2nd World Conference and Exhibition on Biomass for Energy, Industry and Climate Protection
10-14 May 2004, Rome, Italy

Small-scale CHP Plant based on a 75 kW$_{el}$ Hermetic Eight Cylinder Stirling Engine for Biomass Fuels – Development, Technology and Operating Experiences

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ABSTRACT: Within the scope of an EU research and demonstration project (project No. NNE5-1999-00097) a small-scale CHP plant based on a 75 kW$_{el}$ hermetic eight cylinder Stirling engine for biomass fuels was developed and demonstrated. The furnace equipped with underfeed stoker technology is designed for temperature levels of about 1,300 °C. Moreover, an air pre-heater especially designed for the Stirling engine application to increase the electric efficiency has been developed. The Stirling engine heater is directly exposed to radiation from the combustion chamber. The nominal electric power output of the plant is 75 kW and the nominal thermal power output approx. 475 kW. The nominal electric plant efficiency amounts to approx. 12% and the nominal overall plant efficiency to about 86%. The demonstration plant has started operation in October 2003 and runs fully automatically. Up to the end of December 2003 more than 1,000 operating hours have been obtained. Evaluations of operating data show that nominal power and efficiencies specified can be achieved during full load operation. The CHP technology presented in this paper can be considered as a break through in the utilisation of Stirling engines for small-scale CHP plants using natural wood fuels and is the first application of its kind world wide.

Keywords: combined heat and power generation (CHP), Stirling engines, combustion

1 INTRODUCTION

In the range of an electric power output up to 150 kW$_{el}$ Stirling engines are presently the only useful technology for CHP generation based on solid biomass fuels, which has the potential to meet the technical and economic demands of such systems [1, 2].

Within the scope of an EU research and demonstration project (project “Bio-Stirling”; project No. NNE5-1999-00097) a small-scale CHP plant based on a 75 kW$_{el}$ hermetic eight cylinder Stirling engine for biomass fuels was developed in cooperation with the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GesmbH, an Austrian biomass furnace and boiler manufacturer, and BIOS BIOENERGIESYSTEME GmbH, an Austrian development and engineering company. Based on the technology developed, a pilot plant has been erected and tested. This plant has started operation in October 2003 and runs fully automatically.

2 TECHNICAL DESCRIPTION OF THE 75 KW$_{EL}$ STIRLING ENGINE

A Stirling engine especially designed for CHP plants using biomass fuels has been developed at the Technical University of Denmark (see Figure 1). The design of the Stirling engine is based on numerical optimisation of more than 20 parameters describing cylinders, engine heaters, regenerators etc. The engine, which is designed for a nominal electric capacity of 75 kW, has eight cylinders arranged in two separated squares with the cylinders parallel to each other.

Helium is used as working gas at a maximum mean pressure of 4.5 MPa. The eight hot engine heaters (one for each cylinder) are designed as panels forming two separated square combustion chambers, where radiation from the furnace is transferred directly to the panels. Narrow passages in the Stirling engine heater sections are avoided in order to adapt the system to flue gases from combustion systems fired with solid biomass fuels.

The engine is designed as a hermetically sealed unit. The great advantage of a hermetic Stirling engine is that only static seals are necessary between working gas and air. Furthermore, the design of the sealings for pistons and piston rods is comparatively simple. The built-in asynchronous generator, which is also used as starter motor, has 6 poles corresponding to an engine speed of approximately 1,000 rpm when coupled directly to the power grid (50 Hz AC). The weight of the engine is approx. 3,500 kg.

Figure 1: Picture of the 75 kW$_{el}$ Stirling engine (Stirling engine heater not mounted)

The design of the 75 kW$_{el}$ Stirling engine for the plant described here is based on experiences from 3 prototypes of 35 kW$_{el}$ Stirling engines, which have already been tested. The first prototype, SM3A, was tested for more than 1,400 hours with wood chips as fuel, before the tests had to be stopped due to mechanical problems. The second and third engine have been improved considerably compared to the first engine, and the test results achieved were very satisfactory. The third prototype is now in operation for more than 7,500 hours in a pilot plant in Austria fuelled with wood chips [1, 3].

The design of the Stirling engine heater was improved for the 75 kW_{el} Stirling engine. Especially, the inflow section of the collector tubes was newly designed in order to reduce pressure losses. With this new design the electric efficiency of the Stirling engine could be increased considerably.

A single tube connection between the heater manifold and the volume above the regenerator makes it very difficult to obtain an equal distribution of the working gas flow around the circumferential of the annulus regenerator (see Figure 2). The engine heaters of the existing 35 kW_{el} Stirling engines are based on this design.

In order to decrease the internal volume of the connection between heater and regenerator and to improve the distribution of the flow through the regenerator, a new design of the heater was developed. Figure 3 shows the improved design where each heater is divided in four subsections each having its own tube connection to the volume above the regenerator. Moreover, the four tube connections are equally distributed around the circumferential of the regenerator [4].

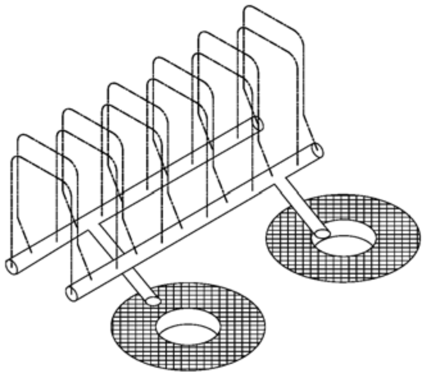

Figure 2: Connection between heater and regenerators - existing design for the four-cylinder Stirling engines

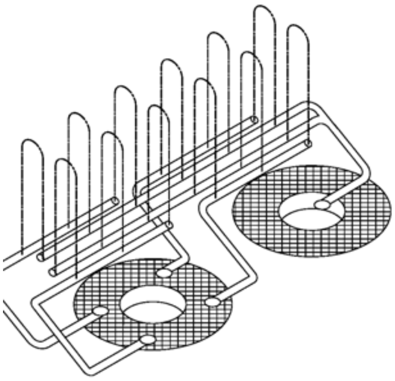

Figure 3: Connection between heater and regenerators - improved design for the eight-cylinder Stirling engine

3 CFD SUPPORTED DESIGN AND OPTIMISATION OF THE FURNACE

The design of the furnace and its adaptation to the special requirements of a CHP plant based on a 75 kW_{el} Stirling engine was an important and difficult task. The plant should operate at a high temperature level to gain a high electric efficiency from the Stirling engine but temperature peeks in the furnace should be impeded in order to reduce ash slagging and fouling as well as material wear [5]. The furnace is designed for temperature levels of about 1,300 °C.

The new combustion system was developed and optimised using CFD simulations. In this respect, more than 9 different furnace geometries were examined. The results achieved showed that it is very important to optimise the design of the furnace geometry, of the secondary air nozzles and the nozzles for flue gas recirculation in order to reduce temperature peaks in the furnace as well as CO emissions. In addition, by the CFD simulations performed an equal distribution of the flue gas flow into the different sections of the Stirling engine heater could be achieved which ensures an equal heat transfer to the eight cylinders of the Stirling engine and thus increases the electric efficiency.

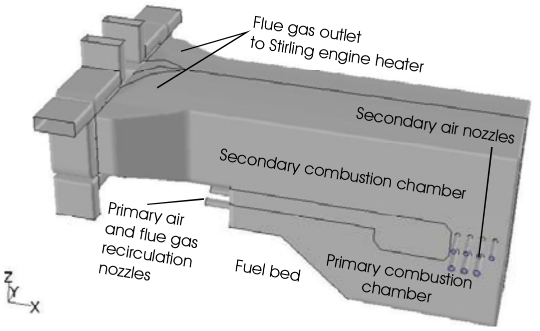

Figure 4: Schematic illustration of the final furnace design

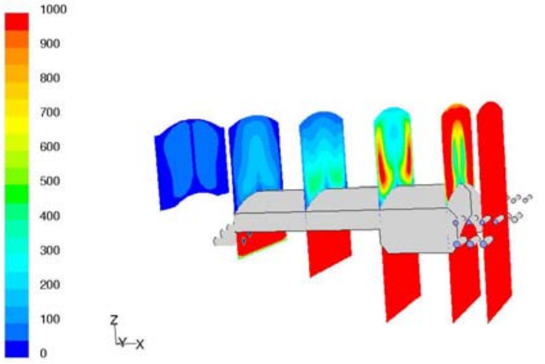

Figure 5: Contours of CO in mg/Nm^3 at vertical planes in the furnace

Explanations: CO emissions at Stirling engine heater outlets: less than 15 mg/Nm^3 (related to dry flue gas and 13 vol% O_2)

Figure 4 shows the furnace geometry with optimised nozzle design and placement. The secondary air nozzles are arranged horizontally in the transition zone between primary and secondary combustion chamber. By this configuration the combustion air gets efficiently mixed with the flue gas and a swirl flow is established in the secondary combustion chamber. Consequently, the resulting CO emissions are low.

Figure 5 shows the contours of CO in mg/Nm^3 calculated for the optimised geometry. CFD simulations predict CO emission less than 15 mg/Nm^3 (related to dry flue gas, 13 Vol% O_2) at the outlets of the Stirling engine heater at an excess air ratio λ of 1.4. This means that a complete burnout as well as a high combustion efficiency can be achieved. The calculation results could be verified through measurements at the pilot plant (see Figure 8, Figure 9 and Table I). Moreover, due to the high combustion air temperatures (500 – 550 °C) wet biomass fuels can also be utilised without problems. The results show that CFD analyses enhanced the design of the combustion system considerably.

4 DESIGN OF THE PILOT PLANT BASED ON A 75 KW$_{EL}$ STIRLING ENGINE

Figure 6 and Figure 7 show pictures of the new small-scale pilot CHP plant. The furnace is equipped with underfeed stoker technology and is suitable for wood chips, sawdust and pellets with moisture contents from 10 of 55 wt% (w.b.). The Stirling engine is mounted in horizontal position downstream the secondary combustion chamber for convenient maintenance. The air pre-heater and the economiser are placed on top of the furnace in order to achieve a compact design of the plant. The CHP plant does not require substantially more space than a normal biomass combustion plant with the same heat output. To remove fly ash particles from the Stirling engine heater, a pneumatic und fully automatic cleaning system has been developed and installed.

The electric efficiencies, the overall plant efficiency as well as the nominal power data listed in Table I could be verified during test runs performed (see section 5).

Table I: Technical data of the CHP plant based on a 75 kW$_{el}$ Stirling engine

Explanations: calculations performed for nominal load conditions; water content of the fuel: 30 wt%; air ratio λ: 1.4

Electric power output - Stirling engine	75	kW
Thermal power output - Stirling engine	205	kW
Thermal power output - CHP plant	475	kW
Fuel power input (based on NCV)	640	kW
Electric efficiency - Stirling engine	26.8	%
Overall electric efficiency - CHP plant	11.7	%
Overall efficiency - CHP plant	85.9	%

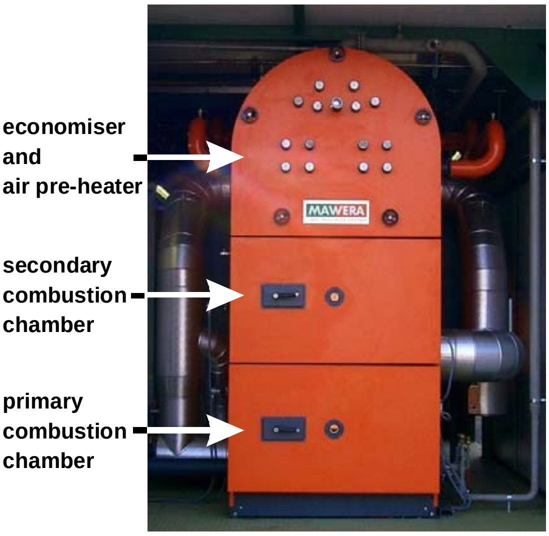

Figure 6: Picture of the small-scale CHP plant based on a 75 kW$_{el}$ Stirling engine – front view

Figure 7: Picture of the small-scale CHP plant based on a 75 kW$_{el}$ Stirling engine – backward view

The pilot CHP plant is equipped with a process control system which ensures completely automatic operation and a combustion temperature around 1,300 °C by the flue gas recirculation system installed. Furthermore, the security and safety system is designed to shut down the plant fully automatically in case of any failure.

5 OPERATING EXPERIENCES AT THE PILOT PLANT BASED ON A 75 KW$_{EL}$ STIRLING ENGINE

The most important task after the start-up phase of the pilot CHP plant was to ensure a stable and efficient operation. The plant was put into operation in the beginning of October 2003. In October several problems concerning helium leakage of the Stirling engine heater had to be solved. In the end of October it was possible to run the plant continuously at partial load. After several adaptations especially regarding the control system as well as the security and safety system, the plant was operated over long periods at full load from mid of November until the end of December 2003. Until the end of December more than 1,000 operating hours have been obtained.

Figure 8 and Figure 9 show operating data recorded over several days in December 2003. At full load the plant produced approx. 75 kW electric energy over longer periods (see Figure 8). The maximum electric power output of the pilot CHP plant amounted to 78 kW$_{el}$. The overall electric plant efficiency ranges between 10 and 12%, which shows that the pilot CHP plant reaches the design target concerning efficiencies. However, the results of test runs performed at the plant show that the efficiency of the air pre-heater is lower than expected which is due to heat losses in the flue gas channel between Stirling engine heater outlet and air pre-heater inlet. Consequently, the insulation between the flue gas and the cooled walls located there has to be improved in order to further optimise the electric plant efficiency.

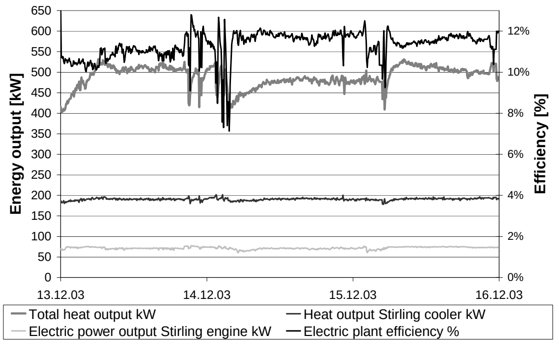

Figure 8: Operating data of the pilot CHP plant based on a 75 kW_{el} Stirling engine – energy output and efficiency

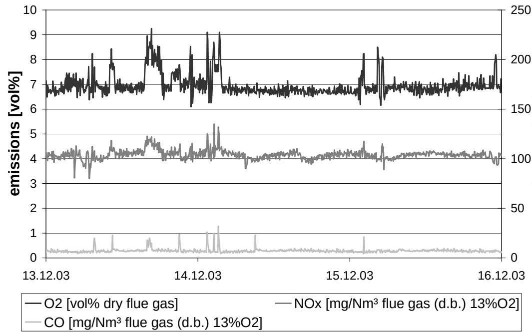

Figure 9: Operating data of the pilot CHP plant based on a 75 kW_{el} Stirling engine – gaseous emissions

Figure 9 shows O_2, CO and NO_x emissions in the flue gas at economiser outlet. The O_2 content in the flue gas is low (in normal operation approx. 6 to 7 vol%) in comparison to conventional small-scale biomass furnaces fired with wood chips, which ensures a high overall efficiency. In addition, the CO emissions can be considered as very low. On an average, CO emissions are below 10 mg/Nm^3. The results verify the CFD simulations performed. The average NO_x emissions amount to approx. 100 mg/Nm^3 which is also low for grate furnaces fired with wood chips and due to the good air staging realised. The results of several isokinetic dust measurements performed show that dust emissions are below 50 mg/Nm³ (related to dry flue gas and 13 vol% O_2) [6].

The automatic cleaning system of the Stirling heater was improved several times. At the moment, manual cleaning of the Stirling engine heater is necessary every 4 to 5 weeks. The ash depositions occurring at the Stirling engine heater are mainly due to the condensation of alkali metal vapours on the tube surfaces. It is expected that further improvements of the automatic cleaning system will increase these intervals to 2 - 3 months.

6 CONCLUSIONS AND OUTLOOK

Concluding, the operating experiences gained at the pilot CHP plant based on a 75 kW_{el} Stirling engine showed that the newly developed CHP system has already achieved a high technological standard and should be suitable for marketable solutions within short term (first small series production is planned for the years 2004/05). Problems to be addressed regarding further development and optimisation of the technology are improvements concerning the overall electric efficiency of the CHP plant (reduction of heat losses) and the reduction of ash deposition on the Stirling engine heater by an efficient automatic cleaning system. The pilot CHP plant based on a 75 kW_{el} Stirling engine is the first of its kind in this power range world-wide and can be considered as a major break-through regarding the utilisation of Stirling engines for small-scale CHP plants using natural wood fuels.

7 ACKNOWLEDGEMENTS

The project presented was supported by the European Commission under the Fifth Framework Programme (project “Bio-Stirling”; project No. NNE5-1999-00097).

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