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Performance of a flexible CHP gasification plant

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Abstract The Harboøre combined heat and power (CHP) plant supplied by Babcock & Wilcox Vølund ApS has been in commercial operation in several years using wood chips as fuel. The gasifier at the plant has operated 100 000 hours, and the two gas engines have been running more than 36 000 hours simultaneously producing power. In 2003 a 4 hours performance test was carried out recording the plant's environmental and energetic performance. This paper reports the results of this test. During the test the plant had a power efficiency (gross) of 29 % and 52 % of the energy going to district heating. The remaining 17 % was stored as a heavy tar. The plant's ability to ramp up and down from almost zero to 100 % within minutes combined with the possibility of storing energy as heavy tar offers a unique flexibility.

Keywords: Gasification, Updraft gasification, Wood chips, Biomass, Combined heat and power.

1. INTRODUCTION

Since 1988 Babcock & Wilcox Vølund ApS has been active in the field of gasification focusing on updraft gasification of biomass and has, recently, licensed its gasification technology to the Japanese company JFE Engineering Corporation.

Over the years a series of studies have been made in pilot-scale up to a 1 MW_{TH} on updraft gasifiers. In 1994 Babcock & Wilcox Vølund ApS was awarded a contract for a full scale updraft gasifier system for district heating in the village Harboøre. The plant was in operation in 1996.

The Harboøre plant is located in a village, Harboøre, on the western shore of Denmark. An image of the plant is shown on Figure 1. The plant was originally intended solely for heat production for the village district heating grid and was build as such. Some years later in the year 2000 the plant was added gas engines for combined heat and power production. Therefore, the offset for the plant is firstly to produce heat for the local village, and secondly to produce electricity and sell it to the grid. The plant is not producing electricity without simultaneously producing and supplying heat which naturally limits the production of electricity due to the seasonal fluctuations in the heat consumption (Denmark has a temperate climate).

The Harboøre plant has been in operation with heat production since 1996, and it has been operating with power production since year 2000. The gasifier has now been operated 100 000 hours and the engines have more than 36 000 hours of operation up to today delivering more than 16 000 MWh to the power grid. The plant is still in continuous commercial operation. In 2003 a comprehensive performance test was made on the plant. This paper describes the flexibility of the Harboøre plant as a representative of an energy system based on an updraft gasifier and the performance hereof based on the performance test.

Figure 1. Image of the Harboøre combined heat and power plant.

2. PLANT DESCRIPTION

The Harboøre plant can for the convenience of this paper be divided into the following main components:

- A 4 MW_{TH} updraft gasifier with fuel feed, ash system, and air humidifier
- A gas cooling and cleaning system
- Two gas engines with generators and exhaust boilers
- A Tarwatc system
- A heavy tar fired boiler with storage tank for heavy tar
- A product gas fired boiler

On Figure 2 a schematic representation of the system is shown.

The system is fed with wood chips converted in the gasifier with hot humid air to a product gas that leaves the gasifier in the top. An ash is continuously removed from the grate in the bottom of the gasifier. With the product gas also aerosols and tar droplets leaves the gasifier. These impurities are removed in the gas cooler and cleaning system. The result is a product gas free of tar and aerosols, a heavy tar fraction, and an aqueous phase with a high content of soluble organics.

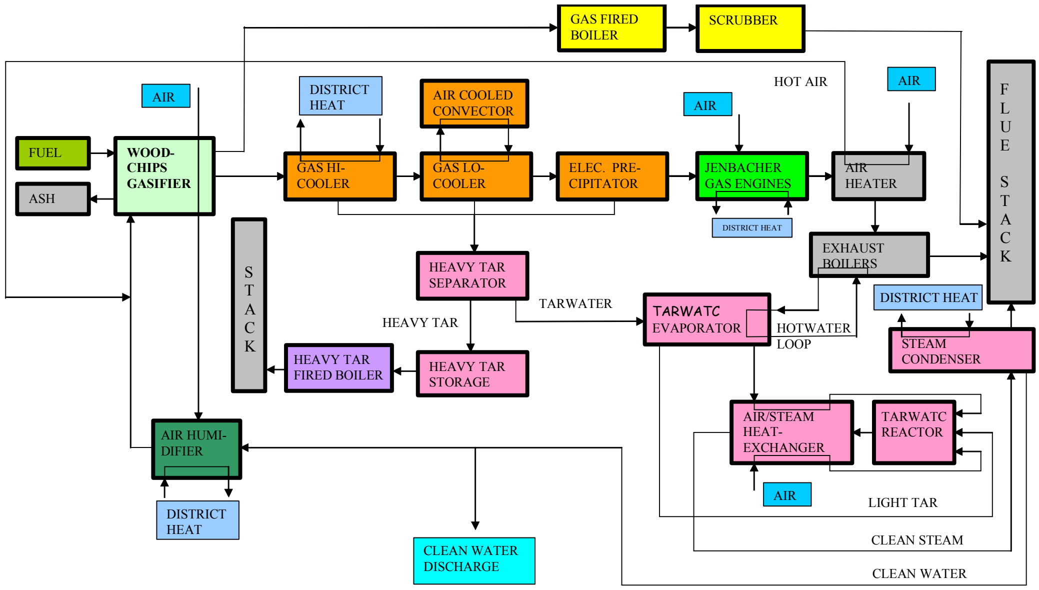

Figure 2. A schematic drawing of the Harboøre CHP plant.

The heavy tar is stored and is used as an auxiliary fuel in a separate heavy tar fired boiler for peak loads and during maintenance of the rest of the system.

The aqueous phase is handled by the Tarwatc system (TAR-WATer Cleaning system), which in principle is a thermal treatment utilising the organic pollutants of the aqueous phase as energy source. The effluents from the Tarwatc system are a flue gas and a condensate consisting of water with only traces of contaminants.

The product gas is used to power two Jenbacher engines with a maximum rating of 648 and 768 kW_E powers. The engines supplies heat for the district heating grid, air preheating for the gasifiers supply of hot humid air, and energy for the Tarwatc system. The latter is subsequently recovered in the flue gas cooler/condenser of the Tarwatc system.

As the plant originally was intended solely for heat supply, it is also equipped with a boiler that can be fired with the product gas. This boiler is used during outages and maintenance on the gas cooling and cleaning system, Tarwatc system and gas engines as no cleaning of the product gas is needed when the product gas is lead to the gas fired boiler. The gas fired boiler is equipped with a scrubber system for flue gas cleaning, which results in a wastewater with a low content of contaminants and is discharged to the sewer with no need for additional cleaning.

3. PERFORMANCE TEST

The performance test had a duration of 4 hours. In this paper the results of the performance at the gas fired boiler are omitted.

Due to practical reasons (one being the actual heat consumption in the village at the time of the test) the performance test on the heavy tar unit was carried out some months after the test on the gasifier/gas engine system. Hence, the heavy tar produced during the test was registered, but not fired simultaneously in the heavy tar fired boiler.

The load of the system was set to 1.0 MW_E. This load corresponds to a fuel input of 3.52 MW which approximately is the MCR (max continuous rating) of the plant on a fuel with properties shown in Table 1. The resulting load of the engines was approx. 100 % load of one engine and 50 % on the other engine (the engines capacity is over-sized).

The wood chips used during the performance test had the specifications shown in Table 1.

Table 1. Specification of the wood chips used as fuel during the performance test.

	Unit	Wood chips
Fuel flow	kg/h	1461
$H_{n,daf}$[1]	MJ/kg	20.24
$H_{n,ar}$[2]	MJ/kg	8.68
Ash	% w/w(dry)	1.0
Water	% w/w	50.4

[1] daf: dry and ash free.
[2] ar: as received

During the test the composition of the product gas, the exhaust gas from the gas engines, and the flue gas from the Tarwatc system was continuously registered. The flow of the product gas was registered. The flows of liquids from the gas cooler and cleaning system and Tarwatc system have been registered, sampled, and analyzed.

The performance test on the heavy tar fired boiler included sampling of the heavy tar, feed flow of heavy tar, and flue gas composition and flow.

4. RESULTS

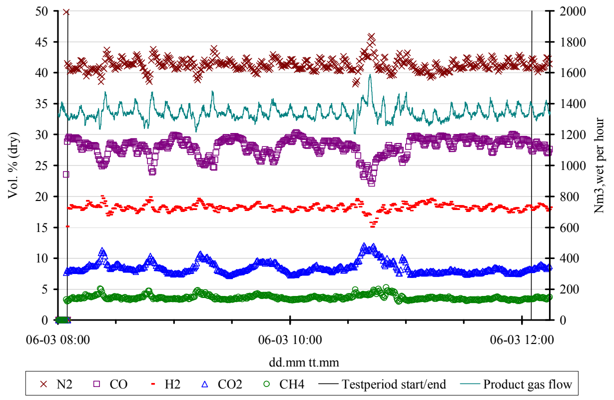

Figure 3. Composition and flow of product gas during the performance test.

Figure 3 shows the composition and variation of the product gas during the performance test. The average composition of the dry product gas is 18 % H_2, 28 % CO, 8.5 % CO_2, 0.4 % O_2, 3.7 % CH_4, and the balance N_2. The temperature of the product gas at the outlet of the gasifier is 73-76 °C. Overall it can be noted that the gasifier is capable of producing a constant flow of product gas with a constant composition and thereby enabling the gas engines to run with a steady power production. During many years of experience with the up-draft gasifier it is not surprising that a constant product gas of high quality can be produced.

Table 2. Emission from one of the gas engines (gas engine 1), the Tarwatc system, and the heavy tar fired boiler. The figures are averages for the test period as $mg/Nm^3_{dry,\ 10\ \%\ O2}$.

	Gas engine	Tarwatc system	Heavy tar
CH_4 – C	53.1	17.4	
CO	1488	1023	5.4
NO_x - NO	229	149	492
Dust	0.5	15.4	6.6

Table 2 shows the emissions from one of the gas engines. A minor part of the exhaust gas is lead through a catalyst to reduce CO emission. This has proven to reduce the CO emission from the prior level of 2200-2500 $mg/Nm^3_{dry,\ 10\ \%\ O2}$. A future modification of the plant could be to fit a full size catalyst on both engines.

The aqueous phase handled by the Tarwatc system has an content of organic carbon of 4 % (w/w). This is mainly aliphatic acids such as formic acid and acetic acid and tar in emulsion (mostly phenol).

Table 3. Analysis of the condensate from the Tarwatc system. The results are averages of 5 analysed samples.

Parameter	Unit	Data
Flow	m^3/h	0.2
pH[1]		4.9-7.1
COD[2]	mg O_2/l	47
Acetic acid	mg/l	10
Formic acid	mg/l	2.3
Phenol	mg/l	39
Total N	mg/l	50

[1] pH er målt on-site stikprøver gennem alle delperioder
[2] COD: Chemical Oxygen Demand

Part of the condensate from Tarwatc with a composition as shown in Table 3 is used for humidifying air for the gasification air, and the remaining part is discharged to the sewer after a neutralisation (just in case the condensate has a pH below 6).

The heavy tar has a water content of 7.6 % (w/w) and a H_n of 29.9 MJ/kg. The latter being based on a hydrogen content of 6.5 % (w/w, dry), which equals a composition with 95 % phenols and 5 % acetic acid. This is a simplification as the heavy tar is composed of multiple organic substances but dominated by phenols.

In Table 4 the heat production of the individual components is shown. During operation of the gasifier and gas engines the heavy tar fired boiler will usually not be in operation as the Table could suggest. The heavy tar fired boiler is operating when additional heating is needed in a peak load situation or during maintenance on the gasifier system. However, to evaluate the total system the heat from the heavy tar fired boiler is included. In Table 4 it can be seen that energy can be accumulated in the Tarwatc system. The Tarwatc system contains two buffer tanks and the variation in the content of these was taken into account during the performance test. However, the total amount of potential heat produced can differ slightly due to difficulties in exact determination of the content of the buffer tanks and the amount of heavy tar produced.

Table 4. Heat production of the Harboøre plant divided on the individual components.

Gas engines	Tarwatc	Heavy tar fired boiler[1)]	Product gas cooler	Accumulated in Tarwatc buffers	Plants own consumption	Used to the gasification air	Produced in net total
971 kW	725 kW	610 kW	373 kW	- 112 kW	22 kW	119 kW	2426 kW

[1)] Based on a fictive situation in which the heavy tar is combusted in the boiler with an efficiency of 91.5 % and at the same rate it is produced in the gas cooling system.

Table 5. The production heat and electricity related to the input of fuel as a percentage.

Input	Heat from Gasifier/gas engines[1]	Heat from heavy tar[2]	Electricity from Gas engines[3]	Heat from Gas fired boiler[4]
100 %	52 %	17 %	29 %	
100 %				103 %

[1] The net total heat production during operation of the gasifier with gas engines. This includes heat produced from the product gas cooler, gas engines, Tarwatc, accumulated in the buffer tank in the Tarwatc system, and taking into account the heat used for heating the gasification air system.

[2] An efficiency of 91.5 % is used, which was determined during the performance test by the indirect method.

[3] The gross electricity produced (1005 kW) and distributed to the grid.

[4] The gas fired boiler (condensing operation) has an efficiency of 103.5 %, which has been determined in a performance test not reported in this paper.

The ash was analyzed and had a content of TOC of 7 g/kg_{dry}, PAH of 0.43 mg/kg_{dry} (mainly Phenanthrene 0.14 mg/kg_{dry}, and dioxin below detection limit (0.3 ng/kg_{dry} for 1,2,3,7,8 PCDD).

Based on the experiences with the Harboøre plant over the years the performance of the plant during the test was as expected.

5. ADVANTAGES AND APPLICATIONS OF THE GASIFICATION TECHNOLOGY

As it can be seen from Table 5 the gasifier system offers flexibility with regard to heat and power production due to the possibility of storing or exporting approx. 17 % of the energy output as heavy tar.

A variable not included in the performance test is the gasifier's ability to ramp up and down. Compared to a traditional combustion based boiler the gasifier in connection with gas engines can operate down to approx. zero load and can ramp up and down from almost zero load to 100 % load in minutes. Presently, the ramp-up time is 15 minutes but this is set to comply with the specifications of the gas engines and not the gasifier. In its present operation the plant is running 100 % load on the gas engines during the winter and then using the heavy tar in especially cold periods. In the summer time the heat uptake in the village is very low, and the plant is running with heat production of 600-700 kW and operating with a little less than 50 % load at one of the gas engines. Hereby, the system's ability to offer a flexible energy supply is illustrated with relatively high power efficiency even at e.g. 25 % load and in compliance with the Kyoto protocol.

6. FUTURE IMPROVEMENTS

During the years of operation the plant has been continuously optimised. However the plant is a first of a kind in continuous full scale operation, therefore, there are still a range of possibilities for improving the plant. These include:

- Improved automatisation and service planning
- Condensing operation on the gas engine exhaust and heavy tar fired boiler.
- Optimisation of plants own consumption of electricity
- Full size catalyst system on the gas engines

A future development could be an utilisation of the heavy tar. Instead of using it as a conventional fuel it can be gasified, which potentially will raise the power efficiency of the total system to 31-32 %. Pilot-scale studies performed by Babcock & Wilcox Vølund ApS have proven successful with gasification of heavy tar in an entrained flow gasifier.

ACKNOWLEDGMENTS

The performance test was done with the support of the Danish Energy Agency.