The Open Chemical Engineering Journal, 2012, *6*, 41-47

Second Round of Studies on Advanced Power Generation Based on Combined Cycle Using a Single High-Pressure Fluidized Bed Boiler and Consuming Biomass

Marcio L. de Souza-Santos* and Juan Villanueva Chávez

UNICAMP - University of Campinas, Faculty of Mechanical Engineering, Cidade Universitaria, Campinas, SP 13083-970, C.Postal: 6122, Brazil

Abstract: Following a preliminary study of power generation processes consuming sugar-cane bagasse; this second round indicates the possibility of almost doubling the current efficiency presently obtained in conventional mills. A combined cycle uses highly pressurized fluidized bed boiler to provide steam above critical temperature to drive steam-turbine cycle while the flue-gas is injected into gas turbines. The present round also shows that gains over usual BIG/GT (Biomass Integrated Gasification/Gas Turbine) are very likely mainly due to the practicality of feeding the biomass as slurry that can be pumped into the pressurized boiler chamber. Such would avoid the cumbersome cascade feeding of the fibrous biomass, usually required by other processes. The present stage assumes slurry with 50% added water. Future works will concentrate on thicker slurries, if those could be achieved. All studies apply a comprehensive simulator for boilers and gasifiers [CSFMB© or CeSFaMB™] and a process simulator (IPES) to predict the main features of the steam and gas turbine branches.

Keywords: Power-generation, biomass, fluidized-bed, boiler, simulation, CeSFaMB.

1. INTRODUCTION

In many instances, biomass can be regarded as a renewable and sustainable energy source. This is particularly true for countries, such as Brazil, with tropical climate combined with large areas available for crops. The country already has a tradition on the use of sugar-cane bagasse as well crops residues as supplementary source for electrical power generation. In addition, the surplus of energy from mills which is commercialized to local electrical grids is increasing.

The current power-generation units installed in most of large mills still employ Rankine-based cycles. Despite applying boilers that generate steam at very high pressure, the efficiencies of those units remain in the neighbourhood of 20% efficiency. Most studies for a technical leap are based on BIG/GT (Biomass Integrated Gasification/Gas Turbine) technology [1-8]. On the other hand, when applied to process where fibrous fuels such as sugar-cane bagasse should be fed into a pressurized vessel, several hurdles are imposed. For instance, cascade feedings are the usual proposal for that, but those rely on the assembling and correct operation of several hoppers kept under inert gas atmosphere. Such is too expensive not to mention prone to interruptions due to many combined parts which have to operate flawless. Usually, the fibrous bagasse forms domes inside the hoppers and that prevents the continuous feeding to rotating valves or screws. Some solutions for that can be applied, but are also cumbersome and not free of problems as well.

The alternative of feeding by pupping fuel slurry has been proposed, but that is not feasible for sugar bagasse gasification processes because it would add more water to the already very wet fuel, which leaves the mill with 50% moisture. Even if relatively low-water slurries could be achieved, one may end with fuel containing 60 to 70% water to be fed into the reactor. No gasification process can economically overcome the loss of efficiency due to the amount of energy required to evaporate those amounts of water in the reactor.

Glycerol is a by-product of biodiesel production, which is increasing fast in many countries. Therefore, the application of that residue to compose slurries has been considered. Nonetheless, such would take away the mill's autonomy in terms of producing power based just on its own resources.

However, boilers can operate well with slurry-feeding because the oxygen excess can be lowered to near the stoichiometric limit and sustainable combustion achieved. The basic simplified scheme of the proposed process is shown in Fig. (**1**).

The combustion chamber operates at high pressure therefore producing a flue gas that can be injected into gas turbines while super-heated steam drives steam turbines.

The present work is one among a series of investigations to determine the best configuration of the whole process in order to achieve the highest exergetic efficiency. The studies are beginning and more points or possibilities would be added. This particular stage shows that the proposed process might lead to higher efficiencies than the achieved by more

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*Address correspondence to this author at the UNICAMP - University of Campinas, Faculty of Mechanical Engineering, Cidade Universitaria, Campinas, SP 13083-970, C.Postal: 6122, Brazil; Tel: +55-19-35213278; Cell: +55-19-97107134; Fax: +55-19-35798275; E-mail: dss@csfmb.com

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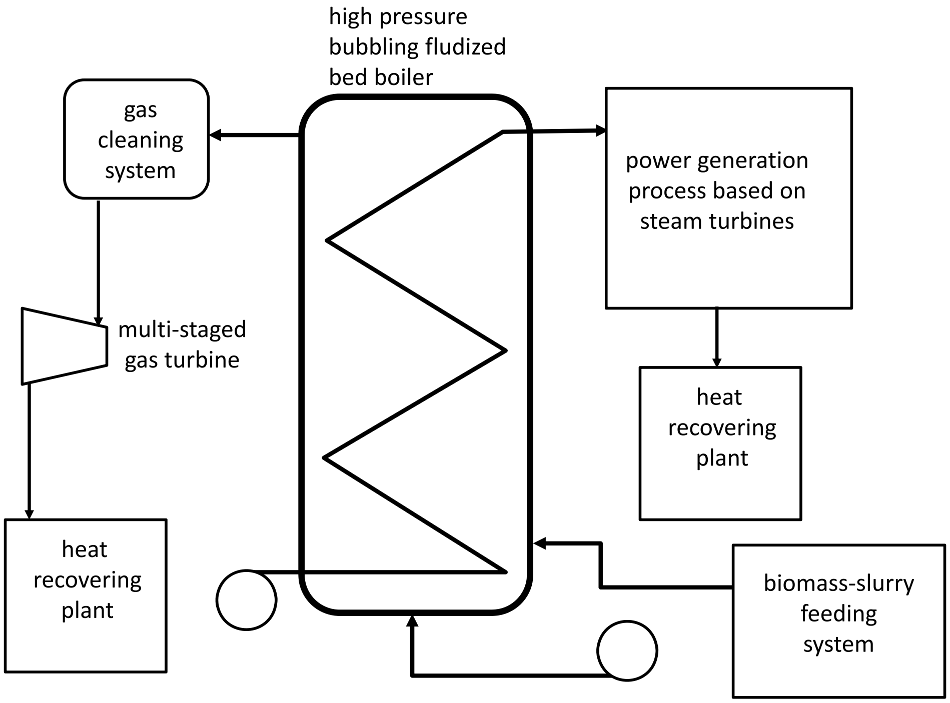

Fig. (1). Simplified scheme of the studied power generation process.

conventional ones. Future studies would improve on the present results and may also point to technological hurdles that need to be overcome in order to reach at a reliable process.

2. MATERIAL AND METHODS

The basic assumptions for the present study were:

1. Typical large sugar mill consuming 2 million ton. of sugar cane per year, which provides 28% on bagasse with 50% moisture. That would lead to fuel input around 180 MW that can be consumed by the boiler. Having in mind timing for maintenance and other random factors, the input around 150 MW was assumed.
2. Bagasse leaves the mill with 50% moisture.
3. Using such moist bagasse, preliminary and simple tests show that 40% water slurries (or a mixture with 40% of water and 60% of moist bagasse) could be pumped into a pressurized vessel. However, to be conservative, the value of 50% added water slurry has been applied. Future works will concentrate on thicker slurries, if that could be achieved.
4. Maximum temperature of gas injected into the turbines was set as 700 K. This is to ensure proper cleaning of flue gas, including conditions for complete condensation of alkaline. There are some discussions on this point in the literature [9] and the chosen value seems to be conservative.
5. Turbine and compressor isentropic efficiencies equal to 87%.
6. Pump isentropic efficiencies assumed as 95%.
7. Minimum temperature difference between parallel streams entering or leaving heat-exchangers is taken as 10 K.
8. Pressure in the fluidized bed chamber set as 2 MPa. That value was chosen to be well within the range of pressure for the flue-gas to be injected into commercial gas turbines.
9. Pressure inside the tubes immersed in the boiler bed and freeboard set as 10 MPa. This is also within the range of commercially available boilers.
10. Particle size distribution of feeding bagasse. The choice was set in order to achieve an area-volume average particle diameter around 1 mm, which is assumed to be easily obtainable by simple gridding or cutting equipment.
11. Internal diameter of the boiler at the bed section as 9 m. This value was reached after a first series of simulation to keep the fluidization within usual values of superficial velocity.
12. Bed depth as 5 m, which provides plenty room for tube banks immersed in that region.
13. Internal diameter of the boiler at the freeboard section as 12 m. Such value was reached after few series of simulations to ensure enough decrease of superficial velocity in the freeboard to facilitate the inertial separation of particles.
14. Freeboard height set as 10 m, which also provides plenty room for tube banks immersed in the freeboard as well above Transport Disengaging Height (TDH).
15. Internal and external diameter of tubes immersed in the bed and freeboard set as 30 and 40 mm, respectively. These values seem to be reasonable within the range of possibilities for such tubes and allow usual half-life for the tubes immersed in fluidized beds.
16. To simplify, in each bank all tubes were assumed in the horizontal position with staggered arrangement and 100 mm between centres.

17. Tube lengths in 2 banks immersed in the bed set as 7.0 m and the third as 5.0 m. The tube lengths of those immersed in the freeboard were set as 9.0 m.
18. Two banks of tubes in the bed are linked to another set in the freeboard. This is to ensure that most of the phase change would take place in the tubes immersed in the bed leaving the super-heating to the sections in the freeboard.
19. A series of 20 cyclones (300mm i.d. each) would allow recirculation of particles collected at the top of the freeboard to the bed.

Of course, those assumptions—especially from 8 to 17--could be modified or set as variables in future studies. In addition, the minimum water content in the slurry should also be verified and perhaps decreased from the level assumed at item 3.

The simulation tools employed in the present investigation were the Comprehensive Simulator for Fluidized and Moving Beds (CeSFaMB^{TM})[1] and IPES (Industrial Plant and Equipment Simulator). Details of those models and respective simulation programs can be found in the literature [10-28].

The strategy used here was:

1) Propose a workable configuration for the pressurized fluidized-bed boiler. After many simulation tests, a basic geometry was reached. The values are listed above along the assumed parameters.
2) Using CeSFaMB$^{©}$, try various options to achieve relatively high exergy efficiency for the boiler. Of course, many variables related to the boiler geometry or configuration and operational conditions could be chosen. Nevertheless, to simplify the work of this first study, the following were taken as variables:
   a. Number of tube banks and number of tubes in each bank. CeSFaMB© automatically verifies if the geometry of any proposed arrangement is physically possible within the available volumes set for the bed and freeboard.
   b. Mass flow of air injected through the distributor at bed base. CeSFaMB© checks if the combustion can be maintained and steady-state regime is achieved within the boundaries of bubbling bed fluidization.
3). Using IPES and the best results for the boiler operation, simulate the steam and gas branches, as shown in Fig. (**2**). Basic parameters regarding the operation of equip-

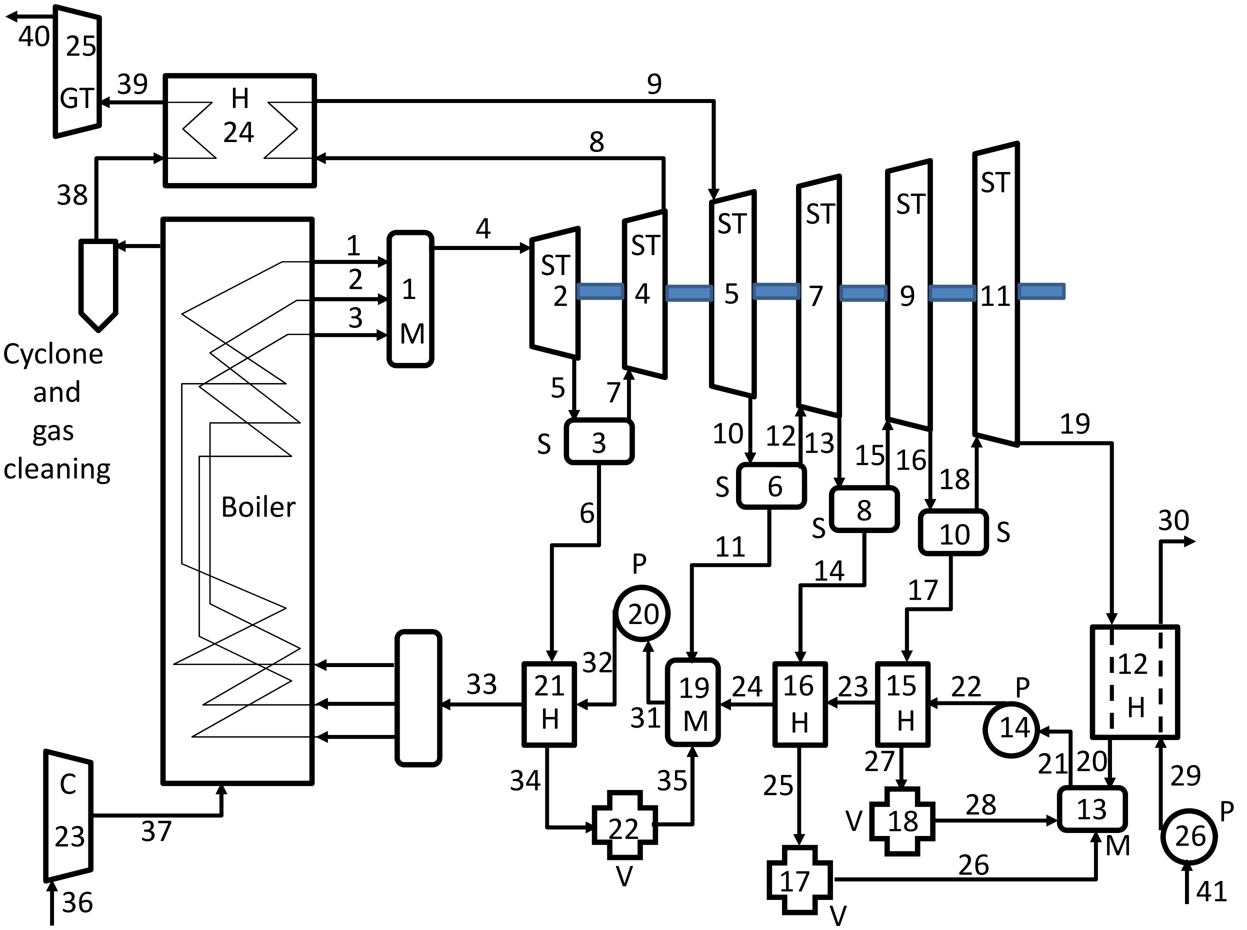

Fig. (2). Scheme of the proposed process. Equipment symbols: C = compressor, GT = gas turbine, H = heat-exchanger, M = mixer, P = pump or pumps, S = splitter, ST = steam turbine, V = valve

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[1] Former CSFMB$^{©}$, www.csfmb.com

ment and properties at streams are listed in the next section.

4) Improve the gas and steam branches having maximum exergy as objective.

3. RESULTS

The information obtained after the above procedure are summarized at the following tables.

As mentioned above, CeSFaMB simulation software was applied to maximize the exergy efficiency for that boiler. The resulting basic configuration as well operational parameters are summarized in Table **1**.

After a series of search and optimizations using IPES simulator, a reasonable composition of equipment have been achieved. The conditions and properties of streams in such process are shown in Table **2**, while Table **3** summarizes the overall energy balance.

Table 1. Summary of Boiler Operational Conditions

CONDITION OR PARAMETER	VALUE
Mass flow of dry bagasse	9.0 kg/s
Mass flow of injected air	56.0 kg/s
Mass flow of flue-gas	91.73 kg/s
Mass flow of elutriated solids	22.54 kg/s
Fluidization voidage (bed middle)	0.6061
Fluidization superficial velocity (bed middle)	0.1982 m/s
Bed dynamic volume	318.1 m^3
Circulation flux of carbonaceous (bed middle)	$0.702x10^4$ kg/(m^2 s)
Mixing index in the bed	1.000
Tar flow at the top of the freeboard	0.000 kg/s
Total carbon conversion	97.79 %
Input energy rate due to fuel	152.66 MW
Total energy rate input	194.77 MW
Total flow of produced steam	31.50 kg/s
Total energy rate transferred to tubes	83.20 MW
Mass held in the bed	$9.96x10^4$ kg
Average residence time of particles based on feeding rate	46.10 mim
TDH	4.26 m
Temperature at the distributor surface	871.11 K
Average temperature at bed middle	871.18 K
Average temperature at the freeboard top	871.06 K
Average temperature of recycling particles	869.06 K
Entering exergy flow	795.12 MW
Exergy flow carried by flue-gas	84.19 MW
Exergy flow carried by steam	50.99 MW
Leaving exergy flow	135.18 MW
Ratio between leaving and entering exergy flows	17.00 %

Table 2. Summary of Stream Properties

STREAM	TEMPERATURE (K)	PRESSURE (kPa)	MASS FLOW (kg/s)	ENTROPY (kJ/kg K)	ENTHALPY (kJ/kg)[a]
1	871.00	10000.0	10.50	10.441	-12352.0
2	869.46	10000.0	10.50	10.436	-12355.0
3	865.10	10000.0	10.50	10.424	-12366.0
4	868.52	10000.0	31.50	10.434	-12358.0
5	635.84	2100.0	31.50	10.523	-12804.0
6	635.84	2100.0	4.92	10.523	-12804.0
7	635.84	2100.0	26.58	10.523	-12804.0
8	458.87	437.0	26.58	10.614	-13137.0
9	841.00	437.0	26.58	11.864	-12345.0
10	660.51	123.0	26.58	11.939	-12725.0
11	660.51	123.0	0.57	11.939	-12725.0
12	660.51	123.0	26.01	11.939	-12725.0
13	560.97	54.0	26.01	11.989	-12926.0
14	560.97	54.0	0.65	11.989	-12926.0
15	560.97	54.0	25.36	11.989	-12926.0
16	471.41	23.0	25.36	12.040	-13103.0
17	471.41	23.0	0.51	12.040	-13103.0
18	471.41	23.0	24.85	12.040	-13103.0
19	378.11	8.0	24.85	12.103	-13282.0
20	313.00	8.0	24.85	2.3903	-15843.0
21	311.02	8.0	26.01	2.3637	-15851.0
22	311.02	123.0	26.01	2.3637	-15851.0
23	322.90	123.0	26.01	2.5210	-15801.0
24	338.55	123.0	26.01	2.7199	-15736.0
25	356.42	54.0	0.65	3.0182	-15637.0
26	314.72	8.0	0.65	3.1763	-15637.0
27	336.28	23.0	0.51	2.7787	-15721.0
28	314.72	8.0	0.51	2.8525	-15721.0
29	298.00	103.0	300.0	2.1844	-15906.0
30	347.04	102.0	300.0	2.8242	-15700.0
31	372.30	123.0	31.50	3.1205	-15593.0
32	372.57	10000.0	31.50	3.1236	-15582.0
33	452.92	10000.0	31.50	3.9573	-15238.0
34	487.90	2100.0	4.92	4.3399	-15074.0
35	378.68	123.0	4.92	4.8435	-15074.0
36	298.00	101.325	56.00	6.7402	-0.21044

Table 2. Contd…..

STREAM	TEMPERATURE (K)	PRESSURE (kPa)	MASS FLOW (kg/s)	ENTROPY (kJ/kg K)	ENTHALPY (kJ/kg)[a]
37	765.67	2020.0	56.00	6.8602	490.80
38	851.06	2000.0	91.73	8.1986	-5481.4
39	692.89	2000.0	91.73	7.8914	-5718.1
40	367.73	105.0	91.73	8.0156	-6159.0
41	298.00	103.0	300.0	2.1844	-15906.0

a: Enthalpy values include the formation and sensible terms

Table 3. Overall Power Balance

Total entering enthalpy rate	$-0.56638\text{x}10^{10}$ W
Total leaving enthalpy rate	$-0.57274\ \text{x}10^{10}$ W
Total entering exergy rate	$0.29352\ \text{x}10^{9}$ W
Total leaving exergy rate	$0.23647\ \text{x}10^{9}$W
Power input	27.862 MW
Power output Net power output	87.636 MW 59.774 MW
Rate of heat exchanged with environment	13.307 MW
Total variation of exergy Rate of energy input due to fuel	30.662 MW 152.66 MW
Efficiency based on 1st Law[a]	39.155 %
Efficiency based on 2nd Law[b]	20.387 %

a: defined as (net rate of useful power out)/(total energy rate in)
b: defined as (net rate of useful power out)/(total exergy rate in)

4. DISCUSSION

The efficiencies of present mills operating with high-pressurized boilers and using 50% moisture bagasse stay around 20%. Therefore, the present stage of studies managed to show that efficiency levels well above those values are possible. In addition, the proposed process can lead to even higher efficiencies. Among the various points to be investigated in that direction are:

a. Confirm if slurries that might be pumped could be achieved with lower contents of water than the assumed here. As mentioned before, there are indications that 40% and even 30% slurries could be pumped. This would substantially increase the efficiency of the present process.

b. Increases in the fluidized-bed pressure.

c. Increases in the steam pressure.

d. Use of more elaborate cycles or process for the steam and gas-turbine branches.

5. CONCLUSIONS

The concept for an advanced thermoelectric power-generation process has been tested through rigorous simulations. It would allow the use of moist bagasse as taken from the mill and avoid cumbersome and expensive cascade feeding systems, usually necessary to operate BIG/GT concepts.

This second round of simulations led to efficiency values well above of those achieved by existing units installed at sugar-alcohol plants.

The next round of studies would confirm the minimum limits of water content in bagasse slurries as well include pressures in the fluidized bed and inside tubes as variables. In addition, improvements on the strategies of gas and steam turbine branches will be tried.

CONFLICTS OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENT

This investigation has been supported by the University of Campinas (UNICAMP).

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Received: February 29, 2012 Revised: March 26, 2012 Accepted: April 02, 2012