Design and operation of a local cogeneration plant supplying a multi-family house (9,5 kW electrical / 35 kW thermic power) – a field report

Thomas Schuster
Department of Electrical Drives and Machines, Graz, University of Technology,
Kopernikusgasse 24, 8010 Graz, (*Austria*)

***Abstract*-- In this paper, design and operation of a small co-generation biomass plant 'Turdanitsch 2' is presented. The plant, powered by woodchips, is suitable to maintain heat supply for a three family house. It is capable of delivering 9.5 kW electrical power to the mains and 30 kW thermal power used for heating the domestic hot water and the building respectively. A detailed description of the plant is followed by a description of the efficiency measurement setup.**

Practical experiences from two years of operation and measurements concerning the electrical as well as the thermal efficiency are presented.

Financial figures of the year 2008 are presented, showing the profitability for the prototype plant.

***Index Terms*— Cogeneration, Renewable sources, Biomasses, Heat generation.**

I. Introduction

The efficiency of electric power generation via caloric power plants is quite low. After over hundred years of improvement the highest reachable degrees of efficiency are about 46% with coal-fired power plants, 58% efficiency can be reached by gas-steam power plants [1]. Producing electric energy from wood by steam or ORC power plants reaches by the current state of technology only about 17-18% efficiency [2]. The overall efficiency can be increased significantly if the rejected heat is not just blown to the environment but used for heating purpose. So in order to utilize the primary energy carrier more efficient, more and more existing district heating grids in Austria are fed from the rejected heat of large and medium scale caloric power plants.

This concept is not suitable for rural (sparsely populated) regions as the heat transport via district heating grids in this case is highly unprofitable.

Secondary especially in agrarian regions most farmers are well provided with heating material from their forests (wood) or fields (e.g. straw) and therefore not interested in a comfortable but for them more expensive heating facility.

In order to reduce the costs for heating of a three family house (lived-in by my parents and brother), for the preparation of the domestic hot water and in order to generate electrical power a cogeneration plant named "Turdanitsch 2" has been planed and built up.

Building up as well as operation of the plant proof that the concept of combined heat and power generation is efficient even for small scale units.

At present no plants providing about 10kW electrical and 30kW thermal power are purchasable. Therefore a prototype had to be designed and built up. The concept of powering the plant by utilizing woodgas was chosen as the efficiency obtained with small units is higher than by using steam or ORC processes. The cogeneration plant was planed as an easily to be operated, low maintenance and reliable unit. This could be confirmed during the last two years since beginning of operation.

II. Concept of the Plant

Figure 1 shows the functional overview of the cogeneration plant "Turdanitsch 2".

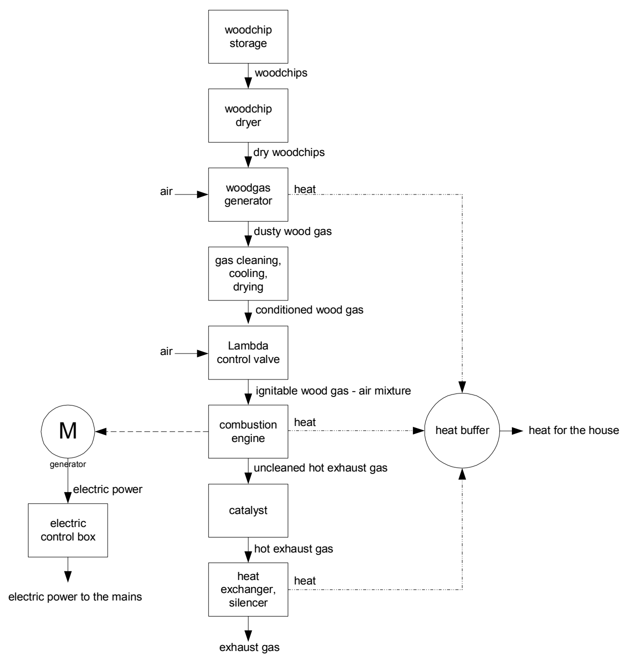

Fig. 1. Functional overview of the cogeneration plant

The basic concept of the plant is to fuel an internal combustion engine with gas produced from wood chips (woodgas). The combustion engine drives an electric generator, the produced electricity supplies the household. The excess electric power is fed to the power grid. The emerging heat is used for heating purposes.

The plant is heat controlled, if no heat is needed the plant stands stil.

III. Detailed description of the plant

A. *Process of wood gasification*

Wood chips are used as energy carrier. These are small pieces of wood produced by shredding waste wood from thinning the forest or the sawmill industry. In the presented power plant, the wood chips are transported automatically from the storage room via the drying unit into the woodgas generator. The dimensioning and construction of the woodgas generator was first taken from [3]. The gas quality of this design was insufficient and the produced amount of wood tar destroyed the internal combustion engine after few hours. It turned out that reaction temperatures had to be about 1400°C to generate tar-poor gas. The whole gasifier had to be completely redesigned to generate tar-poor gas of sufficient quality. (Theory of Gasification [4]). The achieved temperatures are dependent on the gas flow. For this design it is essential to keep the gas flow constant to asure high reaction temperatures to reach sufficient gas quality. Furthermore it is not contemplated to latch gas in a gas buffer, so the gas has to be consumed continuously by the internal combustion engine. Because it's not possible to change the gas flow rate in the reactor the electrical and the thermal output power of this plant can not be adjusted easily.

B. *Gas conditioning*

The gas emerging from the wood gas generator still has a temperature of about 800°C and is loaded with soot particles. A heat exchanger from a central-heating boiler is used to cool the gas down to about 150°C to raise the gas density. The emitted heat energy is given to the domestic heating water. The gas then passes a cyclone and an electrostatic filter system to separate soot particles. A second wet cooling system cools down the gas to about 60°C to let water vapour condensate. The moisture contended in the gas is then intercepted in a demister.

Now the clean and dry gas is mixed with the right amount of air to achieve an ignitable mixture. The necessary amount of oxygen is determined and adjusted automatically by a lambda feedback control.

C. *Internal combustion engine*

The ignitable air gas mixture is then fed to a standard combustion engine which has been dismounted from a motorcar. The engine is a Otto gasoline engine with six cylinders and two valve technology.

For wood gas combustion the ignition timing has been adjusted and spark plugs with low heat rating have been installed, because wood gas burns slower and "colder" than gasoline.

Under standard working conditions the engine makes about 1500-1600 revolutions per minute. This is just a little bit above idle speed, which reduces oscillation losses and permits good combustion of the slow-burning wood gas. Another effort of this slow speed is that wear out of the engine is slow. The disadvantage is, that an engine, designed for gasoline, producing 139 horsepower at 4000 revolutions per minute, powered with wood gas at about 1500 revolutions per minute, brings only 15 horsepower to the shaft, but this continuously.

The combustion engine powers an induction generator which is connected to the three phase mains power.

Due to there is no possibility to control the electric output power, stand alone operation is not possible. The power grid has to take up the excess electric power, if it fails, the plant switches off.

The rejected heat of the combustion engine's cooling water is fed via heat exchanger to the heating water.

To ignite the wood gas generator the combustion engine is bypassed with a fan. This electric fan stets the whole system under vacuum and allows fast start-up of the gas generator. After about 2 to 5 minutes the wood gas is combustible. The engine is started by the original 12 Volt electric starter motor powered by an automotive battery.

D. *Exhaust gas treatment*

The hot combustion gas from the internal combustion engine passes the lambda probe and is after treated in a standard three-way catalytic converter in order to reduce the anyway low CO and HC percentage. A heat exchanging device extracts further useable warmth from the combustion gas and feeds the central heating. After this treatment the utmost temperature of the combustion gas is about 60 degree Celsius. The subsequent muffler reduces the acoustic emission to a scarcely audible measure.

E. *Generator*

An induction machine with 1500 revolutions per minute idle speed (4 poles) has been chosen as generator. Compared to a synchronous generator, one big advantage of an induction generator is that switching the generator to the mains is much more easily. Neither rotor speed nor polar wheel angle has to be controlled very accurately. A second advantage is that no excitation device has to be provided.

The induction machine used is designed to be run as a motor and features a nominal voltage of 420V. As the mains voltage is only 400V, the machine's magnetization state and the magnetizing current are not too high. This is essential for low iron and copper losses in generating mode.

By now the frequency of the ignition pulses of the combustion engine is measured to calculate the generator rotor speed. If, during start-up of the combustion engine, the rotor speed reaches 1500 revolutions per minute, the induction machine is switched to the mains.

In a second stage of expansion a rotor speed measurement unit is designed that allows to measure the speed from the voltage induced into the stator windings by residual magnetism. With this the switching of the generator to the mains can be carried out more smoothly.

The excess electric energy produced during operation of the plant is applied to the public mains. Parallel main operation is carried out.

In order to reduce the reactive power that has to be provided by the public mains, capacitors are switched in parallel to the induction machine after connecting the machine to the mains.

Voltages and frequency of the mains are monitored as required by the Austrian ‘technical and organisational rules for operators and users of power grids’. [5] If the power grid fails the plant has to shut down immideately. If mains is stable for at least 10 minutes the plant can be started up again.

F. Heat Treatment

The rejected heat of the wood gas generator, the combustion engine’s cooling water and the heat of the exhaust gases are fed via heat exchangers to the heating water.

Power modulation is not advisable due to the underlying concept, so an buffer storage of 4m³ heating water is used to meet the different heat quantity requirements of the house.

For efficient use of the produced thermal energy, the plant has to be operated in a heat led mode.

If heat requirements can not be covered by the heat stored in the buffer, the plant has to be started.

During operation the rejected heat of the plant heats the house and the domestic hot water. The excess heat which cannot be used during operation is stored in the heat buffer. If heat consumption of the house is too low and the heating water storage buffer is hot enough, the combustion engine cannot be cooled down any more. The temperature of the engine rises, and if it comes above 95°C the plant shuts down automatically.

During standstill of the plant the house is heated using the previously heated up buffer storage. In this case no electrical power is generated. As there is no electric energy storage system implemented, it is necessary that during standstill of the plant the electric power company provides the necessary electric energy for the house. This applies for the whole non-heating period during summer too.

IV. Operation experiences

Building up of the plant started in January 2005. During spring 2006, extensive test runs were done. In Summer 2006, after considerable tests carried out by the local energy supply company (Kelag), the plant was switched to the mains.

By now the plant has reached over 3500 operating hours. The plant is only in operation during winter, when heat is required.

During winter 2006-2007 and 2007-2008 no major faults occurred.

The first and only bigger breakdown occurred in December 2008. At about 3000 hours of operation the timing belt of the internal combustion engine ripped off during operation. This caused extensive damage of the engine. The engine was then replaced with a new used-one of the same type within one day. The reason of the breakdown was caused by insufficient service of the engine and not by wood gas operation.

Normal operation of the cogeneration plant is quite simple and done by laities. The work is reduced to about 15 minutes of preparation per start-up, and about 10 minutes for the starting procedure itself. If the plant is in operation, no further attendance is required. The plant stops and shuts down automatically when enough heat is generated or if faults occur.

One operation period takes about 2 to 4 days, depending on the amount of needed heat [6].

The preparation for start-up consists of cleaning up the gas filter system and the ashtray of the wood gas generator, and visually checking the whole system. The amount of work has been reduced to about 1-2 minutes by improvement of the gas filter system.

By now an automatically start up procedure, which could allow fully automated operation is not planned.

Figure 2 shows the plant at the development status of January 2008.

Fig. 2. The plant in January 2008.

V. Efficiency analysis

Efficiency analysis has been started in autumn 2008. For this purpose several additional energy-counters have been installed. The measurements are still in progress. Table I shows average efficiency data that has been determined by now.

The biggest inaccuracy with efficiency analysis is to determine the consumed energy of the plant. By now only the volume of the consumed woodchips is measured, with only rare information about the packing density. To weigh the consumed woodchips would be more precisely, but is not possible by now. The energy content of the consumed woodchips can not be determined exactly too. The moisture and the ligneous crop of the woodchips give only a weak hint to the energy content of the wood. Packing density, moisture content and ligneous crop are not homogenous, so just average values can be taken.

TABLE I
EFFICIENCY ANALYSIS RESULT

Consumed woodchips per hour	0.06483	m³/h loose
Woodchip moisture after dryer	18.26	%
Overall el. power dissipation	6.48	KW/h
Dissipated useful heat	26.55	KW/h
Electrical efficiency	13,32	%
Thermal efficiency	54,52	%
Overall efficiency	67,84	%

VI. EFFICIENCY IMPROVEMENT

Several experiments during efficiency analysis show that output power and efficiency could be increased by optimising the gas conditioning process. Cleaning the gas with lower flow losses could improve the filling of the cylinders of the combustion engine, which would result in higher power output and lower maintenance work. Better cooling of the gas will increase the gas density, which will improve performance too.

Modifying the compression rate of the combustion engine or turbo charging of the engine are further perspectives [7] to increase output power.

Another possibility of improvement is to optimize the exhaust gas heat exchangers, which will result in higher thermal power output.

At the electric part of the plant it turned out that during operation the plant consumes about 1200W per hour itself. Most of this power is used for transportation of the Woodchips, for electronics, water pumps and fans. There are few possibilities to improve the transportation of the woodchips at the prototype plant due to the spacious situation. But if the plant would be produced in series, the transportation process could be optimised. Electronics have to be checked for further improvement possibilities, some power supplies could be replaced by more efficient ones. Three water pumps are in use, even these pumps could be replaced by more efficient ones.

Figure 3 shows the plant with just implemented improvements concerning the gas conditioning system. This improvements reduced the amout of preparation work for startup significantly. Before changes the maintenance work was 15 minutes, now it has been lowered to a maximum of 2 minutes.

Fig. 3. The plant with improvements in February 2009.

VII. BASIC FINANCIAL CONDITIONS AND GOVERNMENT AID

Whereas the building up of commercially available biomass heating systems is funded, no government aid is available in case of self-construction prototypes.

The whole project as well as the research and development work carried out (the application of a patent is under examination) are financed privately.

The electric power is payed according to the austrian law concerning green electricity [8]. The fees are 0,12 €/kWh when using saw mill residue as a heating material and 0,16 €/kWh when using wood chips from the forest as a heating material [9]. The fee does not depend on time of day or season.

VIII. ONE YEAR FIGURES

In the year 2008 about 110m³ of wood chips have been consumed, which equals 7700 liters heating oil, or 77000 kWh primary energy. As wood is carbon neutral, an amount of 20 t of carbon dioxide a year is saved.

37708 kwh of heat have been delivered to the household.

9472 kWh of electric power have been generated, 8190 kWh have been delivered to the power grid.1281 kWh of the self-generated electric power have been used by the household during operation of the plant. 6657 kWh of electric power have been consumed by the household from the power grid during downtime of the plant.

It is remarkable that although the plant is only in operation during the heating period in winter, 1533 kWh more electric power is generated then used by the household over the year [10].

About 1400 Euro have been refound for the delivered electricity in 2008, the costs for the woodchips are about 1200 Euro. If we calculate the heat consumed by the household with 0,07 Euro per kWh (inclusive additional costs) [11], it comes to 2640 Euro.

Material costs for the prototype plant ‘Turdanitsch 2’ have been about 10000 Euro, the amount of work has not been taken into calculations.

Overall the price for the produced energy (heat and electricity) is 4260 Euro a year, for the costs of 1200 Euro for woodchips. The figures show that even the prototype plant is highly profitable, assumed that the generated heat can be utilised.

IX. FURTHER INFORMATION

Questions concerning the presented cogeneration plant “Turdanitsch 2” may be addressed to:

Thomas Schuster
Department of Electrical Drives and Machines
Graz, University of Technology
Kopernikusgasse 24, 8010 Graz, Austria
Phone: 0043 316 873 8605, Fax: 0043 316 873 108605
e-mail: thomas.schuster@tugraz.at
www.eam.tugraz.at

X. Conclusion

During winter 2006-2007 and 2007-2008 the cogeneration plant was under operation without major faults [10]. One bigger breakdown occurred in December 2008, due to service faults. In the meantime about 3500 hours of operation are reached.

The amount of maintenance is about 15 minutes per operating period. The operating period lasts about 2-4 days a week depending on the weather. The ease of servicing is still to be improved.

Even though the cogeneration plant "Turdanitsch 2" is just a prototype which works not yet at maximum possible efficiency, it could be shown that the concept of combined heat and power generation is efficient and profitable even for small scale units fed from biomass. The market price for wood chips makes the mere generation of electrical power from biomass unprofitable. The break even point can be reached easily when utilizing the rejected heat for heating purposes.

For rural regions with high potential of waste wood the presented technique could be an option, at raising energy prices, to increase the income for the population. In countries like austria where the majority of electric energy is produced by hydropower plants, wood gas cogeneration plants could support the hydropower plants in winter, when heat is needed and the water levels of the rivers are low.

References

[1] Verbund Austrian Thermal Power; *Gas-Kombikraftwerk Mellach,*18.01.2008, http://www.verbund.at/cps/rde/xbcr/SID-3E1B22D8-6137145A/internet/Folder_GKW_Mellach.pdf

[2] Antennen Umwelt Technik Becker; *Biomasse-Kraft-Wärme-Kopplung mit ORC-Prozess*, 25.01.2008, http://www.atb-becker.com/download/infobroschuere_orc_prozess.pdf

[3] LaFontaine, F. P. Zimmerman, *Construction of a Simplified Wood Gas Generator for Fueling Internal Combustion Engines in a Petroleum emergency*, THE BIOMASS ENERGY FOUNDATION PRESS 1820 Smith Rd., Golden, CO 80401

[4] Anil K. Rajvanshi, *BIOMASS GASIFICATION* , Nimbkar Agricultural Research Institute, PHALTAN-415523, Maharashtra, India, pp 2-7.

[5] E-Control; *Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen*, Version 1.3, Energie-Control GmbH, Rudofsplatz 13a, 1010 Wien, www.e-control.at

[6] Schuster T.; *Aufbau und Betrieb eines dezentralen Heizkraftwerks zur Versorgung eines Mehrfamilienhauses*, 10. Energieinnovationssymopsium, Graz 2008

[7] FAO Forestry Paper 72 M-38; *Wood gas as engine fuel*, ISBN 92-5-102436-7, pp 13-15

[8] Austrian law; *Ökostromgesetz*, BGBl. I Nr. 149/2002, §13.

[9] Austrian law; Ökostromverordnung 2006, BGBl. II, 24.10.2006 - Nr. 401

[10] Schuster T.; *Netzintegration aus der Sicht eines Klein-BHKW Betreibers,* 6. Internationale Energiewirtschaftstagung an der TU Wien, Wien 2009

[11] KELAG Wärme; *Fernwärmetarife Villach,* www.kelagwärme.at