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Experimental and numerical analysis of a micro scale cogeneration system with 100 kW straw-fired boiler

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Abstract

Straw-fired batch boilers, due to their simple structure and low operating costs, are an interesting option for heating systems dedicated to use in houses, farms, schools, industrial facilities and other buildings. Commercially available solutions include typical water boilers and air heaters with a thermal oil jacket. The high temperature of thermal oil (180-200°C) mean straw-fired devices can be used as a source of heat for micro scale cogeneration and trigeneration systems.

The first part of this paper shows an experimental analysis of a micro scale cogeneration system based on modified Rankine Cycle operation. A 100 kWth straw-fired batch boiler with thermal oil jacket was used as a high temperature heat source. Thermal oil, heated in the boiler, was transferred respectively to the evaporator, superheater and oil/water emergency heat exchanger. The steam generated was conditioned and used to power a 20 hp steam engine. Cooling water, heated in the condenser, was pumped to a 4 m^3 water tank connected to two air coolers. Control of the system operation was realized using a dedicated automation system based on the PLC controller.

In the second part of this study, a micro scale cogeneration system was developed and modelled in TRNSYS software on the basis of the experimental installation. The dynamic operation conditions in terms of temperatures and powers were analyzed for the main components of the system (boiler, evaporator steam engine, condenser). Moreover, some modifications in the system construction were proposed to improve its performance.

The results of the experimental tests were used to identify the main aspects of the considered system—temperature, pressure and power levels in oil, steam and water circuits and operating parameters of the steam engine. Dynamic simulations performed in TRNSYS pointed to the nominal operation scenario for the tested system and showed the great potential for further improvements in the system construction.

Keywords: micro cogeneration; renewable energy sources; trigeneration; biomass; straw-fired boiler; TRNSYS; dynamic simulations

1. Introduction

Micro-cogeneration and micro-trigeneration systems based on renewable energy are gaining popularity. In Europe, these systems go some way to meeting the European Union's challenging demands in the field of use renewable energy sources (RES), energy efficiency and CO_2 emission to the atmosphere. In Polish conditions, among the various RES available, biomass is characterized by its high caloric value, wide availability and low prices. Straw is a little-used biomass fuel, which lends itself to combined heat and power (CHP) and combined cooling, heat and power (CCHP) systems. Commercially available units dedicated to straw combustion, include two types of devices:

1. batch boilers for periodic and cyclic combustion of baled straw, devices based on ground straw combustion technology using the burning cigar method (continuous operation) and automatic devices for combustion of straw cut into pieces of 5–10 cm in length (continuous operation);
2. straw-fired air heaters with thermal oil as the working medium, heated to 150-200°C and used in special applications, such as greenhouses, drying rooms, distilleries, etc.

As was shown in [1], typical straw-fired batch boilers may be easily adapted to high temperature heat generation for a micro-cogeneration system based on modified Rankine Cycle operation. This technology is one of the main power generation technologies for biomass utilization. Internal combustion piston engines and CHP plants with a steam turbine working on an Organic Rankine Cycle (ORC) are commonly used alternatives. Other CHP technologies, such as those

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Email address: `mzoladek@agh.edu.pl` (Maciej Żołądek) based on gas turbines, Stirling engines, and fuel cells, are still in the development phase [2, 3].

An analysis of the available literature shows that the possibility of using biomass boilers in small- or micro-scale distributed cogeneration systems (encompassing systems of up to 10 kWel) has been the subject of investigations for several years [4, 5]. For example, three variants of CHP plant based on the ORC cycle and fuelled with sawmill waste were analyzed in [6]. The CHP plant used as a source of energy a boiler, with a capacity of 250 kW, driven by the combustion of biomass waste from sawmills. The results show that the highest electric power was obtained for the system with internal regeneration and methylcyclohexane applied as the “dry” working fluid (other fluids tested were: octamethyltrisiloxane, methanol and water). Another example is the analysis of a 2 kWel ORC system shown in [7]. The electrical efficiency of this system varied from 7.5% to 13.5%, depending on the working fluid (HFE700, HFE7100 or n-Pentane), hot water temperature in the biomass boiler and ORC condenser cooling water temperature.

Trigeneration systems are considered in the cogeneration literature [8, 9, 10]. Technical and economic modelling and performance analysis of biofuel fired trigeneration systems equipped with energy storage for remote households were carried out in [11]. To adapt the dynamic energy demand for electricity, heating and cooling, both electrical and thermal energy storage devices were integrated to balance larger load changes. Techno-economic analysis of the modelled trigeneration systems showed efficiencies of around 64–70% and electricity selling prices of around 356–407 EUR/MWh when fired by biofuels. The methodology to optimize the size (electric power) of a cogeneration plant based on a biomass-fired Organic Rankine Cycle and connected to an existing district heating network is shown in [12]. Calculations show that for a population of between 10,000 and 20,000 inhabitants the size of plant ranges from 2 to 9 MWel. Coverage of thermal energy demand ranges from 40% to 80%. Regarding the trigeneration mode, it is concluded that cooling is only worthwhile in locations with high summer severity and in full load operation mode, with the optimal size of the plant smaller in trigeneration mode than in cogeneration.

This paper encompasses analysis of the practical aspects of operating prototype micro scale cogeneration units with a straw-fired batch boiler. Experimental results are supplemented by dynamic simulations of the installation under nominal operation conditions.

2. Experimental rig

2.1. Experimental rig

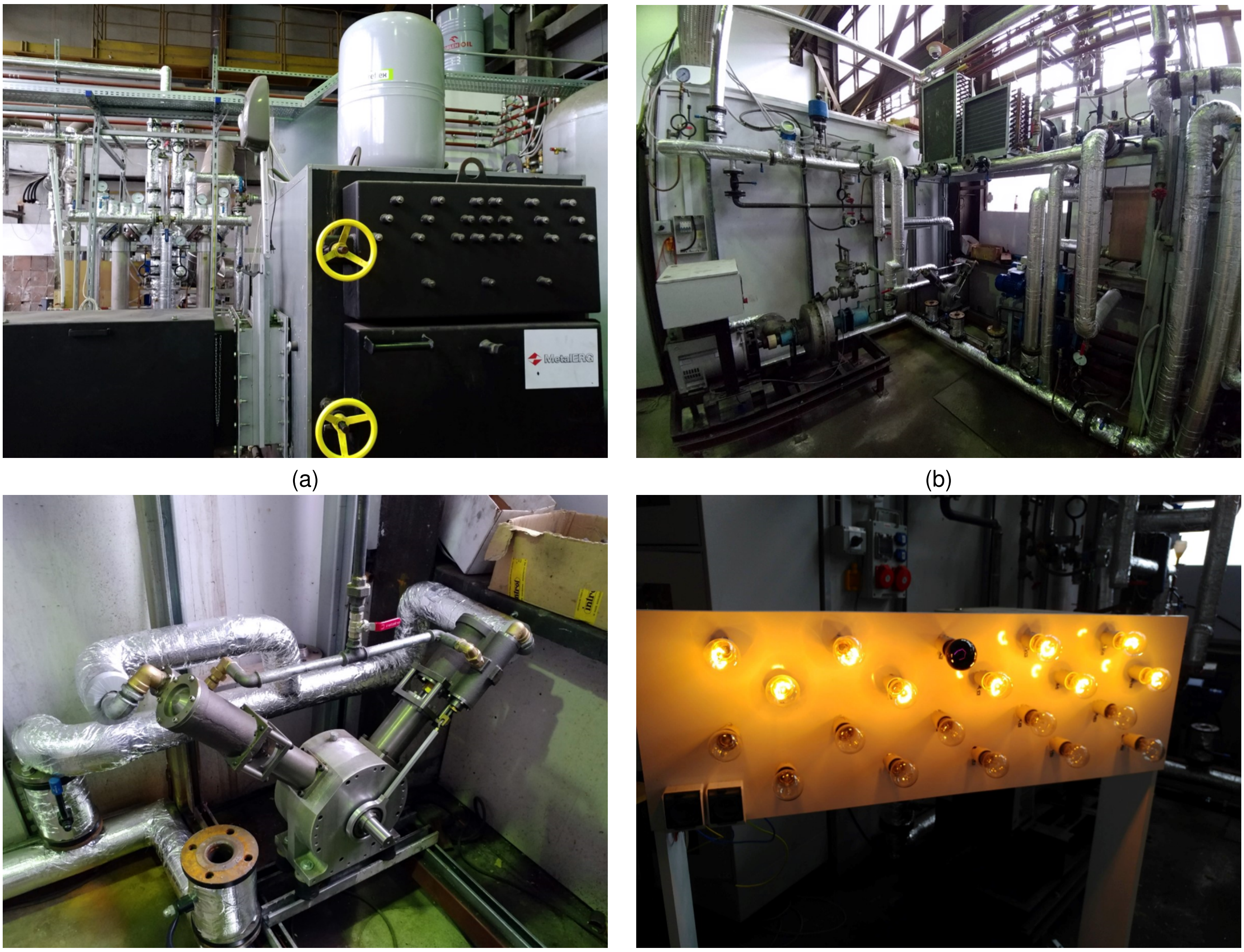
Experimental rig is equipped with a 100 kWth straw-fired batch boiler (working as a high temperature heat source for the developed micro cogeneration system) and oil, steam and water circuits. The boiler has an oil jacket (replacing the water jacket typically used in boilers) and it is equipped with a fuel feeder and additional air nozzles that supply air to the second combustion chamber. Steam is generated in two shell and tube heat exchangers connected in series – the first one acts as an evaporator while the second one acts as a superheater. Generated steam, after being conditioned, powers a 2-cylinder, double-acting, 20-horsepower steam engine. Then it is condensed in a condenser (the third one shell and tube heat exchanger) and pumped to a degasser. Finally, the condensed water is pumped to the evaporator, where it is evaporated once again. Electricity is generated in a 2 kWel power generator connected to a steam engine (a temporary solution, shortly to be superceded by a higher power generator). The main elements of the developed micro cogeneration system are shown in Fig. 1.

More than 80 parameters are measured and controlled via a dedicated automation system based on WAGO PFC200 modular PLC controller. The most important parameters are: temperature, pressure and mass flow of working fluids (oil, water) at selected points of the oil, steam and water circuits, thermal power of the boiler, evaporator, superheater and condenser, rotation speed of the steam engine and consequently voltage, current and electrical power produced in the generator, power of inlet and outlet air fans as well as power of oil and water pumps, performed by means of inverters, emissions from the boiler.

2.2. Dynamic Simulations

The performance of dynamic simulations is crucial from the standpoint of determining theoretically available power generation in the developed system and identifying avenues for further improvements. The nominal operation conditions of the experimental rig were investigated by developing a model of the installation and running simulations.

The model was developed and simulated with the TRaNsient SYstem Simulation (TRNSYS) tool. This tool, commonly used to simulate energy systems, is based on validated components models with respect to experimental and/or manufacturer data. The simulation determined profiles of temperature, pressure, mass flow, and thermal and electrical power for the selected system components. The framework of the implemented components in the system consists of: cross flow heat exchanger (Type 5), heat recovery steam generator (Type 637), flow following steam turbine (Type 592), condenser for steam flows (Type 598), steam condensate pumps (Type 618), storage tank (Type 4), pump (Type 3), pipe (Type 31), fluid diverting valve (Type 647), controlled flow diverter (Type 11) and differential controller (Type 2) among others. It is worth noting that a steam turbine was used instead of an engine since the model of the engine is under development. While the engine and turbine have different operation characteristics, adoption of the turbine made it possible to estimate the operation of the system under nominal operation conditions. Moreover, it is assumed that the system operates continuously under quasi-steady state condition. The simulations produced a huge amount of data, but for brevity only a small part of the results is presented below.



(a) (b)

(c) (d)

Figure 1: (a) boiler, fuel feeder, evaporator and superheater; (b) steam circuit with visible steam engine, steam turbine and condenser; (c) steam engine; (d) bulbs with 2 kW of installed power operating as a load

3. Results and discussion

3.1. Boiler's operation

The volume flow of air at the inlet to combustion chambers and flue gas at the outlet from the boiler were set. Flue gas temperature was maintained at a level of 320–350°C, while maximum oil temperature was set at 200°C. Four rectangular bales of straw (~38 kg) were preloaded into the combustion chamber before the combustion process started and subsequent loads of straw were supplied by the fuel feeder.

Heat generated in the boiler was transferred via thermal oil to an evaporator and superheater (in which water was evaporated and steam was superheated) and a water cooling emergency heat exchanger. During the presented study, thermal power transferred from the oil circuit to evaporate water and superheat generated steam achieved a maximum level of ca. 90 kW (which was about 90% of the thermal power generated in the boiler). Considering, individually, the operation of the evaporator and superheater it can be observed that the evaporator was consuming power at an average level of 50 kW, while the power consumption of the superheater varied significantly over time. In general, the maximum thermal power reached in the boiler exceeded 190 kW at which point the emergency heat exchanger was switched on.

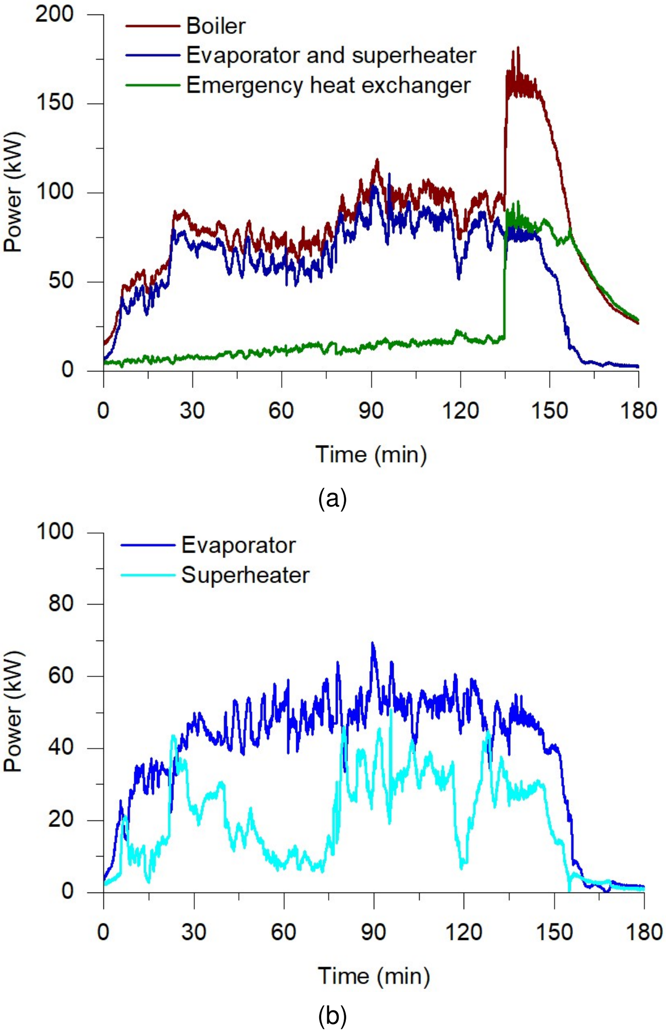
Variations in thermal power generated in the boiler, power taken by the evaporator and superheater, and power taken by the emergency heat exchanger during the considered combustion process, are shown in Fig. 2.

3.2. Steam circuit parameters

The steam engine installed in the prototype system requires steam pressure of 13.8 bars and proper steam flow to work with 700 RPM. Those parameters were not achieved at the current configuration of the tested system. The maximum level of steam pressure during the presented tests was ~5.9 bars at a temperature at the outlet from the superheater of 196°C. During power generation these values varied, depending mainly on the irregular parameters of the straw combustion process. When electric power generated in the generator achieved its maximum (1071 W), steam pressure was 4.3 bars (31.2% of its nominal value) and mass flow of steam was 109 kg/h. The main parameters measured in the steam circuit are shown in Fig. 3. The significant variations in generated power shown in this figure are caused by the I-V characteristics.

3.3. Current-voltage and power-voltage characteristics of the power generator

The current-voltage (I-V) and power-voltage (P-V) characteristics presented below were determined at a time between 110 and 130 minutes of the combustion process (see Fig. 4). Maximum power of 1071 W was reached in minute 124 for voltage 281.8 V and current 3.8 A. This value was limited both by steam parameters (resulting e.g. from the configuration of the developed micro cogeneration system) and construction of the power generator (it is only 10.7% of the steam engine's nominal power).



(a)

(b)

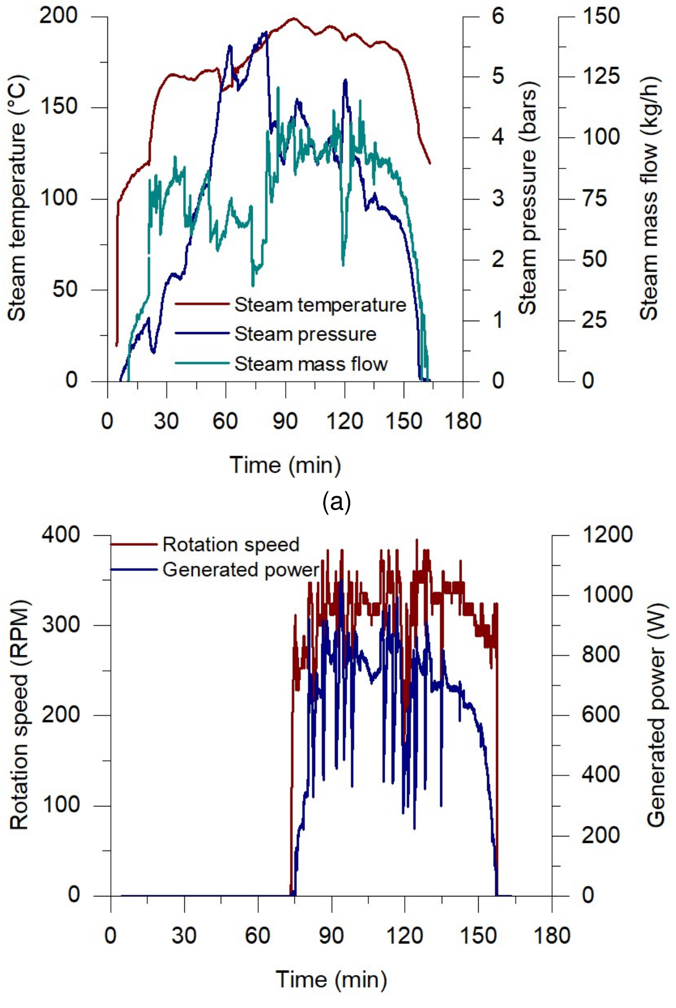
Figure 2: (a) variations in thermal power generated in the boiler and consumed in the evaporator and superheater and the emergency heat exchanger; (b) supplemented by comparison of thermal power consumed individually in the evaporator and superheater

3.4. Results of dynamic simulations

The developed model of the system was based on the parameters of the experimental rig, including components capacities, mass flow rates, set-point temperatures. The thermal demand of the user was simulated assuming that the tank supplies thermal energy to the user in order to keep its top temperature between 50 and 70°C. In particular, in order to avoid the tank overheating, the stored water is supplied to the virtual user when it reaches 70°C. The heat exchange is simulated, the returning temperature being 5°C lower than the supply temperature. This way the temperature inside the tank is lowered to 50°C. The steam boiler produces steam at pressure of about 7.5 bar, while the pressure at the inlet of the turbine is fixed at 7.0 bar. The simulation was performed for constant operation conditions of the system, excluding the cooling of the tank, as previously mentioned.

The main temperatures of the system are plotted in Fig. 5.

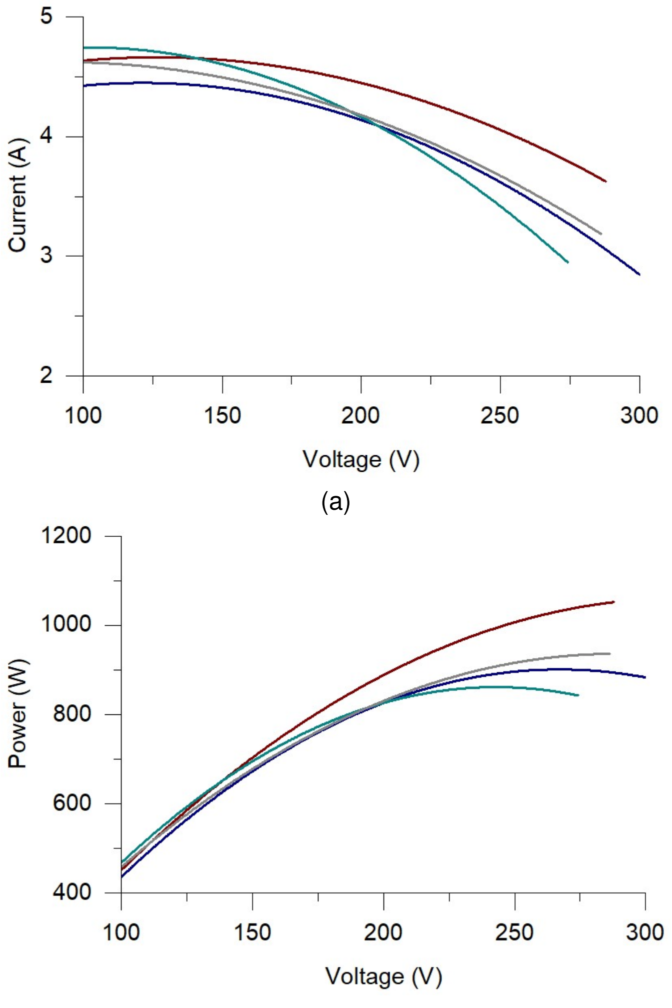
As noted from this figure, the operating conditions of the sys-



(a)

(b)

Figure 3: (a) variations in steam temperature, pressure and mass flow; (b) variations in rotation speed and power generation



(a)

(b)

Figure 4: (a) current-voltage characteristics of the power generator; (b) power-voltage characteristics of the power generator

tem are almost constant, since there is continuous operation and the steady state of operation of the straw boiler is maintained. Only the variation of the tank temperature determines the oscillation of the boiler inlet temperature. In fact, the thermal oil achieves a lower temperature when the tank provides thermal energy to the user. The control strategy of the boiler achieves nominal oil temperature of 200°C which is used by the steam boiler to produce steam at about 180°C at 7.5 bar. The turbine expands the steam to 102.3°C at a pressure of 1.1 bar, then the steam condensates to 86.8°C. Moreover, the operation of the preheater causes an increase in the temperature of the condensed water to 145.3°C due to the still high temperature of the oil exiting the steam boiler.

The thermal powers of the main components and the electrical power of the turbine are reported in Fig. 6. In this figure it is clearly shown that the thermal power provided by the boiler – in order to ensure an outlet oil temperature of 200°C – varies as a function of inlet temperature, a trend which depends on the thermal energy transferred to control the temperature of the tank. The thermal power of the boiler varies between 71.4 and 73.7 kW. As expected, the main part of the boiler's thermal power is used to produce steam (41.7 kW), while the remaining part is used to preheat water (6.4 kW) and is supplied to the user tank (23.4 kW). The electrical power produced is also almost constant at 6.4 kW. The results of the dynamic simulation show that the performance of the experimental installation may be improved significantly, enhancing the production of the steam from the point of view of operation pressure. This improvement will lead to greater power production.

Furthermore, the implementation of the trigeneration scheme (integration of an absorption chiller) in the present system layout is clearly possible due the satisfactory temperature levels. However, attention must be paid to the coupling of thermal demands of the user with the capacity and dynamic operation of the straw boiler. In fact, as outlined by the results, user demand affects the boiler inlet temperature and this effect becomes more significant still in the absorption chiller integration. Therefore, the thermally driven chiller unit must be selected correctly in order to ensure satisfactory

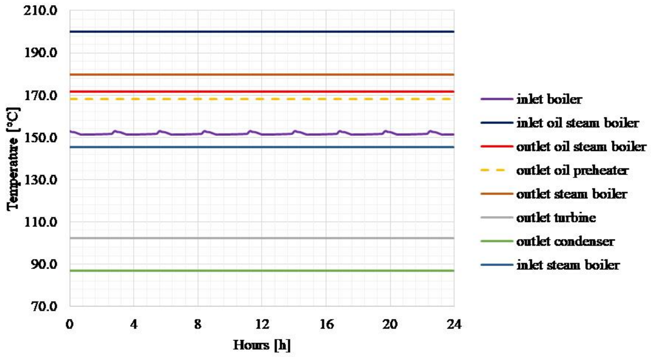


Figure 5: Main temperatures of the system, dynamic simulations

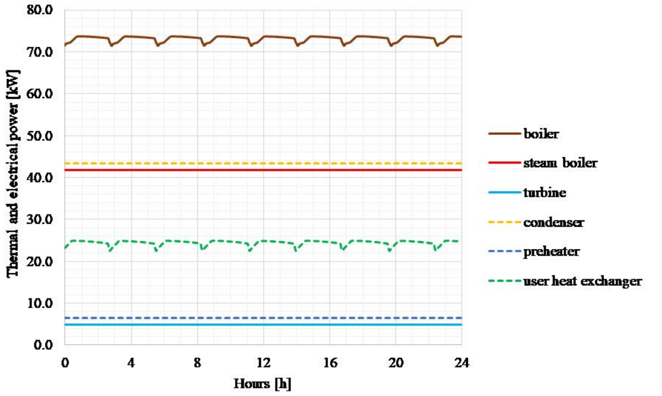


Figure 6: Main thermal and electrical powers of the system, dynamic simulation

operation of the system from the point of view of steam production condition requirements (electrical power) and thermal energy supplied to the user.

4. Conclusion

The paper shows the operation of a combined heat and power generation system based on straw combustion. The electrical power achieved in the study was 1071 W, representing 31.2% of the nominal power of the installed steam engine. Numerical analyses performed in TRNSYS show that through appropriate control of the combustion process and increase of steam pressure 6.4 kW of electric power can be obtained, which is 598% of the power obtained in the study. In addition, the simulation informs the appropriate selection of a thermally driven chiller to implement the full trigeneration cycle.

Acknowledhements

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