Bioresource Technology 179 (2015) 524–533

Contents lists available at ScienceDirect

Bioresource Technology

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

Multi-gene genetic programming based predictive models for municipal solid waste gasification in a fluidized bed gasifier

Daya Shankar Pandey [a], Indranil Pan [b], Saptarshi Das [c], James J. Leahy [a], Witold Kwapinski [a,*]

[a] Carbolea Research Group, Department of Chemical and Environmental Science, University of Limerick, Ireland
[b] Energy, Environment, Modelling and Minerals (E^2M^2) Research Section, Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, United Kingdom
[c] School of Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, United Kingdom

HIGHLIGHTS

- Genetic programming is used to predict the performance of fluidized bed gasifier.
- The performance of the MGGP models is compared with the single-gene GP model.
- Comparisons of complexity and accuracy of GP prediction have been reported.
- The MGGP approach gives better results on both training and validation data.
- The data-driven GP modelling is useful for prediction with analytical expressions.

ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 10 December 2014
Accepted 12 December 2014
Available online 19 December 2014

Keywords:
Municipal solid waste
Genetic programming
Gasification
Fluidized bed gasifier

ABSTRACT

A multi-gene genetic programming technique is proposed as a new method to predict syngas yield production and the lower heating value for municipal solid waste gasification in a fluidized bed gasifier. The study shows that the predicted outputs of the municipal solid waste gasification process are in good agreement with the experimental dataset and also generalise well to validation (untrained) data. Published experimental datasets are used for model training and validation purposes. The results show the effectiveness of the genetic programming technique for solving complex nonlinear regression problems. The multi-gene genetic programming are also compared with a single-gene genetic programming model to show the relative merits and demerits of the technique. This study demonstrates that the genetic programming based data-driven modelling strategy can be a good candidate for developing models for other types of fuels as well.

1. Introduction

The disposal of municipal solid waste is an ever-increasing problem in the European Union (EU) and other developing countries (Guerrero et al., 2013; Pires et al., 2011). Due to strict environmental standards, current solid waste management practices (landfills, inceneration) are under intense examination and innovative technologies are becoming attractive alternative options (Pires et al., 2011). There are several alternatives to dispose municipal solid waste including thermal, biochemical and mechanical processes. Incineration has been extensively used in EU and other developed countries including Japan and Singapore for disposal and energy recovery from the wastes (Narayana, 2009). However, the flue gases from the waste incinerators contains high amount of particulate matter, NO_x, SO_x, dioxins and furans (Cheng and Hu, 2010). Apart from the high amount of emissions, incineration systems have high operating cost with relatively lower energy efficiency (Arena, 2012). One attractive thermal alternative to incineration is the municipal solid waste gasification. The gasification process can generate the electricity from the waste with an efficiency of 34% compared to incineration process, which has thermal efficiency around 20% (Murphy and McKeogh, 2004). It has been suggested that gasification is a viable technology for processing solid wastes, including municipal solid waste, while complying with present emission standards (Arena, 2012). This also offers an alternative solution to the landfilling option. Compared to other treatment processes, gasification technology is an attractive solution for the treatment of municipal solid waste while simultaneously minimising pollution (Malkow, 2004;

* Corresponding author. Tel.: +353 61234935; fax: +353 61202568.
E-mail address: witold.kwapinski@ul.ie (W. Kwapinski).

http://dx.doi.org/10.1016/j.biortech.2014.12.048
0960-8524/

Xiao et al., 2007). The derived syngas from municipal solid waste gasification can be used to generate heat and electricity, which will help to offset the use of fossil fuels.

Gasification is the thermal conversion process of any carbonaceous fuel to a gaseous product with useable heating value. It is commonly performed with only a third of the oxygen necessary for complete combustion. Gasification includes pyrolysis, partial oxidation and hydrogenation whereas the dominant process is partial oxidation (Higman and Van der Burgt, 2011), resulting in gaseous products (hydrogen, carbon monoxide, carbon dioxide, water and other gaseous hydrocarbons), and a small amount of char, ash and condensable compounds (tars). Air, steam or oxygen can be used as a gasifying agent. For solid fuel combustion, gasification reactors can be categorised into three distinctive types: fixed bed (updraft and downdraft), fluidized bed and entrained flow gasifiers (Higman and Van der Burgt, 2011).

Biomass gasification is a complex thermochemical process (Puig-Arnavat et al., 2010). In the recent past, numerous researchers have tried to simulate a realistic gasification process and optimised the process analysis to make it more cost effective. Most of the fluidized bed (FB) biomass gasifier models fit reasonably well with the experiments selected for validation using various empirical correlations. However, there are very few measurements available for detailed validation specifically for large scale gasifiers (Gómez-Barea and Leckner, 2010). Since conducting large scale gasification experiments are quite expensive and time consuming, modelling can be a viable alternative which saves both time and money. However, simulation of municipal solid waste processes are computationally expensive and fast meta-models are required to integrate these models into other systems level models which look at the whole value chain to conduct life cycle analysis, or other system level optimisation procedures. In general, mathematical models are exploited to investigate the influence of the main process parameters on calorific value and yield of the product gas. Irrespective of the type of reactors, several modelling techniques such as thermodynamic equilibrium models, kinetic rate models, Aspen Plus based models and artificial neural networks have been implemented for gasification systems (Puig-Arnavat et al., 2010). The artificial intelligence techniques such as artificial neural networks, genetic programming etc. demands less system information compared to equilibrium and kinetic based modelling, hence, these techniques can be useful for modelling FB gasifiers. In view of the complexity involved with the gasification process, a novel artificial intelligence paradigm known as genetic programming has been used to model the gasification system in the present study. The main objective of the present study is to show the application of the genetic programming approach in predicting syngas yield and heating value. To the best of the author's knowledge this is the first study using the multi-gene genetic programming technique to predict the lower heating value and yield of syngas produced from municipal solid waste.

In the recent past, artificial neural networks techniques have been extensively used by several researchers in the fields of pattern recognition, signal processing, function approximation, weather prediction and process simulations (Guo et al., 1997). Lately it has also received attention as a tool in renewable energy system prediction and modelling (Kalogirou, 2001). A back propagation neural network using the Levenberg–Marquardt (LM) algorithm has been applied to a hybrid upflow anaerobic sludge blanket reactor to predict the bio-degradation and bio-hydrogen production using distillery wastewater (Sridevi et al., 2014). A hybrid neural network model was developed for predicting the product yield and gas composition in an atmospheric steam blown fluidized bed gasifier. The authors tested four different kinds of biomass on a bench scale gasifier for training the hybrid neural network model. This study revealed that the feed forward neural network prediction was better than the traditional regression models (Guo et al., 2001). A feed forward neural network model was used to predict the lower heating value of municipal solid waste from its chemical composition. It was concluded that the neural network model has better precision over the traditional model (Dong et al., 2003). A combined non-stoichiometric equilibrium approach with an artificial neural networks regression model was developed to predict product composition in an atmospheric air gasification fluidized bed reactor (Brown et al., 2006). A complete set of stoichiometric equations were formulated to explain the non-equilibrium behaviour for gas, tar, and char formation by reaction temperature difference. The artificial neural networks regression related temperature differences to fuel composition and operational variables. This first principle approach, illustrated with FB data, improves the accuracy of the equilibrium based model and reduces the data requirement by preventing neural network to learn from atomic and heat balances (Brown et al., 2006). The combination of equilibrium and artificial neural networks models were further investigated and improved by the same authors (Brown et al., 2007). An attempt was made to develop an artificial neural networks model for predict to gasification characteristics of the municipal solid waste (Xiao et al., 2009). Two different artificial neural networks based models were introduced to predict gas production rate and heating value of the product gas in a steady state fluidized bed coal gasifier (Chavan et al., 2012). Recently, two artificial neural networks models were presented (Puig-Arnavat et al., 2013); one for a circulating fluidized bed gasifier and another for a bubbling fluidized bed gasifier for estimating the product gas composition (CO, CO_2, H_2 and CH_4) and gas yield. The results show good agreement with the experimental data.

Despite prediction capability of artificial intelligence based techniques, only artificial neural networks have been used in the modelling of FB gasifiers. Very few applications of genetic programming have been reported in recent literature focused on predicting syngas production and the lower heating value of syngas. An extensive literature review shows that so far only a few studies have been reported where the GP strategy has been employed for the modelling of fluidized bed gasifier. To the best of the author's knowledge this is the first study using the multi-gene genetic programming technique to predict the lower heating value and yield of syngas produced from municipal solid waste.

Recently, the multilayer perceptron neural network model and genetic programming have been used to predict $CO + H_2$ generation rate, syngas production rate, carbon conversion and heating value of the syngas in a pilot-plant scale FB coal gasifier (Patil-Shinde et al., 2014). The output prediction accuracies of the models were indicated by correlation coefficients. The correlation coefficients were lying between 0.92 and 0.996. The authors have claimed that the prediction accuracy of genetic programming model has an advantage over the multilayer perceptron neural network.

The remaining part of the paper is organised as follows. Section 2 gives an overview of the genetic programming based modelling. Section 3 illustrates the simulation results and a comparison with the single gene genetic programming variant. The paper ends in Section 4 with the conclusions followed by the references.

2. Method of genetic programming modelling

Genetic programming is an evolutionary approach which automatically evolves computer programs to solve the problem without specifying the structure of the solution in advance (Koza, 1992; Poli et al., 2008). Genetic programming is a branch of evolutionary algorithms and can be used for development of nonlinear