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# On-off cyclic testing of a micro-cogeneration Stirling unit

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## Abstract

Stirling engines are a promising candidate for micro-cogeneration in residential and small-scale tertiary applications. Due to the variability of energy demand profiles and electricity tariffs, real applications often require to operate the cogeneration unit with multiple daily starts and stops, especially during summer and intermediate seasons. This work focuses on the experimental analysis of a commercial 1 $kW_{el}$ Stirling unit, burning natural gas and generating 8 $kW_{th}$ of useful heat through hot water and up to 12 $kW_{th}$ with an auxiliary burner, when subjected to cyclic on-off operation. The scope is collecting useful data about energy balances and emissions during on-off transients, which can be later used to optimize the management of the cogeneration unit when coupled with real users. Different cyclic tests are experimented (with intermediate stops and operation of either one or two burners), keeping the temperature of the cogeneration water at the unit inlet at 50°C and its mass flow rate at the nominal value of 0.194 kg/s. The Stirling unit has shown an electrical efficiency of 8.9%, based on Lower Heating Value (LHV), in the most favorable cyclic test and 8.2% in the worst case, while thermal efficiency ranges between 91.0 and 92.6%. For comparison, the steady state electrical efficiency is 10.8% (LHV) while the thermal is 90.1% with only one burner running in full cogeneration mode. Steady state efficiencies become 7.2% and 92.0% (LHV), respectively, with the auxiliary burner running. The significant reduction of average electrical efficiency suggests the necessity to limit the frequency of starts and stops in real operation. Emissions show modest peaks in $NO_x$ and CO, which do not compromise the environmental impact, confirming the low emission combustion features of the Stirling unit.

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*Keywords:* Stirling engine; on-off cycling; transient analysis; experimental testing; micro-cogeneration; micro-CHP.

## 1. Introduction

Micro-cogeneration Stirling units are considered a promising candidate for residential and small-scale commercial applications because of high total efficiencies, favorable ratios of thermal to electrical power and lower emissions than internal combustion engines. However, oppositely to the case of large industrial applications where both thermal and electric loads are relatively constant throughout the year, small-scale residential and commercial applications are characterized by large fluctuations of electricity demand as

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well as by large changes of heating and cooling demands, strictly related to climatic conditions. Moreover, electricity tariffs typically feature daily and weekly variations, while the possibility to sell electricity to the grid may result economically not attractive or can be subjected to constraints and limitations in certain countries. From this point of view, different studies show that the optimized management of a micro-combined heat and power (mCHP) unit, optionally equipped with thermal storage, requires switching on and off the unit multiple times during the day and the week [1,2].

This work focuses on the experimental analysis of a natural gas-fired commercial Striling unit under on-off cyclic operations. The mCHP is capable of generating 8 kW of hot water, which can be increased up to about 12 kW by a second auxiliary burner, and 1 kW of electricity. As part of an ongoing study [3], this campaign has been carried out at the Laboratory of Micro-Cogeneration of Politecnico di Milano [4]. The measurements obtained with this work will be used later to model mathematically the unit performances taking into account the effects of startup and shutdown transients on electrical and thermal efficiencies. This will allow tuning existing optimization tools [5] and to manage correctly the mCHP unit, estimating real energy, economic and environmental balances when connected to real loads.

## 2. Experimental campaign

The experimental setup (Figure 1) provides measurements taken both externally and internally to the engine. Regarding the feed gases, which are natural gas from the national grid and ambient air, the setup allows acquiring the inlet temperature and pressure. For the sole natural gas, also mass flow rate and molar composition, the latter by way of a gas chromatograph, are collected. For ambient air, also relative humidity. The temperature of air required for the combustion is controlled by a heating, ventilating, and air conditioning system (set point of 25°C). Regarding the flue gas, the measures include temperature, emissions (CO, NO, $NO_2$, $SO_2$) with an electrochemical analyzer, and molar composition with the same gas chromatograph adopted for the natural gas. For the water loop, temperatures, pressure, differential pressure and mass flow rate are acquired. In particular, the inlet flow rate of the water loop is managed by way of a variable-speed pump (set point of 0.194 kg/s within a typical range of 0.14-0.25 kg/s); similarly, the inlet temperature is managed by a control valves system (set point of 50°C within a typical range of 30-70°C). The other external instruments are an electric power analyzer to measure the electrical production and a load cell to weight the condensate water from the flue gas.

Thermocouples are placed on the engine walls to evaluate the thermal losses. Additional internal measurements on the air, flue gas and water loop are possible for the purpose of a detailed engine analysis [6], but they are not of particular interest for this work. The recorded data are filtered statistically and used to evaluate mass and energy balances as well as electrical and thermal efficiencies.

On-off cycle tests have been developed with the following specifications:

- tests with only one burner, in which the system is brought to full electric power output (label “1” indicates the first burner is running), then stopped (label “0” indicates no burners are running), then taken again to full power and stopped repeatedly according to the sequence 1-0-1-0-…-1;
- tests with the additional ignition of the auxiliary burner, defined by the sequence 1-2-1-2-…-1 or even 1-2-0-1-2-0-…-1 (label “2” indicates full thermal power output with two burners running).

Each test starts from an initial steady state condition, verified observing the variation of the engine electrical power generation, which must remain within ±10 W band, and the water loop inlet and outlet temperatures, which must remain within ±0.5°C of the set point. In all cases, the duration between two steps of the sequence, which is between a burner startup and shutdown, is set so that the steady state conditions are approached at the end of that step. Step durations turn out to be 10, 20 or 30 minutes depending on the specific cycling test. All the test are closed with the unit running with one burner at steady state. During any sequence, measures are acquired and recorded every 2 seconds.

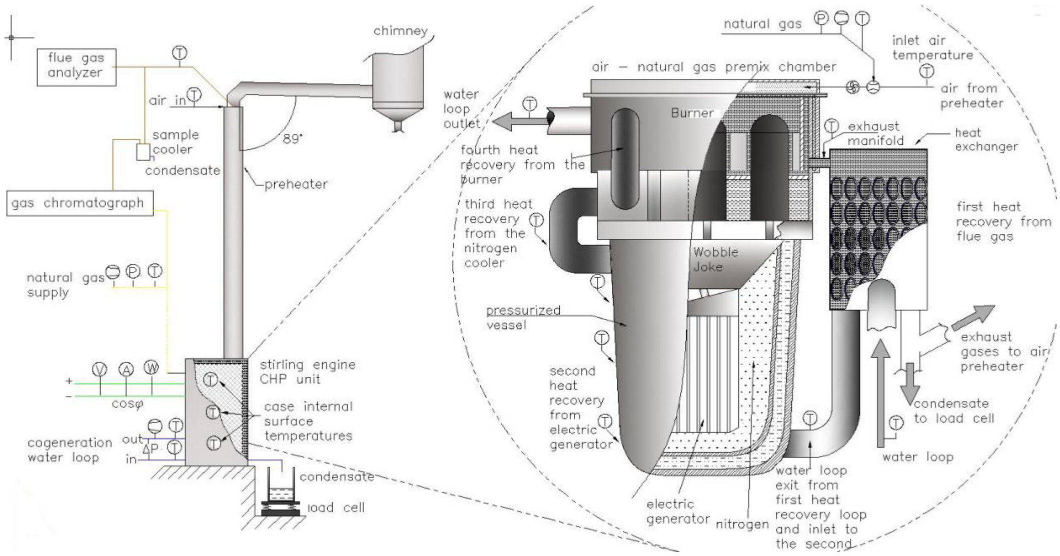

Figure 1. Schematic of the experimental setup showing the measurements acquired externally to the engine.

## 3. Results and conclusions

For sake of comparison, Table 1 reports the steady-state performances of the Stirling unit in “clean and new” conditions. In contrast, Figures 2 to 4 show the mCHP unit performances during on-off cycling in terms of natural gas flow rate [liter/min at normal conditions], electric power output [W] and temperatures of the cogeneration water return and delivery as well as temperature of the exhaust [°C]. System performances integrated over the test durations are given Table 2. The results show a significant decrease of the unit average efficiency when integrated on the entire on-off period. The 1-0-1-0-…1 cycle features an 8.9% average LHV electrical efficiency while, for comparison, the steady-state conditions the corresponding electrical efficiency is 10.8%. Similar conclusions can be drawn from the analysis of the unit emissions, which are shown in Figure 5. Each startup yields peaks in $NO_x$ and, especially, in CO emissions, which however remains below safe maximum values, about 100 ppm for CO and 20 ppm for $NO_x$, confirming the very good environmental behavior and low combustion emissions of Stirling units.

The results from this campaign suggest clearly to limit the frequency of startups during real operations, excluding hence operating strategies that control the units with repeatedly on-off procedures. For instance, a mid-season day application of the mCHP unit featuring 3-4 startup-shutdown cycles of 1-0-1-0-…-1 type (assumed to last 45 minutes each and distributed over 8 hours of total operation) would result in an equivalent electric efficiency reduction from a nominal 10.8% to around 10.1% (LHV), i.e. a 6.6% reduction in relative terms. On the other hand, a winter day application with only 2 startup-shutdown cycles of the same type distributed over 12 hours of total operation would imply an equivalent electric efficiency of around 10.5% (LHV), i.e. a much smaller penalty.

Table 1: micro-CHP performances at steady state (water inlet temperature 50°C). LHV and HHV stand for lower/higher heat value.

| Steady state tests | Electrical efficiency (LHV) | Electrical efficiency (HHV) | Thermal efficiency (LHV) | Thermal efficiency (HHV) |
|---|---|---|---|---|
| 1 burner (8 $kW_{th}$) | 10.8% | 9.7% | 90.1% | 81.4% |
| 2 burners (12 $kW_{th}$) | 7.2% | 6.5% | 92.0% | 83.1% |

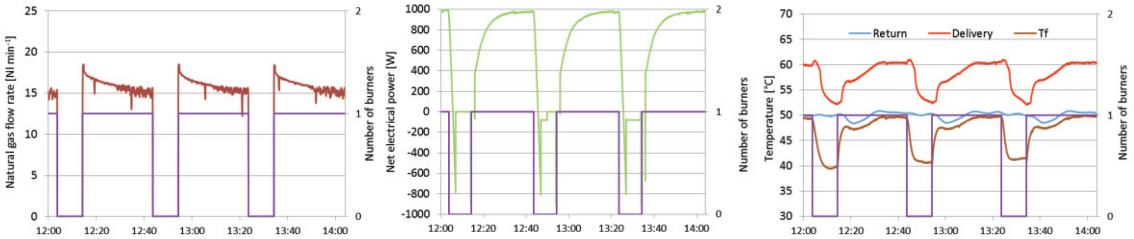

Figure 2. Cyclic test 1-0-1-0-…-1 (violet lines show the burners): natural gas flow rate [Nl/min], net electric power [W] (positive is produced, negative consumed), and temperatures [°C] of water return (blue line), water delivery (red line) and exhaust (brown line).

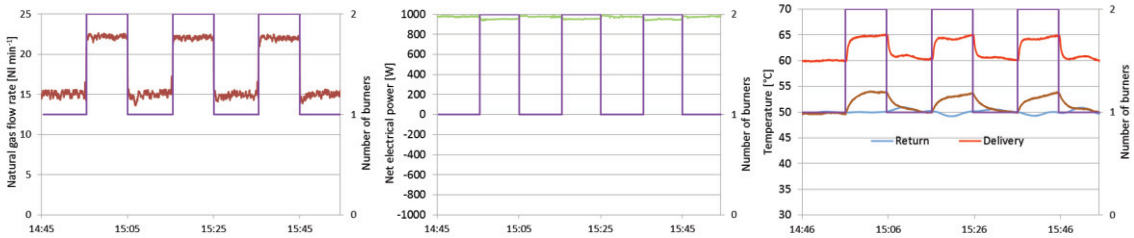

Figure 3. Cyclic test 1-2-1-2-…-1 (violet lines show the burners): natural gas flow rate [Nl/min], net electric power [W] (positive is produced, negative consumed), and temperatures [°C] of water return (blue line), water delivery (red line) and exhaust (brown line).

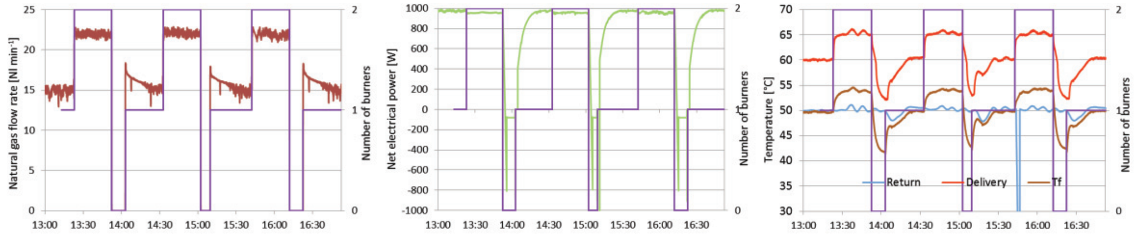

Figure 4. Cyclic test 1-2-0-1-2-0…-1 (violet lines show the burners): natural gas flow rate [Nl/min], net electric power [W] (positive produced, negative consumed), and temperatures [°C] of water return (blue line), water delivery (red line) and exhaust (brown line).

Table 2: Summary of micro-cogeneration performance integrated over the test duration under cyclic operation (water inlet temperature set at 50°C and mass flow rate at the nominal 0.194 kg/s). LHV and HHV stand for lower/higher heat value.

| On-off cyclic tests | Electrical efficiency (LHV) | Electrical efficiency (HHV) | Thermal efficiency (LHV) | Thermal efficiency (HHV) |
|---|---|---|---|---|
| 1-0-1-0-…-1 | 8.9% | 8.0% | 91.0% | 82.2% |
| 1-2-1-2-…-1 | 8.9% | 8.1% | 92.6% | 83.6% |
| 1-2-0-1-2-0-…-1 | 8.2% | 7.4% | 92.6% | 83.6% |

Future activities will include a more comprehensive mapping of the engine performances at steady-state and on-off operation under diverse conditions of the working fluid [6], as well as the discussion of the optimal operation strategies with the aid of an in-house simulation code. More specifically, the numerical simulation will model the application of the Stirling mCHP unit, equipped with a thermal storage, to a typical building characterized by hourly loads of heating and electricity over an entire year. The unit management strategy will be optimized by way of a MILP optimization code [5,7], highlighting the results that are obtained, alternatively, neglecting the effects of on-off transients or taking them into account. Results will be expressed in terms of energy, economic and environmental balances. This analysis will allow to further assess the importance of the optimization of the on-off cyclic strategy.

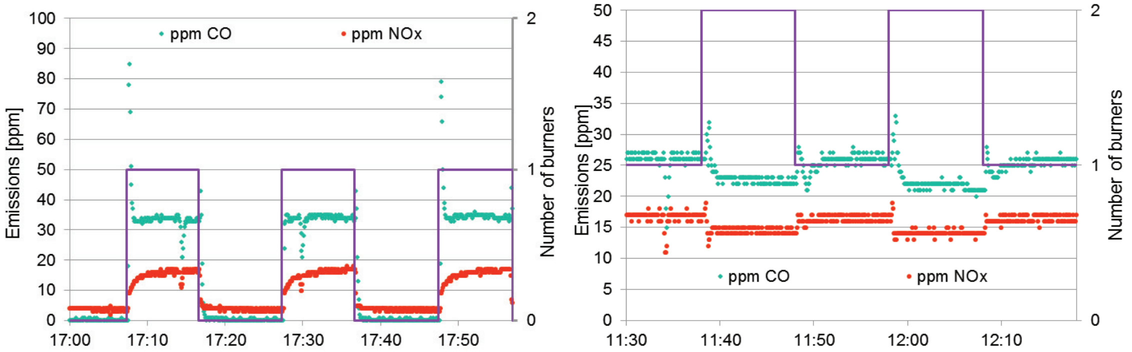

Figure 5. Cyclic test 1-0-1-0-…-1 and 1-2-0-1-2-0…-1 (violet lines show the burners): emissions of CO and NO$_X$ (referred to 6% O$_2$ volume dry conditions).

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