Operating experiences with biomass driven Stirling engines; 3 kW and 30 kW

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Abstract

To respond to the increasing needs of the energy market for small scale biomass fuelled CHP plants in the early 90s, Joanneum Research started with the development of biomass fuelled Stirling engines.

The aims of the projects were the design, the construction and the implementation of wood chip fired Stirling engines to realize environmentally friendly heat and power production.

Two engines were developed and built:

1. A 3 kW_{el} alpha-type Stirling engine
2. A 30 kW_{el} alpha-type Stirling engine

Because of cost reasons both engines are using crank mechanisms of industrial products. The pistons of the original engines are used as crossheads for the Stirling pistons, which are built on top of the original pistons. Based on the experiences with the 3 kW_{el} engine, which was constructed first, the 30 kW_{el} engine was realized as enlarged version.

Due to well known problems that occur with the use of flue gas from biomass combustion, some special developments have been made in order to achieve optimal functionality.

Specially developed components are the compression and expansion pistons, the cylinders, the rod seals, the heat exchangers and the regenerator.

(a) The piston rod seals

The crank shafts used (motorcycle and air compressor) work at ambient pressure. In order to keep the working pressure inside the working rooms a special piston rod seal was developed which is based on the so called “Leningrad seal”. Due to the moving of the piston rod, an oil film is kept inside a conus and the sealing is achieved.

(b) The heat exchanger

Running the engine with flue gas from solid biomass, a conventional heat exchanger with a ribbed surface or with fins could not be used for the heat input into the process. Combustion residues would plug the heat exchanger within short time. To solve this problem a special heat exchanger with smooth tubes was developed. The inlet temperature of the flue gas at the entrance of the heat exchanger is about 1000 °C and the flue gas is released at about 750 °C. The used material is conventional heat resistant steel.

Laboratory test runs demonstrated functionality as well as long time endurance. Minor problems which occurred could be solved and foundation for the successful construction of further engines could be laid.

1. Introduction

The increasing needs of the energy market lead to the development of biomass driven Stirling engine prototypes. The very well developed gas fired Stirling technology is not applicable in combination with solid biomass. The main reason therefore is that the combustion residues within the flue gas of solid biomass clog the ribbed heat exchanger surface of a gas Stirling engine and hence block the heat input into the process. Thus a Stirling engine had to be designed from scratch around a special heat exchanger construction. The article at hand reports on the design and construction of a 3 kW_{el} and a 30 kW_{el} engine and on the running experience that was gained after test runs in the laboratory and installation in the field [1].

2. The 3 kW_{el} Stirling engine

The 3 kW_{el} alpha-type Stirling engine is constructed on the basis of an industrial motorcycle crank mechanism. The pistons of the original engine are used as crossheads for the Stirling pistons, which are built on top. Figure 1 shows the 3 kW_{el} Stirling engine with its special heat exchanger. The smooth pipes are aligned in flue gas direction in order to achieve a self cleaning effect. Ribbed pipes or pipes with fins would be clogged by combustion residues within short time. The size of the engine is determined by the desired shaft power and thus by the heat exchanger surface area as well as by the maximal power transmission that can be processed by the motorcycle crank mechanism. The heat exchanger has to be designed considering the smooth surface of the pipes. The surface area determines the heat input into the process but also the size of the dead space. This leads to a disadvantageous ratio between expansion piston stroke volume and dead space. Certainly the piston stroke volume could be increased for more active volume, but this is limited by the maximum transferable power into the crank mechanism and by an increase of pressure drop within the heat exchanger. The final design is taking this complex interrelationship into account and represents the optimal solution of biomass driven Stirling technology.

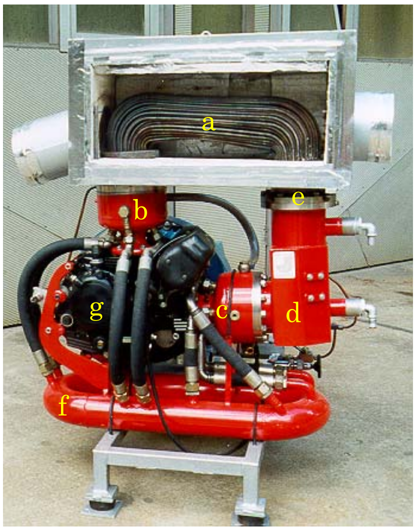

Figure 1 3 kW$_{el}$ alpha-type Stirling engine

a … Flue gas–working gas heat exchanger
b … Expansion cylinder
c … Compression cylinder
d … Cooler
e … Regenerator
f … Compensation tank
g … Motorcycle crank mechanism

Table 1 Technical data of the 3 kW$_{el}$ engine

Technical data	
Nominal power	3.2 kW$_{el}$
Revolutions per minute	512 rpm
Working fluid	Nitrogen
Working pressure	< 32 bar
Temperature of heat input/output	1000/750 °C
Heat rejection temperature, in/out	30/50 °C
Electrical efficiency	23.5 %
Fuel	wood chips

3. The 100 hours non-stop test run

Joanneum Research is partner of the EU project PolySMART which is about the combined generation of heat, cold and power (CHCP) in small and medium scale demonstration plants. The 3 kW$_{el}$ Stirling engine is foreseen to be implemented within the Austrian demonstration project (for detailed information see: http://www.polysmart.org). To ensure endurance and to operate the engine under real conditions, it was tested for 100 hours non-stop.

Figure 2 Stirling test facility at the laboratory

Figure 2 shows the test facility in the Joanneum Research laboratory. The hot flue gas is produced with pellets in a combustion chamber. The combustion air is preheated with exhaust gas to keep the heat within the process and the flue gas is circulated to increase the fuel efficiency. The cooling of the process is accomplished with fresh water using a cooler module (see figure 3). The cylinder walls, the piston rod seals and the crankcase oil have to be cooled. In order to simulate the cooling via a conventional heating system, the temperature levels of the water cooling are set by regulating the flow rate.

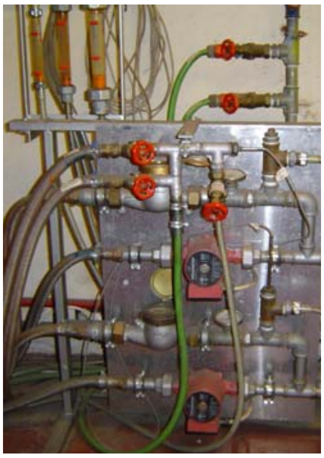

Figure 3 Cooler module

All test runs have been fully monitored. Figure 4 shows the assembly of the measuring station. The generator which also works as starter engine is controlled by a frequency inverter. It also is used to keep the engine speed constant at 512 revolutions per minute. This is the optimal revolution in order to achieve the highest efficiency of the Stirling engine. The reason is that the regenerator efficiency is dependent on a certain engine speed in order to work at its best. As soon as the Stirling engine produces energy (at a heat exchanger inlet temperature of the flue gas of about 550 °C and 10 bar gas pressure), the starter engine is used as generator and the produced electricity is lead to a break resistor. The power measurement is carried out through a scale, a lever arm and the flexible mounting of the generator (see the very right side of figure 4).

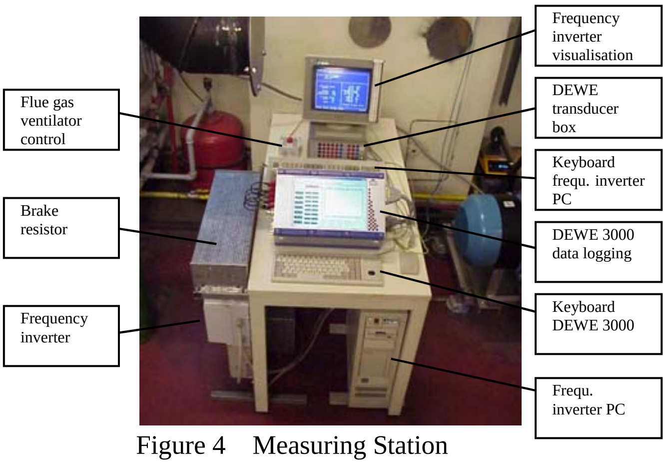

Figure 4 Measuring Station

The 100 hours non-stop test run was carried out in February 2007. Figure 5 shows an overview over the performance of the engine. The average power output was kept below 1000 W_{el}. The main goal of this test run was to demonstrate endurance performance rather than maximum performance.

(a) Power output

The power output of a Stirling engine mainly depends on two parameters. Firstly the average temperature of the heat input and secondly the pressure level of the process. For the testing facility of the non-stop test run, a wood pellet fired combustion chamber was used to produce the hot flue gas. It soon turned out that the amount of hot flue gas was too little in order to achieve an optimal flow rate through the heat exchanger and hence an optimal heat input into the process. The average heat exchanger temperature should be at least around 875 °C. Figure 5 shows that with this testing facility only 800 °C were achieved.

(b) Working gas loss

As figure 5 shows, the pressure loss due to working gas loss of more than 2 bars per hour was very high within the first 36 testing hours. After the detection and reparation of the leakage the working gas loss went down to an acceptable value of around 0.5 bars per hour. But this still represents an area of improvement for further developments.

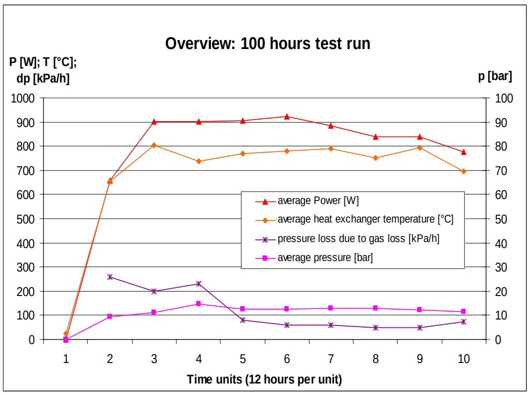

Figure 5 Overview of the 100 hours test run

(c) Noise development

After running the Stirling engine for about 24 hours without any noticeable problems there occurred a noise from the regenerator of the engine. No special trigger boundary conditions could be found. It appeared and disappeared without any relation with pressure or temperature. It turned out that the regenerator which is a package of steel meshes pressed together and mounted within a fitting was loosed and started knocking inside the engine. After the test run, the engine was opened and the regenerator was fixed.

4. Future steps

The 3 kW_{el} Stirling engine was disassembled and improvements concerning the leakage and the noise development are being made. After passing a further leakage test the engine will be modified with the goal to achieve a full automation. Until the end of August 2007 the final installations at the PolySMART demonstration site will be finished and a testing and monitoring period of two years will follow.

5. The 30 kW_{el} Stirling engine

Figure 6 shows the 30 kW_{el} alpha-type Stirling engine at the laboratory at Joanneum Research. The construction is based on the 3 kW_{el} Stirling engine which was developed first and so the key components are the same.

Figure 6 30 kW_{el} alpha-type Stirling engine

See table 2 for the technical data of the engine.

Table 2 Technical data of the 30 kW_{el} Stirling engine

Technical data	
Nominal power	30 kW_{el}
Revolutions per minute	512 rpm
Working fluid	nitrogen or helium
Working pressure	< 30 bar
Temperature of heat input/output	1000/750 °C
Heat rejection temperature, in/out	30/50 °C
Electrical efficiency	26 %
Fuel	wood chips

After a successful testing period at the laboratory of Joanneum Research, the Stirling engine was installed at an industrial heating plant with a thermal output of 800 kW. Operating data still has to be collected and is expected to be available in autumn 2007.

6. Conclusions

The operation of the 3 kW_{el} Stirling engine was very successful. The project goals have been achieved and after correction of minor problems the long term endurance could be demonstrated. Further efforts should consider the development of further prototypes for the demonstration of their maturity as well as the cost reduction to enable successful commercial use.

7. References

[1] Podesser, E., Dermouz, H., Padinger, R., Wenzel, A., Entwicklung eines mit Holz betriebenen Stirling-Kleinkraftwerkes zur dezentralen Strom- und Wärmeerzeugung – Phase II, Bericht Nr.: IEF-B-12/95, JOANNEUM RESEARCH, Institut für Energieforschung, (1996).