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Municipal solid waste to liquid transportation fuels – Part II: Process synthesis and global optimization strategies

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ABSTRACT

This paper investigates the production of liquid transportation fuels from municipal solid waste (MSW). A comprehensive process synthesis superstructure is utilized that incorporates a novel mathematical model for MSW gasification. The production of liquid products proceeds through a synthesis gas intermediate that can be converted into Fischer–Tropsch hydrocarbons or methanol. The methanol can be converted into either gasoline or olefins, and the olefins may subsequently be converted into gasoline and distillate. Simultaneous heat, power, and water integration is included within the process synthesis framework to minimize utilities costs. A rigorous deterministic global optimization branch-and-bound strategy is utilized to minimize the overall cost of the waste-to-liquids (WTL) refinery and determine the optimal process topology. Several case studies are presented to illustrate the process synthesis framework and the nonconvex mixed-integer nonlinear optimization model presented in this paper. This is the first study that explores the possibility of liquid fuels production from municipal solid waste utilizing a process synthesis approach within a global optimization framework. The results suggest that the production of liquid fuels from MSW is competitive with petroleum-based processes. The effect that the delivered cost of municipal solid waste has on the overall cost of liquids production is also investigated parametrically.

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1. Introduction

Recent interest from academia, industry, and government agencies to develop processes that can produce liquid fuels from domestically available carbon sources has emerged largely due to the challenges facing the U.S. transportation sector. These challenges include uncertainty over the future price of crude oil, substantial greenhouse gas emissions from the production of liquid fuels, and political unrest in the Middle East, the largest exporter of crude oil in the world (EIA, 2012). The U.S. consumes an estimated 18.714 million barrels of petroleum-based products per day (MMBD) in 2014 (Energy Information Administration, 2014). The majority of this consumption is attributable to the U.S. transportation section, which consumes 8.282 MMBD of gasoline, 2.695 MMBD of diesel, and 1.372 MMBD of jet fuel (Energy Information Administration, 2014). Three feedstocks that have been touted as alternatives to petroleum and have received the majority of attention include coal, biomass, and natural gas. The key contributions in the production of liquid fuels from single and hybrid combinations of these feedstocks has been highlighted in our recent reviews (Floudas et al., 2012; Elia and Floudas, 2014). This paper addresses the aforementioned challenges by introducing a novel mathematical model for gasification in a thermochemical-based process superstructure utilizing a fourth type of feedstock: municipal solid waste (MSW) (Onel et al., 2014).

The amount of municipal solid waste generated in the United States has increased from 208.3 million tons in 1990 to over 250 million tons in 2011 (EPA, 2011). Paper and paperboard, plastics, food waste, yard trimmings, and metals are the main constituents of MSW (EPA, 2011). In 2011, 53.6% of MSW was discarded in landfills, 34.7% was recycled, and 11.7% was combusted to recover energy (EPA, 2011). In 2010, there were 86 active waste-to-energy plants that processed nearly 100,000 tons of MSW daily (Michaels, 2010). The most prominent reason why municipal solid waste is an attractive precursor to liquid transportation fuels can be attributed to its negative cost. Facilities normally receive a tipping fee, which varies between \$24 and \$70/ton in the U.S., to dispose of MSW (Valkenburg et al., 2009; Jones et al., 2009).

The presence of incombustibles, glass, and metals in MSW poses a serious challenge against the utilization of this feedstock. Typically, a physical separation system is included in order to remove these materials from municipal solid waste (Diaz et al., 1982; European Commission, 2003; Krieth, 1994; White et al., 2001). The physical separation increases the heating value of the feedstock

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while simultaneously homogenizing the feed (Jones et al., 2009). The lower heating value of MSW is around 11.7 MMBtu/ton (EIA, 2007), while the heating value of the processed, homogenized feed is around 16.8 MMBtu/ton (Jones et al., 2009).

Utilizing MSW as a feedstock for the production of energy has been shown to mitigate the disposal problems associated with this feedstock and reduces the need for fossil fuel use (Ruth, 1998). The European Union legislation seeks to reduce landfilled municipal solid waste to 35% by 2020 (Stehlík, 2009). Additionally, it has been shown that combusting 1 metric ton of MSW negates the need of mining 0.25 tons of high quality U.S. coal or importing 1 barrel of oil (Psomopoulos et al., 2009). By utilizing municipal solid waste towards the production of energy, the methane emissions from landfills can be limited, the CO_2 emissions from fossil fuel combustion can be avoided, and the CO_2 emissions from metals production can be eliminated (Michaels, 2010). Previous work by Warren and El-Halwagi assessed the technical and economic feasibility of two process configurations for a plant producing liquid fuels from coal and municipal solid waste (Warren and El-Halwagi, 1996). Additional work investigated the MSW management system that took into account the technical and environmental issues associated with this feedstock (Santibañez-Aguilar et al., 2013). However, this is the first study that presents a complete superstructure for the production of liquid transportation fuels from municipal solid waste using our recently proposed novel mathematical gasification model (Onel et al., 2014).

The use of a large-scale nonconvex mixed-integer nonlinear optimization (MINLP) model that can efficiently determine the optimal process topology for liquid fuels production from many topological alternatives is described in this study. A rigorous global optimization branch-and-bound strategy is employed to mathematically guarantee that the value of the objective function (i.e., cost of liquid fuels production) is within a few percent of the best possible value (Baliban et al., 2012a). The production of liquid transportation fuels proceeds through a synthesis gas (syngas) intermediate that can be directed to either the Fischer–Tropsch refining or methanol conversion sections. The process synthesis superstructure utilizing coal, biomass, and/or natural gas as feedstocks has been described in previous works (Baliban et al., 2010, 2011, 2012a,b,c, 2013a,b,c,d,e; Elia et al., 2010; Niziolek et al., 2014); however, the following section will describe the key process units in the waste-to-liquids (WTL) refinery. An optimization-based heat-integration approach (Duran and Grossmann, 1986) is utilized to include simultaneous heat and power integration that can convert waste heat into electricity in the WTL refinery (Elia et al., 2010; Baliban et al., 2011). A wastewater-treatment section minimizes the amount of freshwater intake into the plant (Elia et al., 2010; Baliban et al., 2011; Karuppiah and Grossmann, 2006; Grossmann and Martín, 2010; Ahmetovic and Grossmann, 2010a,b). Finally, the life-cycle CO_2 emissions of the WTL plant are calculated and compared with petroleum-based processes.

The process synthesis framework for the WTL refinery includes (i) municipal solid waste gasification with/without recycle gas, (ii) syngas conversion via Fischer–Tropsch (FT) refining or methanol synthesis, (iii) methanol conversion via methanol-to-gasoline (MTG) or methanol-to-olefins (MTO), (iv) hydrocarbon upgrading via ZSM-5 zeolite catalysis, olefin oligomerization, or carbon number fractionation and subsequent treatment. The major liquid fuels products from the refinery include gasoline, diesel, and jet fuel, whereas liquefied petroleum gas (LPG) and electricity may be sold as byproducts.

2. WTL process superstructure: conceptual design and mathematical modeling

Previous studies by Baliban et al., Elia et al., and Niziolek et al., have detailed the conceptual design of refineries utilizing coal, biomass, and natural gas (Baliban et al., 2010, 2011, 2012a,b,c, 2013a,b,c,d,e; Elia et al., 2010; Niziolek et al., 2014). This section will outline the major components in the WTL refinery.

2.1. Municipal solid waste handling and gasification

2.1.1. Refuse derived fuel facility

Utilizing municipal solid waste as a potential feedstock for the production of liquid fuels has several challenges. In addition to the variabilities in the composition of the feedstock from location to location, there are undesired components (glass, metals, etc.) that can contaminate the gasifiers and downstream hydrocarbon production and upgrading reactors. Also, the moisture content is non-uniform among different types of municipal solid waste. To avoid these challenges, it is necessary to produce refuse derived fuel (RDF) from MSW before sending it to the gasifier. In the RDF facility, the MSW is converted into a higher-calorific fuel by removing the non-combustibles and recyclables. The RDF fuel leaving the RDF facility has a more consistent quality, composition, and moisture to avoid fluctuations caused by the variability in the inlet composition.

The municipal solid waste is delivered to the refinery gate and treated at the refuse derived fuel (RDF) facility, shown in Fig. 1. After the municipal solid waste is loaded onto a series of cranes and conveyors, the first step in the RDF facility is the reduction in size of the feedstock to liberate the composite material and meet the required dimensions for further processing (Christensen, 2011). The processed municipal solid waste is then sent to a magnetic separator and eddy current separator that remove the ferrous and nonferrous metals, respectively. Disc screens are then used

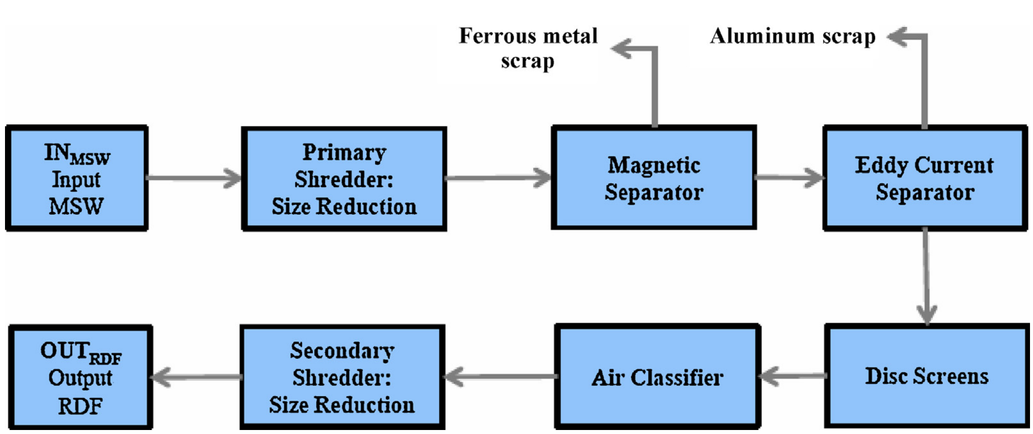

Fig. 1. Refuse derived fuel facility flow diagram. The municipal solid waste is converted into a higher-calorific fuel through removal of the non-combustibles and recyclables.

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