SMARTCATs Final Report

Testing and numerical assessing of MILD-based Stirling engine fed with LCV biogas.

1. Details of the STSM

Applicant Details
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Host Institute
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Period of stay
08/02/2016 – 05/03/2016.

2. Objective

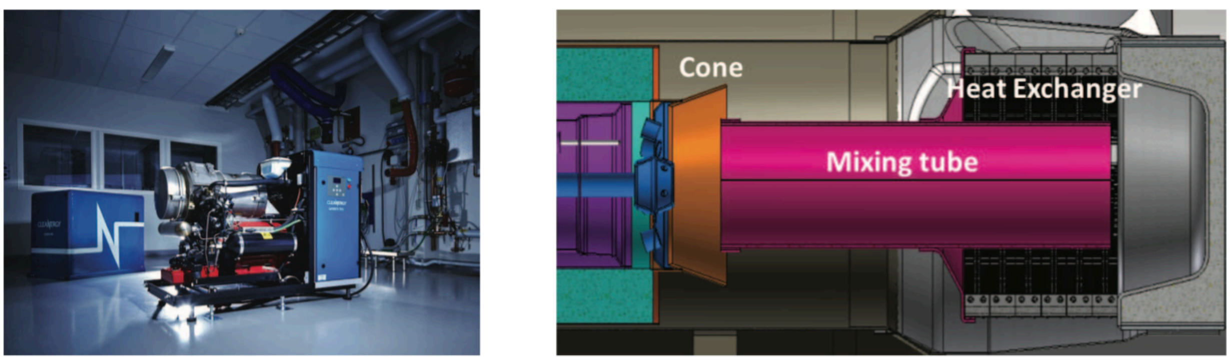
The STSM is part of my PhD project, which has two main objectives: the validation of numerical models for MILD combustion regime and the development and optimization of the combustion chamber of a micro gas turbine, operating in MILD combustion regime.
The growing trend today is that combustors should be fuel flexible. These different fuels are typically of Low Caloric Value (LCV), such as biofuels, syngas and landfill mixtures.
The industrial company Cleanergy provides energy solutions based on the Stirling engine. Cleanergy currently focuses on renewable, gaseous mixtures that are relatively difficult to burn since the energy content is small compared to natural gas. One such gas is Landfill gas. In a landfill gas extraction, the methane content decays with time.
Cleanergy Stirling engine employs a MILD combustion chamber. The collaboration with Cleanergy has been a major contribution to the first objective of my PhD, since it gave me the opportunity of improving my knowledge about experimental tests and it would also provide useful experimental data to further validate the numerical models used to describe MILD combustion.

3. Timeline and activities

The stay at Cleanergy started on the 8th February and finished the 5th March.
During those 4 weeks, experimental tests were performed 4 days per week at Chalmers University of Technology, in Gothenburg.
The main objective of those tests is to assess the effect of the gas composition and the pressure of the engine on the emissions (mainly NO_x, CO and CO_2) of the engine itself.
Several gas compositions resembling different landfill gases available in Sweden were analyzed.
During the last week I also visited Cleanergy headquarter in Åmål, where they perform the assembling of the engines and the end-of-line testing.

4. The experimental facility

As mentioned before, the experimental campaign has been carried on at Chalmers University of Technology in Gothenburg.
The object of the tests is an alpha type Stirling engine equipped with a combustion chamber operating in MILD combustion regime. The burner it is called GasBox and it is shown in Figure 1.



(a) GasBox inside view. (b) Centerline plane of the combustor.

Figure 1: Cleanergy GasBox and combustor.

The engine power output is 7.2 kW electric power and 16 kW heat power. The GasBox burner consists of a main burner and a heat exchanger. The gas is injected from one location and there are 6 main injection holes at the entrance of the burner for the air, which is preheated above the auto-ignition temperature of the fuel. The air and the fuel are also diluted by exhaust gas recirculation.
The controlling parameter for the combustor is the value of the air-fuel equivalence ratio (λ).
λ is kept constant at 1.3, by opening or closing the throttle for the air inlet. For stability reasons, the throttle cannot be open completely. Its opening percentage has to be kept between 10 % and 30 %.
The effect of several parameters can be investigated during the experimental campaigns. Those parameters are:

- Fuel composition.

- Engine pressure.
- Engine speed.
- Duration of the test.

Only the first two parameters were investigated during this experimental campaign. The engine speed has been kept constant at 1500 rpm.
As far as the engine pressure is concerned, 3 different set points were considered: 75, 100 and 125 bar.
The main variation concerns the fuel composition. Seven different mixtures were investigated. The composition of each of them is listed in Table 1.
The mixtures are obtained blending pure gases. The control system is shown in Figure 2.

Table 1: Fuel mixtures composition

	CH_4 [%]	CO_2 [%]	O_2 [%]	N_2 [%]
1	24.2	21.6	2.0	52.2
2	50.05	45.0	1.05	3.9
3	39.57	38.66	2.0	19.5
4	26.78	32.15	2.0	39.0
5	52.63	47.32	0	0
6	60.06	39.94	0	0
7	43.53	35.15	2.0	19.5

Figure 2: Fuel mixture control system.

The fuel flow is regulated with a pressure regulator whose loading mechanism is a spring. The stiffness of the spring can also be changed to achieve different flows and compositions.
The engine starts in flame mode with pure methane. Once that the chamber is warmed up, it switches to MILD mode. Once in MILD mode it is possible to change the fuel composition.
To achieve the different fuel compositions, it is necessary to slowly decrease the methane and at the same time increase the percentage of the other component, one at the time. It can take up to one hour to reach the desired composition.
Due to some logistic issues encountered during the testing, not all the possible combinations pressure-gas composition were studied. Table 2 shows the combinations performed.

Table 2: Engine Pressure-Gas composition combinations

	75 bar	100 bar	125 bar
1			
2	✓	✓	✓
3	✓		
4			
5	✓	✓	✓
6	✓		✓
7	✓	✓	✓

For each experimental run, the emissions of the engines are measured with a Horiba Mexa 7000 tester. It can measure CO, CO_2, NO and THC.

5. Results

The engine performs well at all the conditions analyzed, despite the high variation on the parameters. This is particularly true for the gas composition. Figure 3 shows the lower heating value for all the seven compositions tried.

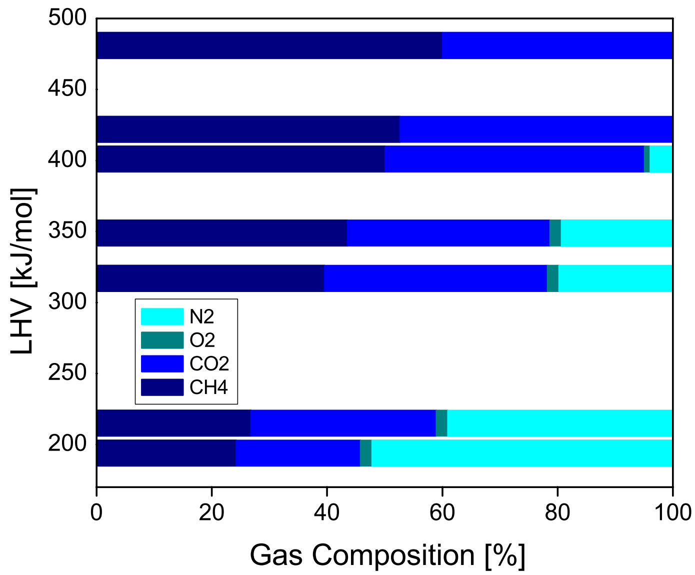


Figure 3: Lower heating value for the different gas mixtures.

It can be noticed that the lower heating value changes over a wide range of values, going from 193 kJ/mol to 481 kJ/mol. All the values are well below the lower heating value of the pure methane (801 kJ/mol).

As mentioned before, experimental tests were run at three different values of the engine pressure. Figures 4, 5 and 6 show the values of emissions at 75, 100 and 125 bars respectively.

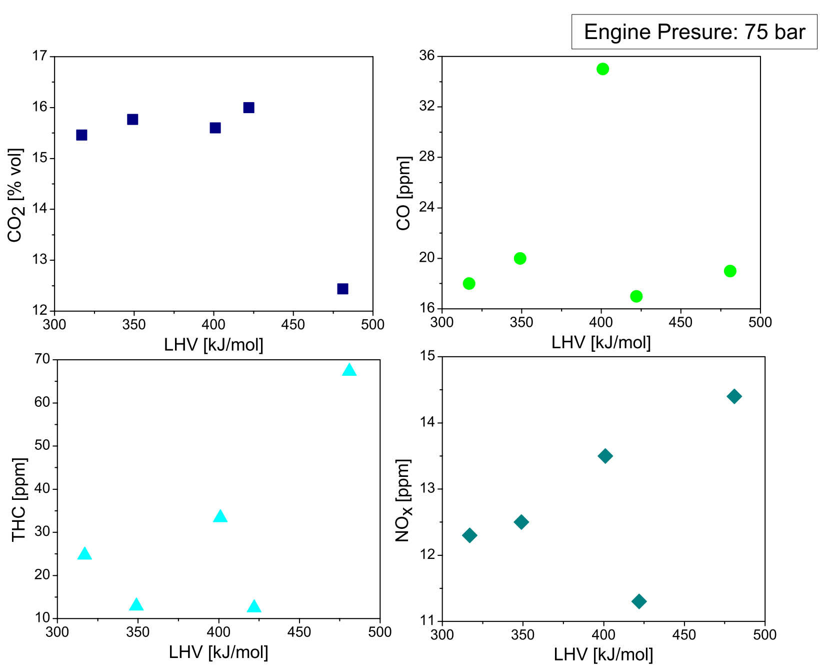


Figure 4: Emissions of the engine at 75 bar.

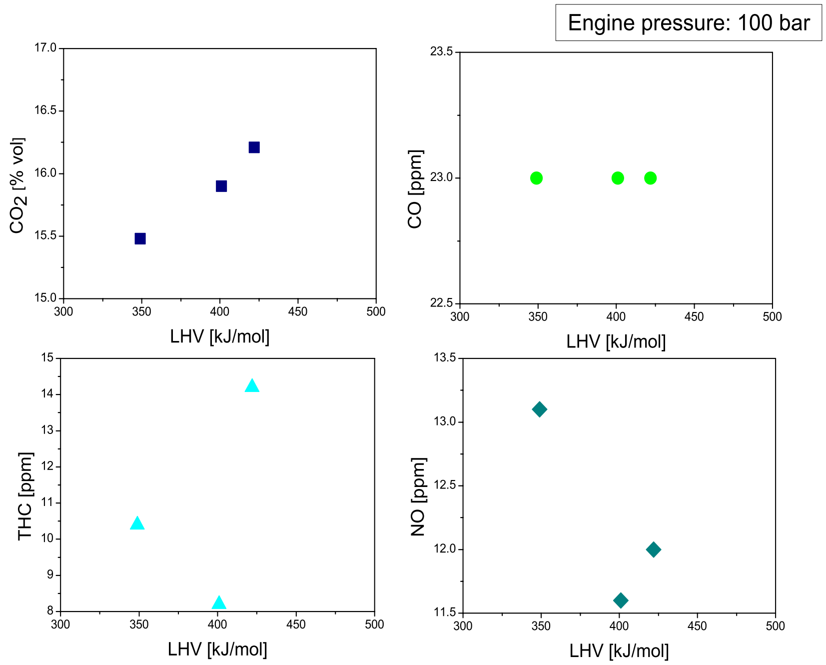


Figure 6: Emissions of the engine at 100 bar.

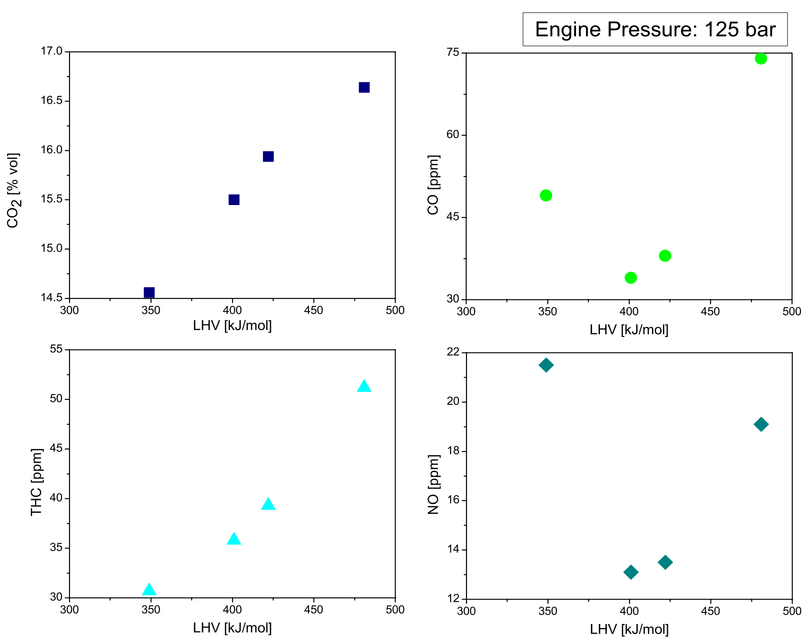


Figure 7: Emissions of the engine at 125 bar.

It is possible to notice that the engine pressure does not have a great influence on the performances of the combustion chamber.
In all three cases NO emissions are very low, below 20 ppm. Their value increase when the N_2 level in the fuel increases.
This is true also for the CO_2 value. It does not change in the three cases, but it increases when the

CO_2 percentage in the fuel increases.
As far as CO and THC are concerned, the emissions slightly increase at 125 bar.

6. Numerical modelling

Numerical simulations on the combustion chamber of this engine are also carried on.
The main objective is to validate models in presence of different fuel compositions.
The simulations, currently on going, are run with the commercial code Fluent as well as with the open source code OpenFOAM. In this way, it will be possible to compare the behavior of the two software.
As far as the models are concerned, in both cases the Eddy Dissipation Concept will be used.
The effect of the kinetic mechanism will be evaluated and the reduced mechanism for NO prediction (described in *Galletti et al, Int. J. Hydrogen Energy 40, 2015*) will be validated.

7. Concluding remarks

During my stay at Cleanergy, the experimental tests on their MILD-based Stirling engine were performed. This experimental campaign was focused on the evaluation of the engine emissions when the fuel composition is changed.
Thanks to this collaboration, I had the opportunity to improve my knowledge about experimental tests and it also provide useful experimental data to further validate the numerical models used to describe MILD combustion.

8. Publications resulting from the STSM

The work carried on in the framework of the STSM will be presented in two conferences in the next months:

- 24^{th} Journées d'Etude of the Belgian Section of the Combustion Institute, 19-20 May 2016, Louvain-la-Neuve, Belgium.
- 17^{th} International Stirling Engine Conference, 24-26 August 2016, Newcastle, England.