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CHP FROM UPDRAFT GASIFIER AND STIRLING ENGINE

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ABSTRACT: The combination of thermal gasification with a Stirling engine is an interesting concept for use in small combined heat and power plants based on biomass. By combining the two technologies a synergism can potentially be achieved. Technical problems, e.g. gas cleaning and fouling of the Stirling engine heat exchanger, can be eliminated and the overall electric efficiency of the system can be improved.

At the Technical University of Denmark a Stirling engine fueled by gasification gas has been developed. In this engine the combustion system and the geometry of the hot heat exchanger of the Stirling engine has been adapted to the use of a gas with a low specific energy content and a high content of tar and particles. In the spring of 2001 a demonstration plant has been built in the western part of Denmark where this Stirling engine is combined with an updraft gasifier.

A mathematical simulation model has been developed as a tool to analyse a system combining the Stirling engine with a gasifier. The paper presents simulation results for the demonstration plant at typical operating conditions. A result from the simulation is that a net electric efficiency of 17,7 % based on the higher heating value of the biomass is obtained. Finally the special features of a system combining thermal gasification and Stirling engine technology are discussed and the status of the demonstration plant is presented.

Keywords: Stirling engine, gasification, combined heat and power generation (CHP).

1 INTRODUCTION

An important step in order to replace fossil fuels with renewable energy is to incorporate the use of biomass in the electricity production system. A large effort is put into the development of small scale combined heat and power plants based on biomass gasification combined with an internal combustion engine. Another promising technology is Stirling engines for direct combustion of biofuels. So far the work has been concentrated on developing each of the two technologies, thermal gasification and Stirling engines, separately but only few attempts have been made to combine the two. However, a combination presents a number of advantages. Producer gas containing tar and particles can be used directly in a Stirling engine without further cleaning, and the combustion chamber of the Stirling engine can be simplified compared to a Stirling engine fired directly on biomass. Furthermore, the combustion can be optimised resulting in potential improvements of the overall efficiency.

As a part of the Danish national research and development programme for small scale CHP a new Stirling engine plant has been built in the western part of Denmark. The plant combines an updraft gasifier with a 35 kW_{el} Stirling engine. To analyse the system a computer based mathematical model of the energy system has been developed. A description of the system is given and results from the model are presented.

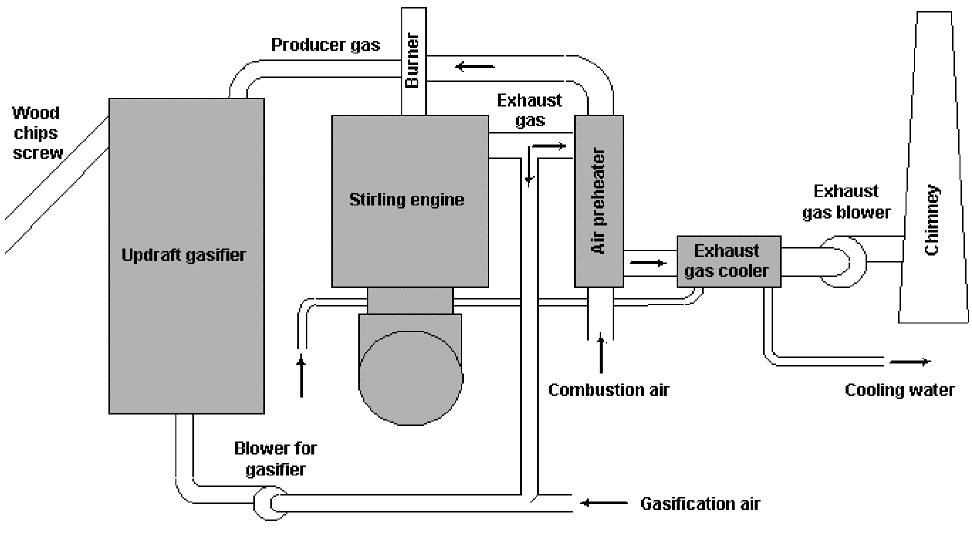

Figure 1: The energy system of the demonstration plant

2 DESCRIPTION OF THE DEMONSTRATION PLANT ENERGY SYSTEM

Figure 1 shows the design of the energy system of the demonstration plant. Wood chips are fed to the 200 $kW_{thermal}$ updraft gasifier with a screw conveyor. The produced gas containing tar and particles is mixed with preheated air in the burner and heat is transferred to the Stirling engine in the combustion chamber. The exhaust gas is split in two streams; one is used for preheating the combustion air and the other is mixed with air and is used as gasification agent in the gasifier. It is expected that approximately 15 % of the exhaust gas from the Stirling engine will be re-circulated to the gasifier.

The cooling water from the system is used in an industrial process where the temperature demand is low. The supply temperature of the water system for the industrial process is 40°C and the return temperature is 25°C.

As shown on Figure 1 the cooling water system is constructed as a serial connection of the Stirling engine and the exhaust gas cooler. The cooling water is first used in the Stirling Engine and then in the exhaust gas cooler. The water temperature is raised from 25°C to 40°C in the Stirling engine, and in the exhaust gas cooler the water is further heated from 40°C to 80°C. The 80°C hot cooling water is then lead to a 60 m^3 heat storage tank. When water is needed for the industrial process the water from the storage tank is mixed with the cold return water in order to obtain the required 40°C. This construction reduces the required volume of the heat storage tank, and at the same time it allows the Stirling engine to operate at a very low temperature on the cold side. The possibility for using low temperature cooling water in the Stirling engine increases the heat-to-electricity efficiency of the engine significantly.

Photos of the Stirling engine and the updraft gasifier of the demonstration plant are shown in Figure 2 and Figure 3.

Figure 2: Photo of the Stirling engine.

Figure 3: Photo of the updraft gasifier of the demonstration plant. The screw conveyor for the ashes is seen in the front of the picture and the wood chips screw conveyor can be seen in the background. The producer gas is taken out through the pipe in the top of the gasifier.

3 THE STIRLING ENGINE

The 35 kW Stirling engine is a four cylinder double-acting engine. It has been developed at the Technical University of Denmark as part of the Danish development programme aimed at using Stirling engines for combined heat and power production based on biomass.

The use of biomass as fuel sets a number of special demands for the combustion and heating system of the Stirling engine. In the design of the 35 kW Stirling engine the process has therefore been to design the heating system first and then adapt the engine design to the heater. Biomass needs more space in the combustion chamber than fossil fuels and the required area of the heat exchanger is therefore large. When using biomass as fuel there is a high risk of fouling of the heat exchanger and it is thus necessary to use a less compact heater in order to reduce the risk of fouling. Figure 4 shows the design of the heater.

Figure 4: Two photos of the heater tubes of the Stirling engine. The four cylinders of the Stirling engine can be seen in the middle of the top picture. A sheet of heat resistant stainless steel separates half of the heater tubes from the combustion chamber and these tubes are therefore not exposed for radiation from the chamber.

Of the heater tubes only about two thirds are exposed for radiation. The remaining tubes are separated from the combustion chamber with a steel sheet. The hot combustion products radiate heat to the exposed heater tubes and are then lead past the remaining heater tubes where heat is transferred mainly by convection. An aim of the combustion system design is to ensure that the heat load is distributed evenly between the 23 U-shaped heater tubes of each cylinder. For further information about the Stirling engine design, see [1].

4 FEATURES OF THE COMBINATION OF GASIFICATION AND STIRLING ENGINE

The characteristics of the Stirling engine introduce a new angle of attack on the traditional problems in thermal gasification of biomass. The effort has so far been put into developing systems where the producer gas is used in an internal combustion engine. In that case the aim has first of all been to produce gas with a very low content of particles and tar that are harmful to the engine. Furthermore, the gas must be cold and have a heating value as high as possible in order to get the highest possible performance of the gas engine.

It is very troublesome to achieve sufficient gas cleaning for updraft gasifiers, which produce gas with a high tar content. Even if the tar cleaning can be achieved in a reasonable manner energy is lost when the tar is taken from the gas. By combining the gasifier with a Stirling engine the requirements of the producer gas are different than those mentioned above. As the gas is burnt in a combustion chamber it does not need to be particularly clean. In other words all the tar can be converted to useful energy.

For the same reason it is an advantage to have a high temperature of the gas. A high gas temperature can even (to some extent) compensate for a low heating value. However, under normal operating conditions of existing updraft gasifiers the temperature of the producer gas is low. Therefore a new question concerning updraft gasification arises in order to improve the overall electricity efficiency of the system: In relation to gas engine operation it is of no interest to produce a gas with a high temperature, whereas in relation to Stirling engine operation that is of major interest.

5 SIMULATION RESULTS FOR THE DEMONSTRATION PLANT

A steady state model of the energy system has been developed. The mathematical model is primarily based on energy and mass balances and consists of blocks describing the main components: Gasifier, combustion chamber, the Stirling engine and heat exchangers. For a detailed description of the model, see [2].

The updraft gasifier is modelled by using empirical data for the composition of the pyrolysis gas and by assuming equilibrium in the water gas shift reaction that is taking place in the gasification of the char. The gasifier model is a development of models reported in [3] and [4]. In the model of the combustion chamber of the Stirling engine the combustion chamber engine is split into two parts: a part where heat is mainly transferred by radiation and a part where heat is mainly transferred by convection. The Stirling engine block is based on a sophisticated, dynamic model combined with experimental results.

The model has been used for simulating the operation of the demonstration plant under stationary conditions. The results can be seen in Figure 5 below. The figure shows the different calculation modules and the mass and energy flows that connect the modules. In the figure the modules “combustion chamber” (radiation part) and “heater” (convection part) together represent the combustion chamber of the Stirling engine. Under the given circumstances 52 % of the heat transferred to the heater tubes of the Stirling engine is supplied in the radiative part of the chamber and 48 % is transferred in the convective part.

The net electric efficiency of the system is calculated to be 17,7 % based on the higher heating value of the biomass and the total energy conversion efficiency is 75,3 %. The electric efficiency (heat to electricity) of the Stirling engine is calculated to be 30,6 %. A significant part of the energy in the fuel is therefore lost in the combustion and heat transfer system outside the Stirling engine. The temperature of the exhaust gas when it leaves the air preheater is as high as 458°C and it represents the main loss from the electricity producing part of the system.

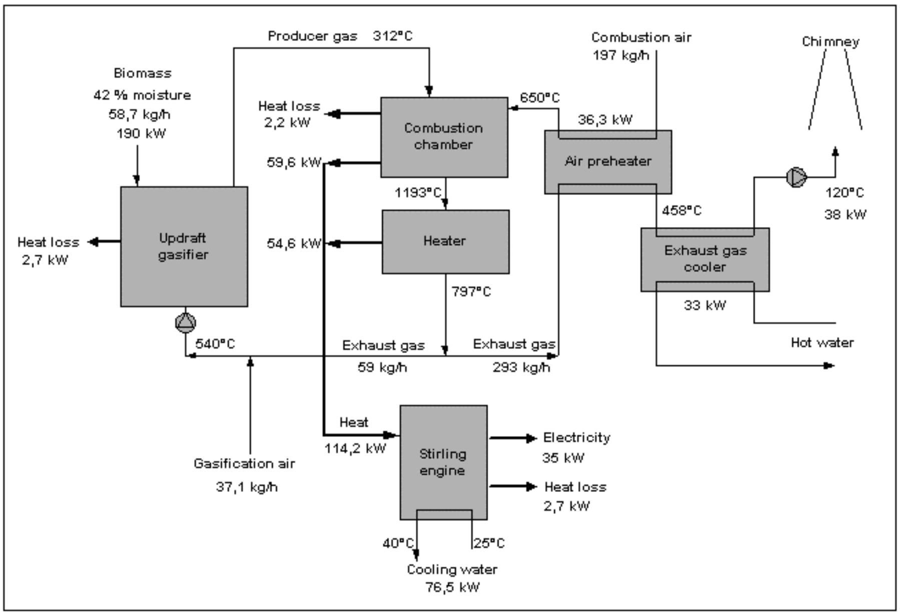

Figure 5: Results from the simulation of the demonstration plant. The thin lines represent mass flows in the system and the thick lines illustrate energy flows.

6 STATUS OF THE DEMONSTRATION PLANT

The demonstration plant has not yet proven the simulation results. Run-in of the gasifier and the boiler took place in the middle of 2001 and the first runs with the Stirling engine immediately after. So far 350 hours of operation has been achieved with the Stirling engine fired with gasification gas. For the first 200 hours it was necessary with approximately 5 % propane to support the combustion. Then the burner was rebuilt, and for the last 150 hours propane gas has only been used for the start up of the system.

A power output of 36 kW calculated as a mean value over 20 minutes of operation has been achieved using gasification gas only. The heat output from the plant is approximately 130 kW indicating an efficiency of 18%.

Until now hot exhaust gas has been used as gasification agent in the gasifier. However, it was found that hot exhaust gas for gasification made the temperature in the gasifier difficult to control. The plant is therefore been further rebuilt, so that it is now possible to test the system with cold exhaust gas for the gasification. A comparison will be made between tests with the two different possibilities for exhaust gas temperature.

A measuring programme is now initiated to verify the mass and energy balance of the system and to investigate the emissions from the plant. When the test program is finished a field test is initiated, in order to obtain experience from operation over a longer period.

7 CONCLUSIONS

A new type of combustion system for the Stirling engine has been developed and a demonstration plant has been built to test the system. The system combines an updraft gasifier with a more traditional gas burning system. Thereby the traditional gas cleaning problems are eliminated and a high producer gas temperature is now an advantage for the electric efficiency of the system. A steady state computer model of the system has been built in order to analyse the system. Simulation of the plant operation gives a net electric efficiency of 17,7 % based on the higher heating value of the biomass.

The demonstration plant has not yet fully proven the simulation results. However, 350 hours of operation has been achieved with the Stirling engine fired with gasification gas, and a power output of 36 kW has been achieved using gasification gas only. The heat output from the plant is approximately 130 kW indicating an efficiency of 18%.

A measuring programme has been initiated to verify the mass and energy balance of the system and to investigate the emissions from the plant.

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