Chemical Engineering Journal 258 (2014) 402–411

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Thermodynamic predictions of performance of a bagasse integrated gasification combined cycle under quasi-equilibrium conditions

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HIGHLIGHTS

- An investigation on the exergetic feasibility of a BIGCC.
- A survey about the influence of process parameters on system performance.
- Use of exergy composite curves to define the saving potentialities.

ARTICLE INFO

Article history:
Received 13 May 2014
Received in revised form 23 July 2014
Accepted 24 July 2014
Available online 4 August 2014

Keywords:
Biomass gasification
Combined cycle
Exergy
Thermodynamic analysis

ABSTRACT

The objective of this study was to develop a comprehensive mathematical model of bagasse gasification integrated with a gas turbine combined cycle (BIGCC). The model uses a quasi-equilibrium approach to evaluate the thermodynamic performance of the plant, considering both first and the second law of thermodynamics. The influence of pressure ratio in the compressor ($1{:}4 < rp < 1{:}10$) and of the gas turbine inlet temperature ($1000\ K < TiT < 1400\ K$) on system efficiencies is explored. The exergy destruction, losses and recovery in the heat exchanger network are analyzed using pinch methodology. A 46.5% exergy saving by recovering heat in the steam cycle and drying stage can be achieved. Best results are obtained when the turbine inlet temperature is 1323 K and for a 1:10 cycle compression ratio: under these conditions the total exergy efficiency is 32.3% and 35.4% energy efficiency. The atmospheric pressure gasifier was operated at 72% hot gas efficiency and 1073 K. Major exergy destruction occur in the gasifier, dryer and heat exchanger network with a combined 94% of total losses.

1. Introduction

Both global and national energy polices promote research to increase the use of biomass-derived fuels, especially in Latin America, where energy from biomass is as much as 20% of the demand [1]. In this framework sugarcane and its harvesting residues have the potential to produce first and second generation biofuels through both: biological and thermochemical conversion route. Each ton of sugarcane contains 142 kg of juice primarily sucrose and molasses, 140 kg of fiber (bagasse) and 140 kg of agricultural residues with an average energy content of 15.7 MJ/kg on dry basis [2,3]. The fibrous fraction of sugarcane (bagasse) on a 50% wet basis contains at about 2.5 bbl of oil equivalent. Many researchers are developing technologies based on the energy potential of bagasse, its renewability, CO_2 neutrality and the possibility of conversion to higher-value-added products. The most common processes for energy and chemical upgrading are combustion, pyrolysis and gasification [4]. Combustion of bagasse is widespread in the combined production of heat and power (CHP) in sugar cane mills. Most of these systems are based on the Rankine cycle and backpressure turbines, resulting in low electricity production (20–30 kWh/ton of sugar cane), high steam consumption (10–25 kg/kW) and low bagasse surplus [2,5,6].

Pyrolysis has been less developed and is focused on the production of bio-oil, while gasification is mainly used to produce a flexible gas stream with both energy and chemical applications [4]. The gases produced in gasification contain mainly H_2, CO, CH_4, C_xH_y, CO_2 and N_2.

Many configurations have been studied to use gasification gases for energy production, the most widespread: gas engines, gas turbines, combined cycles, and more recently, high efficiency fuel

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http://dx.doi.org/10.1016/j.cej.2014.07.104
1385-8947/

Nomenclature

BG	biomass gasifier
BIGCC	biomass integrated gasification combined cycle
BPST	back pressure steam turbine
bbl	barrels
CEST	compression extraction steam turbine
CHP	combined heat and power
Cpg	mass heat capacity, (kJ/K/kg)
CPR	compressor pressure ratio
e^b	chemical exergy of bagasse (kJ/kg)
e_i^{ch}	molar chemical exergy of species i (kJ/kmol)
e_i	total exergy of each chemical species (kJ/kmol)
E_{in}	activation energy (kJ kmol^{-1})
E_j	exergy of the j streams entering the system (MJ)
E_K	exergy of the K streams leaving the system (MJ)
e_i^o	standard chemical exergy of species (kJ/kmol)
e_i^{ph}	molar physical exergy of species i (kJ/kmol)
$F_{hot,cold}$	molar flow of cold and hot stream in heat exchangers (kmol/s)
GG	gasification gases
GGSR	gasification steam reforming
h	enthalpy (kJ/kmol)
HHV	higher heating value (kJ/kg)
HRSG	heat recovery steam generator
$I_{r,tot}$	system exergy destruction (kW)
I_{rCOMP}	exergy destruction in compressor (kW)
I_{rG}	exergy destruction in gasifier (kW)
I_{rHEx}	exergy destruction in heat exchangers (kW)
I_{rTURB}	exergy destruction in the turbine (kW)
LHV	lower heating value (kJ/kg)
m_B	mass flow of bagasse (kg/s)
mg	mass flow of gasification gases (kg/s)
QET	quasi-equilibrium temperature (K)
rp	pressure ratio of cycle
S	entropy (kJ/kmol/K)
SOFC	solid oxide fuel cell
TiT	turbine inlet temperature (K)
TPR	turbine pressure ratio
tc	tons of sugar cane (ton)
W_{AC}	power consumed by air compressor (kW)
W_{GGC}	power consumed by gasification gas compressor (kW)
W_{GT}	power delivered gas turbine (kW)
$W_{net,GT}$	net power of gas turbine cycle (kW)
$W_{net,ST}$	net power of steam turbine cycle (kW)
W_P	power consumed by water pump (kW)
W_{ST}	power delivered by the steam turbine (kW)
y_{tar}	tars concentration in producer gas (g/Nm^3)
$y_{D,k}$	exergy destruction ratio
$y^*_{D,k}$	exergy destruction coefficient

Greeks letters

η_{ex}	exergy efficiency of system (%)
η_{en}	energy efficiency of system (%)
ξ_c	fractional carbon conversion
η_{CG}	cold gas efficiency (%)
η_{HG}	hot gas efficiency (%)
η_T	turbine isentropic efficiency
η_c	compressor isentropic efficiency

cells. One possible configuration has been evaluated by the present authors where a bagasse gasifier was integrated with a solid oxide fuel cell [7]. Another feasible option is to integrate the gasification of bagasse with a gas turbine combine cycle for the production of power and heat [8]. The basic elements of such a BIGCC power plant include a biomass dryer, a gasifier, a cleanup system, a gas turbine-generator fueled by combustion of the biomass-derived gas, a heat recovery steam generator (to raise steam from the hot exhaust of the gas turbine), and a steam turbine–generator (to produce additional electricity) [6].

Several models have been developed to simulate the integration of biomass gasifiers with traditional and novel combined cycles. The main results of such studies are summarized in Table 1. Until now there are many works focused on the mathematical description of gasifier based on equilibrium calculations with a very limited report of experimental data [5,9].

Larson et al. [6] have already presented a general review of several cogenerating technologies in sugar cane mills. They demonstrated the economic feasibility of using BIGCC systems when they are compared with traditional backpressure steam turbines and condensing extraction steam turbines. Moreover, carbon emissions savings for the BIGCC are almost twice CEST's at same milling capacity. However, authors focused their analysis on general issues and no details of gasification systems are given.

Table 1
Performance indicators of different gasification-energy production systems.

System	Biomass	η_{EXE} (%)	Refs.
BIGCC	Sugarcane bagasse	30	[9]
BOILER	Sugarcane bagasse	24–34	[10]
GTCC	Wood	29	[11]
GTCC	Biomass mixture	33	[12]
BIGCC	Sugarcane bagasse	20–33	[6]
CEST	Sugarcane bagasse	16–28	[6]
BIGCC	Cobs	28	[13]
BIGCC	Paper	34	[14]
BG-SOFC	Straw slurry	No	[15]
GGSR-SOFC	Sugarcane bagasse	31	[16]
BG-SOFC	Olive residues	36	[17]
BG-SOFC	Sugarcane bagasse	32	[7]

Pellegrini et al. [9] reported a simplified model for the gasification of bagasse based on chemical equilibrium considerations. Authors developed a parametric study on the influence of several operation parameters and an exergy analysis of the system. They recommend using mathematical correlations of experimental results for the CH_4 composition and for carbon conversion to study different operational modes and to understand exergy and energy behavior.

De Kam et al. [13] analyzed the BIGCC integration into a sugar–ethanol factory using a simulation model that represents the gasification reactor as an equilibrium block. They emphasized on the importance of considering both the economic and environmental criteria in such analysis. Even when this communication was very explicit a low exactitude in the gasification unit predictions associated to the equilibrium consideration (Gibbs model) can be identified.

In a more recent paper, Pellegrini et al. [19] treated economic and environmental issues associated to BIGCC in their assessment of combined production of sugar, ethanol and electricity. These authors demonstrated that the electricity surplus obtained by cogeneration improves the exergo-environmental performance of the system and that modern cogeneration systems can produce 2.5 times the electricity obtained by traditional BPST, generating in this way a remarkable economic profit for the factory.

More recently, Dias [5] analyzed three different cogeneration systems for an integrated sugar–ethanol factory: a traditional Rankine cycle with backpressure and condensing steam turbines, and a