Simulating ON-OFF Regimes on a Micro-CHP Using Biomass

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Abstract. A micro-cogeneration biomass-based Stirling engine unit developed by the ÖkoFEN company has been tested to characterize its energetic performances. The stages of functioning have been described using polynomial equations in function of time, to accurately simulate ON-OFF regimes of functioning, in the context in which the micro-cogeneration unit would be part of a multi-country grid in accordance to the ACA-MODES Interreg program.

1. Introduction

In 2020, the European commission published a new strategy to boost renovation [1]. The document is in line with provisions of the 2030 Climate Target Plan [2] aiming to simultaneously stimulate energy gains and economic growth. The strategy has the goal of doubling the annual energy renovation rates in the following 10 years. The residential sector must undergo the highest reduction in energy demand regarding heating and cooling, between -19 % and 23 % in comparison to the year 2015. The annual rate of heat equipment replacement would have to reach approximately 4 % in both residential and industrial sectors. The share of renewable energy and waste heat recovery systems would have to increase to 38-42 % to reach the objective. The goal could be attained if by 2030 more Europeans would be prosumers, producing heat and electricity for self-consumption and even selling electricity to the grid, while fossil fuels gradually disappear from the heating and cooling processes.

The gradual elimination of fossil fuel use in residential stand-alone systems for heating purposes is possible by increasing the usage of renewable energy sources. Of all renewable energy resources, biomass is important and abundant. [3] Figure 1 shows the energy potential of biomass in Europe. Biomass is increasingly used as an alternative fuel for power generation, space heating and combined heat and power applications [4,5]. In the latest period, biomass-based micro-cogeneration systems have increased in popularity and various researches have been carried out in this field [6]. In the field of residential applications, micro-cogeneration systems with a power range of kWel have been found more suitable [7]. In the case of using solid biomass as fuel, cogeneration units have been coupled with biomass boilers and external Stirling engine combustion engines [8,9]. Several recent biomass-based facilities have been analysed and centralized in table 1. The highest global power efficiency was recorded in an Organic Rankine Cycle (O.R.C.) application with a value of 11.28 % [14], while the total efficiency of this application is comparable to another micro-O.R.C. application [15]. The highest global power efficiencies were found through processes of gasification [10,11], although the global thermal efficiency was low (21.7 % -33.72 %). Direct biomass combustion applications recorded a higher global thermal efficiency [15,18,20], on a thermal power production scale (31-120 kWth)
comparable to that of gasification processes (40 kW). By analysing the efficiencies and power scales of different systems, it would seem that direct biomass combustion is more recommended in processes where heat in its entirety is useful, such as domestic and micro-industrial applications, as opposed to complex industrial applications where residual heat from other processes can also be harnessed in addition to that produced by power-generating systems.

![Figure 1. The energy potential of wooden biomass in Europe (Source: https://heatroadmap.eu/)](image)

**Table 1. CHP systems.**

| Reference | Process type | Power [kW_e] | Thermal power [kW_th] | Global power efficiency [%] | Global thermal efficiency [%] |
|-----------|--------------|--------------|-----------------------|-----------------------------|-----------------------------|
| [10]      | Gasification and syngas conversion Woodchip gasifier Internal Combustion Engine | 20           | 40                    | 13.5%                       | 33.72%                      |
| [11]      | Gasification Fixed-bed Downdraft Gasifier Internal Combustion Engine | 20           | 40                    | 19.5%                       | 21.7%                       |
| [12]      | Micro Organic Rankine Cycle Wood Pellet Combustion | 2.3          | N/A                   | 7.3%                        | N/A                         |
| [13]      | Rankine Cycle Straw combustion Steam Engine | 11.6/5       | 34.2                  | 5.7%                        | 16.7%                       |
| [14]      | Organic Rankine Cycle Biomass Combustion | 1.66         | 37.16                 | 11.28%                      | 77.7%                       |
| [15]      | Micro Organic Rankine Cycle | 6            | 120                   | 3.79%                       | 80%                         |
### 2. Experimental setup

The ACA-MODES project aims to develop cross-system, grid-related operation management strategies, by integrating hybrid energy systems that provide heating, cooling and power through the usage of different renewable energies, linking prosumers in neighbourhoods and city districts with a power load of approximately 1 MW [21].

The Institut National de Sciences Appliquées of Strasbourg has 2 power units based on renewable energy, one of which is a micro-cogeneration unit, manufactured by the Austrian company “ÖkoFEN”. Its maximum thermal power output is of 18 kW\(_{th}\) and its maximum power output is that of 1 kW\(_{el}\). It weighs 294 kg and contains 69 l of working fluid (water). It runs on wooden pellets, being fitted with an internal 30 kg fuel reservoir and connected to an additional 120 kg fuel silo. A principal schema of a generic Stirling engine biomass cogeneration unit is shown in figure 2.

![Figure 2. A biomass cogeneration unit with Stirling engine.](image)

Its’ energetic class is that of A+. Its energy efficiency index is that of 125 and its seasonal thermal energy efficiency is that of 88 %. Its boiler temperature ranges from 25 to 85 °C. Its maximum operating pressure is 3 bar. It has been tested by manufacturers to withstand pressures up to 4.6 bar.

The ÖkoFEN Pellematic Condens E model is shown in figure 3, along with the free-piston Stirling engine which produces power, based on the combustion of biomass. Flue gasses from the combustion chamber provide the heat for the heat source of the engine, while water coming from the consumer lowers the temperature of the cold head, thus allowing both the cooling of the engine and the recovery of its waste heat.
Figure 3. The micro-cogeneration unit and the Stirling engine.

Figure 4 presents the data acquisition system. The orange arrows represent the thermal power, the blue arrows represent the electrical power and the green arrows the mass flow. The thermal power, the electrical power and the mass flow were recorded in a LabVIEW program through a National Instruments apparatus.

The electrical efficiency is between 6% and 7% and according to the manufacturer, its thermal efficiency can reach up to 97.7%, due to a performant flue gas heat recovery system.

3. Results and discussion

To allow a better mathematical modelling of the functioning of the micro-cogeneration unit, the flow of thermal agent was described mathematically with polynomial equations of the 3rd degree, using Microsoft Excel. Table 2 centralizes the input necessary for determining the 4 coefficients of the 3rd degree polynomial. The “INDEX” function finds a certain value in a given array, while “LINEST” applies the “least squares” method to calculate a line that fits the input data.

Table 2. Polynomial coefficients found using in Excel.

| Coefficient | Microsoft Excel function |
|-------------|--------------------------|
| $x^3$       | @INDEX(LINEST(known Y’s, known X’s^1,2,3),1) |
| $x^2$       | =INDEX(LINEST(known Y’s, known X’s^1,2,3),1,2) |
| $x^1$       | =INDEX(LINEST(known Y’s, known X’s^1,2,3),1,3) |
| $x^0$       | =INDEX(LINEST(known Y’s, known X’s^1,2,3),1,4) |
This meant splitting the flow of thermal agent into 3 stages: starting, constant and ending. An example of such a mathematized function is shown in figure 5.

![Mathematized function for thermal agent flow](image)

**Figure 5.** An example of the starting period of thermal agent flow.

The advantage of describing stages mathematically is that by using experimental data, correlations between temperature, flow and time can be made, allowing the user to simulate ON/OFF functioning regimes effectively and accurately, without consuming additional fuel.

Nine configurations have been tested. The powers were 10kW, 12kW, 14 kW. For each power, three different flow rates were tested F1, F2 and F3. The summary of the tests is given in table 3.

| Thermal power | Thermal agent flow |
|---------------|--------------------|
| 10kW          | 10kW F1            |
| 12kW          | 12kW F1            |
| 14kW          | 14kW F1            |

The start, constant and stop phases have been modelled for the 3 different thermal agent flows, with 3 power settings. A valve, meaning that a superior value would be empirically found for each configuration, as seen in figure 6, limited the thermal agent flow.

![Mathematized functions for 3 different flows](image)

**Figure 6.** Mathematized functions for 3 different flows.
This work is relevant in simulating ON-OFF functioning regimes that will be paired with model predictive controllers (MPC) that will anticipate the production of power locally but also in the smart grid linking several cities from France, Germany, and Switzerland.

In the case in which the thermal power produced by the micro-cogeneration unit is sufficient to match the local demand and the power produced exceeds the local demand, while the price to produce power is more costly than to import it from a smart grid partner, the micro-cogeneration unit will enter in the stop phase. If at any moment, the price of acquisitioned power exceeds the fuel price paid to produce both thermal power and power, the micro-cogeneration unit will start functioning again, entering the start phase.

4. Conclusions and perspectives
A micro-cogeneration biomass-based Stirling engine unit any has been tested in order to characterize its energetic performances. The OkoFEN Pellematic Condenser is a micro-cogeneration unit, which produces 1kW of power and 10 to 14kW of thermal power. The start, constant and stop phases have been modelled for the 3 different thermal agent flows, with 3 power settings. The stages of functioning have been described using polynomial equations in function of time, to accurately simulate ON-OFF regimes of functioning, in the context in which the micro-cogeneration unit would be part of a multi-country grid in accordance to the ACA-MODES Interreg program.

Further work is necessary in order to analyze the coupling the biomass micro-cogeneration unit with thermal storage and electrical storage. In particular, coupling the biomass micro-cogeneration with hybrid photovoltaic thermal collectors in two similar climate conditions will be studied [22].

Acknowledgements
The authors would like to thank Interreg V Rhin Supérieur ACA-MODES project for their support and funding of this research.

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