Experimental Characterization of a Micro-CHP unit based on a Stirling Engine, fueled by Wood Pellets

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Abstract

Micro-cogeneration systems (micro-CHP) are based on power systems where electricity is produced and the thermal energy is recovered to be used for heating needs, mainly for residential buildings. Theoretically, simultaneous production of heat and power offers better energetic, environmental and economic performances. Stirling engines are about to come onto the market as a potential technology for micro-cogeneration systems. Due to their external combustion process, they can operate with a large variety of fuels, especially with renewable fuels such as wood pellets.

Actually, due to the emergence of this technology and to still limited feedback, real and optimal performances of such heating and power systems are not clearly established. In order to evaluate the performance of an existing micro-CHP unit, laboratory tests have been conducted at Center for Energy and Processes in MINES ParisTech. A “Sunmachine Pellet®” unit, operating with wood pellets, has been tested. According to the manufacturer, this unit has an electrical power output of 3 kW_{el} and a thermal power output of 10.5 kW_{th}. The electric power has been evacuated through the grid whereas the heat has been evacuated by a heat exchanger through a closed water loop.

Experimental investigations have been performed in order to evaluate the performance of the Stirling cogeneration unit in steady state and transient phases. These experimental tests have identified three different transient operating phases (cold start, hot start and shut down phases) where each of these phases has been described in detail. For steady state operation, the electrical and thermal efficiencies have been evaluated. In addition, several technical problems have been revealed during the experiments, which are discussed in order to propose solutions before the spread out of these systems in dwellings.

The results show that the performance of the tested micro-cogeneration unit was not as announced by the manufacturer. Several explanations are discussed and several solutions are offered to improve its performance and its technical feasibility. The detailed characterization of the micro-CHP unit has been used to develop a mathematical model of behaviour of the micro-CHP unit in order to be used in building simulation tools associated to a model of heat distribution. These dynamic simulation tools could be used in order to better design the micro-cogeneration unit according to the building energetic needs.

Nomenclature

a = Semi-major axis of the hyperbola (K)
b = Semi-minor axis of the hyperbola (s)
C_p = specific heat capacity ($J.kg^{-1}.K^{-1}$)
LHV = Low Heating Value ($J.kg^{-1}$)
$\dot{m}$ = mass flow ($kg.s^{-1}$)
P = power (W)
T = temperature (°C)
t = time (s)

$_{cc}$ = combustion chamber
$_{el}$ = electrical
$_{in}$ = inlet
$_{out}$ = outlet
$_{pellets}$ = wood pellets
$_{ref}$ = reference
$_{th}$ = themal
$_{w}$ = water

1. Introduction

Micro-cogenerations systems are small combined heat and power systems (micro-CHP) that can generate thermal and electrical energy in an individual dwelling on site. These systems present many advantages for residential applications where they could contribute to the reduction of the primary energy consumption, the operating cost and the environmental impacts.

Different technologies of micro-CHP systems have been under development since the last decade such as Stirling engines [1-3], Rankine cycle engines [4] and fuel cells [5]. Nowadays, among these technologies, Stirling engines seem to present the best maturity to be commercialized in the near future. Indeed, Stirling-engined micro-CHPs offer many advantages for a use in buildings, like low noise emission level and high heat recovery efficiency [2]. Moreover, as an external combustion engine, it can use various renewable energies, such as solar, bio-fuel or wood [6].

A literature review reveals the need of a complete dynamic model describing in detail the operating phases of each type of micro-CHP because their overall efficiency depends on these phases [7]. These kinds of models would be useful to simulate the operation of building-coupled, micro-CHP units and to the sizing of the different parts of the heating system. Regarding Stirling-engined micro-CHPs, the available models are either too complicated or strictly focused on the engine [8-11] or too little detailed for that purpose (no description of the different operation phases) [12]. In this paper, a complete characterization of both steady state and transient behaviours of a micro-CHP unit has been carried out using a test bench experiment, in order to develop a simplified parametric model, more schematic and user-friendly than the aforementioned models.

2. Reasoning and method

The micro-cogeneration unit tested is a “Sunmachine Pellet” (Fig. 1) operating on wood pellets. This machine has been selected since it is the only micro-cogeneration system based on a Stirling engine and operating with renewable energy already available and commercialized. The different technical specifications given by the manufacturer are shown in Table 1. The “Sunmachine Pellet” unit incorporates a 1-cylindre Stirling engine in alpha-configuration providing a swept volume of 520 cm^3. The working gas is nitrogen. According to the operating conditions, the working gas pressure may vary from 33 to 36 bar and the rotational speed of the Stirling engine may vary from 500 to 1000 rpm. A condensing heat exchanger for the exhaust gas is included; thus, exhaust gas temperature stays well below 100 °C and compares to conventional condensing boilers.

	Manufacturer
Electric power output	~ 1.5 – 3 kW
Heat rate output	~ 4.5 – 10.5 kW
Electric efficiency (LHV)	~ 20 – 25%
Global efficiency (LHV)	90%
Maximal outlet temperature	70°C
Optimal inlet temperature	< 30°C
Weight	~ 350 kg
Dimensions (width, lenght, height)	800/1200/1600 mm

Table 1 – Technical specification of the “Sunmachine Pellet” unit given by the manufacturer

Figure 1 - The Sunmachine Pellet micro-CHP unit

To measure the electrical and thermal efficiency of the micro-CHP unit in steady and transient operation phases, a test bench has been made in order to reproduce the real operating conditions of the system in a residential building. First, the electric power produced by the system and the thermal power recovered for heating have been measured in steady state and in transient phases. Then, the combustion flow has been evaluated in order to compute the efficiencies of the system in operation. Finally, a dynamic model – not described in this paper – has been carried out.

3. Description of the experimental device

The test bench comprises two water circuits and is connected to the public electric grid so that the various energy and mass flows can be measured (Fig. 2). A closed water circuit simulates the domestic hot water production circuit – including a storage tank. It includes a plate heat exchanger connected to a fresh water open circuit used for heat dissipation, electric heaters used for temperature control and a volumetric flow meter measuring the volumetric flow rate (VFR) of water.

The temperature of water at the inlet and outlet of the micro-CHP unit as well as the fluid flow in the heating circuit can be recorded, which enables the calculation of the heat recovered by the water (1).

$$P_{th} = \dot{m}_w \cdot C_{p_w} \cdot \left(T_{w,out} - T_{w,in}\right) \qquad (1)$$

The electric power output is directly measured and recorded by a wattmeter. The electric consumption of the different auxiliaries of the micro-CHP (pumps, fans, endless screw motor, inverter, monitoring and control panel) is measured separately. The circuit of the exhaust gases comprises a temperature sensor, a volumetric flow meter and a gas analyzer to measure the temperature, the VFR and the composition of the exhaust gases.

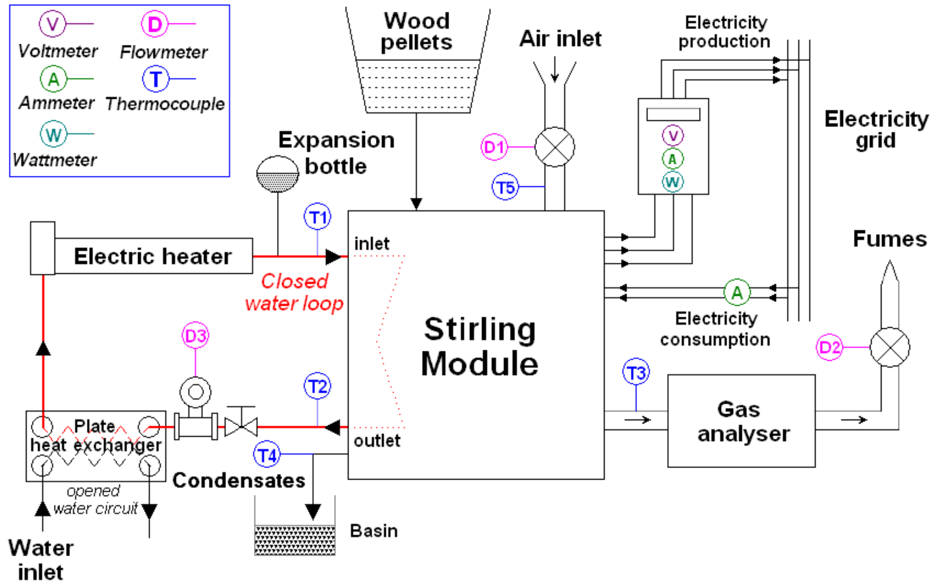

Figure 2 Layout of the test bench

4. Results

First, the performance of the micro-CHP has been characterized in steady state operation over a wide range of inlet water temperatures. Two major key parameters of the steady state performance have been identified: the cold water temperature at the inlet of the CHP system and the heating load of the system. However, the CHP system is designed to operate only at full load. Therefore, a partial load is not possible and the only remaining key parameter is the inlet water temperature.

During the steady state operation, the instantaneous electric and thermal powers have been measured according to various inlet water temperatures (Fig. 3).

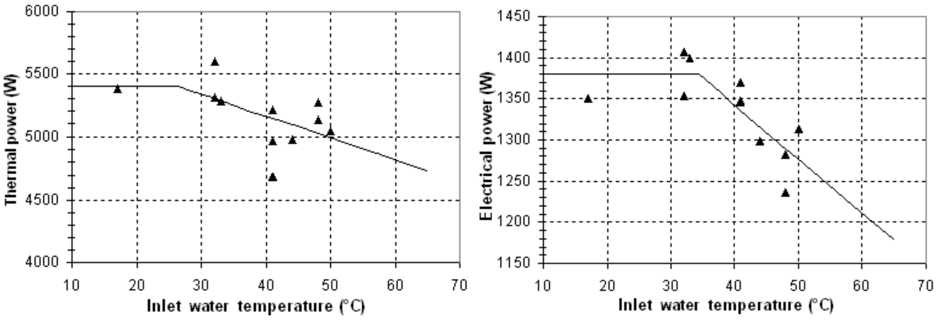

Figure 3 Thermal and electrical performance of the micro-CHP unit

The dispersion of the data seems to be due to the thermal mass of the gasification unit, to the combustion instability and to the heat recovery on exhaust gases. Nevertheless, the evolution of the powers according to the inlet temperature seems to be linear, with a maximal value. Two laws, corresponding to the average tendency of the performance, have been deduced from the data as piecewise linear functions (Eq. 2 and 3).

$$P_{el}\left(T_{w,in}\right) = \min(1380,\ 1600 - 6.5 \text{ x } T_{w,in}) \qquad 2$$

$$P_{th}\left(T_{w,in}\right) = \min(5400,\ 5850 - 17 \text{ x } T_{w,in}) \qquad 3$$

In practice, the inlet water comes from a hot water tank and most of the time its temperature is superior to 30 °C. These correlations show that the performance of the micro-CHP unit decreases while the inlet water temperature increases. Consequently, when coupled to a thermal storage tank, the performance of the micro-CHP unit decreases when the temperature in the hot water storage tank increases.

Then, the dynamical behaviours of both start-up and shutdown processes have been characterized. The temperature in the combustion chamber (T_{CC}) is used by the internal controller of the micro-CHP unit to trigger the activation or the deactivation of several auxiliaries. This temperature has been recorded during the transient evolutions in order to indentify the different phases of each transient process (Fig. 4).

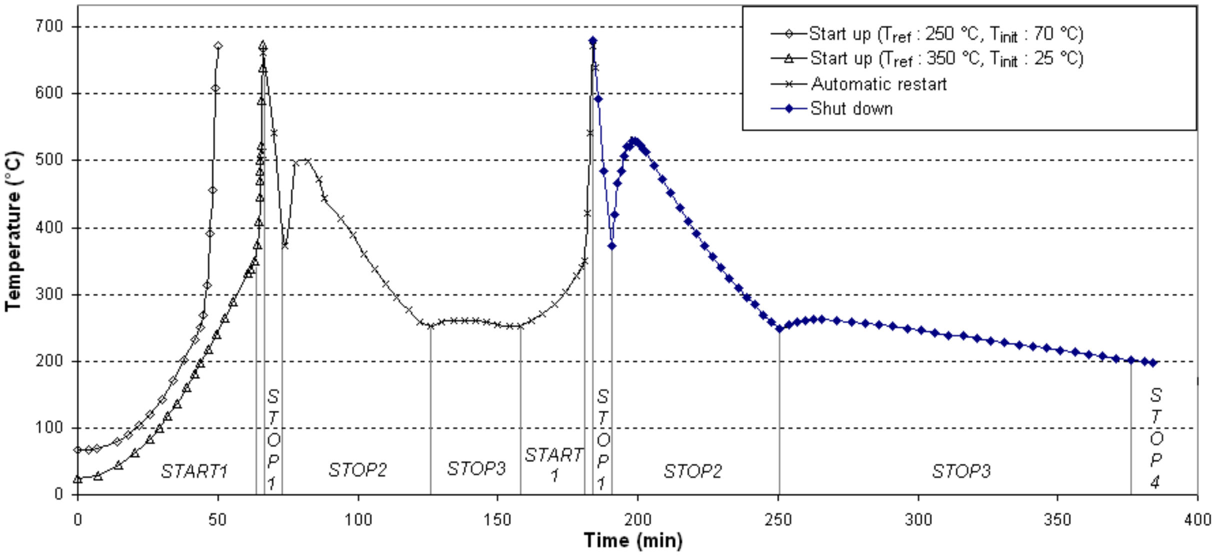

Figure 4 Temperature measured in the combustion chamber for the transient processes

The start-up process begins when the temperature measured in the storage tank (or simulated one) is 10 °C below the control temperature. It is divided into two different phases. The first one (START1) corresponds to the electric heating of the core of the combustion chamber. During this phase, T_{CC} varies following a hyperbolic trend (Eq. 4), where a = 923 K and b = 4120 s (68.7 min). The triggering of the second phase occurs when T_{CC} reaches a reference temperature set by the operator (T_{ref} between 250 °C and 350 °C). Thus, the duration of START1, t_{start}, depends on both the initial and the reference temperatures (Eq. 5); for a cold start-up, it may vary from 43 min to 63.3 min (see two first series on Fig. 4).

$$T_{cc}(t)=\sqrt{1+\frac{t^2}{b^2}}\cdot a-\left(a-T_{cc}\big|_{t=0}\right) \tag{4}$$

$$t_{start}=b\cdot\sqrt{\frac{\left(T_{ref}+a-T_{cc}\big|_{t=0}\right)^2}{a^2}-1} \tag{5}$$

Then, the combustion process begins (START2) until T_{CC} reaches 650 °C, which occurs after 3 to 6 min. This phase ends when the Stirling engine starts. During the whole start-up phase, the generator produces no electricity (the Stirling engine is shut down), but the power consumption of the auxiliaries is 2354 W during START1 and 220 W during START2.

The shutdown process is divided into four different phases. At first, the injection of the wood pellets is stopped, but the Stirling engine keeps running, the thermal power remains constant and the electricity power decreases with time (STOP1). This phase begins when the outlet water temperature is over a control temperature (here 80 °C). The electricity produced during this phase is 85 Wh. After about 6 min, when T_{CC} is inferior to 400 °C, the Stirling engine stops (STOP2). No more electricity is produced, but part of the heat stored by the thermal mass of the system is recovered from the engine and the exhaust gases. The thermal power output decreases at -16 400 $W.h^{-1}$ during the first 13 min and -1100 $W.h^{-1}$ until it reaches 0 W. The electric energy consumed by the auxiliaries in this phase is 411 Wh. After 60 min, when T_{CC} decreases below 250 °C, the exhaust gas fan is stopped (STOP3). The water circuit still evacuates heat. This phase lasts about 133 min and the electricity consumed by the auxiliaries during this phase is 557 Wh. When T_{CC} reaches 200 °C, all water circulation pumps are stopped (STOP4). Thus the combustion chamber is cooled by conduction and natural convection. The temperature decreasing law is exponential with a time constant of 6.16 h. The electric consumption (22 W) corresponds to the consumption of the inverter. The annual consumption of the inverter is about 192 kWh, which is relatively high since it corresponds to the production of 5.7 days operation at full load.

In practice, during the shutdown process, if the temperature measured in the storage tank is 10 °C lower than the control temperature, it can restart a start-up process (hot start-up). Actually this restart process can only occur when T_{CC} is below 400 °C. Therefore, the hot start-up cannot occur less than 36 min after the shutdown process beginning. In this particular case, it will take about 23 min for the temperature of the combustion chamber to reach the 650 °C necessary for the starting of the Stirling engine. The minimum duration between the beginning of the shutdown process and the restart of the Stirling engine is 59 min. It might take more time if the beginning of the hot start-up occurs while T_{CC} is already below 400 °C. Such a hot start-up may occur several times during cold periods when the heating load is high.

To calculate the efficiency of the micro-cogeneration unit, the heating power of the consumed pellets must be evaluated. Two different methods have been used for that purpose.

The first one consists in running the micro-CHP unit for a relatively long period of time at a steady state operation regime. The mass of the consumed pellets is the difference of the masses of the wood pellets measured in the storage tank between the beginning and the end of this period. The heat released by the combustion of the wood pellets is calculated assuming a complete combustion and considering the lower heating value (LHV) of the wood pellets. The average heating power at the burner $\overline{P_{pellets}}$ is given by Eq. 6

$$\overline{P_{pellets}} = \frac{m_{pellets} \cdot LHV}{\Delta t} \qquad 6$$

The measured value was 13.91 kg for 7.1 h of continuous operation, corresponding to a 0.54 g.s^{-1} average mass flow rate of burnt pellets. Considering a LHV of 18 MJ.kg^{-1} for the wood pellets, the average heating power is about 9.72 kW. Therefore, the electric and thermal efficiencies calculated at best performance (inlet water temperature: 30°C) are respectively 14.2% and 55.6%.

The second method consists in measuring the exhaust gas volumetric flow rate and its composition. The instantaneous mass flow rate of burnt pellets, calculated from the combustion equations of the wood pellets [13-14], is found to be 0.45 g.s^{-1}. From this value, the instantaneous heating power is about 8.1 kW and the best electric and thermal efficiencies are respectively 17.0% and 66.7%.

The difference between these results lies in the incomplete combustion of wood, in the uncertainty of the measurements of the mass of wood pellets using the first method, and in the continuous variation of the combustion around a mean value.

5. Discussion on technical issues

The test results of the micro-CHP unit show slightly inferior performance compared to the performance announced by the manufacturer (Table 2). First, the maximal electrical and thermal power measured are lower than the manufacturer data, which is mainly due to the fact that the tested CHP unit was a pre-series version with restrained power; this may also have influenced the various efficiencies.

Table 2 Performance of the tested micro-CHP unit compared to the specifications given by the manufacturer

	Tested micro-CHP	Manufacturer
Electric power output	≤ 1.38 kW	~ 1.5 – 3 kW
Heat rate output	≤ 5.4 kW	~ 4.5 – 10.5 kW
Electric efficiency (LHV)	15.6% ± 1.5%	~ 20 – 25%
Overall efficiency (LHV)	71.3% ± 7.2%	90%

The overall efficiency is also below what was announced. On the one hand, the heat recovery seems very efficient since the measured temperature of the exhaust flue gases has always been below 100°C, but on the other hand, a lot of uncertainties lie in the evaluation of the wood pellets consumption. The efficiency of the combustion remains uncertain and could differ from what has been calculated. This is mainly due to the difficulty in precisely measuring the instantaneous amount of wood pellets burned in the combustion chamber, even in steady state operation.

Regarding the transient phases – which have been analysed in detail – due to the wood pellets use, a special control strategy seems to ensure a good combustion quality. This is done first by heating the combustion chamber to a temperature higher than 250°C before injecting the wood pellets to ensure a good gasification of the wood. Second, after each stop of the unit, a high air flow rate is maintained inside the combustion chamber to evacuate all the ashes before any restart of the unit. These two processes have a major impact on the performance of the unit during the transient phases, essentially because they consume a lot of electricity. The duration of the transient unproductive phases in the whole operation time of the micro-CHP unit conditions the overall efficiency of the system during a normal heating period, alternating starts and stops.

Moreover, several defects have been noticed during the test phases which have a negative impact on the performance of the system. The combustion process presents some defective points as incomplete combustion process due to the non homogeneity combustion of the wood pellets which tends to fill the firebox grid with ashes inside the combustion chamber. Many technical interventions have been performed to clean the firebox from ashes where in real operation should not be as frequent.

In addition, the water pump control is designed to work until the temperature of the combustion chamber is below 250°C which implies to produce water at low temperature (<50°C) where in real operating condition, this continuous operation of the water pump will lead to cool the water tank, therefore, it is absolutely essential to adjust the control strategy of the water pump to better manage the thermal energy inside the storage water tank.

Conclusion

In this paper, a test bench has been carried out to characterize a micro-cogeneration unit based on a Stirling engine and fuelled by wood pellets. The results show that the electrical and thermal efficiency are lower than the performance announced by the manufacturer. The average electrical and overall efficiencies of the unit are 14% and 70% respectively (instantaneous efficiencies can be higher).

The micro-CHP unit used in the test bench was not a commercial version but a pilot production one. Several defects have been noticed on this unit that should be corrected for the commercial version, like the unstable control strategy for the internal water pump and the repeated filling of the firebox grid with ashes discussed below.

The acquired data from the test bench have been used to develop a dynamic model of heating system including a wood pellet micro-CHP unit [15]. This model has been implemented into a multi-zone building dynamic simulation software, COMFIE, developed at the CEP. This tool can be used to better dimension and design a micro-cogeneration system to optimize the overall performance of the heating system over a one year period, according on the building thermal loads.

This study could be extended by the comparison of experimental results to data taken from an in-situ experiment and by the study by the optimal control of the different elements of the heating system. Several other types of micro-CHP units could also be studied, especially for energetic and environmental performance comparison.

Acknowledgements

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