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Development of a hot gas heat exchanger and a cleaning system for a 35kW$_{el}$ hermetic four cylinder Stirling engine for solid biomass fuels

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ABSTRACT

Over the past few years, a small-scale CHP technology based on hermetic Stirling engines has been developed and two prototype plants with a 35 kW$_{el}$ four cylinder and a 70 kW$_{el}$ eight cylinder Stirling engine have been erected in Austria. The prototype plant with a 35 kW$_{el}$ Stirling engine has already been in operation for more than 9,000 hours. Operating experiences gained from these plants formed the basis for the further development of this technology and showed that the efficiency of the Stirling hot gas heat exchanger and of the corresponding cleaning system must be further optimised. A new hot gas heat exchanger and a new cleaning system have been developed and optimised in cooperation of AUSTRIAN BIOENERGY CENTRE GmbH, the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GmbH, Austria, and BIOS BIOENERGIESYSTEME GmbH, Austria within the scope of an RD&D project.

The new design of the Stirling hot gas heat exchanger was developed in order to optimise the performance of the engine and simplify its geometry. The most relevant objectives in this respect were to achieve uniform heat transfer across each tube of the hot gas heat exchanger, a reduction of the internal helium volume, a functional design of the flue gas duct and geometrical adaptations to implement an efficient automatic cleaning system to reduce ash depositions. Previous investigations had shown that it is not possible to efficiently reduce the ash depositions on the surfaces of the hot gas heat exchanger by primary measures. Consequently, a new automatic and pneumatic cleaning system was developed in order to increase the intervals between manual cleaning and thus the availability of the Stirling engine. The system is integrated into the furnace and works fully automatically.

A pilot plant was designed and erected, based on the new technology developed. The nominal electric power output of the plant is 35 kW$_{el}$ and the nominal thermal output approx. 250 kW$_{th}$. The plant has already been in operation since the end of May 2005. First operating experiences have proved that the pilot CHP plant can be operated fully automatically and reaches the design target concerning electric efficiencies and electric power output. Furthermore, the new hot gas heat exchanger cleaning system appears to meet operational expectations. The new CHP technology will be optimised within the scope of detailed test runs planned for autumn 2005.

INTRODUCTION

CHP technologies based on biomass combustion represent a great potential to reduce CO_2 emissions since they are based on the utilisation of renewable energy sources. These CHP technologies have been developed intensively over the past few years. Typical fields of application are wood-processing industries, district heating systems, large hotels and industries with process heat or cooling demand. These applications represent a great market potential in Europe as well as worldwide.

In the range of an electric power output up to 100 kW_{el}, Stirling engines are presently the only useful technology for combined heat and power generation based on solid biomass fuels, which have the potential to meet the technical and economic demands in an environmentally acceptable way [1, 2].

Stirling engines for CHP plants using solid biomass as fuel have been developed for more than ten years at the Technical University of Denmark. As part of these activities, a 35 kW_{el} Stirling engine and a 70 kW_{el} Stirling engine for wood chips were built. These engines are designed as hermetically sealed units where the generator is incorporated in the pressurised crank case in order to avoid dynamic seals between the working gas and the surroundings [3].

Based on this Stirling engine a small CHP technology has been developed within an international cooperation between the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GmbH, Austria, and BIOS BIOENERGIESYSTEME GmbH, Austria. This cooperation resulted in two prototype CHP plants based on a 35 kW_{el} four cylinder and a 70 kW_{el} eight cylinder Stirling engine, which have been erected and tested successfully. The 35 kW_{el} and the 70 kW_{el} Stirling engine plants have been in operation for more than 9,000 hours and 3,000 hours, respectively. Operating experiences showed a potential to improve the efficiency of the Stirling heater (hot gas heat exchanger). The intervals between manual cleaning every 500 to 800 operating hours must also be improved by developing an automatic cleaning system for the Stirling heater.

Within the scope of the R&D project presented, a new heater for the Stirling engine and a fully integrated automatic cleaning system, has therefore been developed, designed and optimised in cooperation of AUSTRIAN BIOENERGY CENTRE GmbH, an Austrian research and development company, 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.

A pilot plant was designed and erected based on the new technology developed. The nominal electric power output of this plant amounts to 35 kW_{el} and the nominal thermal output to approx. 250 kW_{th}. The plant has already been in operation since the end of May 2005.

DESCRIPTION OF TECHNOLOGY

In the following sections the technology of the Stirling engine and of the CHP plant is described in detail.

Stirling engine – description of technology

Stirling engines are based on a closed cycle, where the working gas is alternately compressed in a cold cylinder volume and expanded in a hot cylinder volume. Due to the closed Stirling cycle it is possible to use a working gas with a better heat transfer value than air. The use of helium or hydrogen is most efficient. The design of leak-tight dynamic seals is difficult for these low molecular weight gases. In order to avoid this problem, it is possible to design Stirling engines as hermetically sealed units with the generator incorporated in the pressurised crankcase. This application requires only simple dynamic seals and only static seals for the cable connections between the generator and the grid.

The advantage of the Stirling engine is that the heat is transferred from the outside to the engine via Stirling heater. Further the heat is shifted between the Stirling heater and the Stirling cooler through a regenerator. The regenerator is a heat storage which is used as heat recovery between the Stirling heater and the Stirling cooler in order to reach high electric efficiencies. The heat that is not converted into mechanical and subsequently into electrical power is transferred to the cooling water in the Stirling engine cooler at 25°C - 75°C, depending on the temperature of the cooling circuit (see also Figure 2).

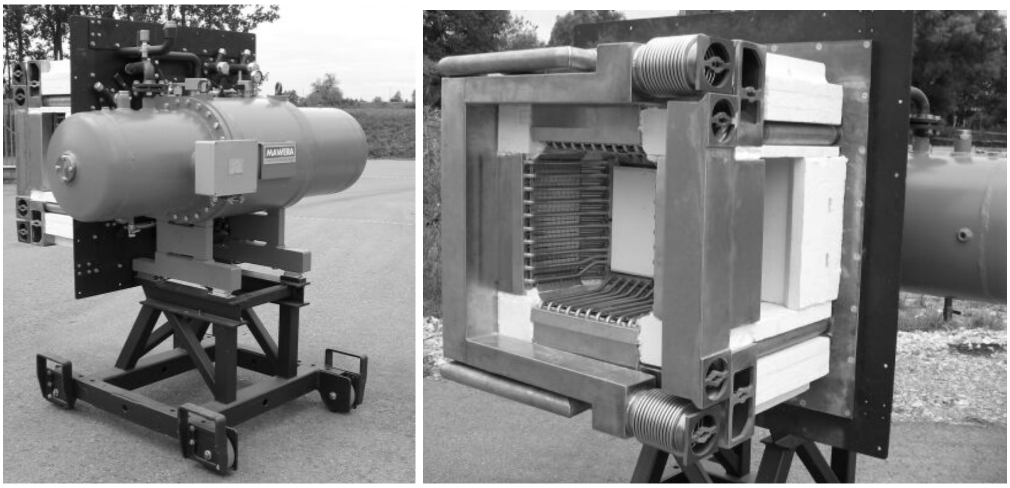

Figure 1: Photographs of the 35 kW_{el} Stirling engine (left: crankcase, generator and balancing system; right: flue gas channels and heater)

A Stirling engine especially designed for CHP plants using biomass fuels has been developed at the Technical University of Denmark [4]. The engine, which is designed for a nominal electric capacity of 35 kW, has four cylinders arranged in a square with the cylinders parallel to each other. Helium is used as working gas at a mean pressure of 4.5 MPa. Since it is not possible to utilise a Stirling engine designed for natural gas, as the Stirling engine heaters would be blocked after less than an hour of operation with biomass fuels, narrow passages in the Stirling heater sections are avoided in order to adapt the system to the high dust load of flue gases from combustion systems fired with solid biomass fuels. The risk of deposition formation in biomass combustion processes is mainly due to aerosol formation and condensation of ash vapours during flue gas cooling [5,6].

The engine is designed as a hermetically sealed unit (see Figure 1). 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 specifications of the new Stirling engine are shown in Table 1.

Table 1: Specifications of the 35 kW_{el} Stirling engine (the nominal water temperature of the Stirling cooler is the average of the net feed and net return)

Bore	[mm]	142
Stroke	[mm]	76
Number of cylinders	[-]	4
Engine weight	[kg]	1,600
Mean pressure	[MPa]	4.6
Working gas	[-]	Helium
Speed	[rpm]	1,010
Surface temperature of the cylinder heads (max.)	[°C]	680
Nominal water temperature of the Stirling cooler	[°C]	55
Nominal electric power output	[kW]	35

Biomass CHP plant – description of technology

The problems concerning the utilisation of solid biomass fuels in Stirling engine based CHP units are concentrated on transferring the heat from the flue gas into the working gas of the Stirling engine.

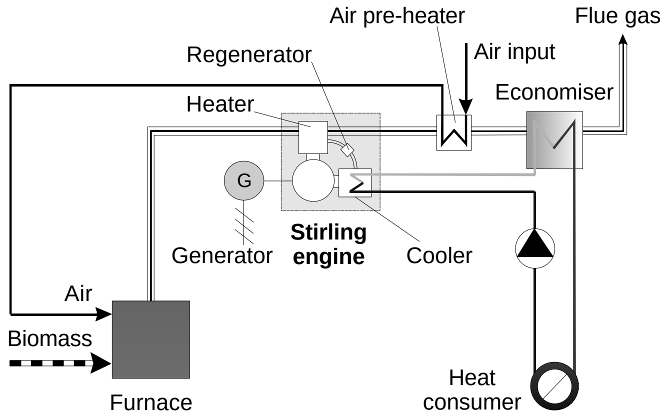

Figure 2: Schematic of a Stirling CHP plant

Figure 2 shows the schematic of a small-scale CHP plant based on a Stirling engine. In order to achieve high electric efficiency, the biomass furnace must operate at a high temperature level, but temperature peaks should be impeded in order to keep the risk of ash slagging and fouling low. In addition, high flue gas temperatures may considerably reduce the lifetime of the combustion chamber due to diffusion processes and reactions between chamotte and alkali metal vapours which are accelerated at high temperatures and can cause damages in the chamotte bricks. The combustion is realised in a two stage design (primary and secondary combustion chamber are geometrically separated) in order to achieve low NOx emissions. The CHP plant developed is designed for furnace temperatures of approx. 1,300°C. The Stirling heater is designed for this high flue gas temperature and is directly connected to the furnace. The surface temperature of the Stirling heater is typically between 750°C and 790°C. In order to obtain high temperatures in the combustion chamber and high electric plant efficiency, the combustion air is preheated to 450°C – 550°C in an air pre-heater situated downstream the Stirling heater. Then the flue gas is cooled in an economiser to approx. 120 – 150°C. The combustion system was developed and optimised using CFD simulation technology (computational fluid dynamics) [1].

Figure 3 shows a picture of the new 35 kW_{el} CHP pilot plant. The furnace is equipped with underfeed stoker technology. The Stirling engine is mounted in a horizontal position downstream of the secondary combustion chamber for convenient maintenance (see Figure 3). 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 should not require substantially more space than a normal biomass combustion plant with the same heat output.

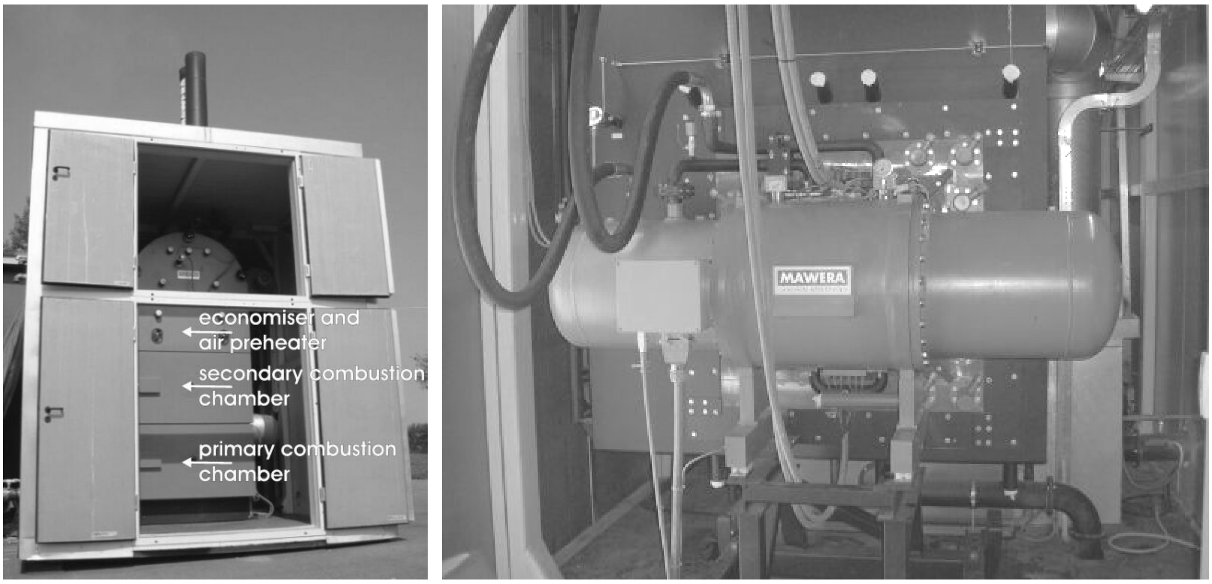

Figure 3: Photographes of the newly developed CHP pilot plant based on a 35 kW_{el} Stirling engine (left: front view of the plant; right: back view with the mounted Stirling engine)

In order to keep the operating costs as low as possible, small-scale plants have to be able to run in unmanned operation. The system has therefore been fully automated, including the start-up and shutdown procedures. If any failure in the CHP plant is detected the combustion system will immediately be shut down without an operator intervention being necessary [6].

FURTHER DEVELOPMENT AND OPTMISATION

Operating experiences at the existing 35 kW_{el} and 70 kW_{el} prototype plants have shown that certain components of the plant and Stirling engine should be further developed and optimised. The developments of a new Stirling heater in combination with a heater cleaning system is the main objective of the project presented. Furthermore, a balancing system to reduce vibrations during operation of the engine was developed and internal mechanical components (bearings, seals, surfaces of moving parts) of the engine were optimised [7,8].

The main target of the development of the new Stirling heater was to ensure a highly uniform heat transfer over all heater tubes, which is very important for the overall efficiency and the power output of the engine. Furthermore, the internal helium volume, the functional design of the flue gas ducts and an appropriate heater geometry to implement an efficient automatic cleaning system in order to reduce ash depositions are important factors in order to improve the efficiency as well as the availability of the Stirling heater.

A simple automatic heater cleaning system is installed at the two existing prototype plants. Manual cleaning of the Stirling heater is required approximately every 500 to 700 operating hours. Previous investigations have already shown that the potential to reduce ash depositions on the Stirling heater surfaces by primary measures is very limited (e.g. by influencing the combustion process) [9]. Consequently, the main target was to further optimise the automatic heater cleaning system itself in order to increase the intervals between manual cleaning.

Development of a new Stirling heater

Figure 4 shows the old design of the Stirling heater which is installed in the first 35 kW_{el} pilot plant. The flue gas flow through the Stirling heater is a combination of cross and longitudinal flow. The Stirling heater has 24 u-shaped tubes which connect the manifolds on the cylinder side with the manifolds on the regenerator side of the four cylinder double acting Stirling engine.

The Stirling heater tubes are divided into 12 half-tubes for radiative heat transfer and 36 half-tubes for convective heat transfer. Fins are used to enhance the convective heat transfer and to obtain a uniform heat transfer at every tube across the whole Stirling heater, which is very important for the efficiency of the Stirling heater and the Stirling engine. In this design, however, the flue gas temperatures are different for every Stirling heater tube, which makes it nearly impossible to achieve uniform heat transfer over all tubes of the Stirling heater. Furthermore, the geometry of the flue gas ducts around the Stirling heater makes the implementation of an efficient cleaning system impossible.

The main goal of the further development of the Stirling heater was to ensure a uniform heat transfer to the heater tubes, beside a reduction of the internal manifold volume and to adapt the geometry of the Stirling heater in order to allow an efficient implementation of an automatic cleaning system.

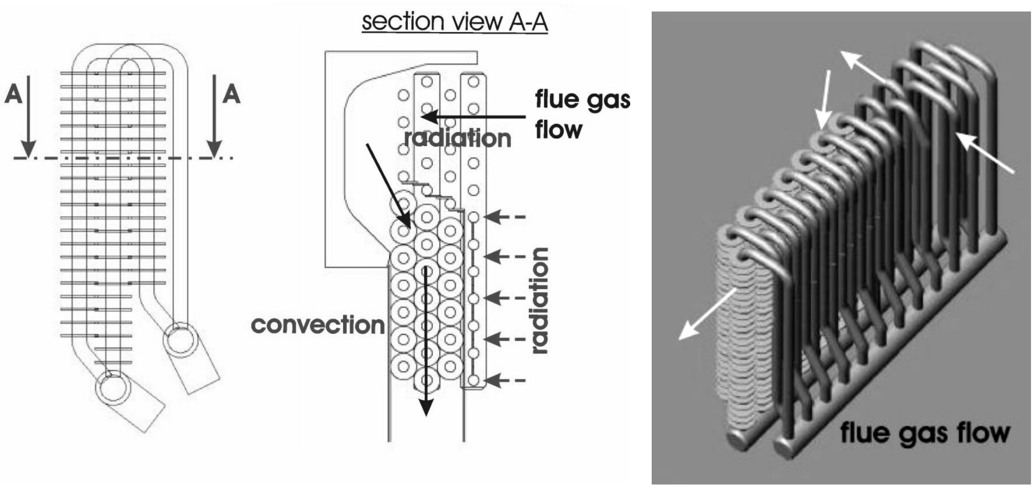

Figure 4: Sketches of the Stirling heater panel and isometric view of the old Stirling heater

Figure 5 shows the newly developed Stirling heater. The new heater design consists of three different flue gas ducts in cross flow. Each tube has 4 bends and is connected to the manifold tubes in a manner similar to that in the Stirling heater design of the old 35 kW_{el} prototype plant. The internal volume of the Stirling heater manifolds was reduced in order to increase the Stirling heater efficiency. Every heater tube transfers heat by radiation and convection from the flue gas to the working gas of the Stirling engine (helium). In principle, the Stirling heater can be divided into 4 different sections. The first section consists of plain tubes with radiation shields on the backside. The heat is mainly transferred by radiation from the secondary combustion chamber. The second section consists of plain tubes where the heat is transferred by radiation and convection. In the two following sections fins are used to enhance the convective heat transfer.

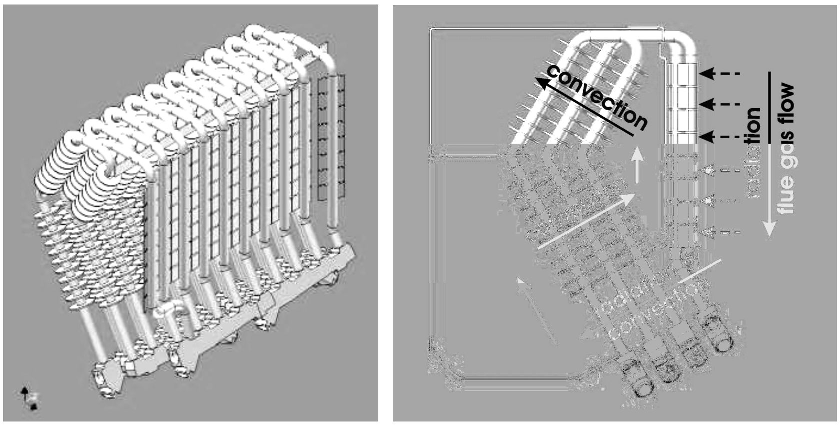

Figure 5: Sketches of the new Stirling heater panel

The flow of the flue gas through the heater channels was optimised using CFD (computational fluid dynamics) simulations. The results of the CFD calculations are shown in Figure 6 and Figure 7. These figures illustrate the calculated flue gas velocities for the heater cross section for a basic and an optimised geometry. The calculations for the basic design shows that the flue gas velocity is not equally distributed across the heater cross sections, resulting in reduced heat transfer efficiencies (see Figure 6). Figure 7 shows the velocity distribution of the optimised heater design. The results show that the velocities are more equally distributed as compared to the basic design and the heat transfer efficiency is, thus improved.

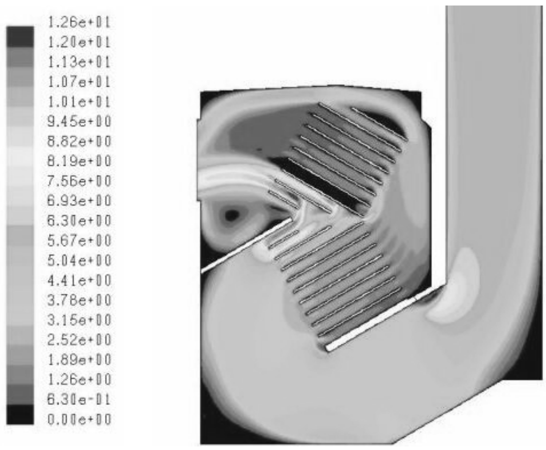

Figure 6: CFD calculation of flue gas velocities (m/s) - basic Stirling heater design

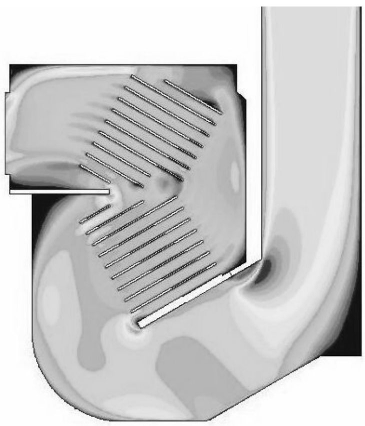

Figure 7: CFD calculation of flue gas velocities (m/s) - optimised Stirling heater design

Development of an integrated heater cleaning system

Operating experiences at the 35 kW_{el} and the 70 kW_{el} prototype plants have shown that there is a considerable potential for optimising the performance of the automatic cleaning system. Figure 8 shows the system installed at these plants, which is based on one air nozzle for each heater panel mounted relatively far away from the Stirling heater tubes. The air jet induced at regular intervals is efficient only for the first rows of the heater tubes. The cleaning efficiency was not satisfactory for the tubes further away from the air nozzles, resulting in short intervals of manual heater cleaning after every 500 - 800 hours of operation. Consequently, a further development and optimisation of the heater cleaning system was required in order to increase the intervals between manual cleaning and, consequently, the availability and efficiency of the CHP plant.

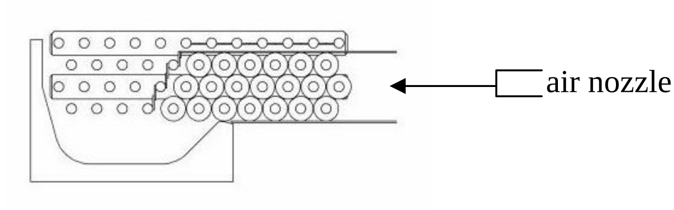

Figure 8: Sketch of the old heater design showing the position of the air cleaning nozzle

Several possibilities to design a new automatic cleaning system for the Stirling heater were investigated. Due to the high flue gas temperatures present in the heater sections (about 800 to 1,300°C) and the high dust loads of the flue gas, conventional air nozzles were not applicable, because they have very small outlets and they would be blocked after a few hours of operation. Consequently, the best solution is to use simple tubes as nozzles with large diameters in order to avoid failures of the system.

Several tests were performed with a model of the new Stirling heater in order to develop an optimised cleaning system and estimate its cleaning performance. Figure 9 shows the heater model used and the experimental setup for the cleaning tests. The test facility consists of a pressure vessel, a high-speed membrane valve, air nozzles and the heater model itself. The heater model and the heater channels are true scale replicas of the newly developed Stirling heater. The surfaces of the heater tubes were coated, with a mixture of flour and water, in order to simulate ash depositions and evaluate the performance and efficiency of different test setups.

Figure 9: Heater model and experimental setup for the cleaning tests performed

The geometry and number of nozzles as well as the distance of the nozzles to the heater tubes were varied during the tests. The results of the tests summarised in Table 2 showed that the number of nozzles, the nozzle diameter and the distance of the nozzles to the Stirling heater are essential factors for the optimisation of the cleaning system. Large nozzle diameters increase the air velocity due to lower pressure losses and, consequently, enhance the cleaning performance. If the air jet is split in order to feed more than one nozzle at the same time, the cleaning performance of each nozzle is decreased due to the increasing pressure losses for the split. Furthermore, it is important to direct strong and short air pulses onto the Stirling heater depositions in order to obtain a high cleaning performance. The duration of the air pulses does not affect the cleaning performance. The distance between the nozzles and the heater tubes is directly related to the size of the possible cleaning area. A larger distance of the nozzle results in a larger area covered by the air pulses but does not reduce the cleaning efficiency significantly.

Table 2: Factors of influence and the consequences on the cleaning system performance (*effect on the cleaning efficiency struck by the air jets)

factors of influence	effect on cleaning area	effect on cleaning depth	effect on cleaning efficiency*	heater erosion
distance of nozzle to the heater	high	none	none	none
outletdiameter of nozzle	high	none	medium	none
air jet split to feed more nozzles	medium	medium	medium	none
duration of airjet	none	none	none	none
load materials (sand, grit)	low	none	high	medium

The cleaning tests also showed that the addition of different cleaning media, like sand and grit, to the air jet is quite effective. The sand and grit particles hit and break up the ash depositions, which is more efficient than the impact of the air pulses alone. However, sand and grit can cause erosion and small deformations on the heater tubes. A comprehensive test series is thus planned in order to optimise grain size and the amount of cleaning media used in order to minimise erosion and deformation problems. Furthermore, it turned out that it is not possible to use water as a cleaning medium. Water vaporises immediately at the nozzle outlet resulting in an increase of volume by a factor of 1,000. This causes high material stresses in the Stirling heater and in the flue gas channels which is not acceptable concerning the lifetime of these parts.

Based on the results of the cleaning tests performed, an optimised cleaning system was developed. The system consists of four nozzles for each of the Stirling heater panels (see Figure 10). The position of each nozzle was optimised in order to obtain a high cleaning performance taking into consideration the geometrical restrictions. Each nozzle is equipped with separate tubes and membrane valves in order to reduce pressure losses.

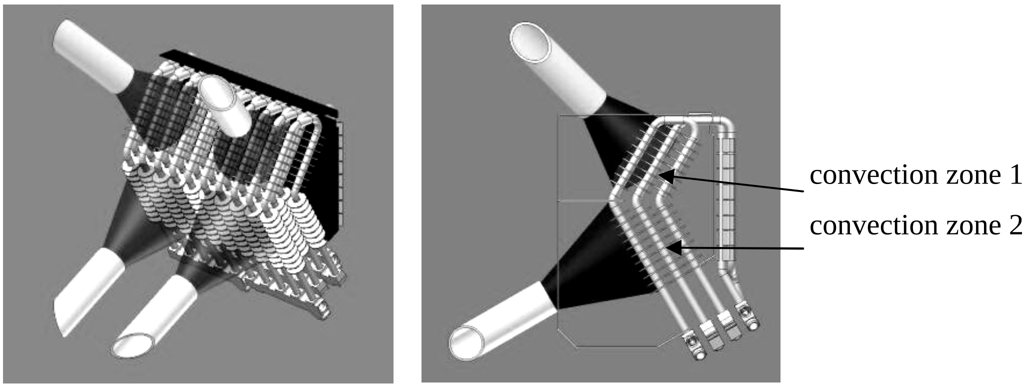

Figure 10: Sketch of the nozzles (light grey) and the resulting air jets (dark grey) of the newly developed cleaning system for the Stirling heater

Figure 11 shows schematically the first and second convection zone of the Stirling heater (see Figure 10). In this figure the light grey zones indicate the areas where the cleaning efficiency is expected to be high. The performance of the cleaning system in the white zones should be moderate. Since the nozzles for the first and second convection zone are positioned in a different way, the shapes and sizes of the estimated cleaning areas are not equal. The estimated area reached by the air jet cleaning system is about 58-90% (58% light grey zone –

90% light grey and white zone) for the first convection zone and about 54-81% for the second convection zone. In total, about 86% of the total heater area is expected to be efficiently cleaned. However the air jet cleaning system is able to clean the three rows of heater tubes (see Figure 10) quite accurately.

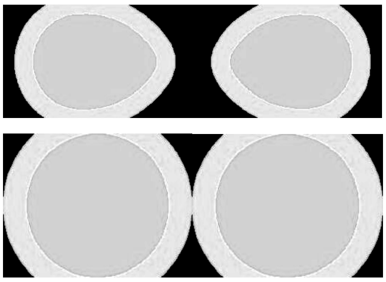

Figure 11: Schematic illustration of the expected performance of the new heater cleaning system in regard to the heater panels struck by the air jets

FIRST OPERATING EXPERIENCES AT THE NEW PILOT PLANT

Based on the new technology developed, a pilot plant was erected in Austria. The pilot plant, which has a nominal electric power output of 35 kW_{el} and a nominal thermal output of approx. 250 kW_{th} was put into operation in May 2005. At the moment, the plant is in fully automatic operation and test runs are ongoing.

First operating experiences show that the design targets concerning nominal electric power output and electric efficiency are not only achieved but even exceeded during normal operation. Figure 12 illustrates the total heat output of the plant, the heat output of the Stirling cooler and the electrical power output of the Stirling engine recorded during a 9 hour test run in June 2005. During this period, the plant operated at about 90% of its nominal capacity, which was due to necessary adaptations of the control system made at that time. The total heat output of the plant was approx. 210 kW (nominal heat output of the plant ~250 kW), with the Stirling cooler contributing about 90 kW (nominal Stirling heat output ~105 kW). The maximum temperature of the cylinder heads was set to approx. 650°C, which is below the maximum full load operating temperature of 680°C. Based on these first operating data, the average efficiencies result in an electric efficiency of the Stirling engine of about 27%, an overall electric efficiency of 13% and an overall plant efficiency of 92%. This exceeds the expected electric efficiencies of the engine (25%) and the plant (11%). Due to the early stage of the test runs and the clean Stirling heater the efficiencies may change during continuous operation. However, during this test run the plant reached the nominal electric output of 35kW_{el} which demonstrates the potential of the newly developed CHP technology based on a 35 kW_{el} Stirling engine. At full load operation it should be possible to even exceed the nominal electric power output of 35kW at normal operation.

A performance evaluation of the newly developed cleaning system cannot be considered due to an insufficient number of hours of operation. Up to now the plant has achieved about 100 hours of a successful operation. In summer and autumn 2005 comprehensive tests runs are planned in order to optimise the efficiency of the plant and to examine the performance of the newly developed cleaning system.

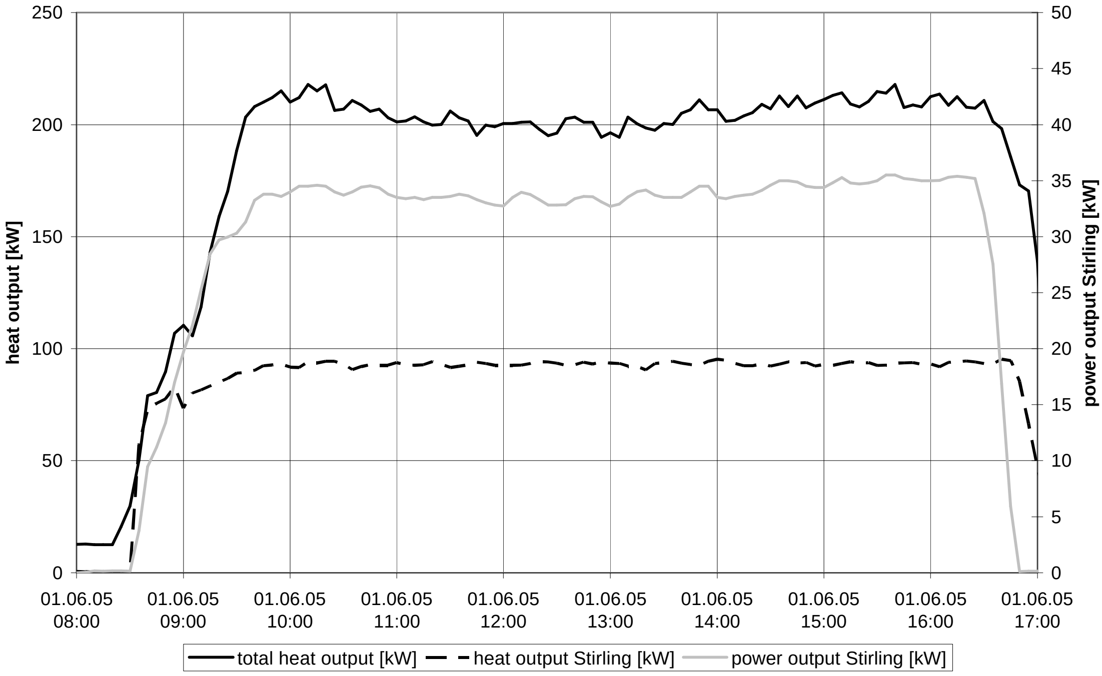

Figure 12: Operating data of the pilot plant (average net return temperature 52°C; average net feed temperature 62°C)

SUMMARY AND CONCLUSIONS

The CHP technology based on Stirling engines, which has already been successfully demonstrated in the past few years, was further developed and optimised within the scope of the project presented. In this respect, a new Stirling engine heater and a fully integrated automatic cleaning system for this heater was developed and designed.

The new Stirling heater was developed in order to guarantee a highly uniform and efficient heat transfer from the flue gas to the internal working gas of the Stirling engine in order to enhance the electric efficiency of the Stirling engine. Furthermore, an efficient automatic cleaning system was developed in order to reduce ash deposition problems on the Stirling heater tubes and increase the intervals between manual cleaning, thus and improving the availability of the Stirling engine.

First operating experiences at the newly erected pilot plant showed that the initial design targets in terms of efficiency and electric power output can be achieved. The nominal electric output of 35kW$_{el}$ was reached during the first days of operation even though the plant was operating only at about 90% of the nominal load. Even better results are expected at full load operation, which will be tested within the next months.

The newly developed automatic cleaning system will be intensively tested in summer/autumn 2005. It is expected that the performance of this system will be considerably better than the system installed at the first prototype plants.

The CHP technology based on Stirling engines has already been successfully demonstrated at two prototype plants with a nominal electric capacity of 35 and 70 kW. These plants have been in operation for more than 9,000 and 3,000 hours, respectively, since June 2005. The new Stirling heater and the cleaning system for this heater developed within the scope of the project presented can be considered as an important step forward in improving the reliability and performance of the CHP technology based on Stirling engines for solid biomass fuels.

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