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Investigation of a new integrated biofuel production process via fast pyrolysis, co-gasification and hydroupgrading

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ABSTRACT

A new integrated process of biofuel production is introduced and analyzed. This process consists of lignocellulosic biomass fast pyrolysis, gasification, electrical power generation and latest bio-oil upgrading in biorefinery processes. Upgrading processes include hydrotreating, distillation, hydrocracking and steam reforming units. Biomass is converted to bio-oil, gas and bio-char through fast pyrolysis which is then used in biorefinery and gasification. Simulation results show that 1 kg/s hybrid poplar biomass generate about 0.68 kg/s bio-oil, 0.16 kg/s gas and 0.17 kg/s char. Also 5.62 MW electrical power can be gained from the steam cycle. The excess heat of gasification can be used as a part of the required heat source in the process. Moreover the produced syngas is used in the steam reforming unit to provide the required hydrogen in the refinery. In addition, by heat integration the consumption of hot and cold utilities decreased and consequently the process performance improved. The obtained results show that synthetic biofuel yield is about 0.49 wt% and 0.51 wt% gasoline/diesel blendstocks. Moreover economic analysis, sensitivity analysis was also done to study the effects of major operating parameters, i.e., steam reforming temperature, steam/carbon ratio of gasification and greenhouse gas emission, on the process performance.

1. Introduction

Environmental concern about the global climate change, increasing energy consumption and reliance on depleted fossil fuel sources are the stimulants to concentrate on renewable energy sources research and utilization [1–3]. Renewable energy sources are considered as a clean, reliable and inexhaustible energy resources that supply more than 10% of the total world energy demand [4]. Several work has been done to use these renewable energies in a variety kind of the processes. For instance, the solar thermal energy as a type of renewable energy is utilized as heat source in the electrical power generation cycle [5] and solar chimney power plant [6]. Biomass is a plentiful renewable energy source that can be used as alternative fuels in the transportation sector that is one of the main infrastructure of social and economical development [7–9]. Using biofuels produced from biomass improves energy security that is vital for any country, on the other hand help to both reduce greenhouse gas (GHG) emission and the world's dependence on fossil fuels [10,11].

Thermochemical conversion of biomass to produce biofuels recognized as the most efficient way to produce liquid product [12–14]. Fast pyrolysis is an advanced process in which biomass is rapidly heated to moderate temperature around 500 °C in the absence of oxygen [15,16]. The main product of the fast pyrolysis is a liquid that recognized as bio-oil and by-products of this process are bio-char and non-condensable gases. Bio-oil as liquid fuel can be readily stored and transported, also has a high potential to upgrade and convert or blend with gasoline and diesel [17,18]. Several researches are reported that maximum bio-oil yields from fast pyrolysis obtained up to 80% [18–20]. While the bio-oil yield and characteristics highly depend on multiple factors. The effects of cassava rhizome pyrolysis and filter temperatures on product yields and bio-oil properties were studied [21]. The study illustrated that by increasing temperature from 400 to 500 °C, bio-oil and gas yield increases, also bio-char is thermally cracked and converted to non-condensable gas and water. Further increase to 550 °C led to decreased bio-oil yield and increases gas yield, because of decomposition of bio-oil to non-condensable gas. Also the effect of temperature, biomass feedstock type, and heating rate on char yield was studied [22]. Comprehensive reviews about several effective parameters on biomass pyrolysis process have been reported too [23–25]. In these papers, several important factors like: biomass type, biomass moisture content, reaction conditions were studied.

Numerous types of catalysts have been investigated in many studies

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Nomenclature

LMTD	logarithmic mean temperature difference, °C
$\dot{m}$	mass flow rate, kg/s
P	pressure, bar
q	heating value, MJ/kg
T	temperature, °C
U	the overall heat transfer coefficient, $W/m^2\,°C$
$\dot{W}$	electricity power, MW

Greek letters

ΔH	heat of reaction, kJ/mol
η	efficiency, %

Subscripts

0	initial
bo	bio-oil
bm	biomass
d	diesel
e	energy
i	discount rate
g	gasoline
p	power generated
t	year of t
tot	total

Abbreviations

ATM	atmospheric distillation column
C	cooler
COMP	compressor
CYC	cyclone
EX	heat exchanger
F/D	feed to distillate
FL	separator
GHG	greenhouse gas
H	heater
I	investment
M	mixer
N	total number of streams
NPV	net positive value
P	pump
PSA	pressure swing adsorption
S	splitter
S/C	steam to carbon
ST	steam turbine
R	revenue
T	cost
ROR	rate of return
VAC	vacuum distillation column
WGS	water gas shift

[26–28]. One of the major important factors in controlling the quality and composition of bio-oil is the application of catalysts.

The alkali metal and Ni based catalysts are effectively used for complete tar destruction and heavy tar elimination, but they become inactive by carbon deposition [29]. Based on the experimental work [30] the optimal operating condition of co-pyrolysis of corn stover and scum was reported at 550 °C, CaO to HZSM-5 ratio of 1:4 and corn stover to scum ratio of 1:2. (The ratio of (HZSM-5 + CaO) to (scum + corn stover) was kept at 1:1.) Moreover, most of the studies evaluate catalyst performance only at a small scale. Therefore, development of efficient and commercial scale catalyst for pyrolysis is a challenge.

As mentioned earlier, bio-oil as a renewable liquid fuel can be a possible alternative of fossil fuels, although comparing to the conventional petroleum fuels it has a lower heating value and upper oxygen content (in the form of water and oxygen-containing). So upgrading the bio-oil is the main route for utilization of this technology [31]. There are some published records that studied this issue. Crude bio-oil conversion in a hydrodeoxygenation (HDO) reaction in an autoclave reactor under different experimental conditions by using a Pd/C catalyst was subjected [32]. It is converted into two phase oil products. Water content and heating values of heavy oil was ranged 0.4–1.9 wt%, and 28.7–37.4 MJ/kg, respectively. Which is about twice higher than that of crude bio-oil.

Fast pyrolysis of pine woodchips was co-processed with fluid catalytic cracking (FCC) demonstration-scale unit using a commercial catalyst [33], that bio-oil and conventional gasoil were cracked into gasoline and diesel range products. It was concluded that aged bio-oil may affect operating conditions and during catalytic cracking, the oxygen content of bio-oil was almost completely removed and mostly converted to water, CO or CO_2. GHG emission of upgrading bio-oil produced via fast pyrolysis of Miscanthus was evaluated [34]. Two processes were considered as upgrading, hydroprocessing and zeolite cracking. The results indicate that rate of soil organic carbon (SOC) in the Miscanthus is the major parameter in GHG emissions for both upgrading processes. Comparison between the biofuels produced from hydroprocessing and zeolite cracking with conventional fossil fuels indicates that GHG emission savings ranged 82–87%, and 68–77%, respectively. Pine wood fast pyrolysis was simulated [35], then produced bio-oil was upgraded into gasoline and diesel via a two-stage hydrotreating process. The results show that combustion of by-products can provide the required energy for drying and fast pyrolysis process operations. Also the economic analysis concluded that final product value of £6.25/GGE, require total capital investment of £16.6 million and annual operating costs of £6.4 million based on Q1. 2013 cost data.

Most previous studied processes focused only on increasing bio-oil yield and improving biofuel's properties, whereas there is a lack of concern in the energy consumption of the processes. Several techniques have been developed to improve the performance of industrial units. Among them, heat integration has been recognized as a promising technique [36,37]. The benefit of process heat integration decreases the required energy and result in significant cost savings in chemical process industry [38]. Thus, it can reduce the overall hot and cold utilities by exchanging heat between the cold and hot streams [39]. In a case study [40], the effect of heat integration only on atmospheric and vacuum unit of an existing refinery was studied. The maximum energy saving was reported to be 14.33% equal to 11.6 MW. In the same study [41], operating cost reduction of up to 9.58% was reported. A novel biorefinery process for cellulosic ethanol production from biomass was

Table 1
Ultimate and proximate analysis and chemical composition of biomass [44,45].

Ultimate analysis	wt%	Proximate analysis	wt% (dry basis)	Chemical composition	wt% (dry basis)
Element		Parameter		Component	
C	50.5	Volatiles matter	85.6	Cellulose	43.8
H	5.97	Fixed carbon	12.3	Hemicellulose	20.4
O	40.8	Ash	2.1	Lignin	29.1
N	0.6				
S	0.02				