Rapport SGC 168

THE POTENTIALS FOR INTEGRATION OF BLACK LIQUOR GASIFICATION WITH GAS FIRED PAPER DRYING PROCESSES

-

A STUDY FROM THE ENERGY COST PERSPECTIVE

Kristian Lindell and Stig Stenström
INSTITUTIONEN FÖR KEMITEKNIK, LTH

Rapport SGC 168 • ISSN 1102-7371 • ISRN SGC-R--168-SE

SGC Svenskt Gastekniskt Center AB

SGC:s FÖRORD

FUD-projekt inom Svenskt Gastekniskt Center AB avrapporteras normalt i rapporter som är fritt tillgängliga för envar intresserad.

SGC svarar för utgivningen av rapporterna medan uppdragstagarna för respektive projekt eller rapportförfattarna svarar för rapporternas innehåll. Den som utnyttjar eventuella beskrivningar, resultat e dyl i rapporterna gör detta helt på eget ansvar. Delar av rapport får återges med angivande av källan.

En förteckning över hittills utgivna SGC-rapporter finns på SGC´s hemsida www.sgc.se.

Svenskt Gastekniskt Center AB (SGC) är ett samarbetsorgan för företag verksamma inom energigasområdet. Dess främsta uppgift är att samordna och effektivisera intressenternas insatser inom områdena forskning, utveckling och demonstration (FUD). SGC har följande delägare: Svenska Gasföreningen, E.ON Gas Sverige AB, E.ON Sverige AB, Lunds Energi AB, Göteborg Energi AB, och Öresundskraft AB.

Följande parter har gjort det möjligt att genomföra detta utvecklingsprojekt:

Statens Energimyndighet
Lunds Universitet
E.ON Gas Sverige AB
Öresundskraft AB
Lunds Energi AB
Göteborg Energi AB
AB Fortum Värme samägt med Stockholm Stad

SVENSKT GASTEKNISKT CENTER AB

Jörgen Held

INNEHÅLLSFÖRTECKNING

1 Introduction

Black liquor gasification (BLG) has shown promising potential to replace the conventional Tomlinson boiler for recovery of the cooking chemicals and energy from the spent black liquor in the pulp and paper industry. The gasification process integrated with a combined cycle system (BLGCC) provides a higher power-to-heat ratio, improved environmental and safety characteristics and the possibility to make more efficient use of the energy available in the black liquor stream. In the gasification process the organic material is converted to a gaseous fuel which can be either used internally in the mill for power and heat generation or exported for use elsewhere, replacing natural gas or propane. The integration of the BLGCC system with the pulp and paper making processes has been thoroughly studied, but the paper mill is typically modelled as a specific steam consumption to describe the conventional steam heated multicylinder drying process. However, several other dryer types are available and some of these are gas heated, such as the Yankee dryer and the air impingement dryer. These gas fired paper drying processes may provide opportunities for more efficient energy integration with the black liquor gasification process.

According to a previous work (Lindell and Stenström, 2005), gas fired paper dryer sections may provide possibilities for increased overall energy efficiency for pulp and paper mills. The possibilities for efficient heat recovery were shown to be superior for a dryer section with combined cylinder and air impingement drying as compared with a conventional multicylinder dryer. In the same work it was however also concluded that the total energy costs are higher for the combined dryer section, despite the increased energy efficiency. The reason for this was found to be the use of natural gas, instead of low-pressure steam, to supply part of the energy required in the paper drying process. Natural gas is a more expensive fuel than bark and other biomass residues typically used for steam production in Swedish pulp and paper mills. In Sweden, energy and carbon dioxide taxes are charged for fossil fuels and since 2005 the cost for using fossil fuels has increased further due to the trade with emission allowances for carbon dioxide. In addition to being a more expensive fuel, the use of natural gas to fire paper dryers reduces the total steam demand in the mill. Also the power production in the backpressure steam turbine is reduced, on the assumption that the entire steam flow passes through the turbine. In-house power generation reduces the required amount of purchased power to the mill and may also provide the mill with so called green certificates. Green certificates can be obtained for electricity generated from renewable resources, for example black liquor, various biofuels and sun and wind energy. All electricity consumers in Sweden, except the electricity-intense industry, must buy such certificates amounting to a certain percentage of their electricity consumption. The incomes from the backpressure power are approximately 250-300 SEK/MWh for the power itself and additional 170-200 SEK/MWh for the green certificates. The cost for bark and biomass residues is approximately 120-150 SEK/MWh and power production from black liquor and biomass fuels is hence profitable for pulp and paper mills. Also, the cost for the low-pressure process steam will be very low. The use of natural gas instead of low-pressure steam in the paper dryer section therefore results in much higher total energy costs for the mill, which cannot be compensated for by the increased heat recovery from the gas fired paper dryers.

To improve the process economics for gas fired paper drying processes, such as the air impingement dryer or the Yankee dryer, alternative gaseous fuels to replace natural gas and propane should be considered. This gaseous fuel should preferably be renewable and suitable to fire a gas turbine cycle for combined heat and power generation. One such fuel could be the product gas from black liquor gasification.

In this work the possibilities for integration of the black liquor gasification process with the paper drying process were assessed based on overall energy costs for an integrated pulp and paper model mill, using computer modelling. The model mill included both the pulp and paper producing processes, and the paper mill included two paper machines; one conventional multicylinder dryer producing fine paper and one gas fired Yankee dryer producing tissue. Three different configurations of the combined heat and power plant were evaluated at a fixed pulp and paper production rate. The study was performed by computer modelling, using a modular simulation tool developed for energy use and cost analysis for the pulp and paper industry in the software entitled Extend (Lindell and Stenström, 2006). The work was performed with financial support from *The Swedish Gas Center* and will be presented at the 15th International Drying Symposium in Budapest, Hungary, in August 2006.

2 Black liquor gasification

Black liquor gasification has been proposed as an alternative process to the conventional recovery boiler technique for recovery of both cooking chemicals and energy from black liquor. During the many years of research and development spent on black liquor gasification several different process alternatives have been proposed. At present only two of these alternatives are considered for further research - one low-temperature process and one high-temperature process. In the low-temperature process the concentrated black liquor is fed to a fluidized bed steam reformer. In the reformer the organic components in the black liquor stream react with the superheated steam, which also acts as the fluidizing medium, to form a gaseous mixture. The gasification is carried out in absence of oxygen and the product gas is rich in hydrogen and the heating value is accordingly high. In the high-temperature process the organic matter in the black liquor is partly oxidized in air or in oxygen at approximately 900°C. The main combustible constituents in the product gas, the so called syngas, are carbon monoxide and hydrogen. Since the organic material is partly oxidized in the gasification process to maintain the required temperature the heating value of the syngas from the high-temperature process is lower than from the low-temperature steam reforming process. If the gasifier unit is air-blown the syngas will also contain approximately 50 % nitrogen, which results in a rather low calorific value.

The syngas from the gasification process can be used either as a fuel for direct heating of a process, for example for air heating in a paper dryer, or be burnt in a gas turbine for power production. The hot exhaust gases leaving the gas turbine at approximately 500-600°C can then be used to raise high-pressure steam in a heat recovery steam generator (HRSG) and the high pressure steam expanded in a steam turbine for additional power generation. This type of system is called black liquor gasification with a combined cycle, BLGCC. The advantages mentioned in the literature for the BLGCC process, as compared with the conventional recovery boiler and steam turbine, are increased energy conversion efficiency, enhanced electrical generation, reduced pollutant emissions and improved process safety (Malte and Nichols, 1998). Another advantage of black liquor gasification is the possibility to add cost-effective incremental recovery capacity for mills operating at their recovery boiler capacity limit (McIlroy and Wilczinsky, 1999).

2.1 Process steps in the BLGCC system

Figure 1 shows a BLGCC system based on the high-temperature gasification process as proposed in the literature (Eriksson and Harvey, 2004). The concentrated black liquor stream is fed to the gasification unit together with the oxidizing media, in this case oxygen. The oxygen is produced in a cryogenic air separation unit (denoted ASU in the figure). The organic matter in the black liquor is partly oxidized in the gasifier, which maintains the required temperature in the reactor, and a smelt is produced from the inorganic substances. This smelt is cooled rapidly in the lower parts of the gasification unit (the quench-zone) by addition of weak wash, and the mixture of weak wash and smelt leaves at the bottom of the reactor as green liquor. The energy-rich product gas, i.e. the syngas, is cooled and fed to a gas cleaning operation where for example sulphur compounds are removed. The gas is then ready to be used as a fuel.

In the process described in Figure 1 the syngas is used to fuel a combined cycle system for production of both electric power and process steam.

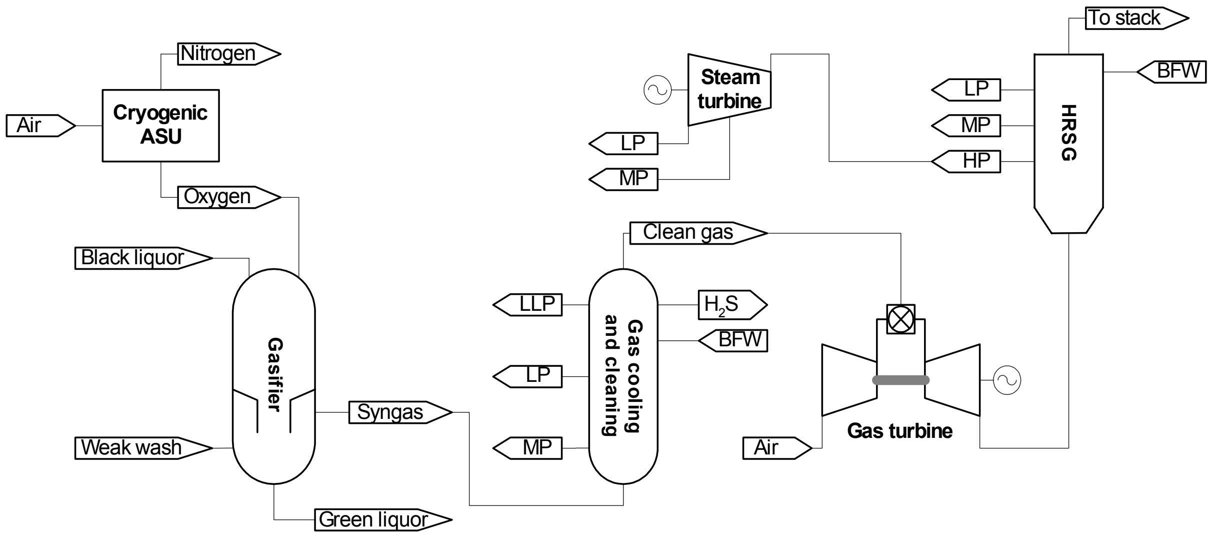

Figure 1. Oxygen-blown, high-temperature black liquor gasification with a combined cycle system as proposed by Eriksson and Harvey (Eriksson and Harvey, 2004).

2.2 Syngas

The chemical composition, and hence the combustion properties, of the product gas leaving the gasification plant depends strongly on the operation of the gasification process. For air-blown gasification the product gas contains a high concentration of nitrogen and the heating value is hence rather low, and for low-temperature gasification the hydrogen content is reported to he higher than for the high-temperature process (Modig, 2005). The chemical composition, the lower heating value and the adiabatic flame temperature and the dew point in the flue gas stream at stoichiometric combustion in air are presented in Table 1 for 5 different reported syngas compositions for the high-temperature gasification process.

The conditions for the various syngas streams are as follows:

Syngas 1 - wet, scrubbed product gas of the air-blown, atmospheric pressure high temperature gasification process (Malte and Nichols, 1998).

Syngas 2 - scrubbed product gas from high-pressure, air-blown gasification (Cantrell, 2001).

Syngas 3 - dry product gas of a high-pressure, oxygen blown, black liquor gasification process (Lorson et al., 1997).

Syngas 4 - wet, scrubbed product gas of oxygen-blown, high-pressure gasification (Berglin and Berntsson, 1998).

Syngas 5 - scrubbed product gas from high-pressure, oxygen-blown gasifier saturated with water at 180°C (Consonni et al., 2003).

Table 1. Chemical composition and combustion properties of syngas from both air-blown and oxygen-blown high-temperature gasification processes.

	Syngas 1	Syngas 2	Syngas 3	Syngas 4	Syngas 5
Oxidizing gas	Air	Air	Oxygen	Oxygen	Oxygen
CH_4 [vol-%]	1.3	0.9	0	0.4	1.4
CO [vol-%]	12.5	13.4	41.4	33.9	26.1
CO_2 [vol-%]	13.6	15.1	17.8	22.9	11.3
H_2 [vol-%]	14.6	14.4	39.7	38.6	27.5
H_2O [vol-%]	10.2	0.5	0	4.2	32.7
N_2 [vol-%]	47.8	55.7	1.1	0	1.0
LHV[1] [MJ/Nm^3]	3.6	3.5	9.4	8.5	6.7
AFT[2] [°C]	1358	1368	2105	1995	1793
Dew point[3] [°C]	56.6	46.9	55.3	58.3	69.0

[1] Lower heating value
[2] Adiabatic flame temperature at stoichiometric combustion in air
[3] Dew point in exhaust gases at stoichiometric combustion in air

The results presented in Table 1 for various syngas compositions presented in the literature should be compared with the properties of natural gas and propane, i.e. the fuel gases thought to be replaced by the product gas from BLG. For natural gas from the North Sea area (90.4 vol-% CH_4, 3.8 vol-% C_2H_6, 0.9 vol-% C_3H_8, 0.8 vol-% C_4H_{10}, 0.3 vol-% CO_2 and 3.8 vol-% N_2) the lower heating value is 36.1 MJ/Nm^3 and the adiabatic flame temperature is 2043°C at stoichiometric combustion in air. The dew point of the flue gas stream is 58.8°C. For pure propane (C_3H_8) the lower heating value is 90.0 MJ/Nm^3. At stoichiometric combustion in air the adiabatic flame temperature is 2107°C and the dew point of the flue gas stream is 55.0°C.

According to Table 1, both the adiabatic flame temperature and the flue gas dew point for syngas from oxygen-blown gasification are very similar to the values for natural gas and propane. The adiabatic flame temperature of the product gas from air-blown gasification is however significantly lower, due to the high concentration of nitrogen in the fuel gas stream. Syngas from oxygen-blown gasification would hence be a good fuel for both gas turbines and for gas fired paper drying processes, at least from a thermodynamic point of view.

3 The model system

The process system that was modelled in this study is an integrated model mill with two parallel paper machines; one producing surface-sized fine paper and one producing tissue. The modelled process system included the pulp mill, the paper mill and the combined heat and power plant (CHP plant). The process layout for the system is shown in Figure 2. The different processes are further described in the following sections.

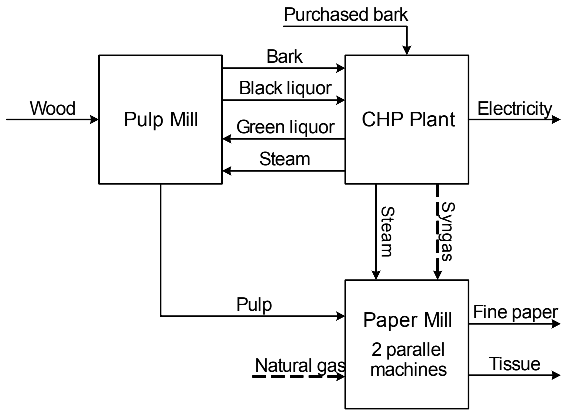

Figure 2. The modelled process system.

3.1 The pulp mill

The pulp mill was assumed to produce chemical pulp from a mix of hard- and softwood and the production rate was adjusted to balance the consumption in the two paper machines, 1644 air dry tonne pulp/24 h (90 % dryness). The steam consumption was calculated from the pulp production rate, assuming the specific heat demand to be as for a mill producing bleached but not dried chemical pulp, i.e. 12 GJ/air dry tonne pulp (Fogelholm and Suutela, 2000). The steam was assumed to be consumed as 0.6 and 1.2 MPa steam (all pressures are given as absolute values) in a 2:1 mass ratio. The specific flow of black liquor from the digester was set to 1.8 tonnes of dry solids/ton air dried pulp, and the lower heating value of the concentrated black liquor to 12.1 GJ/ton dry solids, as for the KAM reference pulp mill (Axegård and Backlund, 2003). From this data the flow of black liquor to the chemical recovery process, and the available energy from the black liquor stream was calculated. Also the mass flow of bark from the debarking process was evaluated, using data presented for the reference pulp mill in the FRAM-programme (Tomani, 2005).

3.2 Fine paper machine

The production rate and overall process specifications for the fine paper machine were chosen as for the FRAM reference mill (Tomani, 2005). The design of the dryer section, i.e. the equipment layout, was made to reflect the situation reported for modern fine paper mills (Atkins, 2003). The specific steam consumption in the wet end was set to be as for a newsprint machine, 1 GJ/ton produced paper (McIvor et al., 1999).

The modelled fine paper machine was assumed to produce uncoated but surface sized paper with a final dry basis weight of 74.4 g/m^2. The machine speed at the pope was set to 1690 m/min and the width of the paper web to 9 m. The total basis weight in the final product, including 2.4 g dry solids/m^2 surface size and residual moisture at 93 % dryness, was 80 g/m^2, and the paper production capacity was 1750 tons per day. The web dryness after the press section was set to 50 %, and the filler content to 20 % by dry mass.

The dryer section was modelled with a pre-dryer and a final dryer section, with the size press in-between. The pre-dryer section was modelled with 56 single tiered drying cylinders. The final dryer section was modelled with 21 drying cylinders of which the last 8 were assumed double tiered. The cylinder diameter was set to 1.8 m for both single and double tier dryers. A flowchart describing the dryer section of the fine paper machine is shown in Figure 3.

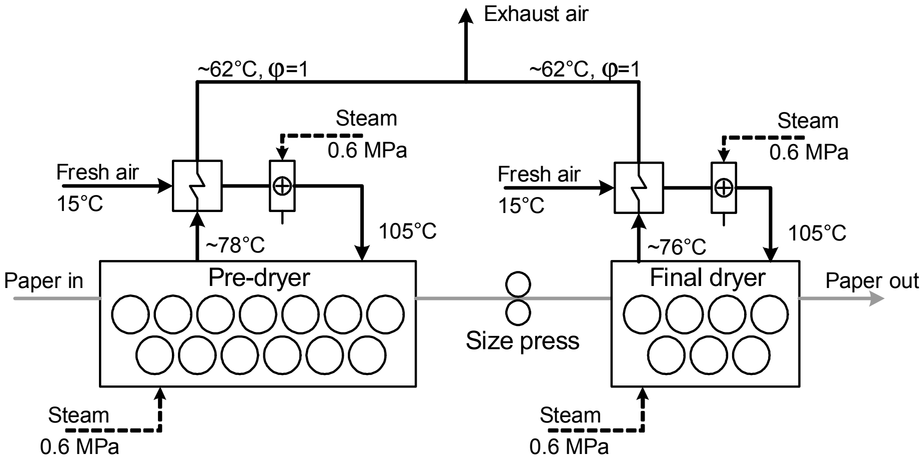

Figure 3. The dryer section of the fine paper machine.

The drying cylinders in the pre-dryer section were divided into 4 steam groups. The steam pressures in the different groups were adjusted to between 120 and 415 kPa to reach the specified moisture content before the size press. The drying cylinders in the final dryer formed a single steam group and the steam pressure was adjusted to 240 kPa to reach the specified final dryness of the web.

The fresh inlet air to each dryer hood was assumed to be heated to the desired temperature, i.e. 105°C, in a two-stage process. In the first stage, the inlet air was pre-heated by heat exchange with the warm and humid exhaust air. In the second stage the inlet air was heated to the desired temperature by condensing steam at 300 kPa. The mass flow of air to each dryer hood was adjusted so that the moisture content in the exhaust air streams was 0.18 kg water/kg dry air. Further heat recovery from the exhaust air streams in addition to pre-heating of the fresh drying air was not studied in this work.

3.3 Tissue paper machine

The tissue paper line was modelled as consisting of a single Yankee dryer, 5.5 m in diameter with total wrap angle of 220°. The machine speed was set to 1500 m/min. The steam consumption in the wet end was calculated as for the fine paper machine. The model tissue machine was assumed to produce tissue of final basis weight 21 g/m^2 at 94 % dryness. The web dryness after the second press nip at the Yankee dryer was set to 42 %, and the filler content in the furnish to 15 %. The production capacity was 272 tons per day. A schematic drawing of the Yankee dryer process is shown in Figure 4.

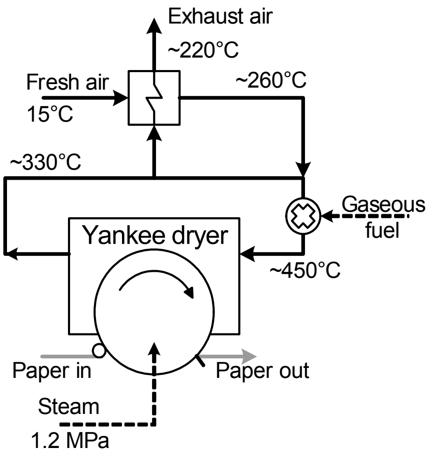

Figure 4. The dryer section of the tissue machine.

The steam pressure in the Yankee dryer cylinder was set to between 700 and 800 kPa and allowed to be varied to obtain the specified final dryness of the web. For the Yankee dryer hood the air impingement velocity was set to 115 m/s and the temperature was adjusted to 450-460°C by varying the fuel input to the hood. The flow of fresh inlet air and the circulation ratio in the air system was adjusted so that the resulting moisture contents in the impingement and outlet air streams were approximately 0.30 and 0.48 kg water/kg dry air, respectively. Heat was assumed to be recovered by heat exchange between exhaust and fresh inlet air.

3.4 Combined heat and power plants

In a pulp and paper mill low-pressure steam is generated in-house in the combined heat and power (CHP) plant. The CHP plant in an integrated pulp and paper mill typically includes two steam boilers - one recovery boiler and one biomass boiler - for generation of high-pressure steam, and a backpressure steam turbine for generation of electrical power. The recovery boiler is fired with the concentrated black liquor for recovery of cooking chemicals and energy and the biomass boiler is fired with bark and other wood residues to balance the steam production to the total consumption in the process. Instead of firing the black liquor in the recovery boiler it can be gasified and the gaseous fuel used either to fuel a gas turbine or for direct heating in the process. In this work three different configurations of the CHP plant were studied and the possibilities for effective integration with the paper drying process evaluated. The process alternatives are denoted Case 1, 2 and 3. Case 1, which is also used as a reference case in the following economic analysis, described a conventional CHP plant with recovery and biomass boilers and a steam turbine. The Yankee dryer was in this case fired using natural gas. In Case 2 a large enough fraction of the black liquor was gasified to eliminate the consumption of natural gas in the Yankee dryer. The remaining black liquor was fired in the recovery boiler. In Case 3 the entire black liquor stream was gasified and the produced syngas used to fire a gas turbine. The hot exhaust gas leaving the gas turbine was used both as make-up air to the Yankee dryer hood and to raise steam in a heat recovery steam generator. The details of the three systems are described below.

In all three cases studied a biomass boiler assumed to be fired with bark to balance the steam production to the total process steam demand was included in the CHP plant model. Based on the estimated bark consumption in the biomass boiler and the calculated flow of bark from the debarking process the developed models could predict whether there would be a bark surplus available at the mill that could be sold, or a shortage that must be compensated for by purchasing additional bark.

3.4.1 Case 1 - Conventional recovery boiler

In Case 1 the entire black liquor stream was assumed to be fired in a conventional recovery boiler for recovery of the cooking chemicals and production of high pressure steam, 9.0 MPa and 500°C. Figure 5 shows the layout of the cogeneration system for this case, and the way of energy integration with the process system.

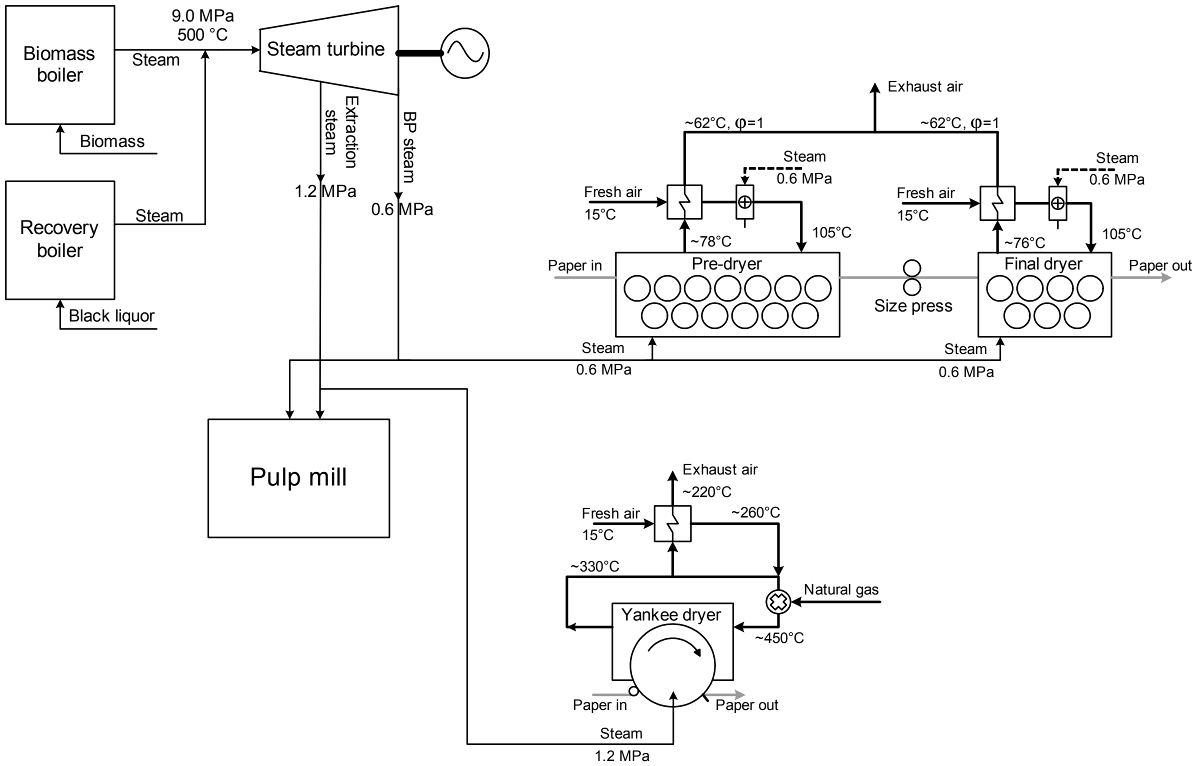

Figure 5. The integration of the CHP plant with the process system in Case 1.

The high pressure steam from the recovery boiler, and from the biomass boiler also included in the steam system to balance the steam production to the total process steam demand, was assumed to be expanded in a backpressure steam turbine with extraction of steam at an intermediate pressure level. The steam pressures for the extraction and backpressure steam were set to 1.2 and 0.6 MPa, respectively. The isentropic efficiency of the steam turbine was set to 90 % and the mechanical and electrical losses of the turbine and generator to 5 %. The boiler efficiency was assumed to be 90 % for both the recovery and the biomass boiler. In Case 1 the drying air in the Yankee dryer hood was assumed to be heated by firing natural gas.

3.4.2 Case 2 - Small scale gasification plant

In Case 2 the fraction of the black liquor stream that balances the syngas flow required to fire the Yankee dryer hood was assumed to be gasified, and the remaining black liquor fired in a conventional recovery boiler. The small scale gasification plant required in this case is comparable to a booster installation. The process layout for the CHP plant in Case 2 and the energy integration with the pulp mill and the paper dryers are presented in Figure 6.

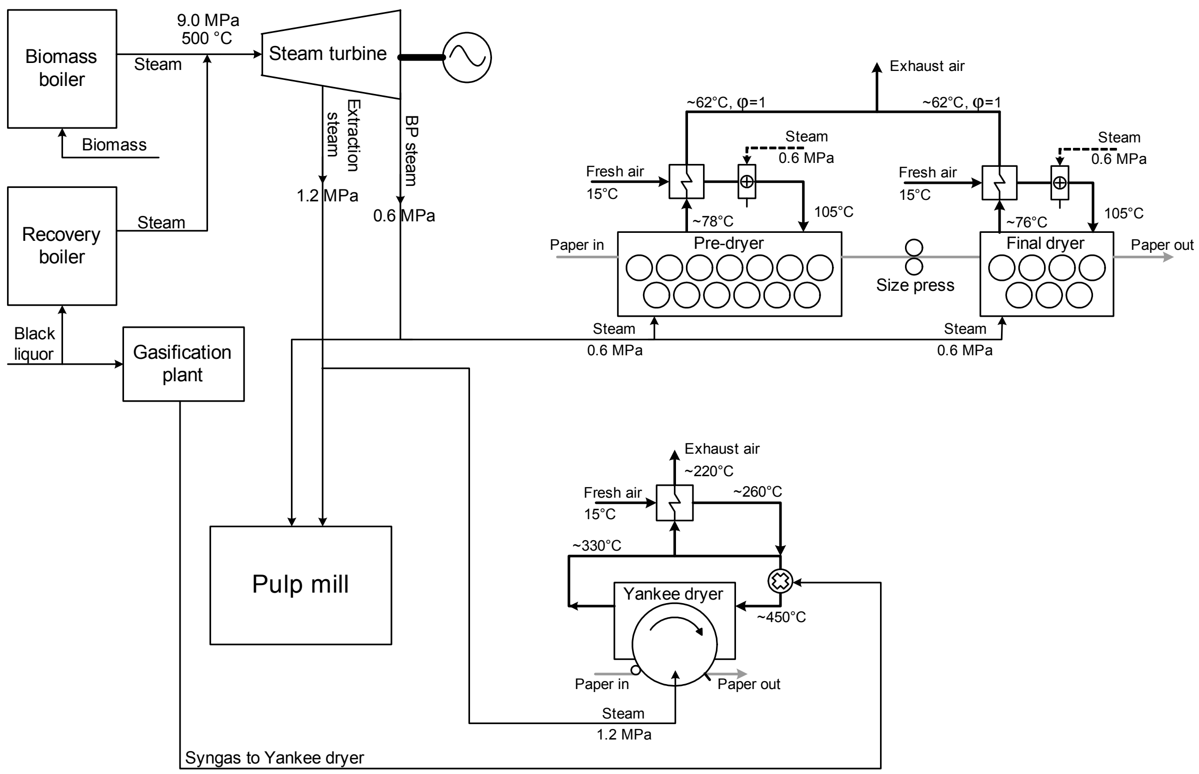

Figure 6. The integration of the CHP plant with the process system in Case 2.

As in Case 1 a biomass boiler was assumed to be included in this CHP model system, and the high pressure steam expanded in a backpressure steam turbine.

3.4.3 Case 3 - Full scale gasification

In Case 3 the recovery boiler was removed from the model and replaced by a full-size gasification plant and a combined cycle system. The gasifier unit was assumed to process the entire concentrated black liquor stream, and the produced syngas fired in a gas turbine for power generation. The main fraction of the hot exhaust gases leaving the gas turbine was used to produce high pressure steam, 9.0 MPa and 500°C, in the heat recovery steam generator (HRSG) unit, but a small fraction was diverted to the Yankee dryer hood as make-up air. The use of natural gas in the Yankee dryer hood was hence eliminated. The high pressure steam from the HRSG unit and the biomass boiler was assumed to be expanded in a backpressure steam turbine. The layout of the CHP system in the gasification case, and its integration with the pulp mill and the paper drying processes, is shown in Figure 7.

For the gas turbine the pressure ratio was set to 1:16, the temperature of the inlet air stream to 25°C and the maximum allowed temperature in the system, i.e. at the expansion turbine inlet, to 1360°C. The isentropic efficiencies for the compression and expansion stages were assumed to be 85 % and 90 %, respectively, and the mechanical and electrical losses in the system to 5 %. Cooling of the gas turbine blades was not included in this study and will in practice result in a somewhat lower electricity production from the unit than predicted by the model.

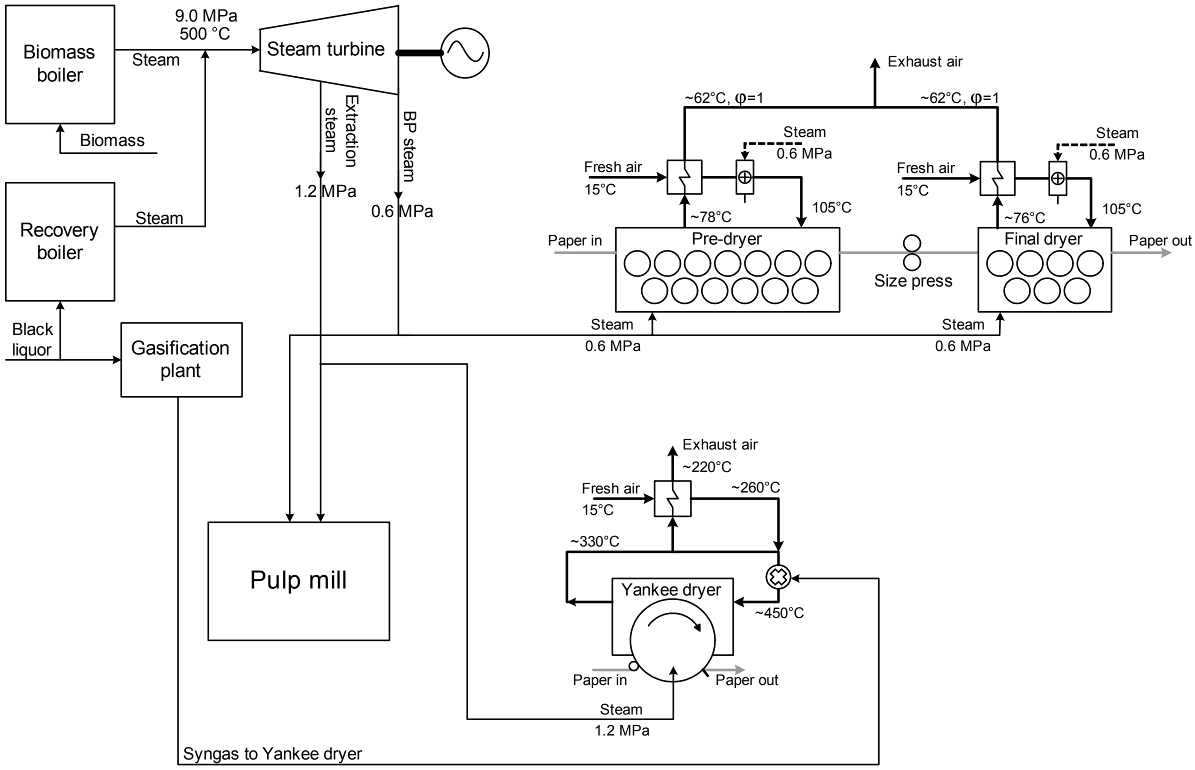

Figure 7. The integration of the CHP plant with the process system in Case 3.

The heat transfer area in the heat recovery steam generator unit was set to 5000 m^2 and the overall heat transfer coefficient to 200 $W/m^2{}^\circ C$. This value may seem rather high, but it accounts for both the convection and radiation heat transfer from the hot gases to the boiling water.

3.4.4 Heat recovery options

When using hot exhaust gases from the gas turbine as drying air in the Yankee dryer hood (Case 3), heat recovery from the dryer exhaust to the supply air is not possible in the Yankee dryer system since the temperature in the supply air stream is higher than that of the exhaust air stream. Therefore, heat recovery from the air stream leaving the Yankee dryer hood to other parts of the process should be considered. One option is to re-direct the exhaust air stream back to the gas turbine exhaust before being fed to the heat recovery steam generator, for increased steam production. Another option is to pre-heat the fresh inlet air to the cylinder dryer hoods, for reduced steam consumption. Both alternatives were evaluated in this study.

4 Results and discussion

For the studied process system, the flow of black liquor from the pulp mill was predicted to 2960 t dry solids/24 h and the available bark from the debarking process 371 t DS/24 h. The total energy required for production of high pressure steam was 409.5 MW for all three cases studied. Also the steam consumption in the various processes was found equal for all cases and the values are presented in Table 2.

Approximately 71 % of the total steam was consumed in the pulp mill, 27 % in the fine paper machine and only 2 % in the Yankee dryer. The resulting specific energy use in the cylinder dryer section of the fine paper machine was 3190 kJ/kg paper, or 2680 kJ/kg evaporated water, and in the Yankee dryer 3760 kJ/kg paper, or 3030 kJ/kg evaporated water. In the Yankee dryer approximately 70 % of the energy required for drying was supplied from the hood side, either in the form of natural gas, syngas or hot exhaust gas from the gas turbine outlet.

Table 2. Steam consumption valid for all cases.

	Steam consumption MW
Pulp mill, MP	73.0
Pulp mill, LP	155.3
Wet end fine paper, LP	20.4
Drying cylinders, LP	59.8
Air heating, LP	4.9
Wet end tissue, LP	3.3
Yankee dryer, MP	3.5
Total	320.2

Case specific results predicted by the model simulations are presented in Table 3. These results show that in Case 1, where the CHP plant was assumed to consist of a conventional recovery boiler, a biomass boiler and a steam turbine, approximately 86 % of the total steam was produced in the recovery boiler firing black liquor. From the 393 MW energy available in the black liquor stream 75 MW was converted into electricity and 279 MW into process steam. The heat loss from the recovery boiler was 39 MW. The consumption of bark in the biomass boiler was found to be lower than the flow of bark from the debarking process, resulting in a surplus of bark corresponding to 41 t DS/24 h. The consumption of natural gas in the Yankee dryer was predicted to 8.4 MW.

In Case 2 a fraction of the black liquor was assumed to be gasified to produce enough syngas to replace the natural gas in the Yankee dryer. The required flow of black liquor to the gasifier was predicted to 83 t dry solids/24 h, i.e. about 3 % of the total black liquor flow, and the steam production from black liquor was consequently reduced by approximately 10 MW. To make up for this loss, the consumption of bark in the biomass boiler was predicted to increase correspondingly, resulting in a need of 19 t DS/24 h purchased bark in addition to the bark from the debarking process. From an overall mill perspective 8.4 MW natural gas was replaced by 10 MW bark fuel.

Table 3. Results specific for each of the three cases studied.

	Case 1	Case 2	Case 3
Steam from recovery boiler, MW	353.7	343.8	0
Steam from HRSG, MW	0	0	102.9
Steam from biomass boiler, MW	55.7	65.7	306.6
Power from steam turbine, MW	86.7	86.7	86.7
Power from gas turbine, MW	0	0	134.8
Power consumption oxygen plant, MW	0	0.5	16.5
Purchased bark, t DS/24 h	-41	19	1446
Natural gas to Yankee dryer, MW	8.4	0	0
Syngas to Yankee dryer, MW	0	8.4	0

In Case 3, where the recovery boiler was assumed to be replaced by black liquor gasification together with a combined cycle system, approximately 157 MW of the total energy in the black liquor was converted into electricity, 135 MW in the gas turbine and 22 MW in the steam turbine, and 81 MW into process steam. Hence, approximately 40 % of the energy available in the black liquor was predicted to be converted into electric power in the combined cycle system, instead of 19 % as for Case 1 and 2. The heat losses in the flue gas from the HRSG unit were predicted to be 55 MW, i.e. about 1.4 times higher than the heat losses from the recovery boiler in Case 1. Due to the increased power production from the black liquor fuel and the increased heat losses from the system, the bark consumption was significantly higher for Case 3 than for Case 1 and 2.

The net power production, i.e. the power generated in the steam and gas turbines reduced by the electricity consumed in the air separation unit, was predicted to be 86.7 MW for Case 1, 86.2 MW for Case 2 and 205.0 MW for Case 3. The power generation in the steam turbine was equal for all cases since the steam flow to the process, and hence through the backpressure steam turbine, was the same. Green certificates were obtained for all the produced power since it was generated from entirely renewable fuels.

For Case 2 and 3, where the use of natural gas was eliminated, the emission of fossil carbon dioxide from the mill was reduced by 0.0182 t/t paper.

4.1 Heat recovery options

If the exhaust air from the Yankee dryer hood was returned to the HRSG process the steam production in the unit would decrease if the heat transfer area was kept constant. This is caused by the reduced temperature difference in the heat exchanger. To maintain the steam flow from the HRSG system a 10 % increase in heat transfer area would be necessary.

If the exhaust air leaving the Yankee dryer hood was used to pre-heat the fresh inlet air to the cylinder dryer hoods, savings in both steam consumption and total heat transfer area required in the air pre-heaters were predicted by the model. The steam consumption for air heating could actually be eliminated, reducing the total steam consumption by approximately 5 MW, and the heat transfer area required in the air pre-heaters reduced by 40 %.

4.2 Energy cost analysis

Based on the results obtained from the simulations and the cost factors presented in Table 4, reflecting current energy prices for the Swedish industrial sector, the operating costs for energy could be evaluated for the different process systems studied.

Table 4. Costs for various fuels and associated climate control policy instruments.

	SEK/MWh
Biomass (bark)	120
Natural gas	300
Electricity	300
Green certificates	170
Emission allowances[1]	45

[1] Current price (march 2006) is 250 SEK/t CO_2

The change in energy costs for Case 2 and 3 as compared with the reference case, i.e. Case 1, were calculated per total ton paper produced (sum of fine and tissue paper). For the modelled paper mill the total paper production was 23.4 kg paper/s (20.3 kg/s fine paper and 3.1 kg/s tissue), or 2024 t/24 h. The changes in various costs for the energy system are presented in Table 5. Positive figures indicate increased costs and negative figures a cost reduction.

Table 5. The change in energy system marginal costs for Case 2 and 3 as compared with Case 1, presented as SEK/t paper.

	Case 2	Case 3
Sold power	1.6	-420.8
Green certificates	0.9	-238.5
Purchased bark	15.8	396.5
Purchased natural gas	-29.8	-29.8
Emission allowances	-4.5	-4.5
Net change in costs	-16.0	-297.1

Both cases including black liquor gasification show reduced energy costs as compared with the reference case, Case 1. The annual savings in energy costs for a mill with production capacity as assumed in this work and running 355 days per year at a total efficiency of 82 %, are approximately 10 and 175 MSEK/year for Case 2 and 3, respectively. The much higher savings obtained with the energy systems as in Case 3 are due to the increased power production from the black liquor. In this study, the black liquor was considered being a fuel without cost for the CHP plant, and for the bark fuel approximately 75 % of the fuel cost is covered by the revenues from the generated power in the steam turbine and the green certificates obtained. Hence, almost the entire income from the additional electric power produced, and the green certificates obtained, from the black liquor when using the BLGCC system can be regarded as profit. If the fresh air to the cylinder dryer hoods was preheated by heat exchange with the exhaust air from the Yankee dryer hood, and the total steam consumption hence reduced by 5 MW, the obtained cost reduction was predicted to 1.2 MSEK/year. The total investment cost for heat transfer area was also estimated to be reduced by 6 MSEK.

5 Conclusions

From this study it can be concluded that the product gas from black liquor gasification is a possible fuel to be used in gas fired paper drying processes, such as the Yankee dryer. The thermodynamic properties of the syngas from oxygen-blown, high-temperature gasifiers are very similar to those of natural gas and propane. In addition to being a renewable fuel, the use of syngas instead of fossil fuels would lead to reduced energy costs for the mill. In the case of installing a small gasification plant for production of enough syngas to replace the natural gas in the Yankee dryer hood the total energy costs would be reduced by approximately 10 MSEK/year. This would probably not be sufficient to justify the investment cost for the gasification process, insofar as the installation not simultaneously increases the pulp production capacity in the pulp mill.

Black liquor gasification together with a combined cycle system, where the syngas is used to fire the gas turbine and the hot exhaust gases from the turbine used for steam production and as drying air in the Yankee dryer hood, shows more promising results. According to this study the total energy costs would be reduced by 175 MSEK/year, mainly due to the increased power generation from the available black liquor. Even though the simulation models developed in this work predicted reduced overall energy efficiency for this system as compared with a conventional recovery boiler and steam turbine, the specific energy costs per ton produced paper were found to be much lower. The increased power-to-heat ratio of the combined cycle system is favourable at present energy cost levels.

6 References

Atkins, J. (2003), The modern paper machine, part 2: Coated and fine paper, Solutions, 86(12), pp. 31-34

Axegård, P. and Backlund, B. (2003), Ecocyclic pulp mill - "KAM" Final report 1996-2002, Pulp mill,energy efficiency, STFI

Berglin, N. and Berntsson, T. (1998), CHP in the pulp industry using black liquor gasification: thermodynamic analysis, Applied thermal engineering, 18(1998), pp. 947-961

Cantrell, J. (2001), Simulation of kraft black liqour gasification - A comparative look at performance and economics, Proceedings of the 2001 TAPPI Engineering/Finishing and Converting Conference and TRade Fair, pp. 1181-1195

Consonni, S., Larsson, E. D., and Katofsky, R. E. (2003), Black Liquor Gasification Combined Cycles: Mill Integration Issues, Performance and Emissions Estimates, Presentation at the Colloquium on Black Liquor Gasification (http://www.eng.utah.edu/~whitty/blackliquor/colloquium2003), Park City, USA, May 13-16, 2003

Eriksson, H. and Harvey, S. (2004), Black liquor gasification - consequences for both industry and society, Energy, 29(4), pp. 581-612

Fogelholm, C.-J. and Suutela, J. (2000), Heat and power co-generation, Chapter No 16 in Papermaking Science and Technology, Volume 6B /ed. Gullichsen, J. and Fogelholm, C.-J./, Fapet Oy, Helsinki, pp. B302-B373

Lindell, K. and Stenström, S. (2005), A study of mill-wide energy use and costs for combined paper dryers with internal and external heat recovery, Proceedings of the 3rd Nordic Drying Conference

Lindell, K. and Stenström, S. (2006), A modular process modelling tool for the analysis of energy use and cost in the pulp and paper industry, Drying Technology, Accepted for publication

Lorson, H., Schingnitz, M, White, V. F., and Dean, D. R. (1997), Black liquor recovery by pressurized, oxygen-blown gasification, Tappi Journal, 80(12), pp. 111-116

Malte, P. C. and Nichols, K. M. (1998), Evaluation of NOx production from black liqour gasification-gas turbine combustion system, Proceedings of the 1998 International Chemical Recovery Conference, pp. 705-720

McIlroy, D. and Wilczinsky, J. (1999), Chemical Pulp Mills, Chapter No 5 in Energy cost reduction in the pulp and paper industry /ed. Williamson, P. N./, Paprican, Pointe-Claire, pp. 77-96

McIvor, A, Dahl, C, and Lindstrom, R (1999), Paper, board, tissue and pulp machines, Chapter No 7 in Energy cost reduction in the pulp and paper industry /ed. Williamson, P. N./, Paprican, Pointe-Claire, pp. 119-146

Modig, G. (2005), Black liquor gasification - an assessment from the perspective of the pulp and paper industry, Licentiate Thesis, Lund University, Sweden

Tomani, P. (2005), Personal communication with Per Tomani, STFI-PackForsk

SGC Svenskt Gastekniskt Center AB

Hemsida www.sgc.se • epost info@sgc.se