologies for combined heat and power generation. On the other hand, they mostly do not include issues related to use of the straw-fired batch boilers as a heat sources for cogeneration units. Moreover, available literature sources consist of investigations devoted to micro scale systems working on the organic Rankine cycle, while Rankine cycle technologies are considered mainly from the standpoint of large scale applications.

In [4] there have been analysed three variants of CHP plant based on the Organic Rankine Cycle and fuelled with sawmill waste (considered plant produced electricity and heat for a drying chamber). A boiler, with a capacity of 250 kW, in which the combustion of biomass waste from sawmills occurs, was used as a source of energy for the CHP plant. Four different working fluids were analysed: octamethyltrisiloxane, methylcyclohexane, methanol, and water. The results show that the highest electric power was obtained for the system with internal regeneration and methylcyclohexane applied as the “dry” working fluid. On the other hand, the highest temperature to supply the drying chamber was obtained for the system with external regeneration and octamethyltrisiloxane applied as the working fluid. Another example of using the ORC system is shown in [5], where analysis of an ORC system, characterized by an electricity output of 2 kW, was performed. The electrical efficiency of this system with the selected ORC fluids (HFE700, HFE7100, n-Pentane) was within the range of 7.5%–13.5%, depending on the hot water temperature of the biomass boiler and the ORC condenser cooling water temperature. The importance of the optimal choice of the working medium was also emphasized in [6,7]. For this purpose, special computational models were created, including advanced models with sufficient accuracy. The models were based on the database from the Design Institute for Physical Properties (DIPPR), which includes nearly 1800 substances, and the Peng-Robinson-EOS.

The energy and economic analyses conducted for various configurations of the biomass-fuelled ORC circuits confirmed the potential behind the application of this type of installation in micro-scale systems. This was illustrated by the installation cost of 5 thousand €/kW with a 3-year payback period [8]. Also, in the case of the industrial sector, the use of biomass-based CHP units may be beneficial. The comparison of using Brazilian available biomass materials (rice husk, coffee husk, and elephant grass) and natural gas applied to an electric arc furnace steelmaking process was shown in [9]. An economic analysis, considering only the operational cost of the plant revealed that elephant grass had the lowest operational cost, accounting for a reduction of about 9–15% compared to natural gas.

Another issues, which should be considered in relation to biomass-based CHP systems, are the energy efficiency and environmental impact of the used heat source. In [10] there is shown the increase in the efficiency of small batch-fired straw boilers, in Denmark, which changed from about 75% in 1995 to about 87% in 2002. Correspondingly, reductions in CO emissions from about 5000 ppm in 1995 to less than 1,000 ppm in 2002 were seen. Additionally, further research shows the possibility to improve performance of the boilers and whole cogeneration plants. The mathematical model for the biomass burning process and its experimental validation was developed and described in [11]. The developed model was used to optimize the performance of the recirculation system of the combustion appliance. The results show that energy savings of 17% of the auxiliary electrical power demand may be reached by reducing the flow rate of the recirculated flue gas fumes. Another example of numerical modelling, focused on the identification of hazardous gaseous pollutants forming during the biomass combustion process (NO, CO and other substances), was shown in [12]. It was discovered that the decrease of the CO molar fraction was significant up to 1,000 K and was barely observable above 1,000 K. On the other hand, the character and the rate of the change of the NO concentration within the considered temperature range was initially very low. Subsequently, it increased significantly, which was connected with the increase of the temperature in the combustion chamber. It was also found that increasing the pressure in the combustion chamber resulted in a higher NO concentration during biomass combustion (below 1,200 K), while the concentration of CO was reduced when the pressure was reduced.

This paper encompasses the analysis of the practical aspects of the high-temperature heat generation in a 100-kWth, straw-fired batch boiler. It is a second approach to the development of a micro scale cogeneration system based on the batch boiler. In the first attempt, a special oil heat exchanger (made of steel pipes) was placed between the second combustion chamber and tubular heat
exchanger of the 180-kWth-batch boiler (a similar unit with higher nominal power). The oil was heated up by the flue gas, but it was identified as a problem with insufficient time, when the oil exchanger worked efficiently (only in first stage of combustion process) [1]. It was concluded that oil should be used instead of water in the boiler’s jacket to ensure continuous operation of the oil circuit, and consequently – cogeneration system.

2. Experimental Rig

The assumption that was made at the beginning of the work was that the basic functionality of the boiler as a heat source had to be maintained (electricity generation was intended to be an additional feature.). Based on the previously conducted studies, a dedicated construction of a straw-fired batch boiler was developed. The new unit had a capacity of 100 kWth and oil jacket replacing the typically used water jacket. It was equipped e.g. with a dedicated fuel feeder and additional air nozzles that supplied air to the second combustion chamber. Thermal oil heated in the boiler was transferred to shell and tube heat exchangers, connected in series, and operated respectively as an evaporator and superheater. There was also used an emergency oil-to-water plate heat exchanger (it works only in time, when an oil temperature is too high). Steam generated in the evaporator and overheated in the superheater was used to power the steam engine or turbine (system works according to the modified Rankine Cycle). The boiler and two heat exchangers (i.e. evaporator and superheater) are shown in Figure 1.

Figure 1. Straw-fired batch boiler, evaporator and superheater.

The process of straw combustion in the boiler is quite complicated. Oil is heated up to a final temperature (180-200°C), controlling the level of the flue gas temperature (it should not exceed 320°C.). Due to the fact that fuel randomly changes its geometry during the combustion process in the combustion chamber, the temperature may fluctuate rapidly. The control of the boiler operation and measurements of selected parameters were realized using a specially developed automation system based on the WAGO PFC200 PLC controller with digital I/O, analogue I/O and special modules (including Modbus RTU). The dedicated visualisation allowed also to acquire measurement data in any defined time range – typically from one to a few seconds. The general scheme, including the main elements of the experimental rig, is shown in Figure 2.
From the perspective of the study aimed at determining the possibilities to use a straw-fired batch boiler as a heat source for a micro-scale cogeneration system, it is crucial to identify the value of the high-temperature heat that can be obtained from the unit. The following measurements were conducted:

- temperature of flue gas at the outlet from the boiler ($t_{fg}$), measured using the K-type (NiCR-Ni) thermocouple sensors with a measuring range from -40°C to 1200°C and accuracy ±2.2°C or ±0.75%;
- oil temperature ($t_{oil,1}$, $t_{oil,2}$, $t_{oil,2a}$, $t_{oil,3}$, $t_{oil,4}$), measured using the Pt100 resistance sensors with a measuring range from -50°C to 400°C and tolerance ±0.3+0.005·[°C];
- oil flow ($m_{oil}$), measured using the ultrasonic flow meter with a measuring range from 0 to 50 kg/h and maximum measuring error up to 2%;
- the temperature of the condensate and steam ($t_{st,1}$, $t_{st,1a}$, $t_{st,2}$), measured using the Pt100 resistance sensors with a measuring range from -50°C to 400°C and tolerance ±0.3+0.005·[°C];
- the pressure of the condensate and steam ($p_{st,1}$, $p_{st,1a}$, $p_{st,2}$), measured using the transducers with a measuring range 0-16 bars;
- the concentrations of selected pollutants in the flue gas (CO, CO2 and O2). The analyser uses the electrochemical method of O2 concentration measurement (0-21% range) and the NDIR method for measuring the concentrations of CO (0-100000 ppm range) and CO2 (range 0-20%).

The control of the boiler’s operation was performed by means of inverters adjusting the flow of the inlet air, the flow of the flue gas, the flow of the thermal oil, and the flow of the cooling water.

3. Results and discussion

Below presented results include the impact of various fuel inputs and the boiler’s operation methods on the oil heating process. Only single fuel input has been burnt in each series. Ignition was started from the rear part of the combustion chamber. The flue gas fan and air fan was started at respectively 15 s and 30 s after fire ignition. The oil pump had been working with 70% of the power, while emergency oil/water heat exchanger was switched off during the combustion process and used only for cooling oil after the fire died out.

3.1. Fuel inputs in each series

The capacity of the boiler’s combustion chamber allows it to burn once from one to six, typically straw bales (rectangular bales with dimensions of 80 x 80 x 40 cm with weights ranging from 7 to 10 kg). Bales can be arranged in two rows of three pieces. The bale arrangement during conducted tests is shown in Figure 3.
Grey straw used for energy purposes has a caloric value at a level of ca. 15.2 MJ/kg (~4.2 kWh/kg) and usually contains 14 - 20% water that vaporises during burning. The ash content is ca; 3% and bulk density ranged from 90 to 160 kg/m³.

The information about fuel inputs in each series is shown in Table 1. The straw used in the tests was seasoned for one year, so it was characterised by really low water content.

| Series No. | Fuel input                  | Total weight | Moisture content |
|------------|-----------------------------|--------------|------------------|
| 1          | 3 rectangular bales         | 25.6 kg      | < 10%            |
| 2          | 4 rectangular bales         | 39.2 kg      |                  |
| 3          | 5 rectangular bales         | 47.3 kg      |                  |
| 4          | 6 rectangular bales         | 55.0 kg      |                  |

3.2. Control scenario for boiler operation

The main control signal for controlling the boiler operation is flue gas temperature. The value of the flue gas temperature was defined as 270–280°C (minimal temperature required to heat up oil to the above assumed level). To provide such a value, the control of the power of the inlet air fan and outlet flue gas fan during the combustion process was realized. Based on the previous experience, the power of the outlet flue gas fan was higher than the power of the inlet air fan in the starting and combustion phases. Only in the afterburning phase, when straw situated in the front part of combustion chamber is burned, power of the inlet air fan was 90–100%, compared to the lower value of power of the outlet flue gas fan. Variations in the inlet air fan and outlet flue gas fan power during combustion of 5 straw bales are shown in Figure 4.
Figure 4. Control of the inlet air fan and outlet flue gas fan during combustion of 5 straw bales.

Figure 4 shows that the assumed temperature level was achieved within 5 minutes of the combustion process (Such a short time is caused by really low humidity of the used fuel.). To maintain a flue gas temperature in the range between 270–280°C, the power of the fans are modified each time, when the temperature increases or decreases. It was strongly observed in 24 minutes (peak no. 1) and 34 minutes (peak no. 2) of the combustion process. In these moments, ignition of the straw located in the front part of combustion chamber occurred and temperature of the flue gas temporary increased respectively up to 320°C and 325°C. The rapid reduction in the flue gas temperature was realized by the significant lowering of the power of both fans. The end of the combustion process (start of the afterburning phase) was observed within 53 minutes (it is a time, when the fire died out and flue gas temperature started to decrease).

3.3. The impact of various fuel inputs on the oil temperature

The hot oil temperature (measured in the point toil,1) was controlled during the combustion process. Temperature variations were stabilized by modifying the inlet air stream and flue gas stream. The oil pump was set at 70% of its nominal power during the whole combustion process. It was assumed that the temperature of the hot oil should be in the range of 170°C to 200°C to obtain steam pressure at a level of 6–10 bars. The variations in the oil temperature at the outlet (toil,1) for the various fuel inputs is shown in Figure 5.

Figure 5. Variations in the oil temperature at the outlet from boiler for various fuel inputs.
Assumed temperature level was achieved only when 5 and 6 straw bales were burned (respectively within 60 and 82 minutes of the combustion process). In both cases, such a temperature occurred for a very short time and was very close to the lower limit of the assumed range. Comparing the time of occurrence of the highest temperature to the variations of flue gas temperatures (Figure 4) we can conclude, that the highest level of oil temperature is achieved when the combustion process is finished. It shows the necessity of using a fuel feeder. On the other hand, both in the case of burning 3 and 4 straw bales, the maximum level of achieved temperature was significantly lower: 160°C for 4 bales (within 45 minutes) and 120°C for 3 bales (within 30 minutes).

3.4. The impact of various fuel inputs on the power generated in the boiler

Besides the temperature level, another crucial parameter is the power generated in the boiler and received by evaporator and superheater. In the first stage of tests, the oil/water heat exchanger (designed for an emergency cooling of oil) was cut off, so the power reached in this time was a power given to the evaporator and superheater. On the other hand, in the second stage of tests (in the afterburning phase), the heat reached in a boiler is given to the oil/water heat exchanger (the time of switching on the oil/water heat exchanger is connected with strong increase in a power received from a boiler.). The variations in power taken from the boiler ($P_{oil}$) is shown in Figure 6.

![Figure 6. Variations in power taken from the boiler by evaporator and superheater (the first phase) and oil/water heat exchanger (the second phase).](image)

The heat taken from the hot oil in the evaporator was used to heat the water from a starting temperature of ~20°C to more than 100°C, and evaporate it. Wet steam was superheated in the superheater and it was then flown to the steam bus. During this study, the steam bus was opened, so the maximum obtained pressure was lower than 1.5 bars.

The calculation of ratio of energy transferred from oil to water and steam (in the evaporator and superheater) to the theoretical chemical energy accumulated in fuel, allows assessment of the efficiency of the boiler as a heat source for the micro scale cogeneration system. Results of such calculations are presented in Table 2.
Table 2. The ratio of energy transferred from oil to water and steam to the theoretical chemical energy accumulated in fuel

| Series No. | Theoretical chemical energy in fuel | Energy transferred from oil to water and steam | Energy ratio defined as above |
|------------|------------------------------------|-----------------------------------------------|------------------------------|
| 1          | 387 MJ                             | 65 MJ                                         | 16.8 %                       |
| 2          | 593 MJ                             | 118 MJ                                        | 19.9 %                       |
| 3          | 715 MJ                             | 153 MJ                                        | 21.4 %                       |
| 4          | 832 MJ                             | 151 MJ                                        | 18.1 %                       |

The ratio of heat taken from the evaporator and superheater to the theoretical amount of chemical energy accumulated in the fuel ranged from 16.8% to 21.4%. Low value resulted from the fact that described combustion processes started from “cold” installation (a high amount of heat was used to preheat the physical parts of the installation.). On the other hand, it should be taken into account that a large amount of energy was received by the water and accumulated in the buffer tank. To more accurately estimate the amount of energy transferred from a burned fuel to the steam circuit, it was provided a continuous combustion process.

3.5. The impact of various fuel inputs on the carbon monoxide emission from the boiler

Analysing the variations in the level of carbon monoxide (CO) emission to the atmosphere, three essential combustion phases were identified: ignition phase, combustion phase, and afterburning phase. The CO emission in each phase for combustion 5 straw bales is shown in Figure 7.

![Figure 7](image_url)

**Figure 7.** Variations in CO emission to the atmosphere (calculated to 13% of oxygen) during combustion of 5 straw bales.

In the first phase, when the combustion chamber is cold and filled with fuel, CO emission reached a maximum level of 4450 ppm. In the combustion phase, the level of emission was significantly lower: from 4 to 11 minutes and from 13 to 16 minutes, not exceeding 500 ppm, and up to 38 minutes with a maximum value not below 2 500 ppm. In this phase, variations in CO emissions were connected with variations in the fan power set. The significant impact of air flown to the combustion chamber on CO emission was observed in 38 minutes, when CO emission increased up to 10 000 ppm, as a consequence of reducing the power of the fans. The last phase of the combustion process, the afterburning phase, was started in 58 minutes. In this phase, CO emission increased up to 25 000 ppm, but such a high level was caused by the high amount of oxygen in the flue gas. Taking into account an initial and combustion phases, the average CO emission was 2 270 ppm.
4. Conclusion

Results of the currently conducted study show the high potential of the usage of the tested straw-fired batch boiler as a source of high-temperature heat for co-generation systems. On the other hand, many aspects should be still considered to provide its reliable operation.

In the proposed system configuration, the oil temperature reached 170°C only when five and six straw bales had been combusted. Such a high temperature was obtained only for a short time (a few minutes) during the combustion process. In the case of burning three and four straw bales, the maximum obtained temperature was significantly lower. It suggests that the use of a fuel feeding system is needed both to provide a higher temperature level (close to 200°C) and to provide a continuous occurrence of such a high temperature level.

The power received by the evaporator and superheater (the first phase of combustion process) reached a level of 48 kW temporarily. The ratio of heat taken from evaporator and superheater to the theoretical amount of chemical energy accumulated in the fuel ranged from 16.8% to 21.4%. On the other hand, a large amount of energy was received by the water and accumulated in the buffer tank.

During the presented study, environmental impact of the boiler was also tested. Taking into account the situation, when 5 straw bales were conducted, the average CO emission was obtained at a level of 2 270 ppm. This value will be significantly lower during a continuous combustion process.

Further research will be focused on the process of steam generation in the evaporator and superheater to provide stable conditions for steam engine operation.

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