Applied Energy 229 (2018) 413–432

Contents lists available at ScienceDirect

Applied Energy

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

Modeling, thermodynamic and techno-economic analysis of coal-to-liquids process with different entrained flow coal gasifiers

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HIGHLIGHTS

- Modeling of coal-to-liquids (CTL) process with different entrained flow gasifiers was conducted.
- Thermodynamic analysis of CTL process was presented.
- Locations and magnitudes of exergy inefficiencies were identified and quantified.
- Techno-economic and CO_2 emissions analysis of CTL process were conducted.

ARTICLE INFO

Keywords:
Coal-to-liquids (CTL) process
Coal gasification
Process simulation
Thermodynamic analysis
Techno-economic analysis
Fischer-Tropsch (FT) synthesis

ABSTRACT

For the coal-to-liquids (CTL) plant, the most important unit is gasification, which determines the composition of the crude syngas, and affects CO_2 emissions and investment of the CTL process. This paper conducts a detailed plant-wide modeling of CTL process with different entrained flow gasifiers. The model is compared with the literature data. Three cases of CTL process with different entrained flow gasifiers (GSP, Shell and Texaco) are researched through thermodynamic, techno-economic and CO_2 emissions analysis. Case GSP represents the CTL process with GSP gasifier, Case Shell represents that with Shell gasifier, and Case Texaco represents that with Texaco gasifier. For a typical CTL process, Case GSP can produce FT liquids of 277.49 t/h, Case Shell can produce 246.25 t/h, and Case Texaco can provide 232.93 t/h. The energy efficiencies of Case GSP, Shell and Texaco are 50.85%, 48.18% and 41.09%, respectively. The exergy efficiencies are 49.89%, 47.20% and 40.44%, respectively. The exergy inefficiencies of the subsystem are quantified. The economic performance and CO_2 emissions of the three cases are also discussed.

1. Introduction

The energy reserve in China is rich in coal, while scarcity in oil and gas. The proven reserves of coal in China are 114.5×10^9 t, and in 2015 the percentages of energy production from coal, oil, and natural gas are 78.2%, 9.2%, and 5.3%, respectively [1]. In a long time, coal will be the dominant energy resource in China. As shown in Fig. 1, the consumption of gasoline and diesel in China has been growing rapidly [1]. The oil consumption is kept increasing, and more than half of oil is imported from abroad, so the development of alternative energy resources is required. The coal-to-liquids (CTL) process can produce diesel and gasoline from coal. The capacity of the biggest CTL plant is 4.0 Mt/y oil in China [2], and the total capacity will grow continuously to 13 Mt/y by 2020 [3].

Gasifiers vary in cold gas efficiency, cost, processing capacity and adaptability of coal type, and this makes a big difference in the whole CTL process. There are mainly three types of gasifiers based on the solid feedstock movement, i.e., fixed bed, fluidized bed and entrained flow gasifiers. For the entrained flow gasifiers, there are two feeding options, slurry feeding and dry feeding. Recent studies on the CTL process with different gasifiers is shown in Table 1. Various of gasifiers are used (Shell, Texaco, BGL, etc.), and most studies focus on the plant configuration (liquid-only or co-production [4–8]), the integration with CCS [4–13] and hybrid feedstock (coal/biomass/natural gas [9–11,14–23]).

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https://doi.org/10.1016/j.apenergy.2018.07.030
Received 3 February 2018; Received in revised form 4 July 2018; Accepted 9 July 2018
0306-2619/

Nomenclature

Abbreviations

AGR	acid gas removal
ASU	air separation unit
ATR	autothermal reformer
BEOP	break-even oil price
BFW	boiler feed water
BOI	balance of indirect costs
BOP	balance of plant costs
BTL	biomass-to-liquids
CBGTL	coal, biomass, and natural gas to liquids
CBTL	coal biomass to liquids
CCP	combined cycle power plant
CCS	CO_2 capture and storage
CEPCI	Chemical Engineering Plant Cost Index
CG	coal gasification
CoP	ConocoPhillips
CTL	coal-to-liquids
EG	ethylene glycol
FCI	fixed capital investment
FG	fuel gas
FT	Fischer-Tropsch
FTL	FT liquids
GE-Texaco	Texaco
GT	gas turbine
GTL	natural gas to liquids
HP	high pressure
HRSG	heat recovery steam generator
IP	intermediate pressure
LACCR	the levelized annual capital charge rate
LFG	light fuel gas
LHV	lower heating values
LP	low pressure
LRC	low-rank coal
LTFT	low-temperature FT
MDEA	methyldiethanolamine
MHX	main heat exchanger
NG	natural gas
O&M	operating and maintenance
OTL	oil-to-liquid fuels
PSA	pressure swing adsorption
SCOT	Shell Claus off-gas treating
Siemens-GSP	GSP
sf	the scale factor
ST	steam turbine
STL	shale-to-liquids
SWS	sour water stripper
TCI	total capital investment
WGS	water gas shift
WWT	wastewater treatment

Notations

a, b, c, d	the coefficients of specific heat capacity
C	cost
c_p	the specific heat capacity (kJ/kg K)
d_p	the diameter of the coal particle
E_x	Exergy (kJ/kg)
H	Enthalpy (kJ/kg)
n	the number of carbon atoms in the hydrocarbon molecules
P	Pressure (kPa)
S	Entropy (kJ/kg K)
S_1, S_2	the production capacity of the benchmark project and the planning project
T	Temperature (K)
t_n	number of trains
x_i	the mass fraction of component i
Y	yield
y_{ineff}	the ratio of the exergy inefficiencies to the total exergy inefficiencies
Z	the coefficient which depends on the concentration of CO and CO_2
[CO]	the concentration of CO
[CO_2]	the concentration of CO_2

Greek symbols

η_x	exergy efficiency (%)
Φ	the coefficient which depends on the diameter of the coal particle

Subscripts and superscripts

0	reference state
daf	dry, ash free
dev	devolatilization
e	electricity
ex	exergy
in	input
ind	indirect
ineff	exergy inefficiencies
out	output
ph	physical
prod	product
th	thermal
VM	volatile matter

Only a few authors considered the effect of gasifier type. The CTL plants in China mainly use three types of gasifiers, i.e., slurry gasifiers, dry powder gasifiers, and fixed bed gasifiers [24]. As the entrained flow gasifiers have four main advantages: (1) the ability to utilize any type of coal, (2) high coal throughput capacity particularly at high pressures, (3) product gas is free of tars, and (4) high carbon utilization due to high reaction rates, this study focuses on the entrained flow gasifiers, and three types of entrained flow gasifiers (GSP, Shell and Texaco) are systematically investigated to assess their performance in the CTL process.

Exergy is defined as the maximum theoretical work obtainable from a system compared with the ambient environment. It is used to assess thermodynamic inefficiencies in the system by considering the magnitudes, locations, and types of exergy inefficiencies [27]. The exergy analysis methodology has been applied in the coal gasification (CG) [28–30], biomass gasification [31–36], CTL process [37], GTL process [38], and BTL process [39–42]. Gräbner and Meyer [28] evaluated the gasification processes in terms of cold gas efficiency, syngas yield and exergy efficiency. CoP and Shell exhibited the highest exergy efficiencies for Pittsburgh #8 coal while Siemens (GSP) offered the highest efficiency for the South African coal. Liszka et al. [29] proposed a hydrogen production process through co-gasification of biomass and coal with CO_2 capture. The overall exergy efficiency of the coal-to-hydrogen system was 57%, and the highest exergy losses took place in the gasifier. Seyitoglu et al. [30] studied an integrated coal gasification system for hydrogen production and power generation, and the overall energy and exergy efficiencies of the entire system was 41% and 36.5%, respectively. Ptasinski et al. [31] used idealized gasifier model to