Computers and Chemical Engineering 33 (2009) 2012–2017

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Synergy in the hybrid thermochemical–biological processes for liquid fuel production

Rakesh Agrawal[a,*], Navneet R. Singh[a], Fabio H. Ribeiro[a], W. Nicholas Delgass[a], David F. Perkis[b], Wallace E. Tyner[b]

[a] School of Chemical Engineering and Energy Center at Discovery Park, Purdue University, West Lafayette, IN 47907, United States
[b] Department of Agricultural Economics and Energy Center at Discovery Park, Purdue University, West Lafayette, IN 47907, United States

ARTICLE INFO

Article history:
Received 30 October 2008
Received in revised form 14 May 2009
Accepted 22 June 2009
Available online 1 July 2009

Keywords:
H_2CAR process
Hybrid hydrogen–carbon process
Biofuels
Hydrogen
Biomass
Transportation fuels
Thermochemical
Biological processes

ABSTRACT

For a successful large scale implementation of biomass-to-liquid fuel for transportation, it is imperative that production of liquid fuel from biomass be maximized. For this purpose, synergistic processes using energy from sustainable carbon-free energy sources are needed. In this paper, we present such novel integrated processes that, when compared to the known conventional conversion methods, have potential to produce nearly three times more liquid fuel from a given quantity of biomass. The new processes treat biomass predominantly as carbon source and rely on the novel integrations to preserve carbon atoms during biomass conversion to liquid fuel. We have named such approach as hybrid hydrogen–carbon (H_2CAR) process. Furthermore, we propose a novel synergistic integration between H_2CAR and fermentation process where high-level heat from the H_2CAR process is used to supply process heat for the fermentation process and CO_2 produced during the fermentation is converted to liquid fuel using H_2CAR process. This synergy leads to increase in process carbon efficiency (~100%) and higher energy efficiency (65.7% vs. 57.2%), significantly decreasing land area requirement to produce liquid fuel compared to fermentation-based processes. Such synergistically integrated processes provide attractive opportunities for process design, operation and control.

1. Introduction

It is highly desirable to produce liquid fuel in a sustainable manner for the transportation sector in order to overcome the rising concerns of energy security, oil peaking, high crude oil prices and global warming (Goldemberg, 2007; Lewis & Nocera, 2006; Ragauskas et al., 2006). The only sustainable environmentally friendly source of carbon for liquid fuel production is atmospheric CO_2 and plants utilize this source to fix carbon as biomass. Therefore, biomass can be a sustainable source for liquid fuel production. However, a major challenge for biomass-based routes is to economically produce the enormous quantities of liquid fuel needed by the transportation sector.

A recent study states that all the US corn and soybeans can meet only 12% of gasoline and 6% of diesel demand of the USA transportation sector (Hill, Nelson, Tilman, Polasky, & Tiffany, 2006). The billion ton biomass study estimates that 1.36 billion tons of sustainable biomass are potentially available per year in the USA (Perlack et al., 2005) It is also estimated that from this quantity of biomass, cellulosic ethanol or thermochemical methods can only meet 30% of the US transportation sector's current need of about 13.8 million barrels per day (Mbbl/d) (Davis & Diegel, 2007). This still leaves a significant gap between the supply and demand for the US transportation sector. Clearly, there is an urgent need for processes which can produce significantly higher liquid fuel yields from a given quantity of biomass.

In this paper, we propose novel process integration at various levels with the sole purpose of increasing liquid fuel production from a given quantity of biomass. Conventional biomass-to-liquid fuel conversion processes use a major portion of the energy needed for conversion from the biomass itself. Thus, while a portion of the biomass is converted to liquid fuel, a significant portion is converted to CO_2. This is true for corn to ethanol as well as biomass gasification followed by Fischer–Tropsch (FT) processes. As a result, generally less than half of the original biomass energy is recovered as liquid fuel. In the first integrative step, we show the dramatic advantage of supplying energy needed for the conversion processes from a carbon-free energy source such as solar or nuclear. In the second integrative step, we show yet another synergistic integration between a fermentation-based process and a gasification–FT based H_2CAR route. We show the calculated results of such integrations in terms of both the increased liquid fuel yield as well as improved efficiency of the conversion from a given quantity of the biomass. The factors leading to synergistic results are also discussed.

* Corresponding author. Tel.: +1 765 494 2257; fax: +1 765 494 0805.
E-mail address: agrawalr@purdue.edu (R. Agrawal).

0098-1354/$ – see front matter
doi:10.1016/j.compchemeng.2009.06.026

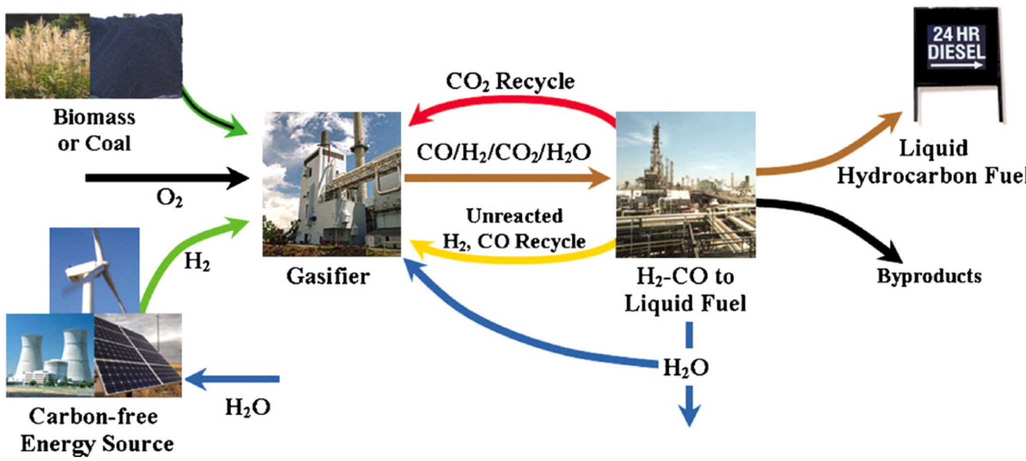

Fig. 1. The H_2CAR process (Agrawal et al., 2007).

2. Integration of a biomass-to-liquid fuel process with a carbon-free energy source (thermochemical process)

Recently, we proposed a novel partnership between biomass and hydrogen derived from carbon-free sources such as solar-thermal, solar PV, wind, and nuclear to produce liquid fuel for the transportation sector (Agrawal, Singh, Ribeiro, & Delgass, 2007). In the conventional processes, a part of the carbon in the biomass is lost as CO_2 and provides the necessary energy required for the conversion process. For example, ethanol production from sugars releases nearly 49% of the total mass as CO_2, and a biomass gasification–FT process has a carbon efficiency of <40% (Agrawal et al., 2007; Huber, Iborra, & Corma, 2006). The proposed partnership is shown in Fig. 1 and results in a significantly higher liquid yield by preserving all the biomass carbon in the final liquid fuel. This H_2–CARbon approach has been nicknamed the H_2CAR process. The H_2CAR approach assures nearly 100% carbon efficiency through recycling of the CO_2 produced during the conversion process to the gasifier operating at higher temperatures where this CO_2 is converted to CO via the reverse water-gas reaction by externally supplying the gasifier with hydrogen from a carbon-free source. This externally supplied hydrogen is also used to adjust the H_2 to CO ratio to about 2 for the FT process and to supply energy for the endothermic gasification reaction and other process losses.

The essential features of the H_2CAR process are: (i) Biomass is primarily a supplier of carbon atoms. (ii) H_2 is supplied from a carbon-free energy source such as solar, wind and/or nuclear. (iii) H_2 is used to convert every carbon atom to liquid fuel. (iv) No CO_2 is released during the biomass-to-liquid conversion process. (v) Solution to H_2 storage problem of the so-called 'H_2-economy'. This can lead to dawning of a "hybrid hydrogen–carbon economy" (Agrawal & Singh, 2008; Agrawal et al., 2007).

Process simulations using ASPEN have shown the thermodynamic feasibility of the process. For a biomass gasifier operating at 70% efficiency and a biomass growth rate of 1.5 kg/m^2/yr, nearly 0.92 million km^2 land area is needed to produce 13.8 Mbbl/d as against 2.5 million km^2 needed for the corresponding conventional biomass gasification–FT process. About 269 billion kg of H_2 per year from solar energy will be needed for this scenario but this represents a significantly lower land area requirement as compared to the land area needed for the biomass growth. The carbon efficiency of the H_2CAR process is expected to be nearly 100% as against 37% for the conventional process. Another interesting aspect is that the energy efficiency based on the energy content of the biomass and hydrogen fed to the conversion plant is expected to be higher for the H_2CAR vs. the conventional approaches (~57% vs. ~41%).

The reason for the dramatic increase in the liquid fuel production from a given quantity of biomass for the H_2CAR process can be

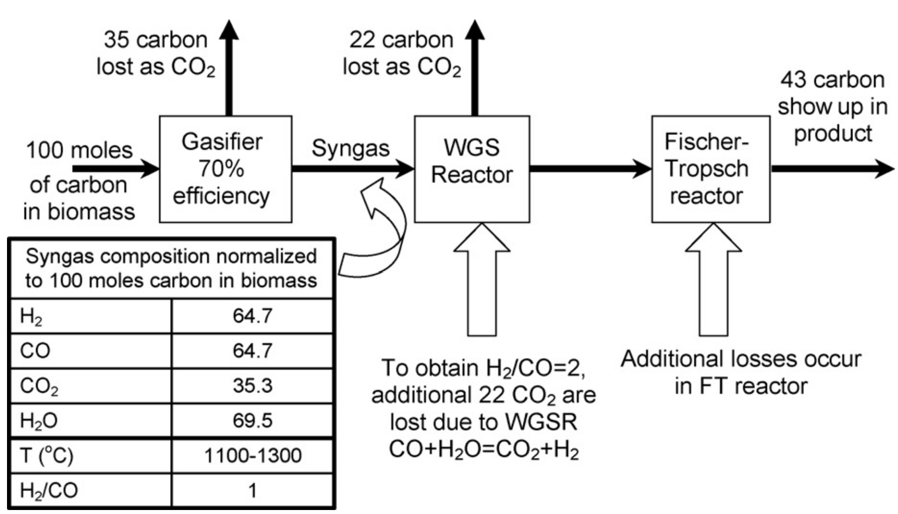

Fig. 2. The process of loss of carbon atoms as CO_2 during the conventional biomass gasification/FT process.