Energy Conversion and Management 124 (2016) 92–103

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Assessment on steam gasification of municipal solid waste against biomass substrates

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ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 29 June 2016
Accepted 30 June 2016
Available online 9 July 2016

Keywords:
Steam gasification
Municipal solid waste
Biomass
CFD
Semi-industrial gasifier

ABSTRACT

Waste management is becoming one of the main concerns of our time. Not only does it takes up one of the largest portions of municipal budgets but it also entails extensive land use and pollution to the environment using current treatment methods. Steam gasification of Portuguese municipal solid wastes was studied using a previously developed computational fluid dynamics (CFD) model, and experimental and numerical results were found to be in agreement. To assess the potential of Portuguese wastes, these results were compared to those obtained from previously investigated Portuguese biomass substrates and steam-to-biomass ratio was used to characterize and understand the effects of steam in the gasification process. The properties of syngas produced from municipal solid waste and from biomass substrates were compared and results demonstrated that wastes present the lowest carbon conversion, gas yield and cold gas efficiency with the highest tar content. Nevertheless, the pre-existing collection and transportation infrastructure that is currently available for municipal waste does not exist for the compared biomass resources which makes it an interesting process. In addition a detailed economic study was carried out to estimate the environmental and economic benefits of installing the described system. The hydrogen production cost was also estimated and compared with alternative methods.

1. Introduction

The world is going through an intense process of urbanization and municipal solid waste (MSW), one of the most important by-products of an urban lifestyle, is growing at higher rate. According to the latest reports [1], in just 10 years the production of MSW increased from 680 to 1300 million tons per year, which represents an average increase of 0.64–1.2 kg of MSW per person per day. Current projections estimate an increase to 1.42 kg of MSW per person per day by 2025, which would translate into an annual generation of 2.2 thousand million tons.

The treatment of these residues is quite expensive and often represents the single largest budgetary item of a city. Worldwide MSW management costs from 2012 exceeded 190 thousand millio n euros and are expected to reach 350 thousand million by 2025 [1]. Of all methods of waste disposal, landfill is still the most used today, although it is becoming less and less popular due to the lack of available land and due to the emission of CH_4 and other landfill gases, which can cause numerous contamination problems. Incineration has gained ground over landfills [2] since it can reduce the solids volume in waste, decreasing the space it takes up and reducing the stress on already overflowing landfills. However, waste incineration is expensive and poses challenges of air pollution and ash disposal.

Gasification is becoming an increasingly attractive technology to treat MSW with fewer emissions than other methods of treatment [3]. It has been mostly used in waste-to-energy (WTE) plants, and one of its most promising results was achieved for the production of H_2-rich gas [4].

Research has shown that steam gasification of MSW provides one of the most cost-competitive means of obtaining H_2-rich gas while meeting environmental requirements set by international committees [5]. He et al. [6,7] are responsible for a considerable body of work on this matter, studying from the influence of various operating conditions to the use of catalysts developed for the production of H_2-rich gas. Later, that same group also developed a modified dolomite catalyst able to significantly eliminate tar produced in the gasification process while increasing H_2 production [8]. Moreover, steam gasification can help minimize tar formation

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http://dx.doi.org/10.1016/j.enconman.2016.06.077
0196-8904/

[9], which is a major concern regarding MSW gasification that needs to be addressed so as to render it the main waste management and treatment process.

So far presented studies were mainly conducted in laboratory-scale facilities but it is imperative to devote efforts to study the process in semi-industrial or industrial conditions in order to convey this technology to commercial stage. In fact, data collected from laboratory studies can rarely be used to design commercial reactors, which can be tens or even hundreds of times larger, since it is necessary to gather information from reactors with similar dimensions to avoid errors and reduce high level risks and uncertainty [10].

Numerical models can be used to facilitate this process without major investments and/or the need for long waiting periods as they provide the ability to simulate any physical condition relatively quickly and inexpensively. However, due to their extreme complexity, realistic models on MSW gasification are still very scarce.

Our research team was able to use our previously published numerical model for biomass air gasification by upgrading it to handle the heterogeneity of MSW [11]. After validating the new model for semi-industrial conditions, an assessment of the potential of syngas produced from Portuguese MSW (PMSW for abbreviation) [12] was carried out.

The aim of this study is to investigate the potential of steam gasification in the treatment of PMSW. A new validation was performed to demonstrate the potential of the previously developed numerical model and semi-industrial conditions were used. To gain better understanding of the potential of the studied residues, a comparison to characteristic Portuguese biomasses was performed and steam-to-biomass ratio (SBR) was used to characterize and understand the effects of steam in the gasification of different substrates. Finally, the reduction of landfills as well as annual savings in imported fuels by using the described process was investigated. The overall hydrogen production cost was predicted and subsequently compared to alternative conversion methods.

2. Materials and methods

2.1. Portuguese municipal solid waste characterization

Until 1996 the management of municipal solid waste in Portugal was carried out by governmental institutions and, due to lack of appropriate legislation, the deposition in open dumps was the dominant method of treatment. Since then the management of MSW has undergone substantial change due to the approval of the National Waste Management Plans (PERSU). Despite the plan's success in eradicating open dumps, most of the targets set were not achieved [13]. Therefore, taking into account the need to modernize the MSW system, PERSU II was ratified in 2006 to target the period of 2007–2016.

In the decade from 2001 to 2010, landfilling remained the dominant option (60% and over) but with a decreasing trend, mainly due to recycling, which steadily increased to 12% in 2010. In 2012, 4.53 million tons of waste were produced in Portugal, 12.5% less than the recorded amount of 5.18 million tons in 2010 and also below the 4.88 million documented in 2011, according to data from the Environment Ministry. These figures show a reversal in the increasing production of municipal waste trend that occurred during the period between 2002 and 2010 (up to 18%) [14], which can be explained by the deterioration of the macroeconomic situation of the country, which reduced the level of consumption and, consequently, the production of waste.

The characterization and analysis of PMSW was carried out using data from the Oporto metropolitan area. LIPOR (Intermunicipal Waste Management Service of Greater Porto) is an association of Municipalities, established in 1982, whose main objective is the management, treatment and recovery of solid waste municipal produced in eight municipalities in the Oporto metropolitan area. Wastes are pre-treated accordingly to the Portuguese management system described by Teixeira et al. [2].

Early reports from 2015 indicate a production of about 361,000 tons of MSW from January to September at an average of 1.363 kg/hab.day [15]. Analyzing previous years and assuming similar tendencies, it is expected a total production of 480,000 tons at an average of 1.357 kg/hab.day by the end of the year. During the management and treatment of MSW collected in 2014, samples were collected to characterize the waste and results are presented in Fig. 1.

Refuse Derived Fuel (RDF) containing cellulosic materials and plastics is obtained from the pre-treatment of MSW via shredding and dehydration. During the pre-treatment process components such as metals, glass, combustive and non-combustive non specified materials as well as hazardous residues and fine elements are removed. After removing said components, cellulosic materials are represented by all the remaining constituents (obviously excluding plastics). Plastic residues are mainly comprised by polyethylene, polystyrene, and polyvinyl chloride [16] while cellulosic materials are composed of cellulose, hemicelluloses, and lignin [17].

Since an ultimate analysis does not distinguish between cellulosic materials, their composition was presupposed to be similar to the one found by Onel et al. [18], whereas report informs of the relative quantities of each monomer in the MSW for plastics, as listed in Table 1. This waste characterization was employed in the formulation of the MSW mixture in Fluent to model the gasification process.

2.2. Biomass substrates characteristics

Biomass utilization represents a crucial component in Portugal's strategic plan in reducing its foreign energy dependence. Portuguese biomass resources are diverse but an important contribution can be found from agricultural-related residues. Coffee husks, forest and vineyard pruning residues are largely available and have attractive low costs.

Portuguese forest covers 3.2 million ha, which corresponds to 35.4% of the national territory and is the basis of an economic sector that generates about 113,000 direct jobs (2% of the workforce).

The wine sector is one of the most important in the Portuguese economy, contributing very significantly to the final value of agricultural production and exportation, with a remarkably high contribution to the balance of trade; it is one of the few agri-food sectors with a positive trade balance. There is a great interest by Portuguese entities to study the best ways to valorize the residues and sub-products generated by this industry.

When processed, coffee generates a significant amount of agricultural wastes. Coffee husks, comprised of dry outer skin, pulp and parchment, are probably the major residues from the handling and processing of coffee. One of the major problems facing industries nowadays is how to dispose of these residues (there are more than two millions tons yearly [19]), since they contain some amount of caffeine, polyphenols and tannins, which makes them toxic in nature.

The total primary energy demand in Portugal amounted to 243,311 GW h in 2014 [20]. According to Ferreira et al. [21], forest and pruning residues alone can potentially produce 13,768 GW h per year (about 5.7% of the total primary energy demand in the country). Additionally, the energy production from bioresources (biomass, solid urban waste, and biogas) was 29,400 GW h in 2014. Previous data showed that both forest and pruning residues can play an important role in the Portuguese energy scenario.