PERFORMANCE OF BLACK LIQUOR GASIFIER/GAS TURBINE COMBINED CYCLE COGENERATION IN THE KRAFT PULP AND PAPER INDUSTRY

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ABSTRACT

The kraft process dominates pulp and paper production worldwide. Black liquor, a mixture of lignin and inorganic chemicals, is generated in this process as fiber is extracted from wood. At most kraft mills today, black liquor is burned in Tomlinson boilers to produce steam for on-site heat and power and to recover the inorganic chemicals for reuse in the process. Globally, the black liquor generation rate is about 85,000 MW_{fuel} (or 0.5 million tonnes of dry solids per day), with nearly 50% of this in North America. New kraft production capacity is being added most rapidly in Brazil, Indonesia, and other regions with low wood production costs and relatively low per-capita levels of paper use. The majority of presently installed Tomlinson boilers in North America will reach the end of their useful lives during the next 5 to 20 years. As a replacement for Tomlinson-based cogeneration, black liquor-gasifier/gas turbine cogeneration promises higher electrical efficiency, with prospective environmental, safety, and capital cost benefits for kraft mills. Several companies are pursuing commercialization of black liquor gasification for gas turbine applications. This paper presents results of detailed performance modeling of gasifier/gas turbine combined cycle systems using four different black liquor gasifiers modeled on proposed commercial designs. A range of process steam demand levels are considered, with supplemental biomass firing in a boiler when needed to meet the process steam demand. A companion paper (Larson *et al*, 1997) gives performance results for systems including gasification of supplemental biomass rather than combustion.

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INTRODUCTION

Black liquor is the lignin-rich byproduct of fiber extraction from wood in kraft pulp production. In 1994, the U.S. pulp and paper industry consumed 1.2 EJ (10^{18} J), or 38,000 MW, of black liquor. This exceeded the 1.0 EJ of total fossil fuel used by the industry (AFPA, 1996). The industry burns black liquor today in Tomlinson recovery boilers that feed back-pressure steam turbine cogeneration systems supplying process steam and electricity to mills. A critical job of Tomlinson boilers is the recovery of pulping chemicals (sodium and sulfur compounds) from the black liquor for reuse (Adams *et al.*, 1997). Technologies for gasifying black liquor and recovery chemicals are under development to replace Tomlinson boilers. Augmenting earlier work (Consonni *et al.*, 1997), this paper assesses the prospective energy performance of four black liquor gasifier/gas turbine system designs that are targeted for commercial application by early in the next decade.

This work is motivated by the interest of the pulp and paper industry in black liquor gasification technology arising from prospective improvements in energy, environmental, safety, and capital-investment characteristics compared to Tomlinson technology (Larson *et al.*, 1996; Industra, 1996; Larson and Raymond, 1997). The industry sees some urgency in realizing the promise of gasification technology because some 80% of all currently operating recovery boilers in the U.S. were built or rebuilt before 1980. Expected recovery boiler lifetimes are 30 to 40 years, so most of the recovery boilers in the U.S. (and Canada, as well) will need major attention or replacement the next 5 to 20 years. If all recovery boilers built after 1965 were replaced with gasifier/gas turbine systems, the total installed gas turbine/combined cycle capacity would be some 8 GW_e (Larson and Raymond, 1997).

Black liquor gasifier development received considerable attention in the U.S. in the early 1980s (Kelleher, 1985; Empie, 1991), but the prospects for commercializing technology appear considerably improved at present. In fact, the first fully commercial black liquor gasifier (Smith *et al.*, 1996) began startup testing at Weyerhaeuser's New Bern mill in North Carolina in late 1996. This unit will provide the mill with incremental capacity for chemicals recovery from black liquor, with the gasifier product gas being burned in a boiler. For the longer-term, there is industry interest in full replacement of Tomlinson-based cogeneration with gas turbine-based systems, the focus of this paper.

Black liquor gasification technologies can be classified according to operating temperature, or equivalently, according to the physical state in which the majority of the inorganic content of the feed black liquor leaves the reactor. High-temperature gasifiers operate at 950°C or higher and produce a molten smelt of inorganic chemicals. Low-temperature gasifiers operate at 700°C or lower in order to insure that the inorganics leave as dry solids. Kvaerner and Noell are two companies developing high-temperature gasifiers for gas turbine applications. ABB and MTCI/Stonechem are developing low-temperature gasifiers for such applications. Pressurized operation (at about 25 bar) is being pursued for the high- temperature gasifiers. ABB has proposed a milder pressurization (perhaps up to 5 bar), and MTCI has proposed an atmospheric-pressure design. Additional details regarding these gasifier technologies are available elsewhere (Larson *et al.*, 1996; Grace and Timmer, 1995; Larson and Raymond, 1997; Stigsson and Hesseborn, 1995; Lorson *et al.*, 1996a; Dahlquist and Jacobs, 1992; Aghamohammadi *et al.*, 1995). Calculated full-load performance of gasifier/gas turbine systems incorporating the four above-noted gasifier designs are reported here.

CALCULATING BLACK-LIQUOR COGENERATION PERFORMANCE

Performance calculations were made using a computation model originally developed to predict the full-load, design-point performance of complex gas-steam power cycles (Consonni, 1992) and modified to accommodate black liquor fuels (Consonni *et al.*, 1997; Larson *et al.*, 1996). The model accurately simulates full-load performance of plant components that are crucial to the energy and mass balances (e.g., the gasifier, the gas turbine, the steam cycle, the heat exchanger network), but treats simplistically other components which, despite their technological relevance, have minor impacts on the plant mass and energy flows (e.g., H_2S scrubbing). The modeling work reported here ignores altogether the important impacts that gasification of black liquor might have on chemical recovery steps outside of a pulp mill's cogeneration plant, e.g., on the lime kiln (NUTEK, 1992; Industra, 1996; Larson *et al.*, 1996). These impacts have little or no bearing on the heat and mass balances of the gasifier/gas turbine system, but would need to be considered at any actual mill. In all cases modeled here, substantial quantities of low grade heat are rejected to the environment. No effort is made to find useful applications of this heat, e.g., as process hot water for the mill.

In the modeling, efforts have been made to optimize the heat integration among components so as to maximize efficiency within practical cost (and material) constraints. With this in mind, heat exchanger networks in each system have been designed following two guidelines. First, high-temperature gas streams transfer heat only to water or steam-water mixtures (evaporators); due to the high heat transfer coefficients achievable with water and two-phase mixtures, this arrangement guarantees acceptable heat exchanger metal temperatures. Second, to the extent possible in practice, heat is transferred across relatively small temperature differences and between flows having similar thermal capacities. This reduces heat transfer irreversibilities.

Gas Turbine Selection

The accurate integrated modeling of actual commercial gas turbines is an important distinguishing feature of the present work relative to other studies that have examined black liquor gasifier/gas turbine applications in the kraft pulp and paper industry, e.g., Berglin (1996), Ihren (1994), and McKeough *et al.* (1995). For specificity, the Siemens KWU 64.3a gas turbine is selected here for all calculations. The crucial parameters that determine turbomachinery efficiencies and cooling flows in the model are calibrated such that the model reproduces published performance of the actual commercial engine operating on natural gas fuel (Table 1). The good match with quoted performance provides a basis for confidence in the results for the gasification-based calculations. In practice, some adjustments in operating parameters and minor hardware modifications would be required when burning a fuel like gasified black liquor, which has a lower energy content than natural gas. The model accounts for such factors (Consonni *et al.*, 1997).

Table 1. Model predictions* and manufacturers quoted performance for Seimens KWU 64.3a natural gas-fired gas turbine.

	Predict	Quoted
Turbine Inlet T, °C	1280	n.a.
Pressure ratio	16.6	16.6
Inlet air flow, kg/s	191.9	191.8
Exhaust flow, kg/s	196.3	194.0
Exhaust T, °C	563	565
Efficiency, %LHV	36.4	36.8
Net Power, MW_e	70.1	70.0

*Turbine inlet temperature, pressure ratio, and inlet air flow are input assumptions to the model.

The same gas turbine is selected here for all calculations to help illustrate intrinsic differences among alternative gasifier designs. A gas turbine/back-pressure steam turbine combined cycle configuration is considered in all cases. The black liquor fuel requirements for a 64.3a turbine correspond (approximately) to the black liquor flow at typical modern kraft mills having production capacities ranging from 1100-1300 air-dry metric tonnes (admt) of final product per day. A perfect matching between the quantity of gasified black liquor available at a mill and the fuel requirements of a specific gas turbine will be rare, because the fuel availability is largely determined by considerations related to pulp and paper production (and, possibly, the cost-effectiveness of generating excess power for external sale), while the size of the gas turbine is determined by the few models available on the market. A practial operating strategy at a mill (not considered here) might involve supplementing the available gasified black liquor with natural gas or gasified biomass to provide the full fuel requirement of a gas turbine. In such a case somewhat less electricity would be produced per admt than for the perfect match considered here.

Results are shown for one gas turbine, but their significance is not restricted to this turbine alone: similar results would be obtained for turbines of other manufacturers that are of the same basic type (heavy-duty industrial), same power output class, and same generation of technology. For example, the General Electric 6001FA is very similar to the Siemens KWU64.3a.

Tomlinson Boiler

To provide a consistent comparison between gasification-based systems and Tomlinson boiler cogeneration systems, the Tomlinson technology has been modeled at a comparable level of detail. (Fig. 1 shows an illustrative heat/mass balance.) The Tomlinson steam pressure is set at 60 bar, a common level in practice to minimize corrosion in the furnace and superheater. The 60 bar steam feeds a back-pressure steam turbine. A requisite amount of process steam is extracted at 10 bar, with the balance of steam exhausting at 4 bar for process use.

Process Steam Demand

The demand for process steam at a market-pulp or integrated pulp and paper mill sets the requirement for steam to be supplied by the cogeneration plant. Depending on many factors (end product, mill location and age, installed process equipment, etc.), mill steam demands can vary significantly (Fig. 2). Calculations are carried out here for a range of process steam demands. For steam demand levels that cannot be met using black liquor alone, supplemental consumption of biomass in a boiler is included. A companion paper (Larson *et al.*, 1997) gives performance results for systems including gasification rather than combustion of biomass.

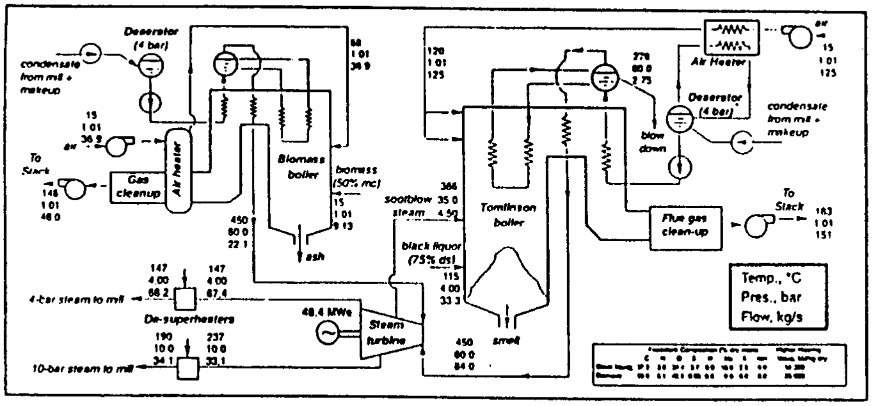

Fig. 1. Heat/mass balance for Tomlinson recovery boiler with integrated biomass boiler. Table 2 shows added detail. Black liquor and biomass compositions used in all cases are also shown here.

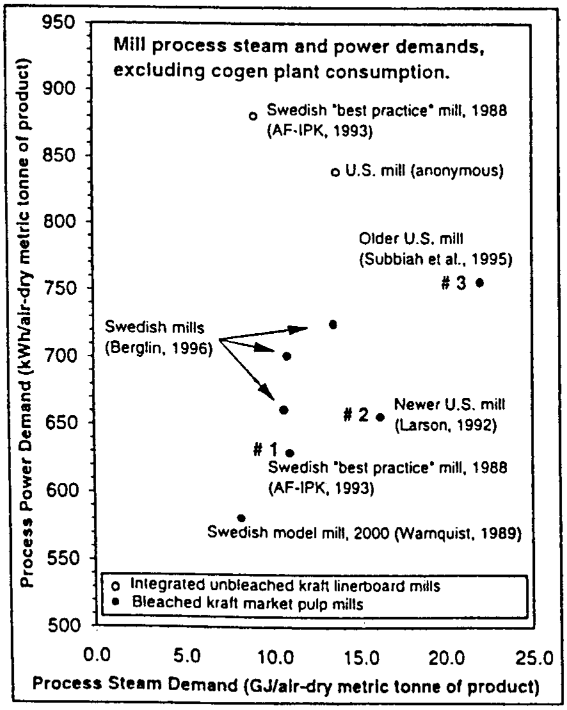

Fig. 2. Kraft-mill energy demands. "Swedish model mill" is an estimate of an economically achievable greenfield mill in year 2000.

PROCESS DESCRIPTIONS

High-Temperature, Oxygen-Blown Gasifier

The basic plant configuration with the pressurized, oxygen-blown, high-temperature gasifier is shown in Figure 3. The gasifier modeled in this case is non-adiabatic (based on the proposed Noell gasifier design, which includes steam recovery from a reactor cooling jacket). The gasifier product gas passes through an integral quench bath and is further cooled by raising low pressure steam and preheating makeup and condensate return water. Water condenses from the product gas in this process and is recirculated to the quench bath. The quench bath water preheats the recirculated condensate. Wash water from pulp making (containing 30 grams/liter of NaOH) is used in the low-temperature scrubber to capture H_2S. The heat content in the fuel gas leaving the scrubber is sufficiently high that a saturator can be included upstream of the gas turbine to heat the syngas and increase its water vapor content. The use of oxygen in the gasifier provides for smaller-capacity gas processing equipment than with air-blown gasification and for the possibility of substantially higher gasification temperature than the 1000°C considered here. In the range 1000-1400°C, higher temperature may provide benefits relating to chemical recovery (Lorson *et al.*, 1996b), but electrical efficiency will suffer (Consonni *et al.*, 1997). Steam is raised at 90 bar in the HRSG (as with all gas turbine systems here) from relatively clean turbine exhaust.

High-Temperature Air-Blown Gasifier

The basic plant configuration (Fig. 4) is similar to the previous system, with oxygen replaced by air bled from the gas turbine compressor. A saturator is not used due to the lower heat content of the gases leaving the scrubber, but some preheating of the syngas is included before firing in the gas turbine. Preheating does not appreciably improve cycle efficiency, but because of the low heating value of the fuel gas it is important in increasing combustion stability.

Low-Temperature, Air-Blown Gasifier

This plant configuration (Fig. 5) involves an air-blown fluidized-bed gasifier (modeled on the proposed ABB technology). A mild pressurization (2 bar) is considered, which offers some advantages over atmospheric pressure: *(i)* scrubbing of the raw syngas can be done at elevated temperature (110°C, as in the other cases here), which improves heat recovery, *(ii)* part of the compression work required for

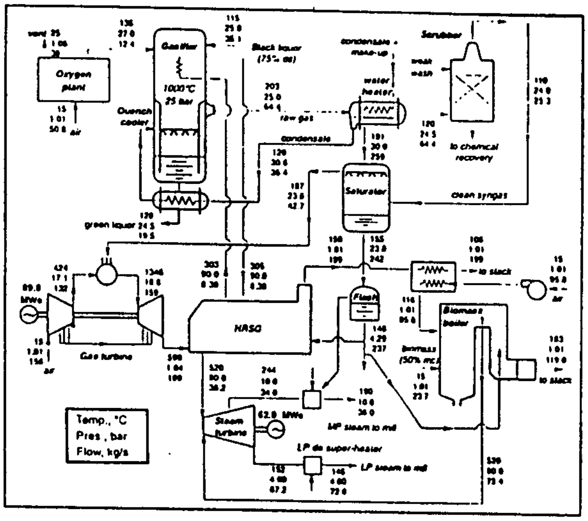

Fig. 3. Heat/mass balance for high-temperature, oxygen-blown gasifier in a combined cycle with integrated biomass boiler. See Table 2 for added details.

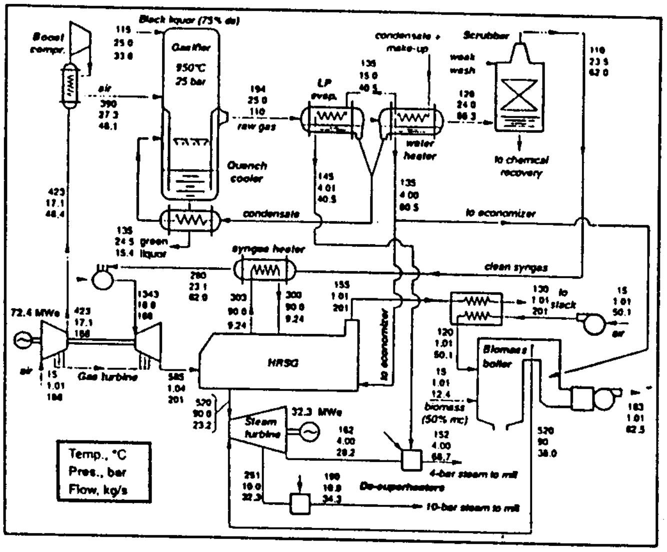

Fig. 4. Heat/mass balance for high-temperature, air-blown gasifier/combined cycle with integrated biomass boiler. See Table 2 for added details.

the fuel gas to be injected into the gas turbine combustor is accomplished by pumping black liquor feed, which is a small parasitic load relative to compressing a gas, and *(iii)* the volumetric flow along the syngas path is cut by about 50%, allowing the size of all components to be reduced. One notable feature included in this process configuration is the recovery of heat from the discharged bed solids before they are dissolved in water for recycling to the pulp mill. This heat is assumed to preheat clean fuel gas before it is fired in the gas turbine combustor. The practical feasibility of such a solid-gas heat exchanger requires examination.

Low-Temperature, Indirectly Heated Gasifier

This scheme is also based on a fluidized bed gasifier operating below the solids melting temperature. The plant configuration (Fig. 6) is based on the MTCI gasification design, where heat for gasification is provided by in-bed heat exchanger tubes. Combustion products from a pulse combustor burning part of the cleaned gasifier product gas flow inside the tubes. The supply of heat from an external source eliminates the need for air or oxygen in the gasifier. With steam as the primary fluidizing agent, the gasifier acts essentially as a black liquor steam reformer.

In the configuration here, raw syngas at 600°C and 2 bar (for consistency, the gasifier pressure is set to that with the other low-temperature gasifier) is cooled first by raising steam and then by pre-heating air for the pulse combustor. After scrubbing, almost half of the syngas goes to the pulse combustor. The rest undergoes intercooled compression and is finally heated using solids discharged from the gasifier. As already mentioned, the practical feasibility of such solid-gas heat exchange requires examination. After releasing heat inside the gasifier, the pulse combustor flue gases (at 700°C) are cooled first by superheating gasifier steam, then by raising steam in a boiler connected in parallel with a boiler recovering heat from raw syngas, then by pre-heating the pulse combustor fuel, and finally by heating make-up water and condensate returning from the mill. Some steam is also generated in the cooling circuit of the pulse combustor. The steam generated by the syngas cooler and the pulse combustor flue gases are fed to the gas turbine HRSG. Some 6% by mass of carbon input to the gasifier leaves ungasified. It is assumed that 75% of the unburnt carbon is recovered and burned in the biomass boiler. As in all other plant schemes, the steam cycle of the gas turbine HRSG is integrated with that of the biomass boiler to optimize heat recovery and allow use of a single steam turbine and condenser. The absence of air and oxygen in the feed to the gasifier substantially reduces the flow of syngas to be compressed for injection into the gas turbine combustor, thereby reducing the parasitic consumption of the syngas compressor.

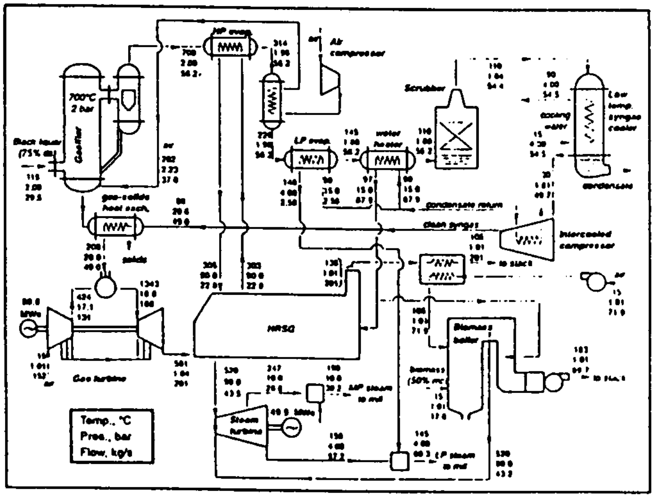

Fig. 5. Heat/mass balance for low-temperature, air-blown gasifier in combined cycle with integrated biomass boiler. See Table 2 for added details.

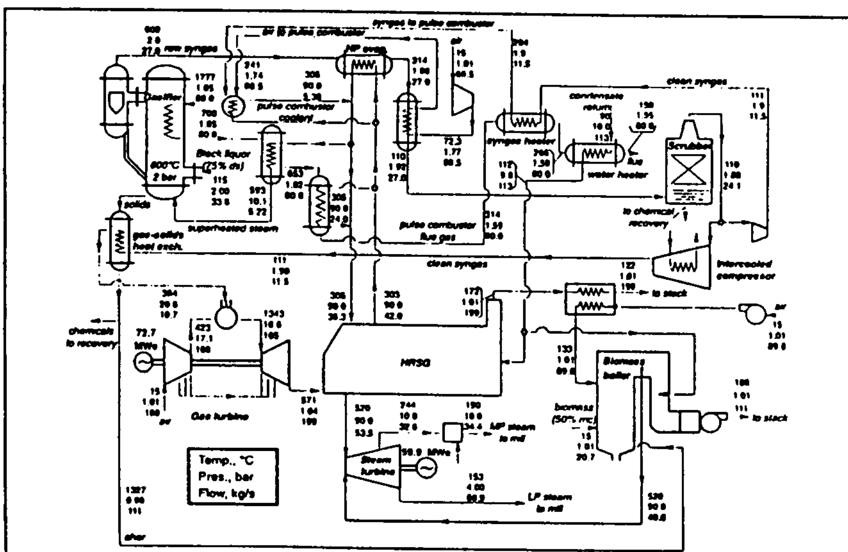

Fig. 6. Heat/mass balance for low-temperature, indirectly-heated gasifier in combined cycle with integrated biomass boiler. See Table 2 for added details.

DISCUSSION OF RESULTS

Performance results are reported for cogeneration systems at kraft market pulp mills, where black liquor is assumed to be produced at a rate of 1.74 tonnes dry solids per air-dry metric tonne of pulp (tds/admt). Black liquor feed rates for the gasifiers were set to the requirements of the gas turbine, as discussed earlier. The feed rate for the Tomlinson boiler (90 tds/hour) is in the same range as the gasifier feed rates. Consonni, *et al.* (1997) and Larson, *et al.* (1996) provide details of modeling assumptions, as well as additional results to those discussed here.

Figure 7 summarizes the heat and mass balance results. Power production per air-dry metric tonne of pulp (kWh/admt) for four gasifier-based systems and for a Tomlinson-based system are shown there. For reference, Mill #1, #2, and #3 are process energy demands corresponding to those shown in Fig. 2. For each technology in Fig. 7, power output is given for a range of process steam production levels. The lower boundary of each shaded region represents the power output assuming that equal masses of medium-pressure (MP, 10-bar) and low-pressure (LP, 4-bar) process steam are generated. The upper bound represents a situation in which all process steam is LP steam. Black liquor fuel alone is sufficient to provide the level of total process steam demand at the lefthand boundary of each region.

For higher levels of steam demand, biomass fuel is burned in a boiler whose steam production is integrated into the steam production from black liquor. The different markers in Fig. 7 indicate different levels of biomass fuel input. For comparison, the waste bark and hog fuel at a typical kraft mill converting logs into pulpable chips might amount to 0.25 dry tonnes of biomass per admt, or about 5 GJ/admt. Many mills may have access to much more biomass. One detailed study around a Weyerhaueser market-pulp mill in North Carolina identified a sustainable supply of up to 3 dry tonnes of biomass per admt (or 60 GJ/admt) at reasonable cost in the form of harvest residues and self- and externally-generated mill residuals (Weyerhaeuser *et al.*, 1995).

The curves for the gasification-based technologies in Fig.7 are steeper than for the Tomlinson technology because of a higher biomass boiler pressure—the pressures match those of the gas turbine HRSG (90 bar) and the Tomlinson boiler (60 bar). As the biomass share of total energy input increases, differences in power output from one technology to the next diminsh in most cases, because the rankine cycle share of total output increases. (At the highest level of biomass input shown, the biomass energy input approaches the black liquor energy input.) Also, combustion air for the biomass burner is pre-heated with the flue gases exiting the gas turbine HRSG, so higher biomass inputs allow for better recovery of low-grade heat overall.

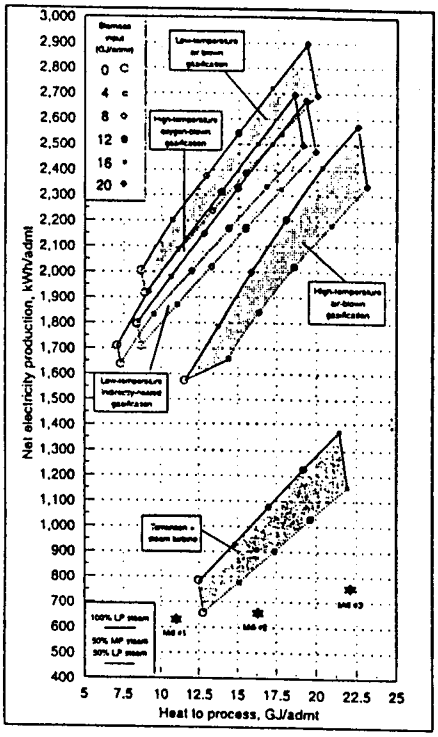

Fig. 7. Performance summary for alternative black liquor-based cogeneration systems. For reference, stars represent process steam and power demands for corresponding mill numbers in Fig. 2.

The gasifier/gas turbine systems produce considerably greater kWh/admt than the Tomlinson-based system. However, more supplemental biomass must be consumed with these systems to meet the same process steam demand. At lower levels of process steam demand (e.g., as at Mill #1), the gasification-based systems produce three times the kWh/admt as the Tomlinson system. At higher process steam production (e.g., as needed at Mill #3), the combined-cycle systems produce about twice as much power. In all cases, including the Tomlison-based system, power production is in excess of a typical pulp mill's process power needs. In contrast, most North American pulp mills today use Tomlinson plus supplemental-fuel boilers with back-pressure steam turbines, but operate relatively inefficiently and so generate little or no excess power.

Several interesting comparisons among alternative gasifier-based systems are illuminated by a more detailed examination of the results in Fig. 7 for a fixed mill process steam demand. Table 2 summarizes performance calculations for alternative cogeneration systems that provide a level of process steam that characterizes Mill #2.

One comparison is between the cases using high-temperature gasifiers, one air-blown and the other oxygen-blown. The O_2-blown system is a more efficient electricity producer, but a considerably less efficient steam producer (Table 2). One contributing factor is the use of the saturator with the O_2-gasifier in place of a low-pressure evaporator, which permits recovery of low-temperature heat into the combined cycle rather than into the rankine cycle alone. An off-setting factor is the parasitic power consumed in producing oxygen. The net result is that to meet the same process steam demand, the O_2-blown system consumes considerably more biomass than the air-blown system, but electricity production per admt is much higher (Table 2).

A second comparison is between systems with high-temperature/high-pressure gasification and low-temperature/low-pressure gasification. The air-blown, low-temperature system provides the highest electrical efficiency of any of the systems considered here. This results primarily because with a lower gasifier outlet temperature, a larger fraction of the gasifier output enters the inherently more-efficient brayton cycle rather than the rankine bottoming cycle. (With higher gasifier outlet temperatures, a larger fraction of the gasifier output is recovered as steam, which can only be used in the rankine cycle. Stated another way, more of the liquor fed to a high-temperature gasifier must be fully oxidized to reach reaction temperature, with the result that less liquor is converted into chemical energy in the product gas.) Also, the irreversibilities involved in cooling the gasifier product gas are smaller with the low-temperature designs, largely because there is no highly irreversible quench. Pressurization of the high-temperature gasifiers, particularly the oxygen-blown case, partly offsets the high electric efficiency of the low-temperature systems.

A final observation is that the achievable adiabatic flame temperatures (AFTs) for the clean syngas streams fed to the gas turbine combustor in all cases (Table 2) are well above current state-of-the-art turbine inlet temperature limits, so that future increases in firing temperatures can probably be achieved with gasified black liquor. The O_2-blown gasifier system delivers a fuel rich in H_2O due to the saturator, which lowers the AFT. Indirectly heated gasification involves no nitrogen dilution of the product gas and, with preheating of the clean syngas, this system gives the highest AFT among all systems modeled.

Table 2. Summary results for cogeneration with black liquor plus biomass boiler that meets steam demands per air-dry metric tonne of pulp (admt) corresponding to those for "Mill #2" in Fig. 2.

	Tomlinson plus biomass boiler	Gasification + Biomass Boiler: Low, Air-blown	Low, Indirect	High, Air-blown	High, O_2-blown
Corresponding Figure # in this paper	1	5	6	4	3
Mill production, admt/day	1241	1098	1252	1251	1307
Black liquor tds/admt	1.74	1.74	1.74	1.74	1.74
tds/hr	90	79.6	90.8	90.1	94.8
MW (HHV)	359	318	362	362	378
Biomass fuel dry t/admt	0.318	0.7	0.41	0.43	0.738
GJ/admt (HHV)	6.35	13.99	14.26	8.56	15.7
Fuel to turbine HHV, MJ/kg	n.a.	4.64	19.87	3.7	6.678
LHV, kJ/mol	n.a.	101	235	85.5	106
Temperature to combustor, °C	n.a.	208	384	280	187
Adiabatic Flame Temperature, °C[a]	n.a.	1770	2300	1634	1690
Process steam, total GJ/admt[b]	16.3	16.3	16.3	16.3	16.3
GJ/admt, 10-bar	5.5	5.5	5.5	5.5	5.5
GJ/admt, 4-bar	10.8	10.8	10.8	10.8	10.8
Gross Power Output, MW_e	48.4	136.7	132.6	105	151.8
Auxiliary consumption, MW_e	1.64	22.04	12.84	4.19	19.77
Net Power Output, MW_e	46.8	114.7	119.7	101	132
kWh/admt	904	2507	2295	1928	2425
Net Excess Power, MW_e	12.8	84.7	85.5	66.3	96.3
kWh/admt	248	1851	1639	1272	1769
Fuel HHV to electricity	10.4	23.2	21	20.7	21.5
steam	52	41.8	41.6	48.6	40.2
electricity + steam	62.4	65	62.6	69.2	61.7
Electricity/steam ratio	0.2	0.55	0.5	0.43	0.53
Incremental Fuel Chargeable to Power (IFCP)[c]					
MJ biomass (HHV) per kWh	8.86	4.8	5.7	2.2	6.1
Expressed as % efficiency	40.6	76	63	167	59

(a) Maximum achievable temperature by combustion in air at 424°C (gas turbine compressor outlet temp.) at 17 bar (combustor pressure).

(b) Assuming 80% condensate return at 110°C and fresh make-up at 15°C, the heat given to steam in the cogeneration plant is 2.315 GJ/tonne for 10-bar steam and 2.276 GJ/tonne for 4-bar steam.

(c) The numerator is the biomass fuel consumed in excess of that required to meet steam demand with the Tomlinson system. The denominator is the power produced in excess of that produced in the Tomlison case.

The final two rows in Table 2 are of interest in a situation where a mill is considering replacing an existing Tomlinson-based cogeneration system, a likely common situation during the next two decades, as noted in the introduction. A baseline alternative in this situation might be the installation of a new Tomlinson recovery boiler plus a supplemental-biomass boiler to augment steam delivery to a back-pressure steam turbine. If the mill has an opportunity to export power, then the incremental fuel chargeable to power (IFCP) shown in Table 2 provides a measure of the marginal fuel costs associated with the production of exported power using each of the gasification options shown in Table 2 in lieu of the Tomlinson baseline. The IFCP, expressed as a heat rate, has as its numerator the biomass consumption required in excess of that in the Tomlinson case to meet the same process steam demand. The denominator is the amount of power generated in excess of the Tomlinson's power production. The low IFCP heat rates (e.g., compared to a typical utility steam power plant heat rate of 10 MJ/kWh) indicate that exporting power from any of the four systems (especially those based on air-blown gasification) would involve relatively low marginal fuel costs. Obviously investment and operating and maintenance costs would also be considered in any full evaluation of alternative cogeneration options.

CONCLUSIONS

Black liquor gasification systems offer the possibility for kraft-based market pulp or integrated pulp and paper mills to generate far more electricity than at present while still meeting process steam demands. Depending on the gasification technology and cycle design, power-to-steam ratios can vary widely, providing flexibility in meeting mill requirements. The present work has focussed on better understanding the prospective energy benefits of black-liquor gasifier/gas turbine systems.

Black liquor gasification for gas turbine applications is not yet proven commercially. The level of development of several gasification technologies appears advanced sufficiently that large-scale demonstrations could be launched toward demonstrating commercial viability of gasifier/gas turbine systems (Larson and Raymond, 1997). Key features that must be demonstrated include gas cleanup to meet gas turbine specifications, stable gas turbine combustion of syngas, heat recovery from syngas streams and (in the case of the low-temperature gasification process) from solids, cost-effective recovery of pulping chemicals, and overall-plant thermal integration.

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